

Distinguishing influence-based contagion from homophily-driven diffusion in dynamic networks

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Node characteristics and behaviors are often correlated with the structure of social networks over time. While evidence of this type of assortative mixing and temporal clustering of behaviors among linked nodes is used to support claims of peer influence and social contagion in networks, homophily may also explain such evidence. Here we develop a dynamic matched sample estimation framework to distinguish influence and homophily effects in dynamic networks, and we apply this framework to a global instant messaging network of 27.4 million users, using data on the day-by-day adoption of a mobile service application and users' longitudinal behavioral, demographic, and geographic data. We find that previous methods overestimate peer influence in product adoption decisions in this network by 300–700%, and that homophily explains >50% of the perceived behavioral contagion. These findings and methods are essential to both our understanding of the mechanisms that drive contagions in networks and our knowledge of how to propagate or combat them in domains as diverse as epidemiology, marketing, development economics, and public health.

dynamic matching estimation | peer influence | social networks | identification

The recent availability of massive networked data sets has enabled studies of population-level human interaction at unprecedented scale (1–3). Such studies document the persistent structural properties of networks (4), how they form, evolve, and dissolve (5), and how their structure is correlated with social interaction (1, 6, 7), individual and collaborative team performance (8–11), health outcomes (12–14), and global product demand patterns (15). Networks of interactions among individuals also provide the primary pathways along which viral contagions spread in social, biological, technological, and economic systems (16–18), which may explain why network structure is correlated with such a variety of outcomes. Yet although many studies model the dynamics of viral spreading by using assumptions about susceptibility rates, transition probabilities, and their relationships to network structure, few large-scale empirical observations of networked contagions exist to validate these assumptions (16–18).

We analyze a new, large scale dataset which comprehensively captures the diffusion of a mobile service product over a social network for 5 months after its launch date. A key challenge in identifying true contagions in such data is to distinguish peer-to-peer influence, in which a node influences or causes outcomes in its neighbors, from homophily, in which dyadic similarities between nodes create correlated outcome patterns among neighbors that merely mimic viral contagions without direct causal influence (19). Although the diffusion patterns created by peer influence-driven contagions and homophilous diffusion are similar, they are likely to result in significantly different dynamics. Influence-driven contagions are self-reinforcing and display rapid, exponential, and less predictable diffusion as they evolve (18, 20), whereas homophily-driven diffusion processes are governed by the distributions of characteristics over nodes. These distinctions make distinguishing true contagions from homophilous diffusions at early stages important for the success or failure of contagion management efforts.

As more of a perceived contagion is explained by homophily rather than peer influence, intervention strategies should shift from peer-to-peer methods based on network structure to outreach based on population segmentation across individuals' characteristics. Formal procedures for separating influence and homophily are therefore essential to support policies that encourage or discourage the spread of behaviors in networks, from health interventions to viral marketing campaigns.

Contagions and homophilous diffusion are both typified by correlations between network structure and individual outcomes over time (1–3, 5–11, 17, 21, 22). Two empirical patterns have been used to substantiate claims of peer influence and contagion in networks (*i*) *assortative mixing*—correlations of behaviors among linked nodes (23, 24)—and (*ii*) *temporal clustering*—temporal interdependence of behaviors among linked nodes (12–14, 25–27). Because peer influence is likely to lead to assortative mixing, some studies claim assortative mixing is evidence of peer influence (12–14, 25–27). Evidence of temporal clustering is used to corroborate these claims because as Anagnostopoulos et al. (25) argue “if influence does not play a role, even though an agent's probability of activation could depend on her friends, the timing of such activation should be independent of the timing of other agents.” Yet, while evidence of assortative mixing and temporal clustering in outcomes may indicate peer influence, social contagion, and viral spreading, such outcomes may also be explained by homophily—the demographic, technological, behavioral, and biological similarities of linked nodes (28). If ties are more likely between similar nodes, their outcomes could be correlated because of inherent similarities in their characteristics rather than as a consequence of their interactions. On one hand, linked nodes may directly influence one another to exhibit similar outcomes, creating viral contagions. On the other hand, linked nodes may simply have greater likelihoods of displaying correlated outcomes, in time and in network space, as a consequence of their similarities.

