Impact of network rewiring on opinion and belief echo chambers

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Abstract. The creation of echo chambers is a well-known phenomenon in social networks. It has been reproduced in experiments with opinion dynamics models based on the dynamic rewiring of the network that agents form. We showed that exchanging beliefs socially as well as opinions and keeping the internal coherence between opinions and beliefs lead agents to create more echo chambers than propagating opinions only. Here, we study the effect of different rewiring strategies on these results. To achieve this, we introduce several strategies: no rewiring, random rewiring, maximal-oriented rewiring, and minimal-oriented rewiring, the latter aiming at improving concordance of neighbors. Simulation results show that the rewiring strategy affects the number and size of created echo chambers. The maximal strategy and, to a lesser extent, the random strategy generate more and smaller echo chambers than the minimal and no strategies which are not distinguishable. Through echo chambers, the rewiring strategies balance cohesion and diversity. Results also show that rewiring is not strictly necessary to the creation of echo chambers, but paradoxically, they occur when agents are very tolerant.

Keywords: Echo chambers · Opinion dynamics · Belief revision · Network rewiring.

1 Introduction

A well-known phenomenon of social networks is echo chambers in which a group of persons only interacts with people who have opinions close to theirs, thus reinforcing their opinions [10,6]. Echo chambers formation has been studied in opinion dynamics [7,8] and more recently when both opinions and beliefs are propagated [3,4]. The former has shown the creation of echo chambers and the latter further reported that synchronizing opinions and beliefs as well as propagating them socially allows agents to create more echo chambers [4].

One key point in these results is the opportunity for agents to dynamically 'rewire' the social network by unfollowing agents with discordant opinions and following other agents with more concordant opinions [2]. If only opinions propagate, it is reported that rewiring accelerates the formation of echo chambers [8].

However, the effect of different rewiring strategies has not been considered. We study the influence of different strategies on the formation of echo chambers under the joint propagation of opinions and beliefs [4]. We aim at answering the following questions: Is rewiring necessary? Can different rewiring strategies be applied? Do they have an impact on the resulting echo chamber creation?

For that purpose, we introduce three unary rewiring strategies: rewiring may be random, it may tries to increase the likeness of followers or instead to be minimal. We compare them with non rewiring agents, while reproducing the experiments of [4]. We observe that no and minimal rewiring lead to at most one echo chamber on average, though random and maximal rewiring generate increasingly more echo chambers. Moreover, the maximal and random rewiring strategies allow for different unique opinions and beliefs to be adopted in these echo chambers bringing more diversity.

The rest of this paper is organized as follows. Section 2 provides a static presentation of social networks and the definition of echo chambers. Section 3 describes how these evolve according to the model in [4]. After that, different rewiring strategies are defined in Section 4. Then, the experimental settings and hypotheses are described in Section 5. Results from the multi-agent simulations are then presented (Section 6) and discussed (Section 7) before concluding this paper (Section 8).

2 Echo chambers in social networks

We summarize the model and echo chamber definition proposed in [4].

2.1 Opinions and beliefs in social networks

Let A be a set of agents. Each agent $a \in A$ has a set of neighbors $N_a^t \subseteq A \setminus \{a\}$ at time t. Then, the network G^t formed by the agents is defined as $G^t = \langle A, N^t \rangle$ such that $N^t = \bigcup_{a \in A} \{\langle a, a' \rangle; a' \in N_a^t\}$.

Each agent $a \in A$ also has a cognitive state $\langle O_a^t, B_a^t \rangle$ composed of its opinions O_a^t and beliefs B_a^t (t is omitted if it is clear from the context).

