Estimating the Impact of Coordinated Inauthentic Behavior on Content Recommendations in Social Networks

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Abstract

Online disinformation is a dynamic and pervasive problem on social networks as evidenced by a spate of public disasters in light of active efforts to combat it. Since the massive amounts of content generated each day on these platforms is impossible to manually curate, ranking and recommendation algorithms are a key apparatus that drive user interactions. However, the vulnerability of ranking and recommendation algorithms to attack from coordinated campaigns spreading misleading information has been established both theoretically and anecdotally. Unfortunately it is unclear how effective countermeasures to disinformation are in practice due to the limited view we have into the operation of such platforms. In such settings, simulations have emerged as a popular technique to study the long-term effects of content ranking and recommendation systems. We develop a multiagent simulation of a popular social network, Reddit, that aligns with the stateaction space available to real users based on the platform's affordances. We collect millions of real-world interactions from Reddit to estimate the network for each user in our dataset and utilise Reddit's self-described content ranking strategies to compare the impact of coordinated activity on content spread by each strategy. We expect that this will inform the design of robust content distribution systems that are resilient against targeted attacks by groups of malicious actors.

1. Introduction

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The success and scope of coordinated online campaigns to spread misinformation and hate speech poses a new set of challenges to a free and open and Internet (Tucker et al., 2018). A great deal of scientific effort has been devoted to building content classifiers that can accurately identify what is deemed as harmful content (Aldwairi & Alwahedi, 2018; Shu et al., 2017; Zhou & Zafarani, 2020; Zhou et al., 2020) in order to remove it from ranking inventory. This approach suffers from limitations inherent in the contentious definition of what "harm" is (Vraga & Bode, 2020), as well as from resource constraints which lead to the uneven application of content-focused integrity mechanisms, particularly in the Global South (Haque et al., 2020). Notwithstanding the challenges of veracity, there are petabytes of data generated daily on these platforms¹ which necessitates algorithmic content distribution. Ranking and recommendation systems have played a tremendous role with platforms relying heavily on large-scale algorithms to populate the content stream that a user interacts with, called their 'feed' or 'timeline'. However, these systems have been shown to suffer from biases, and even promote hateful content² (Jiang et al., 2019; Tomlein et al., 2021; Ribeiro et al., 2020). One of the reasons is that these algorithms often rely on metrics that can be manipulated through coordinated activity including fake profiles and illicit collusion (Giglietto et al., 2019; 2020; Nizzoli et al., 2020). This makes such algorithms a popular attack vector for coordinated campaigns attempting to promote misleading content on social networks.

In fact, a May 2022 post published by a leading cybersecurity firm Nisos reveals the existence of professional botnet tool designed to simulate online personas replete with profile pictures, behaviors specific to the social media platforms, all with the goal of manufacturing fake 'trending social media events en masse'³. The software, clearly targeting mechanisms that drive content virality on social media, existed as early as 2019. In a similar report published in 2020, The Wire (India) conducted an investigation confirming the existence of a tool that artificially promoted hashtag-based trends using coordinated activity across different fake and

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¹https://research.facebook.com/blog/2014/ 10/facebook-s-top-open-data-problems/

²https://about.fb.com/news/2018/11/ myanmar-hria/

³https://www.nisos.com/blog/ fronton-botnet-report/

real social media accounts⁴.

The publication of quarterly transparency reports highlighting networks of such coordinated accounts successfully identified by platforms like Facebook and Twitter sheds light on the issue⁵. These data confirm that similar strategies are being adopted across multiple geographies in order to share misleading content that could influence susceptible users. Some of these are similar in principle to the BEND framework published in (Beskow & Carley, 2019b) that attempts to formalize disinformation manoeuvres observed on social media.

2. Contributions

We provide a multiagent simulation that can serve as a virtual test-bed for platforms and the public to evaluate the impact of such activity and prototype countermeasures to these patterns laying emphasis on a decomposable, transparent, and realistic content ranking mechanism that drives content virality on social networks. Using this simulator, we compare the harms arising from coordinated inauthentic behavior on online communities of users. Our model of agent activity is based on the popular social network Reddit, mapping the state-action space of agents in our simulation to the primary set of actions a user might take on the platform, whilst engaging with content online. Reddit has publicly accessible posts and comments dating back to 2007 and importantly, relies on decomposable content ranking mechanisms that are documented in public-facing posts published by the platform.

Substantively, we investigate the following research questions:

- 1. Can we quantify the effects of coordinated campaigns that target content amplification by ranking and recommendation systems?
- 2. If yes, can this inform the design of algorithms that are less susceptible to harms arising from such behavior?