Here we develop a matched sample estimation framework to distinguish influence and homophily effects in dynamic networks, and we apply this framework to a unique dataset documenting product adoption in a large network. We find that previous methods significantly overestimate peer influence in this network, mistakenly identifying homophilous diffusion as influence-driven contagion.

Data

We apply our statistical framework to a longitudinal dataset that combines: (*i*) the global network of daily instant messaging (IM) traffic among 27.4 million users of Yahoo.com (Fig. 1) with (*ii*) data on the day-by-day adoption of a mobile service application

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of adoption decisions. If friends are more similar, they are more likely to have similar strengths of preference for Go and similar desires to be “early adopters” of mobile technology services, making them more likely to adopt contemporaneously even if they do not influence one another. These alternative explanations frame a foundational puzzle: Do social choices and behaviors exhibit assortative mixing and temporal clustering in networks because of influence (friends induce friends to adopt), or homophily (friends have similar backgrounds and tastes), and when is one explanation more likely than the other? Robust answers to this question require a statistical framework that estimates influence by taking into account how individual characteristics and similarities among linked nodes may drive assortative mixing and temporal clustering. Some work on the identification of peer effects in networks [e.g., Oestreicher-Singer and Sundararajan (15), Brock and Durlauf (30), and Bramouille et al. (31)] has developed following seminal work by Manski (32) and Frank and Strauss (33), or models of the co-evolution of networks and behaviors by Snijders (34), methods based on exogenous shocks to peers [e.g., Tucker (35)], or examination of random assignments [see the Dartmouth Roommate studies, e.g., Sacerdote (36)]. However, identification conditions are strict, methods are not typically scalable to large networks, observation of random assignment is rare, and shocks to peers used as instruments are rarely truly exogenous because social relationships typically signal unobserved reasons why these shocks should be correlated among peers. We therefore attempt to describe a scalable and widely applicable alternative method to distinguish homophily and influence, one of which complements existing research on the identification of peer effects.

Methods

In the context of product adoption, peer influence is associated with the presence of adopters in one's local network (the treatment). However, identification of causal peer influence effects (37) is complicated by the unobservability problem (38). Each user either has adopter friends or not, making it impossible to observe whether those with adopter friends (the treated) would have adopted had they not had adopter friends. Homophily in this case creates a selection bias because treatments are not randomly assigned: adopters are more likely to be treated because of similarity with their neighbors. Thus, frequently used methods such as regression analysis, which can only establish correlation, are insufficient. Causal treatment effects can, on the other hand, be estimated by matched sampling, which controls for confounding factors and overcomes selection bias by comparing observations that have the same likelihood of treatment.

Toward this end we adapt matched sample estimation (2, 38) for use in dynamic networked settings. Conditioning matches on a vector of observable characteristics, behaviors, and attributes yields influence estimates that account for the homophily that may make product adoption decisions cluster in the network even if no influence exists. This procedure establishes upper bounds on the degree to which influence (rather than homophily) explains assortative mixing and temporal clustering in networks. Because influence can vary over time, our framework provides estimates of its evolution. We can also assess the marginal influence of having any number of friends.

We created a dynamic matched sample of treated and untreated nodes over time, where receiving various degrees of the treatment is defined as having 1, 2, 3, or 4 or more friends who adopted the product. We matched treated nodes with untreated nodes that were as likely to have the same number of adopter friends, conditional on a vector of observable characteristics and behaviors (X), but who did not have as many adopter friends. For every period, we estimated p_{it} , the propensity to have been treated at time t , using a logistic regression of the likelihood of having a friend who adopted as a function of users' attributes and dynamic behaviors up to and on day t , as follows:

