Impact of network rewiring on opinion and belief echo chambers

Hiro Kataoka[1], Jérôme Euzenat[2], and Koji Hasebe[1]

[1] Department of Computer Science, University of Tsukuba, Tsukuba, Japan
kataoka@mas.cs.tsukuba.ac.jp, hasebe@cs.tsukuba.ac.jp
[2] Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, LIG, F-38000 Grenoble, France
Jerome.Euzenat@inria.fr

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, homophilic rewiring (in which an agent connects with more similar agents), and heterophilic rewiring (in which an agents connect with less similar agents). Simulation results show that the rewiring strategy affects the number and size of created echo chambers. The homophilic strategy and, to a lesser extent, the random strategy generate more and smaller echo chambers than the heterophilic 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 such 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 be homophilic, by choosing agents with similar beliefs and opinions to replace less similar agents or, on the contrary, heterophilic, by choosing agents with different opinions and beliefs to replace more similar ones. In addition, we distinguish two variants depending on whether agents can drop concordant neighbors or not. We compare them with non rewiring agents, while reproducing the experiments of [4]. We observe that no and heterophilic rewiring lead to at most one echo chamber on average, though random and homophilic rewiring generate increasingly more echo chambers. Moreover, the homophilic 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 a topic, 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 an initial state through updating processes. The network itself evolves through rewiring.

3.1 Processes to update opinions and beliefs

Agents use four processes to update their opinions and beliefs (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 affects only one of its components.

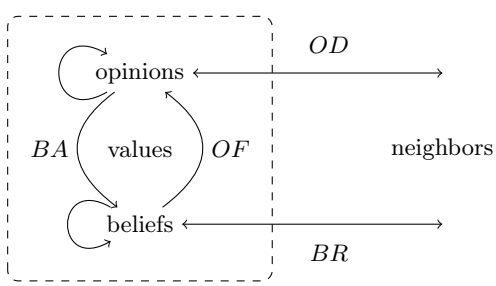


Fig. 1: The four processes (BR, OD, BA, and OF) for interactions between opinions and beliefs (from [5]).

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 to their neighbors and a set of neighbors $U_a^t \subseteq N_a^t$ to remove from their neighbors, 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 study 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.

For selecting it, an agent a at time t will use an order ($\prec_a^t$) between other agents. This order is simply based on the distance of their state with respect to agent a's state. 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

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

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

If several edges satisfy the criteria below, one is taken at random.

This order requires access to opinions and beliefs of non neighbors to which a is not directly related. But a social network recommendation algorithm can

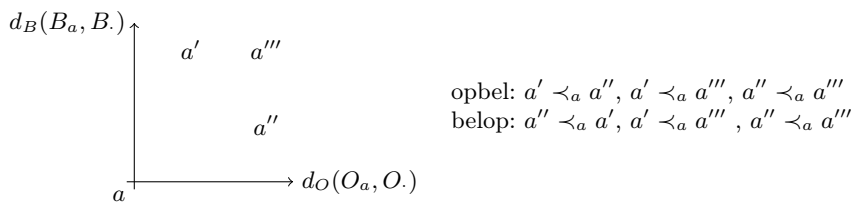


Fig. 2: The two different orders depending on whether opinion distance (opbel) or belief distance (belop) is privileged.

provide recommendations on such a basis. Moreover, these strategies are designed for the purpose of testing their effects, not necessarily to be implemented.

Such orders are visualized in Figure 2.

Hereafter 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''. This mimics an agent trying randomly to interact with an unknown agent and decide to include it in its network if more interesting than a previous random one. If $a'' \prec_a a'$, then $U_a^t = \{a'\}$ 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 Homophilic rewiring

Homophilic rewiring will replace the less concordant neighbor by the most concordant non neighbor, if the latter is more concordant than the former.

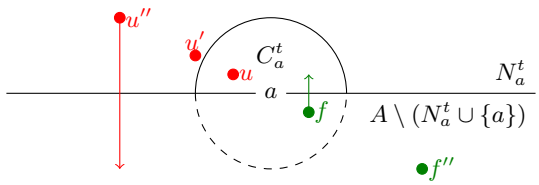
Homophilic rewiring is defined by identifying (in case of ties, elements are drawn randomly)

$$U_a^t = \{a'\} \text{ such that } a' \in \operatorname*{argmax}_{\prec_a^t} N_a^t,$$

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

and rewiring only if $a'' \prec_a^t a'$ (otherwise, $F_a^t = U_a^t = \emptyset$). The new rewiring strategies are illustrated in Figure 3.