Agent a's beliefs are represented as a subset of the propositional language $\mathcal{L}_P$ constructed from the set P of atoms, i.e., $B_a^t \subseteq \mathcal{L}_P$. The set of models of beliefs $B \subseteq \mathcal{L}_P$ is denoted as $\mathcal{M}(B)$. The distance between the two beliefs B and B' is measured by the Hamming distance between their models:

$$d_B(B, B') = |\mathcal{M}(B) \setminus \mathcal{M}(B')| + |\mathcal{M}(B') \setminus \mathcal{M}(B)|.$$

In addition, a's opinions O_a^t are represented as numbers between 0 and 1, i.e., $O_a^t \in [0, 1]$. Here, opinions 0 and 1 correspond to the extremely negative and positive opinions toward ϕ, respectively. In this paper, we consider a single topic ϕ which is a formula, i.e., $\phi \in \mathcal{L}_P$. The distance between two opinions O and O' is measured by their absolute difference:

$$d_O(O, O') = |O - O'|.$$

Each agent can determine the set C_a^t of its concordant neighbors as the set of its neighbors with opinions and beliefs close enough with respect to the bounded confidences (ε and δ, respectively):

$$C_a^t = \{a' \in N_a^t; d_O(O_a^t, O_{a'}^t) \leq \varepsilon \wedge d_B(B_a^t, B_{a'}^t) \leq \delta\},$$

such that $\varepsilon \in [0,1]$ and $\delta \in \{1, 2, \ldots, 2^{|P|}\}$ (the maximum number of interpretations).

2.2 Assessing echo chambers

Echo chambers are defined as groups of agents satisfying the properties of homogeneity, segregation and reinforcement [6]. It partitions the network into groups and count those which are echo chambers through the three measures. Hereafter, *component* denotes sets of agents and $\mathcal{S}^t$ is the set of components at time t.

The *segregation* of a component C is measured by the ratio of its edges whose sources are in the component and whose targets are not in it to those whose sources are in it:

$$L^t(C) = \frac{|\{\langle a, a'\rangle \in N^t; a \in C \wedge a' \notin C\}|}{|\{\langle a, a'\rangle \in N^t; a \in C\}|}.$$

Hence, the lower this measure, the more segregated the network.

How *homogeneous* agents in a component $C \in \mathcal{S}^t$ are is measured by the maximal distance between opinions (resp. beliefs) of agents which belong to the component:

$$M_O^t(C) = \max_{a,a' \in C} d_O(O_a^t, O_{a'}^t) \quad \text{and} \quad M_B^t(C) = \max_{a,a' \in C} d_B(B_a^t, B_{a'}^t).$$

The lower these measures, the more homogeneous the component.

The *reinforcement* of a component C assesses whether its homogeneity measure (maximal distance between agents' opinions or beliefs) decreases during its lifespan. Let $[t_C, t]$ be the maximal window during which a component $C \in \mathcal{S}^t$ exists, then, the measure is defined as:

$$D_O^t(C) \equiv \forall s \in [t_C, t[, M_O^s(C) \geq M_O^{s+1}(C)$$
$$D_B^t(C) \equiv \forall s \in [t_C, t[, M_B^s(C) \geq M_B^{s+1}(C)$$

Following [4], the proposed measure uses the partition into strongly connected components. Based on the above measures, the echo chambers at time t as those components that are segregated and whose opinions and beliefs are homogeneous and reinforcing:

$$\mathcal{E}_O^t = \{C \in \mathcal{S}^t; \overbrace{L^t(C) \leq \theta}^{\text{segregation}} \wedge \overbrace{M_O^t(C) \leq 10^{-4}}^{\text{homogeneity}} \wedge \overbrace{D_O^t(C)}^{\text{reinforcement}}\},$$
$$\mathcal{E}_B^t = \{C \in \mathcal{S}^t; L^t(C) \leq \theta \wedge M_B^t(C) = 0 \wedge D_B^t(C)\},$$

such that $\theta \in]0, 1[$. The measures are made independent from ε and δ, which vary in experiments, by choosing stricter thresholds (10^{-4} and 0) for homogeneity. In the following, we use $\theta = 0.5$. Here, $L^t(C) \leq 0.5$ indicates that at most half of the edges whose source are in C, have their targets out of C. This automatically disqualifies singletons (components C such that $|C| = 1$) as echo chambers.

3 Model dynamics

Opinions and beliefs evolve from the initial ones through updating processes. The network itself evolves through rewiring.

3.1 Processes to update opinions and beliefs

Four processes to update opinions and beliefs are provided (Figure 1): social processes to update opinions and beliefs based on those of their neighbors (OD and BR, respectively) and cognitive processes which ensure the coherence of one agent's opinions and beliefs (OF and BA). Each process is defined as a map from (cognitive) states to states, though it only affects only one of its components.