$$p_{it} = P(T_{it} = 1 | X_{it}) = \frac{\exp[\alpha_{it} + \beta_{it}X_{it} + \varepsilon_{it}]}{1 + \exp[\alpha_{it} + \beta_{it}X_{it} + \varepsilon_{it}]}$$

where T_{it} is the treatment status of i on day t and X_{it} represents the vector of demographic and behavioral covariates of i . As treatment status (the number of friends who have adopted), adoption outcome (whether the focal node has adopted), and the vector of observable characteristics X_{it} all vary over time, we performed daily, weekly, and biweekly matched sample tests over the 4-month period. We dropped matched pairs for which the distance of pro-

pensity scores exceeded two standard deviations of the observed distribution of propensity score differences. For all treated nodes i , ($\forall i, T_{it} = 1$) we chose an untreated match j such that $\|p_{it} - p_{jt}\|$ is minimized subject to $\min\|p_{it} - p_{jt}\| < 2\sigma_d$ where $d = p_{it} - p_{jt}$. This process yielded matched pairs who are equally likely to have a certain number of adopter friends because of observed and correlated latent homophily, contrasting them on the sole dimension of their neighbors' actual adoption status—treated nodes had more adopter neighbors than their untreated matches. We then compared fractions of treated (n_{+}) and untreated (n_{-}) adopters over time.

To apply this framework to explain temporal clustering we defined treated users as those with friends who had adopted within certain time intervals of one another (1 day, 2 days, 3 days, etc). For a given recency (R), we considered a user as treated if one of his friends had adopted Go within the specified time interval ($\Delta t = t_i^a - t_j^a = R$) where t_i^a is the adoption time of the adopter i , and t_j^a is the adoption time of adopter j , a friend of i . Multinomial logistic regression was again used to compute estimates of the propensity of a user to be treated, i.e., the likelihood to have had a friend who had adopted R days earlier. Once propensity scores were computed, treated users were matched with untreated users having the closest likelihood of being treated. Untreated users, as before, were those who have no adopter friends within the time window. We again dropped pairs for which the distance of propensity scores exceeded two standard deviations of the observed distribution of propensity score differences. Influence estimates are thus bounded from above by the ratio of the number of treated adopters (n_{+}) to the number of untreated adopters (n_{-}). This procedure was repeated for a range of time intervals from 0 to 6 days ($\Delta t \in [0, 6]$) (Fig. 3D) where 0 corresponds to friends adopting Go on the same day. Full details regarding propensity score matching methods are provided in [SI, Propensity Score Matching](#).

Results

To assess the upward bias in influence estimates created by homophily we compare our method (Fig. 3B) to random matching (Fig. 3A) which matches each treated node to a randomly selected node without conditioning the match on the vector of observable characteristics X_{it} and is analogous to methods commonly used to assess influence in networks: comparison to randomized or shuffled networks (12–14, 25, 26). Because friendship is not random, the selection of a random control group does not control for homophily, which may lead to a greater assessed likelihood of adoption among those with adopter friends. Indeed, in the first biweekly comparison, the fraction of treated adopters is 9 times greater than the fraction of randomly matched untreated adopters when treatment is defined as having 1 or more friends who adopt the product (Fig. 3A, open circles), implying that those with 1 or more adopter friends are 9 times more likely to adopt than a randomly selected “control” group. The implied marginal increases in adoption likelihoods for having 2, 3, and 4 or more adopter friends (for which the results imply a 15-fold increase in the average adoption likelihood) are also shown.

When we compare these results to those produced by dynamic matched sampling, which accounts for homophily and individual characteristics, estimates of influence are substantially reduced (Fig. 3B). In the first biweekly comparison the fraction of treated adopters is only ≈ 3 times greater than the fraction of matched untreated adopters when the treatment is defined as having 1 or more adopter friends (filled circles). The random matching estimates are 7 times greater than our matched sample estimates for the effect of having four or more adopter friends, implying that random matching overestimates influence by up to 700%.

