

THE DYNAMICS OF INFORMATION DIFFUSION ON ON-LINE SOCIAL NETWORKS

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Although there has been a long history of studying the diffusion of information in various social science fields, existing theories are mostly built on direct observations in small networks or survey responses from large samples. As a result, it is hard to verify or refute these theories empirically on a large scale. In recent years, the abundance of digital records of online interactions has provided us for the first time both explicit network structure and detailed dynamics, supporting global-scale, quantitative study of diffusion in the real world. Using these large scale datasets collected from social media sites, we are able to dissect and study the process of information diffusion in its three components: people, information, and network. This thesis mainly addresses a few long-standing questions about each component, including: “who influences whom?”, “how do different types of information spread?”, and “how does the network structure impact the diffusion process?” In our search of answers for these questions, we realize that these three components are interconnected, constantly interacting with each other in real-world diffusion processes. Thus our results on each component should not be taken in isolation but be viewed interdependently.

To understand who influences whom in today’s hybrid communication environment, we study people’s influence on social media based on their role in the global media ecosystem. By categorizing Twitter accounts into elite (i.e. celebrities, media outlets, organizations, and bloggers) and ordinary users, we

find a striking concentration of attention on a minority of elite users, and significant homophily within elite categories. On the other hand, following the definition of “opinion leaders” in the classical “two-step flow” theory, we find a large population of opinion leaders who serve as a layer of intermediaries between the elite users and the masses.

The next question we ask is the role of content in the diffusion process. In contrast to previous research on the virality of information, we switch our focus to the persistence of information, trying to understand why certain content keeps on spreading in social media for a long time while most does not. First, we see an interaction effect, from both people and content, on the lifespan of information. As a result, there is a significant difference in lifespan, for information broadcast by different categories of users. Second, we find a strong association between the linguistic style of content and its temporal dynamics: rapidly-fading information contains significantly more words related to negative emotion, actions, and more complicated cognitive processes, whereas persistent information contains more words related to positive emotion, leisure, and lifestyle.

In the end, we conduct a longitudinal study of the local and global structure of several large social networks, asking how and where disengagement happens in the social graph. We find that, although there is a significant correlation in both arrival and departure among friends, the dynamics of departure behave differently from the dynamics of arrival. In particular, for the majority of users with a sufficient number (e.g., greater than 20) of friends, departure is best predicted by the overall fraction of active friends within a user’s neighborhood, independent of the size of the neighborhood. We also find that active users tend to belong to a core that is densifying and is significantly denser than the inactive

users, and the inactive set of users exhibit a higher density and lower conductance than the degree distribution alone can explain. These two aspects suggest that nodes at the fringe are more likely to depart and subsequent departures are correlated among neighboring nodes in tightly-knit communities.

BIOGRAPHICAL SKETCH

Shaomei Wu is a PhD candidate in Information Science department, Cornell University. Coming from a computer science background, she applies computing technologies and methodologies to examine social phenomena. Particularly, she studies how opinions and behaviors emerge, spread, and evolve in social media, using network algorithms, statistical models, language technologies, and social science theories.

Hoping to bridge the gap between computer science and the social sciences, she has worked closely with researchers from different disciplines such as sociology, communication, psychology, and political science. Her work has been quoted in the press, including the Economist, New York Times, Time magazine, San Francisco Chronicle, and USA Today.

She received her M.S. in Computer Science from University of California, Santa Barbara and her B.S. in Computer Science from Tsinghua University.

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CHAPTER 1

INTRODUCTION

Information diffusion is the process of information spreading among people in the society. Common examples of information diffusion include the spread of rumors, beliefs, and behaviors. Having attracted a long-term interest from scholars in different fields, the study of information diffusion is an essential element of many interesting problems, such as the diffusion of innovations [71], the formation of public opinions [46, 82], and the adoption of new products [12]. Historically, most of the research in this area has been done through field observations and/or phone surveys [45, 71] over a small or sampled population. Confined by this methodology, results are usually based on the spread of a specific opinion or product in rather localized networks.

From the spread of telegraphy and telephony, to the wide popularity of social media, the development in digital communication tools has largely changed the way we produce, share, and consume information. The advancement of personal publishing technologies - such as the web, blogs, photo sharing sites, online social networks, and micro-blogs - has made the process of creating and disseminating content much easier and more decentralized. As a result, we are entering - perhaps for the first time in human history - an age with an abundance of information, of tools to generate and share information, of channels to access information, and of freedom to select and filter information. As pointed out by Herbert Simon [76], the factors that limit the speed and scale of today's diffusion process is no longer the availability of information, but the "attention of its recipients". In response to the scarcity of attention, it is the massive, vibrant, hybrid communication environment, in which ideas, opinions, and news

stories travel in an unforeseen speed, breaking the boundary between media, striving for their audience [58].

In this context, diffusion theories from previous work are challenged both at scale and at accuracy. Mostly drawn from single-medium, small-scale diffusion of a particular opinion (or product), are these results still applicable in the viral spread of YouTube videos or news stories over millions of people in various new communication platforms? To answer this question, we need to conduct large scale empirical studies on real-world diffusion processes over many different communication channels. Such a task used to be unimaginable for diffusion researchers. Nowadays, it has become not only possible but also necessary, for the understanding of how information and behavior spread over large population in the information world.

There are two material bases for the large-scale empirical studies presented in this thesis: one is the recent availability of digital electronic records of human behaviors; and the other is the advancement in computing infrastructure to handle the huge amount of data. The popularity of digital electronic communication tools offers great opportunities for us to obtain much better data on how viral cascades actually happen. Comprising both explicit network structure and detailed interaction dynamics, these data sets support large-scale, quantitative studies on real-world diffusion processes. At the same time, big data requires a whole range of new technologies to efficiently store and process large data sets. In the past few years, we have experienced a rapid development in data-intensive computing tools and platforms, especially, the availability of affordable high-performance computation resources (e.g., Amazon Elastic Compute Cloud [1]), and the popularization of low-cost, easy-to-setup MapReduce [32]

environments (e.g., Hadoop [2], Pig [3]). These tools have made it possible to work with the immense data sets, and to uncover interesting patterns of information cascades in large on-line social networks.

These two elements are not only the foundation, but also the active ingredients of our study. They largely expand the study of information diffusion, from a traditional social science, to a natural science involving more quantitative methods and more measurable, replicable results. Most of my work has taken the natural science approach, aiming at qualitative understandings of diffusion processes with quantitative evidences and mathematical models.

Leveraging the power of “big data” and data-intensive technologies, this thesis focuses on the flow of information (and activity) in an on-line environment at a large scale — on-line social media and social networks over millions of people.

In particular, we frequently study the spread of URLs on Twitter. As a highly popular micro-blogging service, Twitter provides a natural environment for the study of diffusion processes. Unlike other online social networks, Twitter is expressly devoted to disseminating information in that users subscribe to the information broadcast by other users; thus the network of potential adoption can be reconstructed by crawling the corresponding “follower graph”. In addition, because of the need of users to share web content, with the restriction of maximal tweet length as 140 characters, URL shortening services (e.g., bit.ly, TinyURL, t.co, etc) are used widely, and effectively tag numerous pieces of information with unique and easily-identifiable tokens. As a result, we are able to observe and trace essentially everything that is spreading on Twitter. Thus although we have only one communication channel, we have a very high level of

resolution and coverage regarding what is being diffused. Meanwhile, although it may be non-representative in some respects, Twitter is very representative in at least one respect — namely it includes essentially all actors of any consequence in the information diffusion process in the society: media outlets and formal organizations of all sizes, bloggers, and public figures like celebrities, as well as tens of millions of ordinary individuals. In this sense, it really is a complete sample of one (admittedly narrow) slice through the diffusion landscape.

We also include studies that are based on data sets from on-line social networks and collaboration social networks, as both an extension and a complement to the results drawn from Twitter. The biggest difference between Twitter and most other social networks is that social networks are usually built on top of bi-directional friendship links, and assume a strong, consistent identity provided by their users, whereas most of the edges in the Twitter network are directed and non-reciprocal, and user identity is rather weak¹. Such differences give rise to some interesting and distinctive patterns for diffusion processes in these two media, ultimately, making the communication through Twitter more similar to traditional mass media broadcasting than to word-of-mouth style information exchange.

Considering information diffusion as the process of *information* traveling among *people* through communication *networks*, we study three key components of this problem:

- *People*, who are the “influentials” and whom are they influencing?
- *Content*, does different types of information spread differently?

¹A small number of users with consistent, real identities are marked explicitly as “Verified Accounts”

- *Network*, what can the macro- and micro-level structure of the network tell us about the underlying mechanism that drives the diffusion process?

Centered around these questions, this thesis is structured in six chapters. Chapter 1 contains an introduction and states the purpose of this work. Chapter 2 includes the basic theories, models, and concepts used in this thesis. Chapter 3, Chapter 4, and Chapter 5 each focuses on one of the three components mentioned above - people, content, and network, respectively. They form the core of this thesis, and will be introduced separately in the following sections of this chapter. In the end, we conclude this work and offer some insights for future work in Chapter 6.

1.1 The Influencer Problem

The role of the influentials as trend makers has been a center piece of many classic theories on information diffusion process [46, 71]. The existence, and the importance, of the influentials also populated by several best-selling books such as *The Tipping Point* [38] and *The Influentials* [47]. Today, challenged by the unbounded opportunity (and efforts) to reach the masses, marketers and PR firms are especially eager to leverage the power of the influentials to “tip” their products. But, who are the influentials?

Classic theories characterize the influentials as a group of very special people. Dating back to the 50s, Katz and Lazarsfeld coined the term “opinion leaders”. They claimed that, comparing to ordinary people, opinion leaders have more social connections and are more media-savvy [46]. Later, scholars study-

ing the diffusion of innovations also suggested that opinion leaders usually own “greater exposure to mass media than their followers”, “are more cosmopolitan”, “have greater social participation”, “have higher socioeconomic status”, and “are more innovative” [71]. Similar ideas were illustrated in best-selling books, in which authors claim that the influentials are “connectors”, “mavens”, and “salesmen” [38], and that influentials play their role actively and constantly, disseminating ideas on various issues - from what to buy to who to vote for [47].