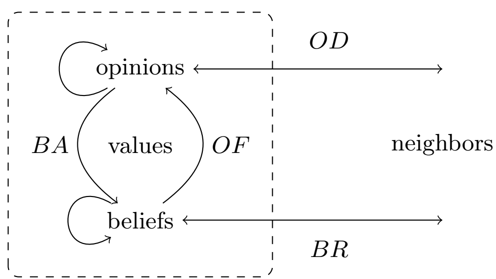

Fig. 1: The four processes (BR, OD, BA, and OF) for interactions between opinions and beliefs (from [5]).

The four processes used in this paper are those defined in [4]. In summary:

Opinion dynamics (OD) applies the operation of the bounded-confidence opinion dynamic model used in [8] to the opinions only.

Belief revision (BR) applies the R^3 belief merge operation of [9] with the Hamming distance between models and summation to the beliefs only.

Opinion formation (OF) scores, thanks to agents' values, the models of agents' beliefs revised by the formula ϕ. This evaluation is further balanced by an inertia factor $\alpha \in [0, 1]$ expressing the willingness of agents to change their opinions. It only changes opinions.

Belief alignment (BA) adopts the belief set for which OF would provide the closest opinion to the current one. It only alters beliefs.

3.2 Protocol

At time t, agents are activated with probability p_{activate}. Only active agents update their opinions and beliefs and try to rewire their network; other agents do nothing. The updating rule for active agent a is:

$$\langle O_a^{t+1}, B_a^{t+1} \rangle = OF(\ BR(\ BA(\ OD(\ \langle O_a^t, B_a^t \rangle\ )\ )\ )\ ).$$

All active agents perform each of the four operations synchronously.

Then, active agents can rewire the network with probability p_{rewire}. This means that they identify a set of non neighbors $F_a^t \subseteq A \setminus (N_a^t \cup \{a\})$ to add and a set of neighbors $U_a^t \subseteq N_a^t$ to remove, such that $|F_a^t| = |U_a^t|$. The rewiring is performed by

$$N_a^{t+1} = N_a^t \setminus U_a^t \cup F_a^t.$$

This corresponds to replacing edges between a and other agents preserving the number of outbound edges of each agent.

[4] confirmed [8] and [3] that the above protocol leads to the generation of echo chambers. Here, we question the impact of the rewiring strategy on the creation of echo chambers.

4 Rewiring Strategies

In this work, following [4], rewiring strategies replace at most a single edge. If several edges satisfy the criteria below, one is taken at random. Here are the different considered strategies.

4.1 No rewiring

Agents using the 'no rewiring' strategy never rewire the network. This is obtained by $F_a^t = U_a^t = \emptyset$. If all agents follow this strategy, G^t remains the same over time.

4.2 Random rewiring

In random rewiring, if $A \setminus (N_a^t \cup \{a\})$ and $N_a^t \setminus C_a^t$ are non empty, agent a chooses randomly one non concordant neighbor a' and one non-neighbor a'', so that $U_a^t = \{a'\}$ and $F_a^t = \{a''\}$. Otherwise, $F_a^t = U_a^t = \emptyset$. The latter happens, for instance, when all neighbors are concordant.

4.3 Maximal-oriented rewiring

Maximal-oriented rewiring will replace the neighbor with the lowest concordance by the non neighbor with the highest concordance, if the latter has higher concordance than the former. Lowest and highest requires defining an order ($\prec_a^t$) between agents from the standpoint of agent a at time t. Depending on whether priority is given to opinion distance or belief distance, two different orders (opbel and belop) are obtained: $a' \prec_a^t a''$ if

$$\begin{cases} d_O(O_a, O_{a'}) < d_O(O_a, O_{a''}), \text{ or} \\ d_O(O_a, O_{a'}) = d_O(O_a, O_{a''}) \wedge d_B(B_a, B_{a'}) < d_B(B_a, B_{a''}), \end{cases} \tag{opbel}$$

$$\begin{cases} d_B(B_a, B_{a'}) < d_B(B_a, B_{a''}), \text{ or} \\ d_B(B_a, B_{a'}) = d_B(B_a, B_{a''}) \wedge d_O(O_a, O_{a'}) < d_O(O_a, O_{a''}). \end{cases} \tag{belop}$$

The rewiring is defined by identifying (in case of ties, elements are drawn randomly)

$$U_a^t = \{a'\} \text{ such that } a' \in \operatorname*{argmax}_{\prec_a^t} N_a^t,$$
$$F_a^t = \{a''\} \text{ such that } a'' \in \operatorname*{argmin}_{\prec_a^t} A \setminus (N_a^t \cup \{a\}),$$

and rewiring only if $a'' \prec_a^t a'$ (otherwise, $F_a^t = U_a^t = \emptyset$).