We also consider conservative homophilic rewiring (or homophilic$^-$ rewiring in short), a variant of the homophilic rewiring. This will replace the *discordant*



rewiring	U_a^t	F_a^t
homophilic	$\{u''\}$	$\{f\}$
homophilic$^-$	$\{u''\}$	$\{f\}$
heterophilic	$\{u\}$	$\{f''\}$
heterophilic$^-$	$\{u'\}$	$\{f''\}$

Fig. 3: Example of the effect of different rewiring strategies with respect to the order ($\prec_a^t$) displayed as concentric distance to agent a. Arrows show the effect of homophilic rewiring. Although homophilic and homophilic$^-$ rewirings are the same in this example, this will not happen if all neighbors are concordant, which is typically what occurs in an echo chamber.

neighbor with the lowest concordance instead of the neighbor with the property which may be concordant. Hence, only how U_a^t is obtained is different from how this is achieved in plain homophilic rewiring:

$$U_a^t = \{a'\} \text{ such that } a' \in \operatorname*{argmax}_{\prec_a^t} N_a^t \setminus C_a^t.$$

4.4 Heterophilic rewiring

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

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

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

We also consider conservative heterophilic rewiring (or heterophilic$^-$ rewiring in short), a variant of plain heterophilic rewiring, that is based on U_a^t defined as below instead of the definition above:

$$U_a^t = \{a'\} \text{ such that } a' \in \operatorname*{argmin}_{\prec_a^t} N_a^t \setminus C_a^t.$$

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 opinion/belief 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:

$$\text{no rewiring} \leq \text{hetero}^- \leq \text{hetero} \leq \text{random} \leq \text{homo}^- \leq \text{homo},$$

stating that homophilic rewiring generates more echo chambers than random rewiring, which generate more echo chambers than heterophilic rewiring which has more echo chambers than no rewiring. It also states that the homophilic$^-$ or heterophilic$^-$ rewiring creates fewer echo chambers than homophilic or heterophilic rewiring, respectively.

This is expected because no rewiring should not allow to satisfy (at least) segregation, heterophilic rewiring can create some echo chambers but not so many (e.g., it ends with a single large echo chamber), random rewiring should create several echo chambers like reported in [4], homophilic rewiring should create more as this always allows agents to connect to others with close opinions and beliefs, and homophilic$^-$ and heterophilic$^-$ rewirings stop rewiring if all neighbors are concordant unlike homophilic and heterophilic rewiring, respectively.

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 with (opbel), random with (belop), homophilic with (opbel), homophilic with (belop), heterophilic with (opbel), heterophilic with (belop), homophilic$^-$ with (opbel), homophilic$^-$ with (belop), heterophilic$^-$ with (opbel), heterophilic$^-$ with (belop).
- 20 different seeds that are the same as those used in [4].

5.3 Measures

In addition to the number of echo chambers ($eo^t = |\mathcal{E}_O^t|$ for opinion echo chambers and $eb^t = |\mathcal{E}_B^t|$ for belief echo chambers), we collect the following measures:

- The number of agents in echo chambers:

$$po^t = \sum_{C \in \mathcal{E}_O^t} |C| \text{ and } pb^t = \sum_{C \in \mathcal{E}_B^t} |C|$$

- The number of unique beliefs shared in echo chambers:

$$ub^t = |\{B; \exists C \in \mathcal{E}_B^t, \forall a \in C, B_a^t = B\}|$$

- The number of unique opinions shared in echo chambers:

$$uo^t = |\{O; \exists C \in \mathcal{E}_O^t, \forall a \in C, O_a^t = O\}|$$

To avoid applying 'equal to' relationship (=) like beliefs to continuous values, 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 and Table 2 display the average numbers of opinion and belief echo chambers grouped by thresholds (ε and δ) and by rewiring strategies. The tables show, independently from the parameter values, the very small number of echo chambers for the no rewiring and heterophilic strategies (less than 1 and most of the time 0), with respect to the higher average values for random and especially homophilic rewiring (always more than or equal to 1.).