One critique to the classic theories is their lack of empirical supports. Although intuitively sound, these theories about influentials are too general to be operationalized or examined in practice. It was only since the abundance of online interaction data that we saw a new line of empirical work on measuring and quantifying personal influence in diffusion. Most of these works studied influence in two aspects: personal attributes such as demographics and activities, and network attributes such as connectivity and position in the network. Although both aspects are usually considered and studied, most work showed the network attributes more relevant to personal influence [78, 11, 48, 54, 56, 22].

However, we find current knowledge on influence and influentials still limited for several reasons.

First, as most work focused on big cascades, the results can be biased towards the “successful” events that are deemed to be rare. Given the very high failing rate in social media, research [82, 11] argued that influentials have a greater than average chance of triggering big cascades, but “only modestly greater”, and their effect is much less reliable than practitioners had expected.

Second, the *context* of influence is usually overlooked. Influence does not ex-

ist in vacuum. It needs to be exercised by people, with certain communication medium. The context of influence is important, because individuals influence can differ by their expertise [20], the subject [56], and the communication channels [87].

Last but not least, the inconsistency in existing influence metrics is problematic, for two reasons. First, as existing empirical studies measure influence in a variety of ways - from the size of diffusion tree to the probability of passing the cascade to the next hop, it is hard for researchers to compare the results quantitatively across studies. Second, the inconsistency also introduces ambiguity: different types of influence are studied as a whole, regardless different mechanisms that operate behind them. Depending on its origin, there are three well-known mechanisms for influence: interpersonal influence, homophily, and external factors. Accordingly, we need to be able to understand and distinguish three types of influence. The interpersonal influence(a.k.a. social influence, induction) is attributed to the interaction between the influencer and the influencee², and the influencee's adoption of certain idea or behavior is purely induced by the earlier adoption of that idea or behavior by the influencer. The homophily influence comes from the fact that the influencer and the influencee share similar taste and interests, thus the influencee is more likely to adopt even before interaction happens, no matter whether the influencer has adopted or not. The last type of influence is induced by external factors, such as the influencer's expertise or authority in certain domain. The external influence (a.k.a. confounding influence) does not require personal relationship between the two, either involves much of the personal preference or taste. For example, a person is more likely to follow a dietary plan suggested by a medical doctor

²Here, and in the rest of this thesis, when we say *influencee*, we mean the person who are influenced by the influencer.

than a random friend. Knowing these three types of influence, we notice that the influence measured by different empirical metrics is in fact driven by very different mechanisms. For example, the probability of single-hop transmission is associated with a mix of all three types of influence; whereas, the size of big diffusion trees (or the length of long diffusion chains) usually does not reflect the interpersonal influence of the seeding node [78]³. Many previous work did not recognize such difference in the source of influence, and studied the observed hybrid influence as if driven by a single mechanism. Consequently, they may reach a much less accurate picture about the underlying diffusion process. For example, it has been a common mistake to confuse homophily-driven diffusion as influence-based contagion, and to over-estimate social influence. As a result, we have seen an emerging line of research on distinguishing the induction influence from homophily influence. However, there is still little known about the external influence: in most empirical studies, the exogenous influence is mixed and treated as social influence.

In Chapter 3, we approach the influencer problem by focusing on the external influence migrated from other media channels to online social media. First of all, we consider online social media as a medium that carries a whole spectrum of communications, from personal and private interactions to mass media broadcasting. We thus categorize users based on their role in the global communication ecosystem. To reduce the bias towards successful cascades, we study the influence of each category of users in terms of visibility and the ability to stimulate and sustain attention from other users. Our work makes three main contributions:

³The reason behind is that, as some research has shown, personal influence can reach up to three degrees from the ego [24].

- We introduce a folksonomy model for classifying users into “elite” and “ordinary” users according to their role in the media ecosystem, further classifying elite users into one of four categories of interest: media, celebrities, organizations, and bloggers. Our selection of these five categories is to cover a spectrum of communication styles, from mass media, to “mass-personal”, to interpersonal.
- We investigate the distribution of attention among these categories, finding that although audience attention is highly concentrated on a minority of elite users, much of the information they produce reaches the masses indirectly via a large population of intermediaries - local opinion leaders. These local opinion leaders distributed among all classes of users, but are more media-savvy and in general have more followers.
- We find that different categories of users emphasize different types of content, and that content originated by different users exhibit dramatically different characteristic persistency, ranging from less than a day to months.

1.2 The role of content

Although it has been a common belief that different types of information spread differently, the role of content in diffusion process has not been examined thoroughly and systematically. Most empirical work in this area focused on the relationship between information virality and content [13, 42], while some explored the connection between the temporal patterns and the content - but at a very high-level [41, 29]. Generally, due to the skewness of virality and the infor-

mal and sporadic nature of social media content, these studies are limited either by the lack of observations, or — when viewed as content-base predictions — by the relatively weak predictive power.

There are several major challenges here. First, the content (a.k.a. topic) itself is difficult to track, especially when it travels and mutates across multiple media channels over a long period time [58]. Second, predicting the virality of information for each individual person is a very hard problem by itself [11, 79]. Third, given the focus of past work on how people interact with information, modeling such dynamics becomes extremely complicated with many unpredictable elements involved [90, 91, 87, 11].

In Chapter 4, we study the role of content in diffusion process by showing the relationship between the textual characteristics of content and its temporal dynamics when spreading on Twitter. Our approach overcomes the challenges mentioned above in the following ways.

First, we tackle the information tracking problem by taking advantage of the URL shorteners (e.g. bit.ly, TinyURL, etc) commonly adopted by Twitter users. Considering each webpage as a unit of information, the URL shortening services tag a page with a unique token that is easily traceable in Twitter communications. As a result, we are able to track the whole lifespan of a specific webpage by the inclusion of the shortened URL in tweets.

Second, in response to the difficulty of predicting the virality (e.g., scale, transmission probability), we shift our attention to the persistency of information. We compare two extreme temporal patterns in the decay rate of URLs embedded in tweets, defining a predicting task to distinguish between URLs

that fade rapidly following their peak of popularity and those that fade more slowly. Our experiments show a strong connection between content and the temporal dynamics of information.

Third, by studying the webpages instead of individual tweets, we have a much richer, and more static corpus of content that allows us to simplify our model by focusing on the textual content instead of the people or the highly dynamics interactions among them, while still maintaining sufficient degree of freedom to generate a meaningful set of features for our machine learning models.

In the end, another advantage of our approach is that if we can predict the temporal pattern of information based on content alone, we will be able to do that at a very stage, presumably when the information is first generated - which can be of interest to practitioners.

In summary, Chapter 4 presents our study on intrinsic qualities of the content that may effectively determine the dissemination process, especially, the persistence of information. Our two main contributions include:

- We build a classifier that predicts the decay/persistence of information with textual features, providing one of the first empirical studies of the connection between content and temporal variations of information diffusion processes in online social media.
- We investigate the properties of the text that are associated with different temporal patterns, finding significant differences in word usage and sentiment between rapidly-fading and long-lasting information.

1.3 The network effect of disengagement

The structure of network is another interesting component of diffusion research. Although the value of personal connectivity in promoting big cascades was recognized in early diffusion research [72, 46, 45], most classic work emphasized more on the influencers and the content under diffusion. However, as we entering the “the connected age” [83] and living in “the web of influence” [24], the importance of network structure in the process of information transmission and consumption has become more and more prominent. Some of the most groundbreaking work that highlights such importance might be the *Small World* network model [84] and the *PageRank* algorithm [17]: the former shows us how information can travel so fast over a very large population and the later tells us how much we can trust the source of information - based on purely the linkage structure. Inspired by these research, there has been a growing body of work that study network structure systematically and computationally, at various scales. Here, we categorize these work into the following two categories: local aspect and global aspect.

At a local level, many studies have shown the correlation of activity among friends in online communities, and tried to understand the effect of neighborhood structure on the clustering of behaviors (see examples in [5, 9, 28, 64, 73]). Most of these work are built on the premise that user activity is contagious. As such, a user is more likely to adopt new products or behaviors if his friends do so [9, 57]; and large cascades of behavior can be triggered by the actions of a few individuals [38, 72]. With regard to the effect of local structure on the spread of behavior, empirical work has shown that the adoption probability follows a “diminishing return” curve in which it first grows rapidly with a small number

of adopted friends k , then gradually saturates and stops (or even declines) as k gets large [9, 73]. Furthermore, the probability of a user adopting a behavior not only correlates with the number of neighbors who have already adopted, but also with the connectivity among his local neighborhood. For example, the structural closeness of local community (measured by triadic closures or cluster coefficient) has a significant effect on the probability of adoption [9, 73], however, such effect may differ by the types of content under diffusion [73] - idioms and political topics saturate much faster than entertainment topics. Network structure does not only interact with content, some new research also showed the interaction between influence and structure. Burt [18] argued that, besides personal characteristics, the positions in social networks is also very important to opinion leaders. In particular, opinion leaders usually hold the position as “bridges” between otherwise separate communities, thus are able to act as “information brokers”. Influence also decays as it travels away from the source: Wu *et al.* found that the transmission probability decreases as the distance to the center increases [86]. In [25, 26, 36], the authors extended this result and argued that social influence only reaches three hops along the diffusion chain.

In addition to the research efforts on local structure, a number of studies looked at global structure of networks, for the understanding of macro-level dynamics of diffusion. First, given a specific diffusion model of local dynamics (e.g., epidemic models, independent cascade models, threshold models, see next chapter for details), the global structure of network can influence (and explain) certain characteristics of cascades that run on top of it. For example, in [67], the authors simulated the propagation of computer virus in power-law networks, and argued that the persistence of some low-contagious virus is a result of the scale-free structure of the network: when the transmission probability is

less than one, an epidemic has much higher chance to occur in a scale-free network than in a regular network. However, in a following-up work [34], Eguíluz and Klemm showed that a virus with low transmission probability will have very low chance to cascade in power-law networks, when the cluster coefficients are high. On the other hand, the global structure of the diffusion network can also help us to understand the underlying mechanism that drives the process. In many other work, the global structure of the diffusion network is used as benchmark for generative models that simulate the mechanism of diffusion [34, 41, 61]. By modeling the process of nodes arrival and edges creation, these models can generate graphs with observed evolving macro-level structural properties such as degree distribution, edge densification, and diameters shrinking.