3. Related Literature

Early work on detecting influence operations focuses on graph-theoretic approaches studying misinformation mitigation in social network graphs (Nguyen et al., 2012; Zhang et al., 2015; Amoruso et al., 2017; Saxena et al., 2020). These contributions assume traditional means of information propagation over static friend-follower networks and employ influence models (Kempe et al., 2015; Chen et al., 2013) to measure responses to interventions such as the debunking of information in social networks.

Agent-based models were also employed to simulate the spread of misinformation in a manner analogous to the spread of an infection in a population, drawing on epidemiological dynamics theories to determine the bounds on detection methods under specific assumptions on information propagation (Dong et al., 2013; Wang et al., 2014). Common applied methods from epidemiology utilise basic compartmental models like the Susceptible-Infected-Recovered (SIR) model (El-Saved et al., 2012; Tambuscio et al., 2015; Wang et al., 2014; Shelke & Attar, 2019) or the Susceptible-Exposed-Infected-Recovered (SEIR) model (Zhou et al., 2019) to simulate spread with some work framing interventions on it in the form of 'vaccinated' agents that debunk misinformation claims in the network (Serrano & Iglesias, 2016). On the theoretical end of agent-based modeling, the authors of (Beskow & Carley, 2019a) simulate bot disinformation manoeuvres that target susceptible online communities. While useful as a prototyping tool for which they provide the BEND framework to categorize malicious patterns of behavior (Beskow & Carley, 2019b; Carley, 2020), there is no mention of any platform-specific mechanisms driving agent interactions with content, assuming that content distribution occurs via friend-follower networks. The existing literature on agent-based models involving social networks has largely ignored algorithmic confounding (Chaney et al., 2018) and other micro-mechanisms in their aim to explain macro-level phenomena, in the process marginalising away individual uniqueness in behavior.

3.1. Agent-based Models of Social Networks

The novelty of employing agent-based models has been in trivial introductions of micro-mechanisms that collectively cause complex macro-trends, as evidenced in Schelling's model of segregation (Schelling, 1969) over five decades ago and Conway's Game of Life Simulations thereafter (Conway et al., 1970). Now-abandoned work towards agentbased social simulations typically focused on high-fidelity user interactions (Ryczko et al., 2017) and their network evolution over time (Stadtfeld, 2015) without accounting for the platform-level mechanisms that underpin most of these interactions. Recent work continues to accord due importance to such micro-mechanisms and accounts for some of the platform-level nuances including recommendation algorithms such as (Lucherini et al., 2021) permitting the introduction of user and item-level attributes as part of the system. Similarly, the authors of (Mladenov et al., 2021) emphasize the need for simulated recommender systems to operate in an ecosystem involving complex, multi-turn interactions similar to modern-day recommendation systems operating on dynamic social networks. While these are use-

⁴https://thewire.in/tekfog/en/1.html

⁵https://about.fb.com/news/tag/

⁷ coordinated-inauthentic-behavior/, https:

^{//}transparency.twitter.com/en/reports/

information-operations.html

ful frameworks to examine socially-meaningful outcomes 111 and design complex recommendation algorithms respec-112 tively, they neither utilise real-world data to inform their 113 simulation choices, nor examine coordinated activity in the 114 context of ranking and recommendation systems on a so-115 cial network which forms the primary contribution of our 116 work. That said, we hope to provide a compatible imple-117 mentation of our simulation in their respective frameworks, 118 to stimulate collaborative research in this direction. The 119 notion of coordinated inauthentic behavior (CIB) was in-120 troduced by Meta (formerly Facebook) quite recently, in 121 2018. Most existing work in the area of coordinated in-122 authentic behavior focuses on its detection or mitigation 123 with little emphasis on the mechanism through which the 124 accounts involved in these activities attempt to game the 125 ranking and recommendation algorithms. As the first step 126 towards addressing this challenge, we contribute to the mea-127 surement of harms arising from coordinated disinformation 128 campaigns on social networks. Operationally, we combine 129 multiagent simulations with algorithmic content distribution 130 via ranking and recommendation systems and track metrics 131 that are relevant to a healthy ecosystem. We rely on priors 132 informed by a large-scale dataset comprising millions of in-133 teractions between users of Reddit, a pseudonymous social 134 network. The emphasis on priors informed by real-world 135 data reduces our reliance on an arbitrary choice of simula-136 tion parameters increasing our confidence in the results. We 137 adopt information-theoretic definitions similar to (Lucherini 138 et al., 2021) to quantify the harms arising from coordinated 139 inauthentic behavior and conduct a comparative study of 140 risk-quantification conditional upon choice of recommen-141 dation algorithm. Lastly, we generalize the components of 142 our simulator to different social media platforms to describe 143 how our software serves as a framework for analyzing the 144 impact of coordinated attacks on end-users of any of these 145 platforms.