The tables also show 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.

Opinion echo chambers. The results from ANOVA and its post-hoc test (Tukey HSD) show that the rewiring strategies can be classified into the following four groups:

$$\begin{array}{r} \text{heterobo}(0.19) \\ \text{heteroob}(0.19) \\ \text{no rewiring}(0.19) \\ \text{hetero}^{-}\text{bo}(0.23) \\ \text{hetero}^{-}\text{ob}(0.23) \end{array} < \begin{array}{c} \text{randombo}(3.30) \\ \text{homo}^{-}\text{bo}(3.24) \end{array} < \begin{array}{c} \text{randomob}(3.74) \\ \text{homo}^{-}\text{ob}(3.81) \end{array} < \begin{array}{c} \text{homoob}(6.22) \\ \text{homobo}(6.05) \end{array}$$

Here, 'ob' and 'bo' show that the order (opbel) and (belop) are applied, respectively. For example, the difference between random rewiring with (belop) and homophilic^{-} rewiring with (belop) is not significant ($p > 0.01$) while between the random rewiring with (belop) and (opbel) is significant ($p \ll 0.01$). Each number attached to each rewiring strategy shows the average number of opinion echo chambers created with the corresponding strategy.

Belief echo chambers. We applied the same statistical tests to the number of belief echo chambers. The results show that these rewiring strategies can be split into five groups:

$$\begin{array}{r} \text{heterobo}(0.19) \\ \text{heteroob}(0.19) \\ \text{no rewiring}(0.19) \\ \text{hetero}^{-}\text{bo}(0.23) \\ \text{hetero}^{-}\text{ob}(0.23) \end{array} < \begin{array}{c} \text{randomob}(2.78) \\ \text{homo}^{-}\text{ob}(2.63) \end{array} < \begin{array}{c} \text{randombo}(3.03) \\ \text{homo}^{-}\text{bo}(3.14) \end{array} < \begin{array}{c} \text{homoob} \\ (4.90) \end{array} < \begin{array}{c} \text{homobo} \\ (6.00) \end{array}$$

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

δ	rewiring \ ε	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
1	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	7.17	7.97	8.07	7.80	7.97	8.03	7.60	7.60	7.72	7.92
	homo$^-$	8.85	9.68	9.38	8.93	8.95	9.15	9.18	9.20	9.22	9.10
	homo	8.95	10.15	10.07	10.05	10.10	10.18	10.18	10.30	10.30	10.28
2	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	9.00	6.90	**4.90**	**4.00**	**3.33**	**3.00**	**3.27**	**3.05**	**2.88**	**3.05**
	homo$^-$	9.47	7.97	**3.20**	**3.08**	**2.75**	**2.40**	**2.20**	**2.12**	**2.15**	**2.08**
	homo	9.62	9.72	8.85	8.07	7.80	7.33	7.08	7.28	7.12	7.17
3	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	8.70	**4.72**	**3.33**	**2.80**	**2.25**	**2.20**	**1.80**	**1.65**	**1.70**	**1.62**
	homo$^-$	9.05	**3.92**	**2.15**	**2.23**	**1.45**	**1.40**	**1.43**	**1.25**	**1.25**	**1.18**
	homo	9.65	8.10	6.60	5.78	5.35	5.10	4.33	4.70	4.72	4.30
4	none	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.25	0.35	0.40
	hetero	0.00	0.00	0.00	0.00	0.00	0.05	0.10	0.25	0.35	0.42
	hetero$^-$	0.00	0.00	0.00	0.00	0.03	0.12	0.23	0.70	0.62	0.75
	random	7.85	**3.58**	**3.00**	**2.67**	**1.77**	**1.52**	**1.35**	**1.12**	**1.12**	**1.15**
	homo$^-$	8.47	**3.17**	**2.23**	**2.23**	**1.45**	**1.35**	**1.15**	**1.00**	**1.02**	**1.00**
	homo	9.25	7.35	5.85	5.40	4.42	3.75	3.58	3.42	3.27	3.17
5	none	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.85	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.88	0.97
	hetero$^-$	0.00	0.00	0.00	0.00	0.10	0.53	0.80	0.90	1.00	1.00
	random	7.35	3.50	**2.85**	**2.60**	**1.75**	**1.20**	**1.10**	1.00	1.00	1.00
	homo$^-$	7.97	3.50	**2.27**	**2.30**	**1.52**	**1.12**	**1.00**	1.00	1.00	1.00
	homo	9.25	7.42	5.42	5.05	4.33	3.60	3.25	3.23	2.98	3.10
6	none	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.17	0.75	0.85	0.95	1.00	1.00
	random	7.35	3.70	**2.90**	2.20	1.50	**1.23**	1.00	**1.00**	1.00	1.00
	homo$^-$	8.10	3.90	**2.48**	2.25	1.62	**1.15**	1.00	**0.97**	1.00	1.00
	homo	9.15	7.35	5.17	4.85	4.05	3.38	3.10	3.45	3.02	2.80
7	none	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.17	0.78	0.85	0.95	1.00	1.00
	random	7.55	3.62	**2.75**	**2.38**	**1.43**	1.18	**1.05**	1.00	1.00	1.00
	homo$^-$	7.97	3.70	**2.27**	**2.35**	**1.38**	1.20	**1.00**	1.00	1.00	1.00
	homo	9.30	7.28	5.28	4.70	4.08	3.58	3.45	3.23	2.95	2.90