While most existing work focuses on the growth of networks and the increase of activity, our work differs by shifting efforts to the dynamics of user departure from social networks, and the decline of activity. What leads people to depart from their social networks? Is inactivity also contagious? Previous studies on user churn in mobile phone networks suggest the existence of social influence at user’s disengagement. Dasgupta *et al.* showed in [30] that the probability of a user churning grows with the number of contacts who already churned. Richter *et al.* studied users in groups based on communication intensity [70], finding a strong correlation between individuals’ propensity to churn and the group-level characteristics, especially, the (in)activity of the “leader” of the group. Does the same group effect exist when people disengage from a social network? A big difference here is the visibility of the behavior. In the case of a mobile phone network, leaving the service usually involves notifying existing contacts and signaling them about the disengagement; in online social

networks, inactivity is less visible and thus should have less influence on others' behavior. However, the extreme case in which all friends depart suggests that there must be some effect. Given such effect, how would a graph evolve structurally after it stops growing, or starts shrinking? There has been some recent theoretical work on modeling the evolution of network structure in the process of "unraveling" [15]. However, built on top of simple game theory principles, these models are not yet examined by empirical data.

In Chapter 5, we study these questions empirically in the context of the DBLP co-authorship network and a large online social network. We show that the network effect of departure operates differently from the network effect of formation. In particular, the departure of a user with few friends may be understood most accurately as a function of the raw number of friends who are active. For the majority of users with larger numbers of friends, however, departure is best predicted by the overall fraction of activity within a user's neighborhood, independent of size. We then study global properties of the subgraphs induced by active and inactive users, and show that active users tend to belong to a core that is densifying and is significantly denser than the inactive users. Further, the inactive set of users exhibit a higher density and lower conductance than the degree distribution alone can explain. These two aspects suggest that nodes at the fringe are more likely to depart and subsequent departures are correlated among neighboring nodes in tightly-knit communities.

CHAPTER 2

BACKGROUND

In this chapter, we will cover some fundamental theories, methods, and applications of information diffusion research. Although not complete, they contain both theoretic and empirical work that are most related to our work, and form the foundation for the research presented in the rest of this thesis.

Before jumping into the literature of information diffusion, we would like to compare the diffusion of information with the physical diffusion process - in which one material gradually diffuses and mixes with another material. There are many similarities between these two processes: they are both familiar phenomena that we see everyday; they both describe the transportation of one material/information in a medium; they are both directional¹; they both involve a certain amount of randomness and irregularity. However, through the development of physics, we have understood the physical diffusion phenomena much better than information diffusion. We know the driving force of diffusion is the “antigradient” of concentration². And we know that although the movement of individual particles is largely random, with an enormous amount of particles, the process can be described and modeled by a few mathematical formulas (Fick’s law [4]). Using these formulas, we can predict very precisely how the diffusive flux travel in medium: the speed, the scale, the density of mixed medium at any time. Comparing to the study of physical diffusion process, our knowledge on the diffusion of information is still very primitive. There has been sev-

¹Physical diffusion goes from non-mixed state to well-mixed state; information diffusion goes from the information source to others.

²There are multiple theories explaining the physical diffusion process, all the results we mentioned here are based on the classic theory - Fick’s law. A more recent theoretic framework from the quantum mechanics point of view were developed by Albert Einstein [35].

eral challenges when studying the process of information diffusion: it is much less tangible, harder to measure or to run experiments, and perhaps less deterministic. However, with today's extensive digital communication logs, and infrastructures set up explicitly for information cascades (such as Twitter and Pinterest), information diffusion process has become more and more tangible, traceable, and measurable. As a result, we have reasons to believe that, soon in the future, we will reach a comprehensive understanding of information diffusion as what we did for physical diffusion. This chapter synthesizes some of the most up-to-date progress in this direction, in three aspects:

1. The theories on the mechanism of diffusion: the essential piece for the understanding of the phenomenon - what is the underlying driving force of information diffusion?
2. Mathematical diffusion models: this line of work has brought diffusion research to a quantitative, computational level, incorporating tools and methods from physicists, mathematicians, economists, and computer scientists to the research of information diffusion.
3. The predictability of virality: one of the most popular applications of diffusion research, and the ultimate goal for most practitioners is to predict, control, and generate viral cascades.

2.1 Mechanisms for diffusion

There are several social theories about the mechanism of how information spread in population.

One of the most popular theories is the social influence theory (also called induction theory), which focuses on the viral spread of contagion through social contacts, and consider the reason that people adopt new ideas, behaviors, and products is *because* their friends already did so. The social influence theory assumes the causal relationship between individual's activities and the activities of those they interact with, stressing the influence people received from their friends when deciding whether to adopt new products or ideas. Social influence can be exerted through word-of-mouth or imitation. And the diffusion process driven by social influence is also called social contagion as it spreads through social interactions like epidemic diseases. There are many work studying the effect of social influence in different settings, such as the diffusion of innovations [77], the adoption of norms [8], and the spread of topics in blog-spheres [43]. Among them, the most striking results are a series of studies on longitudinal personal health data, claiming that obesity [25], happiness [36], and smoking [26], are all contagious through social networks³.

An alternative theory attributes homophily as the driving force of diffusion process. Homophily, is the phenomenon that people tend to befriend with others similar to them, in other words, "birds of a feather flock together". As a result, products or ideas that are appealing to one's friends are likely to be appealing to the ego as well, thus will naturally spread among the group of friends. The key idea here is that individuals adoption is a result of their inherent characteristics instead of their interactions with friends. Homophily, or "selection mechanism", has been studied by sociologists for a long history. People found that social relationships such as friendships and marriages are more frequently

³There have been many debates around the validity of these results and methodology applied. For example, [27, 63] argues that the authors of these work mistaken environmental factors and homophily as social influence.

formed between people with similar demographics characteristics or cultural background [55, 65]. Later work also found the homophily effect prevalent in online social networks, contributing to correlated tastes, opinions, and online behaviors among those who are alike [62, 51, 52].

The third explanation for the spread of products or actions in a social network are exogenous factors that exist outside of the network (also referred as contextual/confounding factors). Such exogenous factors include environment, events, advertising exposure, qualities of the products under diffusion, etc. For example, the popularization of hybrid cars in California between 2008 and 2009 can be attributed mostly to the state policies such as the tax credits, rebates, and car pool privileges. In this case, two friends who both live in the bay area may purchase a hybrid car one after another, however, their decisions are made independently and mostly driven by the state incentives. Thus we can not conclude that one purchases a hybrid car because his friend did so, or people in bay area have an inherent preference for hybrid cars (as people in this area may not purchase hybrid cars any more after the policy ends). Although as prevalent as homophily in real world settings, the importance of exogenous factors are largely neglected in the studies of diffusion until very recently [7]. The nature of information and external events can both drives the diffusion process. In their study of the temporal dynamics of YouTube videos, Crane and Sornette found a class of videos that do not spread virally through social networks, but still receive a lot of attention due to exogenous reasons such as the quality of videos or their association with real world events [29]. Advertisement and brand exposure has a long history driving the spread of products, and such effect still exists on the on-line media. When studying how people “fan” Facebook pages on Facebook social network, Sun et al found the set of fans grow in a large num-

ber of short cascade chains, and the best predictor for the size of diffusion is not the characteristics of individuals who first “fan” the page but the exposure of the page on people’s news feed [78]. Location and environment also largely constraints people’s behavior. In [27], Cohen-Cole et al re-examined the studies about the social contagions of health behaviors [25, 26, 36] and argued that most of observed correlation of behaviors among friends can be explained by environmental factors.

Diffusion processes driven by these three mechanisms have very similar temporal and structural patterns, and are proved to be extremely difficult to be distinguished from each other based on only observational data [6, 75]. As a result, many studies, led by the viral story, have a strong bias towards the social influence while overlooking homophily and exogenous factors. However, in most online and off-line settings, all these mechanisms usually take effect simultaneously when the diffusion is taking place. For example, although the state incentive policies may stimulated the sales of hybrid cars at the first place, early adopters of hybrid cars may also have a very positive opinion about their purchase and recommend it to their friends; at the same time, given the relatively high income and education level of the early adopters, the homophily principle may also determine that these people and their friends are naturally more likely to appreciate and afford the “go green” lifestyle. These factors can also interact with each other and generate a feedback effect that accelerates the spread of new products and ideas [28], making it even more difficult to separate one mechanism from the others. Although difficult, it is still important to identify the major mechanism that drives the diffusion in empirical studies, as it will not only reveal the fundamentally different underlying social mechanisms, but also predict the trend of the diffusion.

Different diffusion mechanisms have different origins. Social influence is usually triggered by other mechanisms such as social identity, trust, or mutual utility, and is always operationalized through social networks. On the other hand, the origin of homophily is individual's preference and benefits of communicating with alike, and it usually operates through social selection, or environmental/structural constraints [50]. In this case, both the social network and the diffusion process running on top of it are results of homophily. Exogenous factors are confound variables that are independent from the social network. Many things can be confound variables, some are external and environmental such as geographical conditions and seasons, some are more internal such as the quality of content [29] and types of people [87] (see Chapter 3). Identifying exogenous factors is crucial to diffusion research as it is necessary to control and understand their effect before we can compare results from different datasets or computer simulations. Also, as exogenous factors are not the properties of the networks but elements related to environment, policy, culture, or psychology, the study of them will connect diffusion research to many other disciplines and bring our understanding about diffusion process to a higher level.

Distinguishing the underlying mechanisms can also help us to better predict the pattern of diffusion process. Different mechanisms will lead diffusion process into different directions in a long run. As authors in [28] pointed out, while social influence usually leads to uniformity in entire social network, homophily tends to fragment the network into smaller communities. On the other hand, the effect of exogenous factors is usually more temporary and context-dependent.