Random matching overestimates influence to a greater degree earlier in the product lifecycle, whereas matched sample estimates are consistent over time (Fig. 3A and B). We speculated that exaggerated homophily among early adopters leads to greater upward bias in random matching influence estimates in earlier periods. Cosine distances of attribute vectors between adopters and their adopter and nonadopter friends over time confirm that early adopters are indeed more similar to each other and less similar to their nonadopter friends than later adopters are to their respective adopter and nonadopter friends (Fig. 3C). Intuitively, estimates of influence that do not account for homophily display greater upward bias in contexts where greater homophily exists, as is the case with

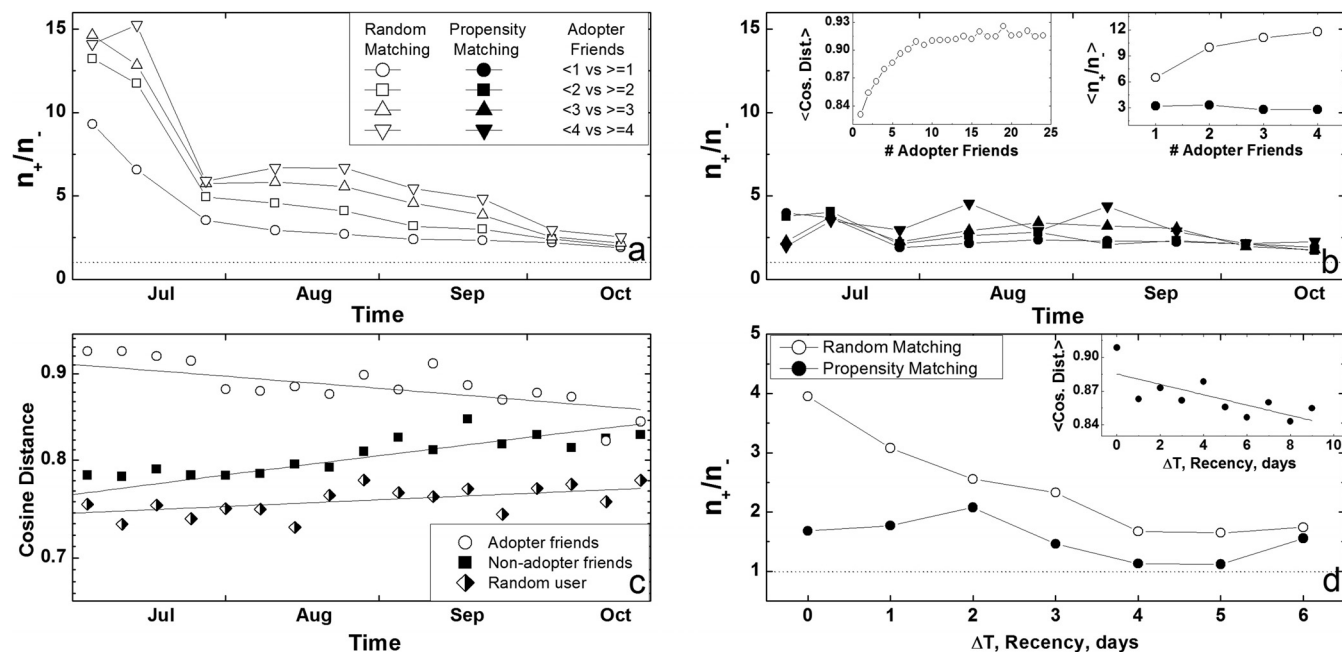


Fig. 3. Distinguishing homophily and influence. (A and B) The fraction of observed treated to untreated adopters (n_+/n_-) under random (A) and propensity score (B) matching over time. The dotted line shows a ratio of 1, when treatment has no effect. The *Right Inset* in B graphs the average marginal influence effects of having 1, 2, 3, or 4 adopter friends implied by random (open circles) and propensity score (filled circles) matching. The *Left Inset* graphs the average cosine distance of attribute and behavior vectors of adopters to adopter friends as the number of adopters in the local network increases ($\sum_{i,j} \cos(x_{it}^a, x_{jt}^a)/n$). (C) Graphs the cosine distances of adopters to their adopter friends $\cos(x_{it}^a, x_{jt}^a)$, their nonadopter friends $\cos(x_{it}^a, x_{jt}^b)$, and a random alter $\cos(x_{it}^a, x_{rt}^a)$ over time with trend lines fitted by ordinary least squares. (D) The fraction of treated and untreated adopters, where treatment is defined as having a friend who adopted within a certain time period (or recency) ($\Delta t = t_i^a - t_j^a = R$), under random matching (open circles) and propensity score matching (filled circles). The *Inset* graphs the cosine distances of dyads of adopters $\cos(x_{it}^a, x_{jt}^a)$ by the time interval between their adoption.

early Go adopters. Random matching also implies that the marginal influence of an additional adopter friend grows with the number of adopter friends, whereas propensity score results show linear to diminishing marginal influence effects of additional adopter friends (Fig. 3B *Right Inset*). This occurs in part because there is exaggerated homophily among larger clusters of adopter friends (Fig. 3B *Left Inset*). The more adopters there are in a group of friends the more likely they are to be more similar to one another. Comparisons to random therefore incorrectly imply that influence grows super-linearly with the number of adopter friends, whereas there is simply greater homophily in larger groups of adopters.