4.4 Minimal-oriented rewiring

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$$U_a^t = \{a'\} \text{ such that } a' \in \operatorname*{argmin}_{\prec_a^t} N_a^t,$$
$$F_a^t = \{a''\} \text{ such that } a'' \in \operatorname*{argmax}_{\prec_a^t} A \setminus (N_a^t \cup \{a\}),$$

and rewiring only if $a'' \prec_a^t a'$ (otherwise, $F_a^t = U_a^t = \emptyset$).

5 Experimental Settings

To compare the effect of the different rewiring strategies defined in the previous section, we focus on the number and size of opinions/beliefs echo chambers.

5.1 Hypothesis

The hypothesis that we test, is that the more drastic the rewiring, the higher the number of echo chambers. This can be expressed by the following formula:

$$\text{no rewiring} \leq \text{minimal-oriented} \leq \text{random} \leq \text{maximal-oriented},$$

stating that maximal-oriented rewiring generates more echo chambers than random rewiring which generate more echo chambers than minimal-oriented rewiring which has more echo chambers than no rewiring.

This is expected because no rewiring should not allow to satisfy (at least) segregation, minimal-oriented can create some echo chambers but not so many (e.g., ends with the single large echo chambers), random should create several echo chambers like reported in [4], and maximal-oriented should create more as this always provides agents to connect others with close opinions and beliefs.

5.2 Parameters

Beside the rewiring strategies, we used the same parameters as in [4] (number of agents $|A| = 100$, number of iterations $T = 2000$), except that we are only considering the full workflow presented in §3.2. Hence, the parameters are:

– the set of atoms $P = \{p, q, r\}$
– $\varepsilon \in \{0.05, 0.1, \ldots, 0.5\}$
– $\delta \in \{1, 2, \ldots, 7\}$ as $2^{|P|} - 1 = 7$
– $p_{\text{rewire}} = p_{\text{activate}} = 0.5$
– $\alpha = \mu = 0.5$
– rewiring: no rewiring, random rewiring, maximal-oriented with (opbel), maximal-oriented with (belop), minimal-oriented with (opbel), maximal-oriented with (belop)
– 20 different seeds that are the same as what is used in [4].

5.3 Measures

In addition to the number of echo chambers ($eo^t = |\mathcal{E}^t_O|$ for opinions echo chambers and $eb^t = |\mathcal{E}^t_B|$ for beliefs echo chambers), we collect the following measures:

– The number of agents in echo chambers, i.e., $po^t = \sum_{C \in \mathcal{E}^t_O} |C|$ and $pb^t = \sum_{C \in \mathcal{E}^t_B} |C|$;
– The number of unique beliefs shared in echo chambers, i.e., $ub^t = |\{B; \exists C \in \mathcal{E}^t_B, \forall a \in C, B^t_a = B\}|$;
– The number of unique opinions shared in echo chambers (uo^t), e.g., $|\{O; \exists C \in \mathcal{E}^t_O, \forall a \in C, O^t_a = O\}|$. To avoid applying 'equal to' relationship (=) like beliefs to continuous numerical numbers, instead of directly counting the number of unique opinions, we process the Ward agglomerative hierarchical clustering method and count the number of clusters with the threshold 10^{-4}.
– The number of connected components of G^t.

6 Results

Table 1 displays the average number of opinion and belief echo chambers grouped by thresholds (ε and δ) and by rewiring strategies. The table shows, independently from the parameter values, the very few number of echo chambers for the no rewiring and minimal strategies (less than 1. and most of the time 0.), with respect to the higher average values for random and especially maximal (always more than or equal to 1.).