Historically, most empirical studies have been built on top of the social influence mechanism and focused on the Word-of-Mouth(WOM) propagation of

information. In recent years, there has been a rising concern on the mixture of homophily and social influence and a number of work dedicated to tell them apart [5, 28, 6, 7]. However, the effect of exogenous factors is still rarely studied, especially, with empirical data. This can be due to mainly two reasons: first, there has been a wide range of mathematical models and computational tools developed based for analyzing network-based diffusions, thus it is natural to apply these methods to newly available datasets; second, exogenous factors can be latent, heterogeneous, context-sensitive, and usually involve expertise from other domains (e.g. law, politics, communication, art, culture, psychology, environment), making it very difficult for social network researchers to observe and study them with existing methods. In this thesis, we study diffusion of information with special emphasis on the effect of exogenous factors, such as the external role of users (see Chapter 3), and the linguistic characteristics of content (see Chapter 4). Although we also present results on the correlation of user disengagement in relation to local and global network structure (see Chapter 5), we are aware that there may be other confound variables that we did not include in the study, thus will not declare the causal relationship between the disengagement of friends and the disengagement of the ego.

2.2 Diffusion models

People have long observed some regularities in diffusion process. Some first attempt to depict such regularities can be traced back to French sociologist Gabriel Tarde’s plot of “S-shaped” adoption curve [31]. As described by the S-shaped curve, the adoption rate usually starts as low, rises up quickly, slows down later, and eventually goes flat. Frank Bass later developed a more general model that

describes the process of diffusion as the interaction between existing and potential adopters, in a large population [12]. In Bass model, adoption rate $F(t)$ can be calculated using the following formula:

$$f(t) = (1 - F(t)) \times (p + qF(t)), \quad (2.1)$$

where:

- t is time;
- $F(t)$ is the adoption fraction (i.e., the ratio of adopted population to the ultimate market potential population);
- $f(t)$ is the rate of change of adoption fraction $F(t)$;
- p is the coefficient of innovation, representing the “external influence or advertising effect”;
- q is the coefficient of imitation, representing the “internal influence or word-of-mouth effect”.

Developed almost half century ago, Bass model has been one of the most influential diffusion model in economics and marketing. One strength of Bass model is that it insightfully incorporated two distinct diffusion mechanisms: the social influence (word-of-mouth) mechanism and the exogenous factors mechanism. Using Bass model, the S-shaped curves can be understood as a special condition for diffusion when advertising effect p equals to 0. Traditionally, Bass model has been very powerful at predicting the impact of advertising effect p : given that advertising has been the dominant force for product diffusion, if we ignore the WOM effect, $F(t)$ becomes a constant with value $1 - \frac{1}{p}$, thus can be directly calculated with an empirical estimation of p . However, with the popularity of on-line social networks, there has been more and more attention, and

evidence on the WOM effect q . Sometimes, the entire ad campaign runs only through WOM propagation (e.g., the early launch of Gmail), without any formal advertising. In this context, Bass model becomes limited, as it assumes the WOM effect q is known, while in reality it is very difficult to measure or control the WOM effect q , which can also vary from person to person. In summary, Bass model can only describe the diffusion process at the population level, and it is not able to capture the dynamics among individuals in the networks.

To study the diffusion process through social networks, people have exploited the similarity between the spread of information and epidemics through social contacts, and adopted a series of epidemics models to describe social contagions [10]. The key concept of classic epidemics models is the status of a host (or node in social networks): a person is first *susceptible*(**S**) to the disease, then becomes *infected*(**I**) (and thus *infectious*) after enough exposures to infectious contacts, eventually, he will be *recovered*(**R**) (or *removed*, depending on the type of disease). After recovered, a person can be immune to the disease for a certain period of time, until he becomes susceptible again. Depending on the length of immunity period, we can apply the *SIR* model in which all recovered people have lifelong immunity, or the *SIRS* model which allows a recovered person to become susceptible again. When studying the adoption of products or behaviors, we can easily apply the epidemics model: after corresponding the product to the disease, the potential customers are the susceptible nodes, the existing customers are the infected nodes, the existing customers who used up the product are recovered, and then recovered nodes become susceptible again if they will possibly purchase the product again. *SIR* models are widely applied to simulate diffusion processes over large social networks. In [37], Girvan et al used *SIR* model to explain and simulate periodic outbreaks of diseases.

In [33], Dodds et al studied SIR models over small-world network [84], and presented several strategies for preventing or facilitating diffusions over such network structure. Many empirical studies also use SIR model as the framework to describe real-world diffusion phenomena. For example, In [21], Cha et al used SIR model to characterize the cascade of users “favorite” a photo in Flickr network; and in [53], Kumar et al used two variants of the traditional SIR model to model the diffusion of topics in blogosphere.

One problem of traditional epidemic models is that they assume a constant propagation across the network, thus can not fully address the interpersonal dynamics of diffusion at the individual level. As a result, two classes of diffusion models have been developed to better describe the adoption process for individuals in social networks. The first class are *threshold models* [40]. In threshold models, each node u has an adoption threshold $p_u \in [0, 1]$, and a set of *connection weights* $w_{u,v}$, for all nodes v that are connected to u . A node u will adopt the product once the connection weights of his neighbors who already adopted the product pass his adoption threshold, $\sum_{v, (u,v) \in E, v \text{ already adopted}} w_{u,v} \geq p_u$. The more recent class of these models are *cascade models*, which focus on the influence from an adopted node u to his friends v , $p_{u,v} \in [0, 1]$. In cascade models, after a friend u adopts the product, node v will also adopt it with a probability $p_{u,v}$. These two classes models have been proved to be statistically equivalent [39, 48]. In applications, threshold models highlight the “accumulated effect” and can easily describe the “complex contagion” process [19], whereas cascade models are more used for simulation of diffusion [39].

These diffusion models are very helpful at characterizing the diffusion process and have formed the foundation of today’s diffusion research. New ex-

tension to these models includes applying them on different topological structures [67, 34, 33], and adding constraints of the adoption threshold and the cascade probability [86]. However, the network-based diffusion models are usually applied with the assumptions that the underlying diffusion mechanism is social influence, and their parameters such as connection weight $w_{u,v}$ and cascade probability $p_{u,v}$ are usually interpreted as personal influence from one person to the other. Here, we would like to call for attention to the possible bias towards social influence, and suggest to use these models more cautiously.

For most of the work presented in this thesis, we did not employ these models directly, but we adopted many concepts described in these models (e.g., susceptible, infectious, connection weight, cascade probability), and employed the quantitative methodology derived from these models.

2.3 The predictability of virality

With viral videos and memes outbreak and circulating in the Internet almost everyday, brands and politicians are eager to leverage the power of social networks and run online campaigns that “go viral”. The demand from the market, contrasted with our lack of knowledge on the mechanism behind these viral events, has catalyzed many studies focusing on modeling and predicting the virality of diffusion process. In this line of work, virality is usually defined and measured in three aspects:

1. *Scale*: the size of cascade tree originated from the original node. e.g., the cascade Facebook fanning pages [78];

2. *Range*: the maximal chain length in the diffusion network. e.g., reference links between blog posts [60].
3. *Transmission probability*. As most existing research describe diffusion process with epidemic models, transmission probability is the probability a virus travels through a directional edge in the network and infects the end node. In the context of social networks, transmission probability is mapped to the success rate of interpersonal recommendations in electronic market [56], the probability a tweet is retweeted by the followers of the tweet's author [11], and the likelihood a user mark a Flickr photo as favorite after seeing a friend doing so [22].

With the availability of electronic communication logs and large-scale computing infrastructures, researchers are able to study these aspects of cascades - together with other elements possibly related to these aspects - in great details. However, in practice, it is still very difficult to engineer a success viral campaign [11]. In fact, most marketers and public relation professionals still rely heavily on experience and intuition when launching online campaigns, which mostly received attention in a short time span [91, 29, 89, 87]. Although the virality is still the holy grail for marketers, there has been an ascending suspicion on the whole idea of "predicting virality".

In their Science article published in 2006, Salganik *et al* [74] explored the unpredictability of song ratings, argued that, despite the quality of music, the best predictor for a song's popularity is actually the popularity itself: the songs that received first few thumbs-ups usually rise up to be the hit, even if the first thumbs-ups are given randomly. In this case, the virality is unpredictable until it actually happens, and the first thumbs-ups seem to be crucial. Some later

work [78, 11] further explored the relationship between virality and the early dynamics of cascade, but the findings are rather negative. First, to generate a big cascade, it is not enough to have only a few initial “thumbs-ups”, instead, it requires a large number of seeds initiating small cascade chains altogether. Second, most observable characteristics of the initiators can not predict the final scale of the cascade. Meanwhile, some studies showed that the structure of the subgraph induced by existing adopters do have a role in behavior adoption [9, 73, 60]. However, such role is not consistent in other studies [11], and may depend heavily on the context of diffusion [19].

There are two major factors that might contribute to the difficulty of predicting virality. First, as most studies observed, the long-tailed distribution of the popularity of online content results in a skewed training set consisting of many unsuccessful examples and only a few successful examples. While most machine learning algorithms are not robust to skewed training sets [69], the common practice of biased sampling can over-compensate the successful cases and overlook the unsuccessful ones. As a result, most characteristics we discovered in the positive class can also be found in the negative class - the predictive model would fail to tell one from the other. Second, as we mentioned before, given the fact that online communications is an integrated part of the global communication networks, there are many exogenous factors that can not be controlled or observed in the communication channel where the data is collected. The complexity and the fuzziness of real world diffusion process is innately inadequate to be fully captured by epidemic models [11, 20].

Understanding the difficulty of this task does not mean that it is unsolvable. We have seen tremendous progress towards a better understanding of the vi-

ality, incorporating theories and methods from multiple fields (e.g., [19, 11]). Among these efforts, we argue that, the most urgent task is to expand the definition of virality, and examine viral phenomena in new, and multiple, dimensions.