Table 2: Average number of belief echo chambers for each ε, δ, and rewiring strategy. Cell colors correspond to the number of echo chambers.

δ	ε / rewiring	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
1	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	3.45	4.17	4.30	4.10	4.40	4.38	4.17	4.08	4.20	4.28
	homo$^-$	4.58	5.75	5.55	5.17	5.03	5.20	5.17	5.15	5.25	5.17
	homo	4.75	5.85	5.80	5.78	5.80	5.83	5.80	5.95	5.95	5.75
2	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	7.53	6.25	**4.22**	**3.75**	**2.85**	**2.58**	**3.02**	**2.73**	**2.50**	**2.70**
	homo$^-$	8.12	7.35	**2.88**	**2.88**	**2.50**	**2.25**	**1.95**	**2.02**	**1.70**	**1.65**
	homo	7.97	8.60	8.05	7.17	6.97	6.55	6.50	6.60	6.45	6.53
3	none	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	random	8.22	**4.65**	**3.25**	**2.70**	**2.20**	**2.15**	**1.75**	**1.50**	**1.65**	**1.52**
	homo$^-$	8.60	**3.92**	**1.90**	**2.02**	**1.40**	**1.35**	**1.30**	**1.20**	**1.18**	**1.12**
	homo	9.10	8.25	6.50	5.80	5.25	5.10	4.40	4.75	4.83	4.42
4	none	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.25	0.35	0.35
	hetero	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.25	0.35	0.38
	hetero$^-$	0.00	0.00	0.00	0.00	0.03	0.10	0.23	0.70	0.62	0.72
	random	7.60	**3.62**	**3.02**	**2.70**	**1.77**	**1.52**	**1.35**	**1.12**	**1.10**	**1.15**
	homo$^-$	8.30	**3.20**	**2.27**	**2.15**	**1.48**	**1.38**	**1.12**	**1.00**	**1.02**	**1.02**
	homo	9.12	7.30	5.97	5.58	4.47	3.90	3.65	3.55	3.33	3.20
5	none	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.85	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.40	0.65	0.80	0.88	0.97
	hetero$^-$	0.00	0.00	0.00	0.00	0.10	0.53	0.80	0.90	1.00	1.00
	random	7.15	3.58	**2.85**	**2.58**	**1.77**	**1.20**	**1.10**	1.00	1.00	1.00
	homo$^-$	8.10	3.62	**2.23**	**2.38**	**1.55**	**1.12**	**1.00**	1.02	1.02	1.02
	homo	9.35	7.62	5.67	5.17	4.38	3.70	3.33	3.35	3.08	3.12
6	none	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.70	0.80	0.95	0.95	1.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.17	0.75	0.85	0.95	1.00	1.00
	random	7.22	**3.77**	**2.92**	2.23	1.52	**1.23**	1.00	**1.00**	1.00	1.00
	homo$^-$	8.15	**3.95**	**2.42**	2.42	1.55	**1.15**	1.00	**0.97**	1.00	1.00
	homo	9.28	7.45	5.53	4.92	4.08	3.52	3.33	3.50	3.10	2.83
7	none	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	hetero	0.00	0.00	0.00	0.00	0.05	0.50	0.75	0.90	0.95	1.00
	hetero$^-$	0.00	0.00	0.00	0.00	0.15	0.78	0.85	0.95	1.00	1.00
	random	7.42	3.67	**2.77**	**2.42**	1.38	1.18	**1.05**	1.00	1.00	1.00
	homo$^-$	8.12	3.73	**2.23**	**2.38**	1.38	1.20	**1.00**	1.00	1.00	1.00
	homo	9.47	7.40	5.45	4.85	4.15	3.73	3.50	3.35	3.05	3.08