4. Simulating Coordinated Inauthentic Behavior

150 "Coordinated inauthentic behavior" (CIB) is a term coined 151 by Facebook in late 2018, describing the promotion of con-152 tent via coordinated networks of accounts on its platform, 153 with the 'intent to mislead people about who they are and 154 what they are doing'⁶. The operationalization of CIB is 155 often through different attack vectors for the exploitation 156 of ranking and recommendation algorithms to target con-157 tent visibility. The harms arising from CIB are difficult 158 to quantify due to a lack of the apparatus to track the im-159 pact of coordinated inauthentic behavior across evolving 160 networks in an open and transparent manner supported by 161

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platforms. Furthermore, due to the inherent lag caused by internal investigations, most data about CIB is published weeks or even months after attacks. This delay further limits researchers' ability to quantify CIB harms. Due to the nature of disinformation campaigns involving unsuspecting users (Starbird et al., 2019), it is critical to verify authentic users are not part of the takedowns by site integrity teams. Simulations of social media provide a means to study CIB by modeling the ecosystem in which it takes place. In this paper we propose to model two popular patterns of coordinated activity and present preliminary results from the first:

- Brigading, in the Reddit context describing intercommunity conflicts during which antagonistic members of one subreddit actively downvote comments in order to deprioritise them for content recommendation systems and effectively censor them⁷ (Datta & Adar, 2019).
- 2. Influence Operations, wherein a set of 'puppet' accounts are used to push a certain narrative through repetitive posts and comments reiterating the same, falsifying the appearance of credibility and popular sentiment.

4.1. Simulating Social Network Activity for Reddit

Reddit is a pseudonymous online social network that primarily comprises a network of communities, as stated on their website, reddit.com. Our interest in Reddit as a content-sharing platform arises from the fact that it has largely passed under the radar due to the high-visibility consequences of disinformation on social networks like Twitter and Facebook despite having nearly the same number of monthly active users as Twitter⁸. That has not been for want of controversy; Reddit also dealt with the controversial removal of thousands of communities sharing misinformation, particularly United States politics (Chandrasekharan et al., 2022) and misinformation relating to the COVID-19 pandemic. It is possible that Reddit's community structure and human-moderated posting may have reduced the effectiveness of disinformation. It seems equally plausible that there is simply more research being conducted into the impact of disinformation on Twitter and Facebook than into Reddit. In any case, given the open nature of Reddit data and open-source tools to sift through these troves of user activity provided by Pushshift (Baumgartner et al., 2020), it is a useful platform to model activity on. Our conclusion was confirmed by the authors of a large-scale survey (Proferes et al.,

com/statistics/272014/

⁶https://about.fb.com/news/2018/12/

⁷https://institute.global/policy/

social-media-futures-what-brigading

⁸https://www.statista.

global-social-networks-ranked-by-number-of-users

165 2021) who state that Reddit is only recently turning into a increasingly popular avenue for research, having examined 167 several hundred publications employing Reddit datasets in 168 their analyses. Our design choices are informed by a care-169 ful examination of past simulation tools (Lucherini et al., 170 2021; Mladenov et al., 2021; Ryczko et al., 2017; Stadtfeld, 171 2015) and a forward-looking perspective, as stated earlier, 172 to provide a compatible API to interface with other tools 173 as well as run Monte Carlo-based inference algorithms in a 174 tractable manner. We employ the probabilistic programming 175 language Pyro (Bingham et al., 2019) to develop a forward 176 simulator Among other advantages it extends the popular 177 Pytorch framework (Paszke et al., 2019) and is packaged to 178 include Monte Carlo and variational inference methods that 179 will enable us to condition the simulation on user activity 180 collected from various social networks. This implies that 181 while making design choices, we will rely on simpler control 182 flow logic to enable efficient inference of agent-level latent 183 variables that will be defined in the simulator. As a general 184 principle, we strike a balance between the fidelity of the 185 state-action space available to the user and the tractability 186 of statistical inference to obtain posterior estimates over the 187 parameter values given access to user data from social net-188 works. In practice, this means making choices to simulate 189 only the voting, posting, and commenting behavior, with 190 little emphasis laid on modeling the shifts in the network 191 (or subreddit-membership) of the users. Here is a technical overview of our framework following which we provide a 193 description of the agent activity model for Reddit.