One of the most intriguing new dimensions is the temporal dynamics of cascade. There has been a growing interest at studying the temporal patterns of diffusion process [91, 29, 59, 58]. Most work in domain has concentrated on the peak of popularity, studying how long it takes to reach the peak, the intensity of the peak, or the interval between multiple peaks. These work has offered interesting insights about diffusion process, such as the connection between content and burstiness [29], and the rhythm of news propagation on social media [58]. While current work focus on bursty events, during our study of the spread of information on Twitter, we discovered and explored a new class of cascades that have been largely overlooked - persistent cascades⁴. We noticed that, although skewed as well, the distribution of the lifespan of information has a much heavier tail towards the end. In other words, there is a substantial amount of information that is consistently tweeted over a long period of time, in the fast-paced medium such as Twitter. When examining the persistent items in depth, we realized that, most of them can not be characterized by any of the traditional metrics for virality: they do not receive many retweets, they do not spread through long-chains, and they are usually not part of super-sized cascades. However, as they generate comparably large interest that lasts for a significantly long period of time, we believe that persistent content are interesting enough to be studied as “success” examples of diffusion as well. We thus propose a new metrics for virality, namely, the longevity of information. In our work, we study in-

⁴In the few previous work that observed the persistent of certain content [29, 79], as most efforts went to content with intense peaks of attention, long-lasting content is usually treated as corner cases.

formation longevity in relation to the initiator and the content (see Chapter 3 and Chapter 4). We show that, using textual features from the content, we can predict the persistent of information at a high accuracy (Chapter 4).

CHAPTER 3

EXOGENOUS INFLUENCE AND OPINION LEADERS ON TWITTER

The belief in influentials and their ability to tip the trend has been the fundamental premise of viral marketing [38, 14]. With a reported “more than \$1 billion spent a year on word-of-mouth campaigns targeting Influentials” [80], quantifying personal influence has become not only a popular research topic, but also a lucrative business¹. Several work studied user influence on Twitter with different topological and activity measures [54, 20, 85]. Most of them found these measures inadequate at describing the notion of influence on Twitter, only capturing part of the dynamics observed. In addition, people noticed a significant presence of “mass-media” communications on Twitter [54], and top users are influential not only by “information value” but by the “name value” they hold outside of Twitter [20]. Our work explored the mass-media aspect of Twitter, and studied the influence of different categories of “elite” users, from “mass-media” (e.g. newspapers, TV channels) to “mass-personal” (e.g., celebrities, professional bloggers).

There is a distinct difference in the mechanisms that drive “mass” influence and “interpersonal” influence. According to classic communication theories, mass influence is exerted through “oneway message transmissions from one source to a large, relatively undifferentiated and anonymous audience”, whereas, “interpersonal” influence plays out through “two-way message exchange between two or more individuals.”

¹Companies that provide influence metrics have emerged and received large amount of attention and financial investments. For example, Klout, Q score, and Appinions.

Recent changes in technology, however, have increasingly undermined the validity of the mass vs. interpersonal distinction. On the one hand, over the past few decades mass communication has experienced a proliferation of new channels, including cable television, satellite radio, specialist book and magazine publishers, and of course an array of web-based media such as sponsored blogs, online communities, and social news sites. Correspondingly, the traditional mass audience once associated with, say, network television has fragmented into many smaller audiences, each of which increasingly selects the information to which it is exposed, and in some cases generates the information itself. Meanwhile, interpersonal influence has become amplified through personal blogs, email lists, and social networking sites to afford individuals ever larger audiences. Together, these two trends have greatly obscured the historical distinction between mass and interpersonal influence, leading some scholars to refer instead to “masspersonal” influence [81].

Twitter has showcased this erosion of traditional categories of influence. The fragmentation of traditional media channels, along with the concomitant rise of social media, have blurred the boundaries between mass and interpersonal communications on Twitter. In particular, audiences associated with formerly “mass” media have shrunk, while social media platforms have empowered individuals to communicate directly with large public audiences; that is, without the intermediation of a media organization. To illustrate, the top ten most followed users on Twitter are not corporations or media organizations, but individual people, mostly celebrities. Moreover, these individuals communicate directly with their followers, often managing their accounts themselves, thus bypassing the traditional intermediation of the mass media between celebrities and fans. In addition to conventional celebrities, a new class of “semi-public”

individuals like bloggers, authors, journalists, and subject matter experts, have come to occupy an interesting role on Twitter, in some cases becoming more prominent than traditional public figures such as celebrities and elected officials. Finally, in spite of these shifts towards masspersonal communication on Twitter, media organizations, along with corporations, governments, and NGO's all remain represented among highly followed users, and are often extremely active.

Twitter, therefore, provides an interesting context in which to study the effect of exogenous factors on social media, especially as Twitter—unlike television, radio, and print media—enables one to easily observe information flows among the members of its ecosystem. However, the effects (e.g. changes in behavior, attitudes, etc) remain difficult to measure on Twitter, and so our study of influence is limited to the distribution of attention and the intensity of interaction within Twitter platform.

To this end, our paper makes three main contributions:

- We introduce a method for classifying users with their external status, using Twitter Lists, into “elite” and “ordinary” users. We further classify elite users into one of four categories of interest—media, celebrities, organizations, and bloggers.
- We investigate the potential influence of these categories, based on how their opinion reach and stimulate the public. We find that although audience attention is highly concentrated on a minority of elite users, much of the information they produce reaches the masses indirectly via a large population of intermediaries.
- We show that different categories of users place slightly different emphasis

on different types of content, and that different content types exhibit dramatically different characteristic lifespans, ranging from less than a day to months.

This section is based on the joint work [87] with Jake Hofman, Winter Mason, and Duncan Watts. Many thanks also go to Sid Suri and Sharad Goel for insightful discussions.

3.1 Data And Methods

3.1.1 Twitter Follower Graph

In order to understand how information is flowing in the Twitter system, we need to know the channels by which it flows; that is, who is following whom on Twitter. To this end, we used the data shared² by Kwak *et al.* [54], which included 42M users and 1.5B edges. This data represents a crawl of the follower graph seeded with all users on Twitter as observed by July 31st, 2009.

3.1.2 Twitter Firehose

In addition, we were interested in the content that was being shared—particularly bit.ly URLs—so that we could trace the flow of information through the Twitter graph. We examined all tweets over a 223 day period from July 28,

²At the time of this study, the data was free to download from <http://an.kaist.ac.kr/traces/WWW2010.html>

2009 to March 8, 2010 using the data from the Twitter “Firehose”. From these 5B tweets we observed 260M bit.ly URLs.

3.1.3 Twitter Lists

Our method for classifying users exploits a relatively recent feature of Twitter: Twitter Lists. Since its launch on November 2, 2009, Twitter Lists have been welcomed by the community as a way to group people and organize one’s incoming stream of tweets by specific sets of users. To create a Twitter List, a user needs to provide a name (required) and description (optional) for the list, and decide whether the new list is public (anyone can view and subscribe to this list) or private (only the list creator can view or subscribe to this list). Once a list is created, the user can add/edit/delete people in the list. As the purpose of Twitter Lists is to help users organize people they follow, the name of the list can be considered a meaningful label for the listed users. List creation therefore effectively applies the “wisdom of crowds” to the task of classifying users, both in terms of their importance to the community (number of lists on which they appear), and also how they are perceived (e.g. news organization vs. celebrity, etc.).

There is not yet a standard way to classify users by lists, or even a central portal to obtain lists for all users. In order to capture the variety of users involved in mass media, masspersonal, and interpersonal communication described previously in a reasonably parsimonious manner, we restrict our attention to four classes of what we call “elite” users: media, celebrities, organizations (including both public and private), and bloggers. In addition to these elite users, we also

study the much larger population of “ordinary” users, as well as the relationships between elite and ordinary users.³

Given the rate limits established by Twitter’s API, moreover, crawling all lists for all Twitter users (reportedly over 100M, where some users are included on tens of thousands of lists) would be prohibitively time consuming. Thus we instead devised two different sampling schemes—a snowball sample and an activity sample—each with some advantages and disadvantages, discussed below.

3.1.4 Snowball sample of Twitter Lists

The first method for identifying elite users employed snowball sampling. For each category, we chose a number of seed users that were highly representative of the desired category and appeared on many category-related lists. For each of the four categories above, the following seeds were chosen:

- Celebrities: Barack Obama, Lady Gaga, Paris Hilton
- Media: CNN, New York Times
- Organizations: Amnesty International, World Wildlife Foundation, Yahoo! Inc., Whole Foods
- Blogs⁴: BoingBoing, FamousBloggers, problogger, mashable. Chrisbrogan, virtuosoblogger, Gizmodo, Ileane, dragonblogger, bbrian017,

³Some third-party sites such as Listorious (<http://listorious.com/>) now maintain categorized directories of Twitter Lists; however, their methodology is not sufficiently transparent for our purposes. We also found their data largely not-up-to-date.

⁴The blogger category required many more seeds because bloggers are in general lower profile than the seeds for the other categories

hishaman, copyblogger, engadget, danielscocco, BlazingMinds, bloggers-blog, TycoonBlogger, shoemoney, wchingya, extremejohn, GrowMap, kikolani, smartbloggerz, Element321, brandonacox, remarkablogger, jsinkeywest, seosmarty, NotAProBlog, kbloemendaal, JimiJones, ditesco

After reviewing the lists associated with these seeds, the following keywords were hand-selected as representative of the desired categories:

- Celebrities: star, stars, hollywood, celebs, celebrity, celebrities-on-twitter, celebrity-tweets, celebrity-list, celebrities, celebsverified
- Media: news, media, news-media
- Organizations: company, companies, organization, organisation, organizations, organisations, corporation, brands, products, charity, charities, causes, cause, ngo
- Blogs: blog, blogs, blogger, bloggers

Having selected the seeds and the keywords for each category, we then did a snowball sample of the bipartite graph of users and lists (see Figure 3.1). For each seed, we crawled all lists on which that seed appeared. The resulting “list of lists” was then pruned to contain only lists whose names matched at least one of the chosen keywords for that category. We then crawled all users appearing in the pruned “list of lists”. We then repeated these last two steps.