Opinions and belief echo chambers do not necessarily coincide. For example, the components surrounded by the green dashed line in Figure 4d are not belief echo chambers but opinion echo chambers (see Figure 5d).

7 Discussion

Hypothesis. Table 1 and Table 2 show 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 between the random rewiring and the homophilic$^-$ rewiring (boldface values in the table). According to the significance tests, these results support the hypothesis with respect to homophilic rewiring creating more echo chambers than random rewiring which creates more echo chambers than heterophilic and no rewiring. The only unsupported part is that heterophilic rewiring creates more echo chambers than no rewiring. This is not the case.

Disconnectedness. Although the initial situation starts with a connected graph, this is not the case at the end of the process. The homophilic rewiring allows agents to form twice as many connected components as the random rewiring (4.4 and 2.2, respectively). For example, in Figure 4, there are 3 and 6 connected components in Figure 4c and Figure 4d, respectively.

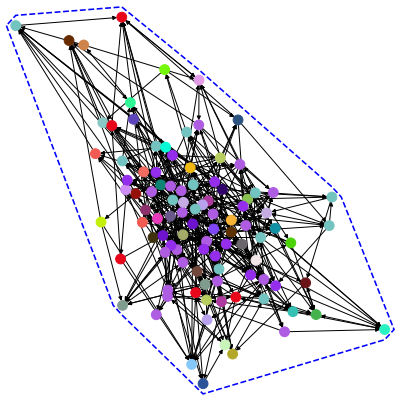
This pictures a society in which some parts no longer listen to one another. However, in our experimental setting agents may rewire to others even if the graph is disconnected.

Table 3: Average number and size of echo chambers and average number of unique beliefs and opinions for each rewiring strategy.

	number of echo chambers		size of echo chambers		unique opinions/beliefs	
	eo	*eb*	*po*	*pb*	*uo*	*ub*
none	0.19±0.34	0.19±0.34	97.76±1.76	97.74±1.76	0.19±0.34	0.19±0.34
hetero	0.19±0.34	0.19±0.34	**97.78**±1.69	**97.77**±1.69	0.19±0.34	0.19±0.34
hetero$^-$	0.23±0.38	0.23±0.38	97.56±1.76	97.56±1.76	0.23±0.38	0.23±0.38
random	3.52±2.63	2.90±1.89	23.80±29.86	27.02 ±31.53	3.10±2.09	2.88±1.88
homo$^-$	3.52±3.15	2.89±2.25	92.58±20.19	88.66 ±23.55	2.97±2.36	2.77±2.12
homo	**6.13**±2.59	**5.45**±1.84	12.27±13.15	12.85±13.82	**4.73**±2.06	**4.92**±1.88

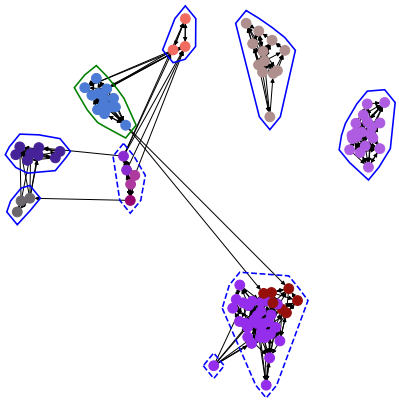
Agents per echo chamber. Homophilic rewiring and, to a lesser extent, random rewiring create smaller echo chambers than random rewiring globally and on average (Table 3). This suggests that applying stricter rewiring creates more but smaller echo chambers.