Homophily also accounts for temporal clustering. We redefined treatment to capture the effect of having a friend who adopted within a certain time period (or recency) ($\Delta t = t_i^a - t_j^a = R$) and reevaluated results under random and propensity score matching (Fig. 3D). Random matching overestimates the contribution of influence to the temporal clustering of adoption decisions by >200% for dyads that adopt on the same day ($\Delta t = 0$), >100% for dyads that adopt 1 day apart ($\Delta t = 1$), and so on. Friends who adopt contemporaneously are again more similar along observable demographic and behavioral dimensions [measured by $\cos(x_{it}^a, x_{jt}^a)$, Fig. 3D *Inset*], indicating that homophily explains a good deal of variance in the temporal clustering of Go adoption decisions.

Thus, homophily can, to a large extent, explain what seems at first to be a contagious process driven by peer influence. Over half of the cumulative adoption of treated users (those with at least one adopter friend) can be attributed to homophily effects (Fig. 4A and B). The remaining adoption events (49.8%) represent the upper bound of influence effects established by our matched sample estimates. We also evaluated these influence effects under various environmental conditions (by holding out and varying one characteristic (x_i) at a time while matching on all other characteristics, *SI, Environmental Conditions*) and found the upper bounds of influ-

ence vary across different segments of the population. When ego's average strength of ties to adopter friends is above the median, the likelihood of adoption controlling for homophily is on average 2 times higher than when below the median (Fig. 4C). Those with cohesive, dense local networks (with more ties among their friends) adopt at a higher rate in the presence of an adopter friend controlling for observed homophily (Fig. 4D), reinforcing prior arguments that cohesive networks magnify information exchange and persuasion via redundancy and trust (39). Finally, greater consumption of news content makes ego more susceptible to potential influence. Because Yahoo! Go delivers personalized news, those with greater interest in such content are more susceptible to influence, demonstrating the importance of creating robust matches based on contextual behavioral variables (Fig. 4E). These estimates provide examples of the types of environmental conditions that affect the prevalence of influence in networks and demonstrate how to test them.

Discussion

We present a generalized statistical framework for distinguishing peer-to-peer influence from homophily in dynamic networks of any size. Application of this framework to a network of 27 million individuals connected by instant message traffic provides an estimate of the degree to which peer influence and homophily affect the diffusion of a new mobile service application across this network. Most critically, the results show that previous methods overestimate peer influence in this network by 300–700% and that homophily explains >50% of the perceived behavioral contagion in mobile service adoption. These findings demonstrate that homophily can account for a great deal of what appears at first to be a contagious process.

Overestimates of influence are magnified at early stages of the diffusion process because those who are most susceptible are also