Table 3.1 shows how many (a) users and (b) lists were obtained at each level of the snowball sample. In total, 495,000 users were obtained, who appeared on 7,000,000 lists. Because users can be listed in multiple categories (e.g., Oprah

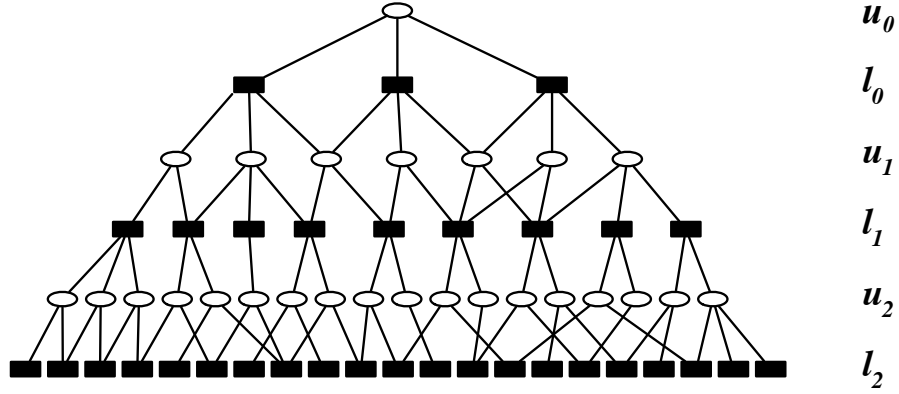


Figure 3.1: Schematic of the Snowball Sampling Method

Winfrey is frequently included in lists of “celebrity” and “media”), we next compute a user u ’s membership score in category c :

$$w_{uc} = \frac{n_{uc}}{N_c}, \quad (3.1)$$

where n_{uc} is the number of lists in category c that contain user u and N_c is the total number of lists in category c . We then assign each user to the category in which he or she has the highest membership score. Users that appear in the follower graph but not in the snowball sample are assigned to the “ordinary” category.

3.1.5 Activity Sample of Twitter Lists

Although the snowball sampling method is convenient and is easily interpretable with respect to our theoretical motivation, it is also potentially biased by our particular choice of seeds. To address this concern, we also generate a sample of users based on their activity. Specifically, we crawl all lists associated with all users who tweet at least once every week for the entire observation

Table 3.1: Snowball Sample

Level	celeb	media	org	blog
u_0	3	2	4	32
l_0	2342	11403	1170	1347
u_1	3607	5025	20122	16317
l_1	30490	71605	4970	9546
u_2	108836	309056	115034	140251
l_2	91873	171912	22518	19946

	Snowball Sample		Activity Sample	
<i>category</i>	# of users	# of lists	# of users	# of lists
celeb	108,836	91,873	22,803	68,810
media	309,056	171,912	66,300	145,176
org	115,034	22,518	19,726	16,532
blog	140,251	19,946	49,987	17,259

Table 3.2: Statistics of crawled lists. The number of users refers only to people who appear in at least one list of the specific category.

period.

This “activity-based” sampling method, which yields 750,000 users and 5,000,000 lists (see Table 3.2 for comparison to the snowball method), is also clearly biased towards users who are consistently active. Importantly, however, the bias is likely to be quite different from any introduced by the snowball sample; thus obtaining similar results from the two samples should give us confidence that our findings are not artifacts of the sampling procedure.

3.2 Distribution of attention

After categorizing people into categories, we can calculate the amount of attention sent and received by each category, at a global level. The approach we take is to measure the reach of the “elite” categories, which can be considered as the influence of each category, as well as an estimate of the impact of the information introduced by each category. In other words, it is the maximal reach of the information produced by each category.

3.2.1 Concentration of attention

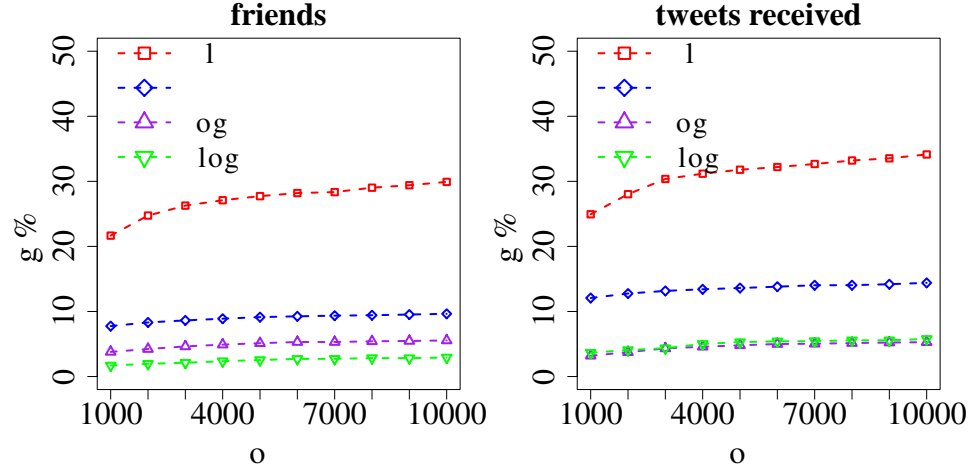
With either sampling method, the initial categorization of users is quite coarse and noisy as a result of the arbitrary labeling allowed in Twitter Lists. To filter categories to the most representative users, we further rank the users in each of the 4 elite categories by how frequently they are listed in each category, and take only the top k users in each category, relabeling the remainder as “ordinary” users. To determine the appropriate k , we measure the flow of information from the four elite categories to an average “ordinary” user in two ways: the proportion of people the user follows in each category, and the proportion of tweets the user received from everyone the user follows in each category. We sampled 100K random “ordinary” users and calculated the average information flow from the “elite” users using these two measures.

Figure 3.2(a) shows that each category accounts for a significant share of both the following links and also the tweets received by an average user, where celebrities outrank all other categories, followed by the media, organizations,

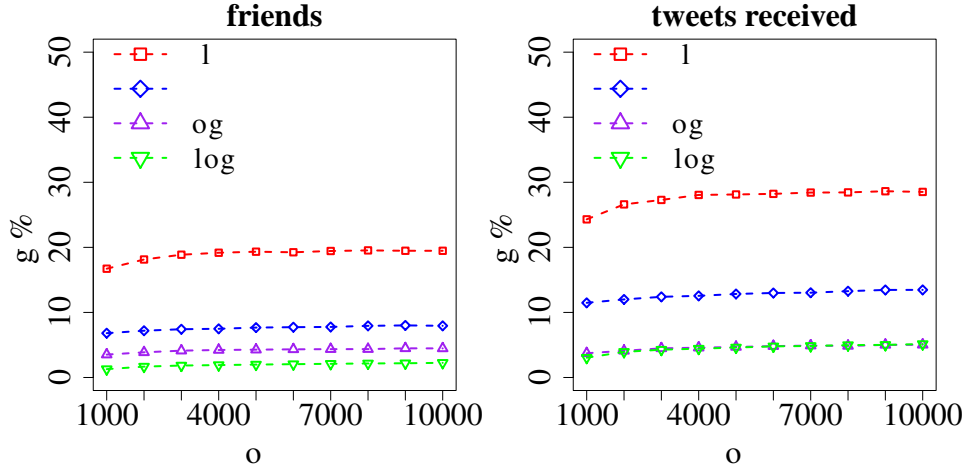
and bloggers. Also of note is that the bulk of the attention is accounted for by a relatively small number of users within each category, as evidenced by the relatively flat slope of the attention curves in Figure 3.2(a). In order to define which users should be classified as “elites”, we seek a tradeoff between (a) keeping each category relatively small, so as not to include users who are not distinguishable from ordinary users, while (b) maximizing the volume of attention that is accounted for by each category. In addition, it is also desirable to make the four categories the same size, so as to facilitate comparisons. Balancing these requirements, we therefore choose 5K as a cut-off for the elite categories.

Consistent with this view, we find that the population of users identified by the activity sample is somewhat different from the snowball sample: the intersection of the two populations is only 20% (100,000 accounts). However, the intersection of the top k users in each population increases as k decreases: for the top 5,000 users in each category, the intersection is 41%, and for the top 1,000 users it is 51%. Thus, although the population of consistently active users is somewhat different from those reached with the snowball sample, the most frequently listed users in both populations tend to be similar. In addition, Figure 3.2(b) shows that the attention paid to the top k users in the four categories is essentially the same as for the snowball sample. Thus in the rest of this chapter, when we talk about “celebrity”, “media”, “organization”, “blog”, we mean the top 5K users listed as “celebrity”, “media”, “organization”, “blog”, respectively, drawn from the snowball sample. Table 3.3 shows the top 5 users in each of the four categories.

To confirm the validity of these categories, we now consider the number of URLs introduced by various categories. As Table 3.4 (left column) shows, the



(a) Snowball sample



(b) Activity sample

Figure 3.2: Average fraction of # following (blue line) and # tweets (red line) for a random user that are accounted for by the top K elites users crawled

vast majority of URLs are initiated by ordinary users, not by any of the elite categories. This result, however, is deceptive: as we have just determined, our elite categories number only 20K users in total, whereas we classify over 40M users in the “ordinary” category. A more calibrated view is presented in the right hand column of Table 3.4, which shows the per-capita number of URLs originating from various categories. Here it is clear that users classified as “me-

Table 3.3: Top 5 users in each category

<i>Celebrity</i>	<i>Media</i>	<i>Org</i>	<i>Blog</i>
aplusk	cnnbrk	google	mashable
ladygaga	nytimes	Starbucks	probblogger
TheEllenShow	asahi	twitter	kibeloco
taylorswift13	BreakingNews	joinred	naosalvo
Oprah	TIME	ollehkt	dooce

Table 3.4: # of URLs initiated by category

<i>category</i>	# of URLs	per-capita # of URLs
celeb	139,058	27.81
media	5,119,739	1023.94
org	523,698	104.74
blog	1,360,131	272.03
other	244,228,364	6.10

dia” far outproduce all other categories, followed by bloggers, organizations, and celebrities. In contrast to the previous result, ordinary users originate on average only about 6 URLs each—far fewer than any category of elite users.

Conceivably, our classification scheme above has omitted an important category; that is, within the current “other” category may be hidden additional categories of opinions. As Figure 3.3 shows, however, even the top 10,000 most followed of these users accounts for a negligible fraction of attention among the remaining population.