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1. Our simulation comprises of 'Content' and 'User' which are the two atomic entities defined in an objectoriented manner–each comprising a set of properties that are used to simulate interactions in the ecosystem.

For the 'Content' object, these properties are its unique identifier, author, time of creation, topic attributes (what it is about), scoring statistics (number of comments, shares, and votes), and recency (last active);

For the 'User' object, these properties are its unique identifier, interests, session activity (determines number of posts per session), influenceability, response (determines tendency to comment or vote), and posting probabilities.

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 2. Specializing our model to Reddit, the subreddit membership is determined based on the user's interests and the content's topic attributes.
- 3. We parametrize behavioral models describing agentlevel activity shown in 5 by placing data-driven priors on parameters driving their behavior.
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These refer to the 'interaction' and 'response' properties of the 'User' based on their frequency of posting and commenting in different subreddits These also include the static membership of subreddits for each user that is a part of the simulation.

- 4. We use counterfactual simulations to estimate the effects of accounts engaging in CIB by targeting specific content to amplify, lying beyond a reasonable agreement with their existing set of interests inferred from community membership.
- 5. For agents that do not engage in CIB, activities (vote, comment, post, do nothing) are sampled while browsing through the content feed curated by a particular content distribution algorithm.
- 6. In the simulation, some agents target specific communities based on a predetermined agenda, in a coordinated fashion.
- 7. Such activity affects the inputs that go into a recommendation algorithm which filters and ranks content on a user's feed.
- 8. To determine the level of impact, we track metrics of interest and compare them across multiple runs of the simulation for a CIB setting versus a counterfactual setting without the presence of CIB to determine how much damage is done as a result of CIB. We examine:

The content diversity or the variance of all recommended content at each timestep to measure the degree of homogenization of visible content similar to (Chaney et al., 2018; Lucherini et al., 2021)

The share of views allocated to misleading content promoted via coordinated activity relative to the counterfactual scenario.

The share of engagement with such content in comparison to the counterfactual scenario.

5. Running the Simulation

The algorithm in 5 describes a single run of the simulator called an 'execution trace'. Each execution trace provides a set of metrics over time that we collect over multiple runs in order to provide a confidence interval over the metrics of interest. We conduct such an experiment for each choice of ranking and recommendation algorithm as well as behavior type in order to provide a complete picture of algorithmic susceptibility towards that kind of coordinated inauthentic behavior.

6. Dataset

For data-driven simulations, we collect a dataset of Reddit user activity that contains millions of posts from 2011 - 2021. We start by scraping all of the posts on the 'r/politics' subreddit and a sample of upto 10,000 comments per post, with

the motivation that it often provides different, disjoint per-221 spectives on policy issues and would comprise interesting 222 behaviors and a variety of tones of discourse. We filter the 223 most active 5,000 users based on recent activity and limit the 224 time period for modeling to 2016 - 2021 for computational 225 reasons. For each user in our dataset we scrape a history of upto 6,000 past Reddit posts and comments that we col-227 lectively term as 'interactions'. This results in a total of nearly 32,000 different subreddits. We present an analysis 229 involving 2,500 of these users as a pedagogical example of 230 conducting research into the impact of coordinated behavior 231 on social networks. The challenge in simulating a realistic 232 subreddit network is the sparsity of subreddit membership 233 and long-tail of behaviors corresponding to these commu-234 nities (Krishnan et al., 2018). however, in order to utilise 235 all available information about users without creating an 236 intractable computational simulation, we develop a strategy 237 that we call 'subreddit categorization' which uses a super-238 vised labeling approach to cluster subreddits into a five-level 239 hierarchy of subreddit 'categories'. 240

241 **6.1. Subreddit Categorization**

242 We manually collect data from 'Wikis' that are user-243 generated labels for describing what content category is 244 associated for a given subreddit. For example the subreddit 245 'r/cats' would fall under the category 'Animal Kingdom' and 246 subcategory 'Animals'. We find 26 top-level categories, 151 247 sub-categories, and 304 sub-sub-categories. While there 248 is technically no limit to the number of levels associated 249 with such a hierarchy, we examine the sparsity of labeled 250 subcategories and accordingly limit the number of levels 251 to a maximum of 5 for the data collection In practice we 252 utilise the top-level category for the current model. We eval-253 uate our subreddit categorization model to find that it has a 254 top-k precision of 0.485 @ k = 1. This strategy gives us a 255 massive computational advantage by reducing our modeling granularity to only 26 subreddit categories for the simula-257 tion instead of the previous 32,000. We provide a visual 258 description of a few top-level content categories in figure 259 6 and the real-world interactions collected for 5,000 of the most active users on 'r/politics' divided into these categories 261 shown in figure 4.