Actually, what happens is that on the one hand no and heterophilic 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 and Table 2, to the more tolerant agents (but not in the

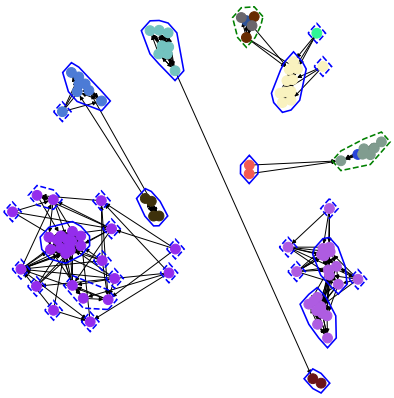


(a) Final network with no rewiring and heterophilic rewiring.

(b) Final network with random rewiring with order (opbel).

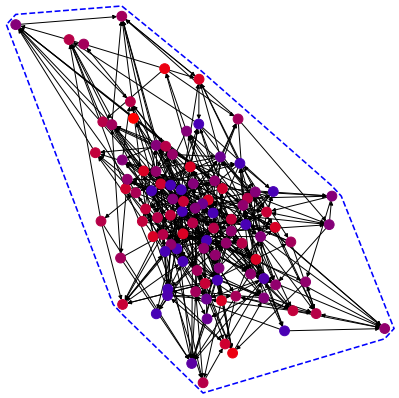


(c) Final network with random rewiring with (belop).

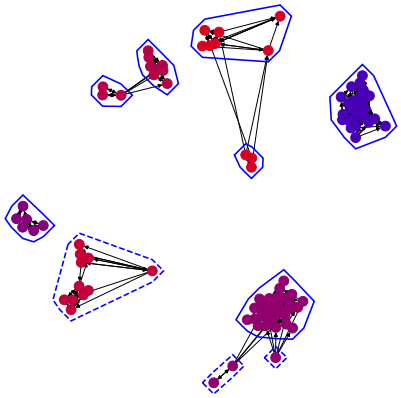


(d) Final network with homophilic rewiring with (opbel).

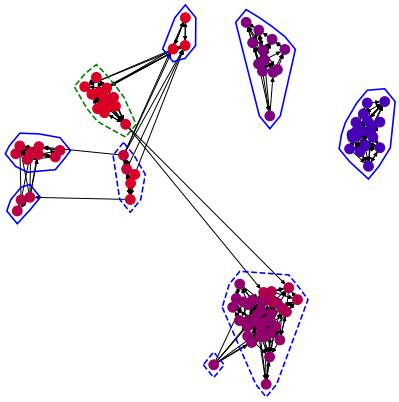
Fig. 4: Final networks with $\varepsilon = 0.15$, $\delta = 2$, and the same seed, colored with respect to the final beliefs (same color corresponds to the same beliefs). Components surrounded by blue solid and dashed lines are echo chamber and non-echo chamber components, respectively; components surrounded by a green line are components such that opinion and belief echo chambers do not coincide.



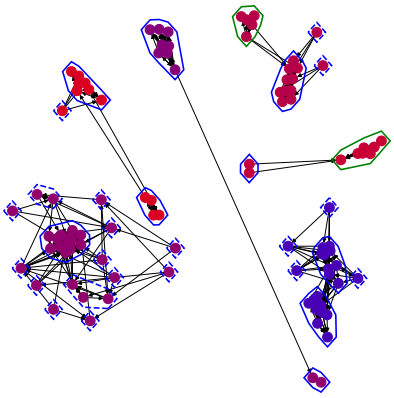
(a) Final network with no rewiring and heterophilic rewiring.



(b) Final network with random rewiring with order (opbel).



(c) Final network with random rewiring with (belop).



(d) Final network with homophilic rewiring with (opbel).

Fig. 5: Final networks with $\varepsilon = 0.15$, $\delta = 2$, and the same seed as Figure 4, colored with respect to the final opinions (same color corresponds to the same opinions; opinions 0, 0.5, and 1 correspond to blue, purple, and red, respectively). Components surrounded by blue solid and dashed lines are echo chamber and non-echo chamber component, respectively; Components surrounded by a green line are components such that opinion and belief echo chambers do not coincide.

case of Figure 4a with $\varepsilon = 0.15$ and $\delta = 2$). On the other hand, homophilic 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 homophilic than with random rewiring which is higher than heterophilic and no rewiring (Table 3). The same occurs for opinions. This suggests 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 distribution and distance between these beliefs and opinions [1].