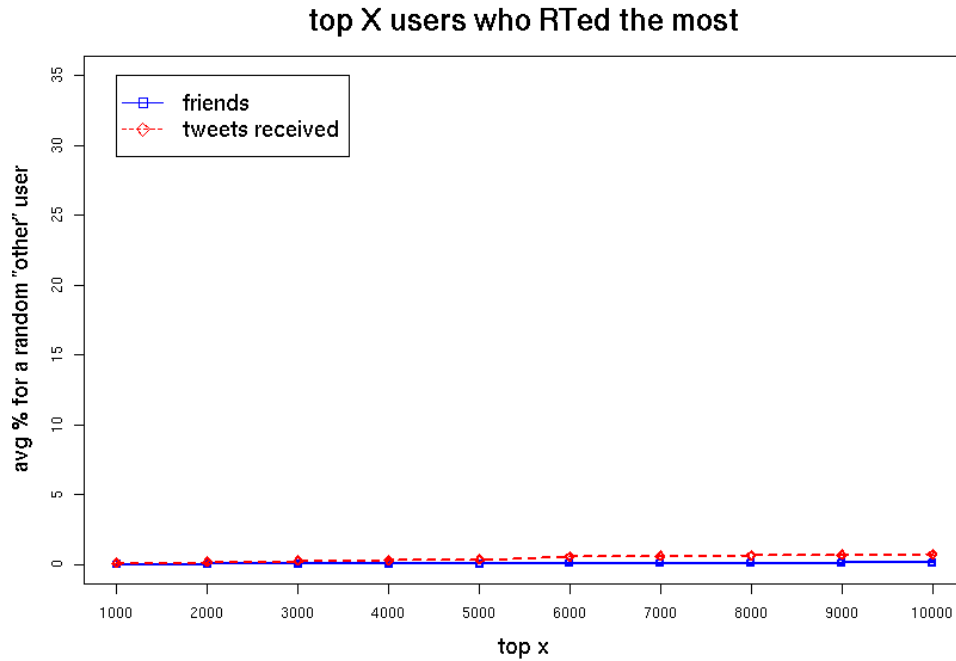


Figure 3.3: Average fraction of # following (blue line) and # tweets (red line) for a random user that are accounted for by the top K most retweeted users in the “Other” category

3.2.2 Homophily of influence

As indicated above, the top 20K elite users account for almost 50% of all attention within Twitter; yet this population of users comprises less than 0.05% of the population. In other words, although Twitter clearly reflects the conventional wisdom that audiences have become increasingly fragmented, it nevertheless shows remarkable concentration of information production and received attention among a relatively small number of actors. Even if the media has lost attention relative to other elites, information flows have not become egalitarian by any means.

The prominence of elite users raises the question of how these different categories listen to each other. To address this issue, we compute the percentage of

Table 3.5: Information flow among the elite categories

% of friends	in celeb	in media	in org	in blog
celeb	30.56	3.63	1.99	1.64
media	3.59	16.67	2.07	2.15
org	3.62	3.33	7.38	2.65
blog	4.41	2.27	2.03	10.25
% of tweets	from celeb	from media	from org	from blog
celeb	38.27	6.23	1.55	3.98
media	3.91	26.22	1.66	5.69
org	4.64	6.41	8.05	8.70
blog	4.94	3.89	1.58	22.55

following links and received tweets among elite categories. Specifically, Table 3.5 shows the average percentage of friends/tweets category i get from category j . Table 3.5 shows striking homophily with respect to attention: celebrities overwhelmingly pay attention to other celebrities, media actors pay attention to other media actors, and so on. The one slight exception to this rule is that organizations pay more attention to bloggers than to themselves. In general, in fact, attention paid by organizations is more evenly distributed across categories than for any other category.

Figure 3.2, it should be noted, shows only how many URLs are received by category i from category j , a particularly weak measure of attention for the simple reason that many tweets go unread. A stronger measure of attention, therefore, is to consider instead only those URLs introduced by category i that are subsequently retweeted by category j .

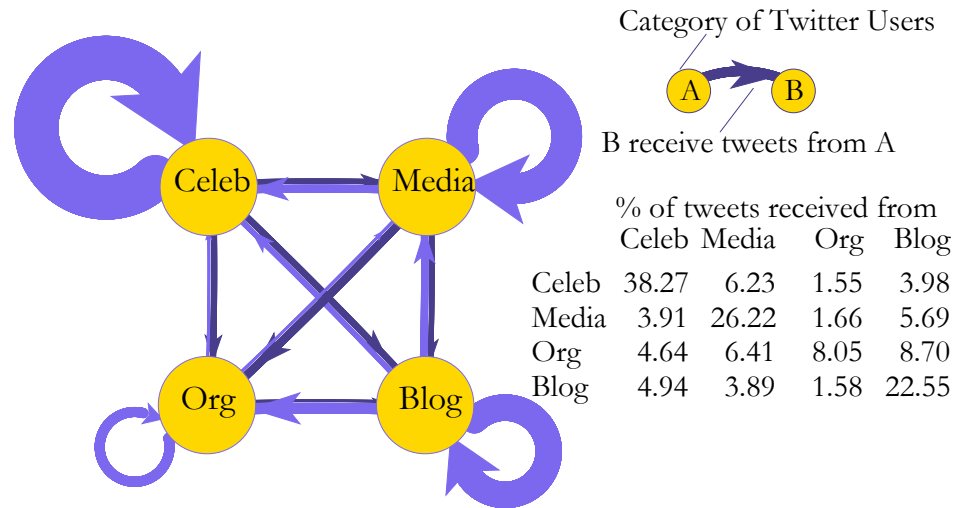


Figure 3.4: Share of attention among elite categories

Before proceeding, it is helpful to differentiate between two mechanisms by which information can diffuse in Twitter. The first is via retweeting, when a user, having received a tweet, subsequently rebroadcasts it to his or her own followers. In some instances, users retweet each other using the official retweet function provided by Twitter, but in other cases they credit the retweet with an informal convention, most commonly either “RT @user” or “via @user.” The second mechanism is what we label reintroduction, where a user independently tweets a URL that has previously been introduced by another user.

In addition to attention, Table 3.6 shows how much information originating from each category is retweeted by other categories, while Table 3.7 shows how much is subsequently reintroduced. As with attention, both retweeting and reintroduction activities are strongly homophilous among elite categories; however, bloggers are disproportionately responsible for retweeting and reintroducing URLs originated by all categories. This result reflects the characterization of bloggers as recyclers and filters of information; however, Table 3.6 and 3.7 also

Table 3.6: RTs among categories

	by celeb	by media	by org	by blog	by other	TOTAL
celeb	4,334	1,489	1,543	5,039	1,070,318	1,082,723
media	4,624	40,263	7,628	32,027	5,204,719	5,289,261
org	1,570	2,539	18,937	11,175	1,479,017	1,513,238
blog	3,710	6,382	5,762	99,818	3,457,631	3,573,303
other	34,455	93,934	86,630	318,537	34,814,456	35,348,012

Table 3.7: Re-introductions among categories

	by celeb	by media	by org	by blog	by other	TOTAL
celeb	2,868	1,239	522	1,664	488,229	494,522
media	1,678	205,165	2,439	9,681	2,006,888	2,225,851
org	816	1,511	8,628	3,711	610,373	625,039
blog	1,415	5,644	1,416	52,909	1,148,137	1,209,521
other	45,547	793,741	69,441	335,690	86,853,224	88,097,643

show that the total number of URLs either RT'd or reintroduced by bloggers is vastly outweighed by the number retweeted or reintroduced by ordinary users. Even though on a per-capita basis, therefore, bloggers disproportionately occupy the role of information recyclers, their actual impact is relatively minimal (see Figure 3.4).

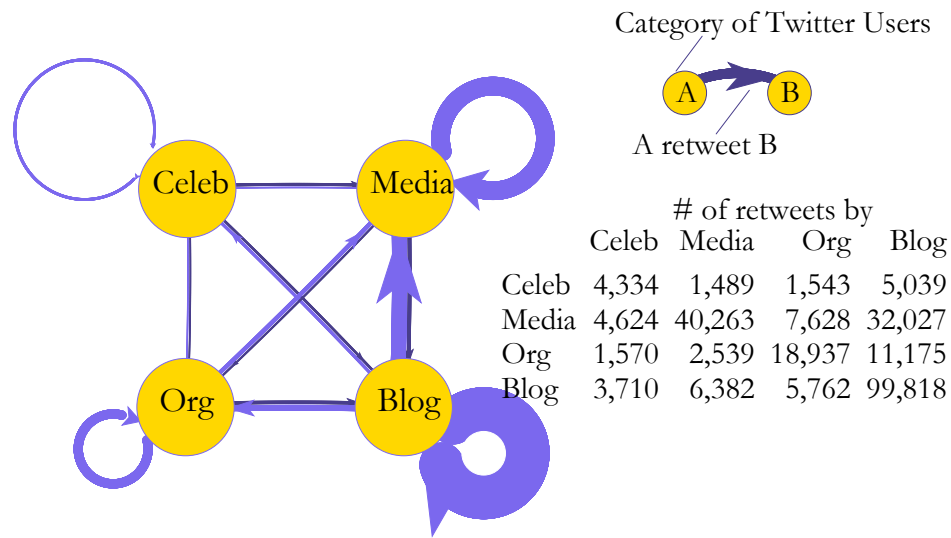


Figure 3.5: RT behavior among elite categories

3.3 Revisiting two-step flow theory: what are the opinion leaders?

The two-step flow theory, first proposed in the 50's, is still one of the most successful theories that captured the dueling importance of mass media and interpersonal influence. The essence of the two-step flow is that information passes from the media to the masses not directly, as supposed by early theories of mass communication, but rather via an intermediary layer of *opinion leaders*, who act as filters and interpreters for their followers. Although deeply acknowledged by marketers, it has been difficult to identify opinion leaders at a large scale, or quantify their impact to the public. As we have already gathered a confident list of mass media accounts, it becomes a natural problem for us to verify the two-step flow theory on Twitter, and ask, what are the opinion leaders, and what proportion of the information originating from media sources is broadcast directly to the masses, and what proportion is transmitted indirectly via some

population of intermediaries. In addition, we may inquire whether these intermediaries, to the extent they exist, are drawn from other elite categories or from ordinary users, as claimed by the two-step flow theory; and if the latter, in what respects they differ from other ordinary users.