The table also shows, that rewiring is not strictly necessary for obtaining echo chambers. Even with no rewiring, very tolerant agents (higher ε and δ) propagate their beliefs and opinions so that they converge for a large number of these agents which thus satisfy the echo chamber properties.

In the following analysis, we use 0.01 as the significance threshold for statistical tests.

Table 1: Average number of opinion (o) and belief (b) echo chambers for each ε, δ, and rewiring strategy. Cell colors correspond to the number of echo chambers.

δ	rewiring	ε / ec	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
1	no rewiring	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	minimal	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	b	2.75	3.85	3.70	3.95	4.25	4.35	4.35	4.30	4.40	4.45
		o	2.75	3.85	3.70	3.95	4.25	4.35	4.35	4.30	4.40	4.45
	maximal	b	4.75	5.85	5.80	5.78	5.80	5.83	5.80	5.95	5.95	5.75
		o	8.95	10.15	10.07	10.05	10.10	10.18	10.18	10.30	10.30	10.28
2	no rewiring	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	minimal	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	b	7.50	7.15	4.30	5.25	3.75	3.90	3.40	3.50	3.15	3.60
		o	7.60	7.20	4.10	5.30	3.40	3.75	3.40	3.40	3.15	3.70
	maximal	b	7.97	8.60	8.05	7.17	6.97	6.55	6.50	6.60	6.45	6.53
		o	9.62	9.72	8.85	8.07	7.80	7.33	7.08	7.28	7.12	7.17
3	no rewiring	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	minimal	b	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		o	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	b	8.50	4.35	3.35	2.85	2.30	2.40	1.85	2.10	1.85	1.85
		o	8.50	4.40	3.40	2.90	2.30	2.40	1.90	2.15	1.95	2.05
	maximal	b	9.10	8.25	6.50	5.80	5.25	5.10	4.40	4.75	4.83	4.42
		o	9.65	8.10	6.60	5.78	5.35	5.10	4.33	4.70	4.72	4.30
4	no rewiring	b	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.25	0.35	0.35
		o	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.25	0.35	0.40
	minimal	b	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.25	0.35	0.38
		o	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.25	0.35	0.42
	random	b	8.45	3.80	2.80	2.30	1.85	1.70	1.45	1.10	1.10	1.05
		o	8.50	3.85	2.75	2.30	1.85	1.70	1.35	1.10	1.10	1.05
	maximal	b	9.12	7.30	5.97	5.58	4.47	3.90	3.65	3.55	3.33	3.20
		o	9.25	7.35	5.85	5.40	4.42	3.75	3.58	3.42	3.27	3.17
5	no rewiring	b	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.85	**1.00**
		o	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.85	**1.00**
	minimal	b	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.88	**0.97**
		o	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.88	**0.97**
	random	b	8.00	3.55	2.95	2.45	1.80	1.25	1.10	1.05	1.00	1.00
		o	8.00	3.60	2.95	2.45	1.75	1.25	1.10	1.05	1.00	1.00
	maximal	b	9.35	7.62	5.67	5.17	4.38	3.70	3.33	3.35	3.08	3.12
		o	9.25	7.42	5.42	5.05	4.33	3.60	3.25	3.23	2.98	3.10
6	no rewiring	b	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
		o	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	minimal	b	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
		o	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	random	b	7.70	3.25	2.55	2.50	1.65	1.20	1.05	1.00	1.00	1.00
		o	7.75	3.30	2.60	2.50	1.65	1.20	1.05	1.00	1.00	1.00
	maximal	b	9.28	7.45	5.53	4.92	4.08	3.52	3.33	3.50	3.10	2.83
		o	9.15	7.35	5.17	4.85	4.05	3.38	3.10	3.45	3.02	2.80
7	no rewiring	b	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
		o	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	minimal	b	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
		o	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	random	b	7.70	3.40	2.70	2.40	1.35	1.20	1.05	1.00	1.00	1.00
		o	7.75	3.40	2.75	2.40	1.40	1.20	1.05	1.00	1.00	1.00
	maximal	b	9.47	7.40	5.45	4.85	4.15	3.73	3.50	3.35	3.05	3.08
		o	9.30	7.28	5.28	4.70	4.08	3.58	3.45	3.23	2.95	2.90

Opinion echo chambers The results from the Welch's t-test show that the effect of changing the rewiring strategy is globally significant between the minimal-oriented and the random rewiring and the random and the maximal-oriented rewiring ($p \ll 0.01$); the differences of eo^T between experiments with no rewiring and with the minimal-oriented rewiring is not ($p > 0.01$). In addition, the effect of changing the order $\prec_a^t$ over A is also not significant ($p > 0.01$).