6.2. Ranking and Recommendation on Reddit

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Reddit has historically been a platform with lightly personalized content; as a result community dynamics are the key drivers of content visibility. Content ranking in their user 'feeds' is primarily done by considering various properties of the content such as its score, total upvotes and downvotes, age, recent activity, and number of comments, with the personalization focused on the time spent by a user on a subreddit. They offer a neat breakdown⁹ of their content recommendation algorithms that are visually accessible on the platform as in figure 1 to generate ranked content 'feeds' for users to browse. Our simulation makes the simplifying assumption that a single algorithm drives all the interactions for users in a single execution trace in order to address the concerns of interaction effects as we study algorithmic integrity in this setting. This is a trivial assumption to drop as we could simulate interactions with potentially a different choice of recommendation algorithm at each timestep.

7. Results

We parametrize our simulator with informed priors drawn from historical agent-level behavior. This includes accounts that have a history of engagement with misleading posts and continue to engage in coordinated behavior on the platform. The simulator is then run in a 'forward' execution mode in order to generate interaction data between users and content on the social network. In order to examine the robustness of the recommendation algorithm to the type of coordinated activity, we track the metrics across multiple execution traces of the simulation. We consider four recommendation algorithms on Reddit:

- 1. Controversial: Promotes content with a large number of upvotes as well as a large number of downvotes
- 2. Rising: Promotes recent content with a large number of comments and upvotes
- 3. Top: Promotes content from a fixed time period with a large number of upvotes
- 4. New: Promotes content based on lower age

The preliminary results in 3 indicate interesting dynamics are emerging in the system such as the controversial recommendation algorithm resulting in much higher views of disinformation over time while the rising algorithm almost entirely diminishes the disinformation views. We continue to examine interesting patterns in our ongoing experiments.

8. Future Work

8.1. Measuring Interventional Impact on Misinformation Spread

It is well-documented that recommender systems, underpinning most engagement on social networks, have egregious design flaws resulting in disturbing consequences. Yet, a causal understanding of the impact of recommender systems

⁹https://www.reddit.com/r/blog/comments/ o5tjcn/evolving_the_best_sort_for_reddits_ home_feed/

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Figure 1. Reddit's Feed permits users to choose their content ranking and recommendation algorithm



Figure 2. Collecting a large-scale dataset of user interactions from Reddit via Pushshift

has remained tenuous in practice, partly owing to a lack of opportunities for long-term studies involving empirical data. We provide a rich test-bed for estimating the longitudinal impact of interventions on social networks, in particular on content ranking and recommendation algorithms. This extends the means to study the societal impact of recommendations (?) including the side-effects of interventions on user behavior. Our work also makes it possible to study the adversarial nature of combating online disinformation by employing reinforcement-learning based policy-learning mechanisms to check what strategies are learnt by agents trained to promote disinformation or gain influence over longer time horizons and how they could be countered.

8.2. Community-specific Behavioral Modeling

The ecosystem we present can be used to study novel agent behaviors specific to a community with specialized simulations to detect problematic user-level patterns particular to a subreddit. One can model user activity on subreddits that are known to contain a history of misleading posts. For further evaluation, we can collect verified misleading posts relating to the COVID-19 pandemic from the subreddit 'r/coronavirus'. One can then divide these posts into a training and test set and collect historical user activity for those accounts that engage with the misleading posts. The detection strategy could employ simulation-based inference to identify instances of coordinated behavior among these accounts which would be evaluated using the test dataset. In such a setup, one can also track the false positive rate of a detection strategy using the fraction of detected CIB occurrences involving the account that share a verified post containing misinformation. This also provides insight into the long-tail of agent behaviors particularly in communities

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where there is a skewed record of agent-behaviorsin the collected dataset (Krishnan et al., 2018). By encoding theories
of social influence (Hsu et al., 2021) in combination with
community dynamics in an intuitive simulation, one can
communicate the learnings to a broader audience than was
previously possible . This is a part of ongoing work within
the simulation framework we provided.

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Figure 3. Preliminary Results of Simulating the impact of Brigading on Reddit for (1) Controversial (2) New (3) Rising (4) Top Ranking Algorithms





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Sample of unique subreddit categories ordered by no. of subcategories