However, this already draws different pictures: with no rewiring or heterophilic rewiring, there is no echo chamber or the whole population has similar beliefs and opinions; with homophilic 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. To answer the initial questions, results showed that rewiring is not strictly necessary for the creation of echo chambers, however no rewiring does generate significantly fewer echo chambers than rewiring, but surprisingly, heterophilic rewiring. Obviously, it is possible to design different rewiring strategies as we have proposed 10 different strategies when taking the two orders into account. Moreover, these strategies have a significantly different effect on echo chamber creation with random and conservative homophilic rewiring bringing a similar number of echo chambers and the homophilic strategy, authorising disconnection of concordant neighbors in favor of closer non neighbors, leading to a significantly higher number of echo chambers. In addition, the simulation results show that 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 involves more than one edge at once (we expect the process to converge faster), echo chamber identification relies on 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 and Scope actions 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`, `https://sake.re/20260610-BROD`, `https://sake.re/20260615-BROD`, and `https://sake.re/20260621-BROD`. They contain reference to simulator and version, processing instructions, results and jupyter notebooks analyzing them.

References

1. Bourahla, Y., David, J., Euzenat, J., Naciri, M.: Measuring and controlling knowledge diversity. In: Prince Sales, T., Hedblom, M., Tan, H., Gómez Álvarez, L., Peñaloza, R., Vesic, S. (eds.) Proc. 1st JOWO workshop on formal models of knowledge diversity (FMKD), Jönköping (SE) (2022)
2. Ferraz de Arruda, H., Maciel Cardoso, F., Ferraz de Arruda, G., R. Hernández, A., da Fontoura Costa, L., Moreno, Y.: Modelling how social network algorithms can influence opinion polarization. Information Sciences **588**, 265–278 (2022). `https://doi.org/10.1016/j.ins.2021.12.069`
3. Kataoka, H., Euzenat, J., Hasebe, K.: Exchanging and updating opinions and beliefs reinforces echo chambers. In: Proc. 39th annual conference of the Japanese society for artificial intelligence (JSAI), Osaka (JP) (2025)
4. Kataoka, H., Euzenat, J., Hasebe, K.: Coherent belief and opinion propagation produces more echo chambers. In: Proceedings of the 25th international conference on Autonomous Agents and Multi-Agent Systems (AAMAS), Paphos (CY). pp. 1737–1745 (2026). `https://doi.org/10.65109/PQIV4263`
5. Kataoka, H., Euzenat, J., Hasebe, K.: How can beliefs alter opinions? Joint opinion and belief evolution. In: Proceedings of the 18th International Conference on Agents and Artificial Intelligence (ICAART), Marbella (ES). pp. 15–26 (2026). `https://doi.org/10.5220/0014290200004052`
6. Mahmoudi, A., Jemielniak, D., Ciechanowski, L.: Echo chambers in online social networks: A systematic literature review. IEEE Access **12**, 9594–9620 (2024). `https://doi.org/10.1109/ACCESS.2024.3353054`
7. Prasetya, H.A., Murata, T.: A model of opinion and propagation structure polarization in social media. Computational Social Networks **7**(1) (Jan 2020). `https://doi.org/10.1186/s40649-019-0076-z`
8. Sasahara, K., Chen, W., Peng, H., Ciampaglia, G.L., Flammini, A., Menczer, F.: Social influence and unfollowing accelerate the emergence of echo chambers. Journal of Computational Social Science **4**(1), 381–402 (2020). `https://doi.org/10.1007/s42001-020-00084-7`
9. Schwind, N., Inoue, K., Bourgne, G., Konieczny, S., Marquis, P.: Belief revision games. In: Proceedings of the 29th AAAI Conference, Austin (TX US). pp. 1590–1596 (2015). `https://doi.org/10.1609/aaai.v29i1.9415`
10. Springsteen, J., Yeoh, W., Christenson, D.: Algorithmic filtering, out-group stereotype, and polarization on social media. In: Proceedings of the 23rd International Conference on Autonomous Agents and Multiagent Systems. p. 1782–1790 (2024)

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