Belief echo chambers The effect of changing rewiring strategies is also globally significant ($p \ll 0.01$) except between no rewiring and the minimal-oriented rewirings ($p > 0.01$). In addition, the effect of changing the order $\prec_a^t$ is also significant between maximal-oriented rewiring only ($p \ll 0.01$); the differences between the minimal-oriented rewirings are not significant ($p < 0.01$).

Opinions and belief echo chambers do not necessarily coincide. For example, the components surrounded by the green dashed line in Figure 2c are not belief echo chambers but opinion echo chambers only.

7 Discussion

Hypothesis. Table 1 shows that regardless of the values of ε and δ, the hypothesis is supported from the standpoint of both opinion and belief echo chambers, except for when $\varepsilon = 0.5$ and $\delta = 5$ (boldface values in the table). According to the significance tests, these results support the hypothesis with respect to maximal rewiring creating more echo chambers than random rewiring which creates more echo chambers than minimal and no rewiring. The only non supported part is that minimal rewiring creates more echo chambers than no rewiring.

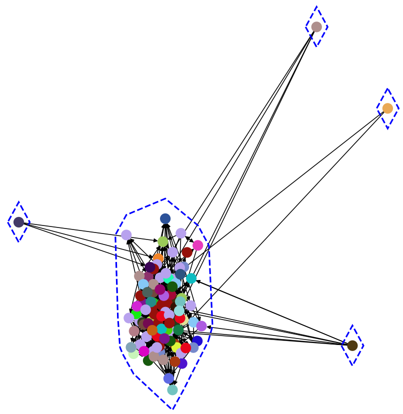
Disconnectedness. Although the initial situation starts with a connected graph, this is not the case in the end of the process. The maximal-oriented rewiring allows agents to form three times as many connected components as the random rewiring (4.4 and 1.3, respectively). For example, in Figure 2, there are 1, 8, and 8 connected components in Figure 2b, Figure 2c, and Figure 2d, respectively.

This shows a pictures in which parts of the society are not listening to the other any more. However, in our experimental setting agents may rewire to others even if the graph is disconnected.

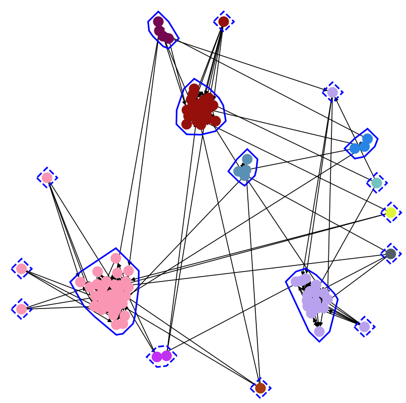
Agents per echo chambers. Maximal-oriented rewiring and, to a lesser extent, random rewiring create smaller echo chambers than random rewiring globally and on average (Table 2). This suggests that applying stricter rewiring creates more but smaller echo chambers.

Actually, what happens is that on the one hand no and minimal rewiring provide very large echo chambers when a large part of the agents converge to unique beliefs and opinions. This happens in one fifth of the cases, corresponding, according to Table 1, to the more tolerant agents (but not in the case of Figure 2a with $\varepsilon = 0.15$ and $\delta = 2$). On the other hand, maximal and, to a lesser extent, random rewiring generate more polarization of smaller groups.

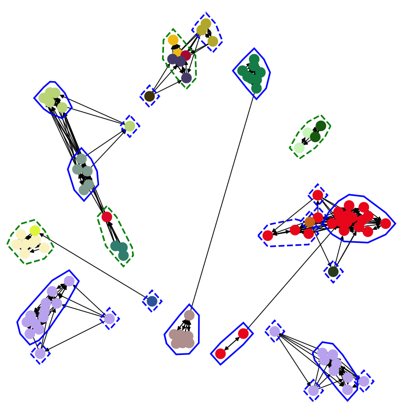
Unique beliefs and opinions and diversity. The number of unique beliefs is higher with maximal-oriented than with random which is higher than minimal-



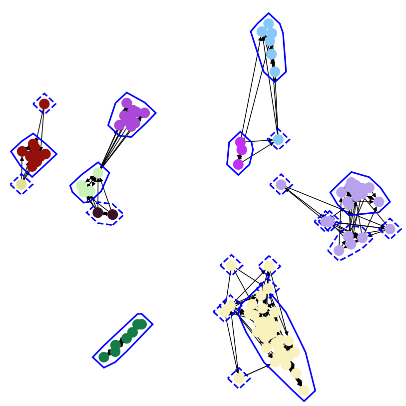
(a) Final network with no rewiring and minimal-oriented rewiring.



(b) Final network with random rewiring.



(c) Final network with maximal-oriented rewiring with (opbel).



(d) Final network with maximal-oriented rewiring with (belop).

Fig. 2: Final networks with $\varepsilon = 0.15$, $\delta = 2$, and the same seed, colored with respect to the final beliefs (same color corresponds to the same beliefs). The component surrounded by the blue solid and dashed line is a echo chamber and non-echo chamber component, respectively; the components surrounded by the green dashed line are not belief echo chambers but opinion echo chambers.

Table 2: Average number and size of echo chambers and average number of unique beliefs and opinions for each rewiring strategies.

measure	ec	no rewiring	minimal	random	maximal
number	b	0.19 ±0.34	0.19 ±0.34	3.04 ±2.01	**5.45** ±1.84
	o	0.19 ±0.34	0.19 ±0.34	3.04 ±2.01	**6.13** ±2.59
size	b	97.74 ±1.76	**97.77** ±1.69	26.50 ±31.07	12.85 ±13.82
	o	97.76 ±1.76	**97.78** ±1.69	26.90 ±31.23	12.27 ±13.15
unique	b	0.19 ±0.34	0.19 ±0.34	3.02 ±2.00	**4.92** ±1.88
	o	0.19 ±0.34	0.19 ±0.34	2.88 ±1.84	**4.73** ±2.06

oriented and no rewiring (Table 2). The same occurs for opinions. This may lead to think that stronger rewiring leads to more diversity.

Although we used the word diversity to describe the number of different opinions and beliefs in the population, this is a narrow view of diversity to just count the number of different opinions or beliefs. This should be further investigated through the use of a diversity measure taking into account the distance between these beliefs and opinions [1].

However, this already draws different pictures: with no rewiring or minimal rewiring, there are no echo chamber or the whole population has similar beliefs and opinions; with maximal-oriented rewiring the population is fragmented into many small echo chambers (nearly) each having distinct beliefs and opinions. In between, random rewiring seems to lead to a more balanced situation in which larger echo chambers are created bringing some diversity.

8 Conclusion

We studied the effects of different rewiring strategies in the propagation of beliefs and opinions on the creation of echo chambers.

The simulation results show that applying rewiring strategies that allow agents to connect to agents with opinions and beliefs close to theirs create more echo chambers. In addition, these strategies preserve different levels of diversity in the opinions and beliefs of the population.

Further investigation can be carried out to complete this picture. In particular, one could consider settings in which rewiring can be made with more than one edge at once (we expect the process to converge faster), echo chambers identification is made with stricter criterion (larger θ, we expect more disconnected networks), diversity is measured with a distance-aware measure, and different cognitive operators are used.

Acknowledgments. This work was partially supported by the Fukuro INRIA-University of Tsukuba associate team and the Echo action of the NTU-UGA-UT trilateral center. JE has been partially supported by the ACBE project (ANR-25-CE23-7134).

Disclosure of Interests. The authors declare no competing interests.

Ethical statement. The authors are not aware of any ethical issue with this work.

Data Availability. All experiments were performed with the *SOBA* software environment[3]. The experiment notebooks are openly available from `https://sake.re/20260210-BROD`. They contain reference to simulator and version, processing instructions, results and jupyter notebooks analyzing them.

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[3] `https://github.com/tsukuba-mas/soba`