Before proceeding with this analysis, we note that there are two ways information can pass through an intermediary in Twitter. The first is via retweeting, which occurs when a users explicitly rebroadcasts a URL that he or she has received from a friend, along with an explicit acknowledgment of the source—either using the official retweet functionality provided by Twitter or by making use of an informal convention such as “RT @user” or “via @user.” Alternatively, a user may tweet a URL that has previously been posted, but without acknowledgement of a source; in this case we assume the information was independently rediscovered and label this a “reintroduction” of content. For the purposes of studying when a user receives information directly from the media or indirectly through an intermediary, we treat retweets and reintroductions equivalently. If the first occurrence of a URL in Twitter came from a media user, but a user received the URL from another source, then that source can be considered an intermediary, whether they are citing the source within Twitter by retweeting the URL, or reintroducing it, having discovered the URL outside of Twitter.

To quantify the extent to which ordinary users get their information indirectly versus directly from the media, we sampled 1M random ordinary users⁵, and for each user, counted the number n of bit.ly URLs they had received that had originated from one of our 5K media users, where of the 1M total, 600K had

⁵As before, performing this analysis for the entire population of over 40M ordinary users proved to be computationally unfeasible.

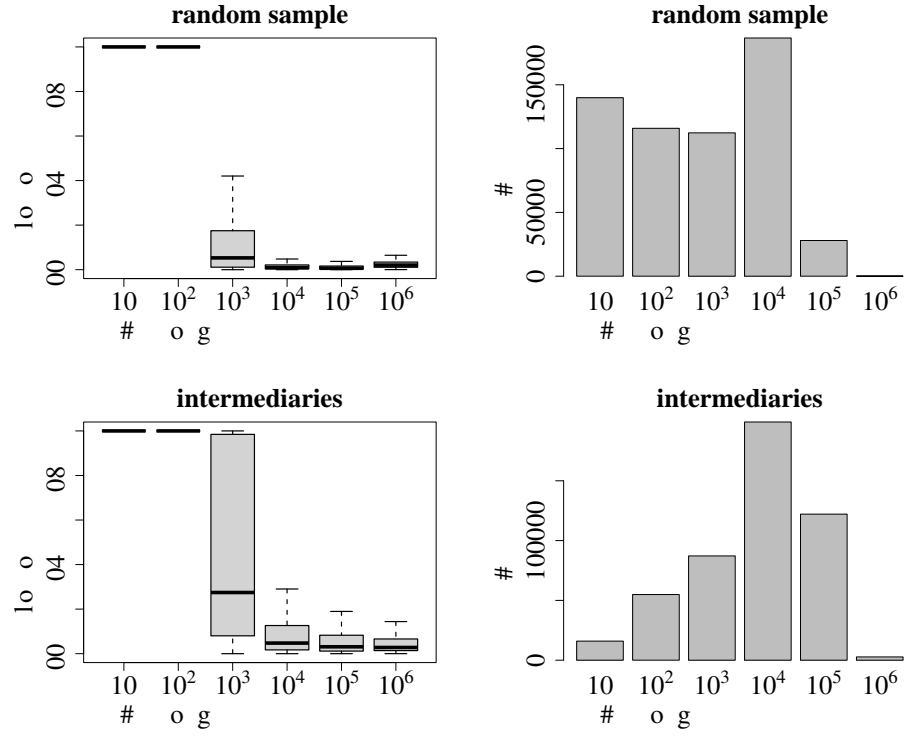


Figure 3.6: Percentage of information that received via an intermediary as a function of total volume of media content to which a user is exposed

received at least one such URL. For each member of this 600K subset we then counted the number n_2 of these URLs that they received via non-media friends; that is, via a two-step flow. The average fraction $n_2/n = 0.46$ therefore represents the proportion of media-originated content that reaches the masses via an intermediary rather than directly. As Figure 3.6 shows, however, this average is somewhat misleading. In reality, the population comprises two types—those who receive essentially all of their media-originating information via two-step flows and those who receive virtually all of it directly from the media. Unsurprisingly, the former type is exposed to less total media than the latter. What is surprising, however, is that even users who received up to 100 media URLs during our observation period received all of them via intermediaries.

Who are these intermediaries, and how many of them are there? In total, the population of intermediaries is smaller than that of the users who rely on them, but still surprisingly large, roughly 490K, the vast majority of which (484K, or 99%) are classified as ordinary users, not elites. To illustrate the difference, we note that whereas the top 20K elite users collectively account for nearly 50% of attention, the top 10K most-followed ordinary users account for only 5%. Moreover, Figure 3.6c also shows that at least some intermediaries also receive the bulk of their media content indirectly, just like other ordinary users.

Comparing Figure 3.6a and 3.6c, however, we note that intermediaries are not like other ordinary users in that they are exposed to considerably more media than randomly selected users (9165 media-originated URLs on average vs. 1377), hence the number of intermediaries who rely on two-step flows is smaller than for random users. In addition, we find that on average intermediaries have more followers than randomly sampled users (543 followers versus 34) and are also more active (180 tweets on average, versus 7). Finally, Figure 3.7 shows that although all intermediaries, by definition, pass along media content to at least one other user, a minority satisfies this function for multiple users, where we note that the most prominent intermediaries are disproportionately drawn from the 4% of elite users—Ashton Kucher (aplusk), for example, acts as an intermediary for over 100,000 users.

Interestingly, these results are all broadly consistent with the original conception of the two-step flow, advanced over 50 years ago, which emphasized that opinion leaders were “distributed in all occupational groups, and on every social and economic level,” corresponding to our classification of most intermediaries as ordinary [46]. The original theory also emphasized that opinion

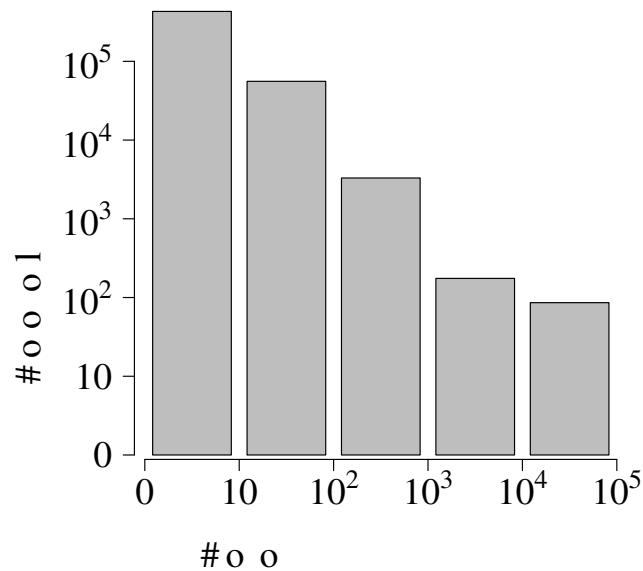


Figure 3.7: Frequency of intermediaries binned by # randomly sampled users to whom they transmit media content

leaders, like their followers, also received at least some of their information via two-step flows, but that in general they were more exposed to the media than their followers—just as we find here. Finally, the theory predicted that opinion leadership was not a binary attribute, but rather a continuously varying one, corresponding to our finding that intermediaries vary widely in the number of users for whom they act as filters and transmitters of media content. Given the length of time that has elapsed since the theory of the two-step flow was articulated, and the transformational changes that have taken place in communications technology in the interim—given, in fact, that a service like Twitter was likely unimaginable at the time—it is remarkable how well the theory agrees with our observations.

3.4 The interaction between people and content

The results in Section 3.2.1 demonstrate the “elite” users account for a substantial portion of all of the attention on Twitter, but also show clear differences in how the attention is allocated to the different elite categories. As illustrated previously, users have natural preferences on content, and influence on Twitter is topic-dependent [56, 20]. It is therefore interesting to consider what kinds of content is being shared by these categories.

Given the large size of the URL population in our observation period (260M), and the large number of ways in which one can classify content (video vs. text, news vs. entertainment, political news vs. sports news, etc.), classifying even a small fraction of URLs according to content is an onerous task. Bakshy et al [11], for example, used Amazon’s Mechanical Turk to classify a stratified sample of 1,000 URLs along a variety of dimensions; however, this method does not scale well to larger sample sizes.

Instead, we restrict attention to URLs originated by the New York Times which, with over 2.5M followers, is the second-most followed news organization on Twitter after CNN Breaking News. NY Times, however, is roughly ten times as active as CNN Breaking News, so is a better source of data. To classify NY Times content, we exploit a convenient feature of their format—namely that all NY Times URLs are classified in a consistent way by the section in which they appear (e.g. US, World, Sports, Science, Arts, etc) ⁶. Of the 6398 New York Times bit.ly URLs observed, 6370 could be successfully unshortened and assigned to one of 21 categories. Of these, however, only 9 categories had more

⁶<http://www.nytimes.com/year/month/day/category/title.html?ref=category>

than 100 URLs over the observation period, one of which—"NY region"—was highly specific to the New York metropolitan area; thus we focused our attention on the remaining 8 topical categories. Figure 3.8 shows the overall RT and reintroduction rates by category. World news is the most popular category, followed by US news, business, and sports, where increasingly niche categories like Health, Arts, Science, and Technology are less popular still. In general, the overall pattern is replicated for all categories of users, but there are some minor deviations: In particular, organizations show disproportionately little interest in business and arts-related stories, and disproportionately high interest in science, technology, and possibly world news. Celebrities, by contrast, show greater interest in sports and less interest in health, while the media shows somewhat greater interest in US news stories.

In addition, we also consider the accumulated RT/Reintroduction behavior for a small selection of the most popular URLs. As Figure 3.9 shows, the link to the official White House blog, which expressed the administration's initial response to the Haiti earthquake, was rebroadcast in largely the same manner by all categories of users, as was the announcement of President Obama winning the Nobel Peace Prize. By contrast, the news story announcing the unexpected death of the actress Brittany Murphy was rebroadcast largely by bloggers, while the breaking news about Tiger Woods' accident and affair was picked up mostly by the news media and other celebrities. Finally, Figure 3.9 shows two examples of URLs that exhibit very different patterns from news stories. First, the URL for DealPlus, a website for "finding, discussing, and sharing thousands of deals and coupons for all types of stores," was popular among ordinary users, but almost completely ignored by all categories of elite users. And second, the video for the song "Brick by Boring Brick," by the band Paramore, was again reposted

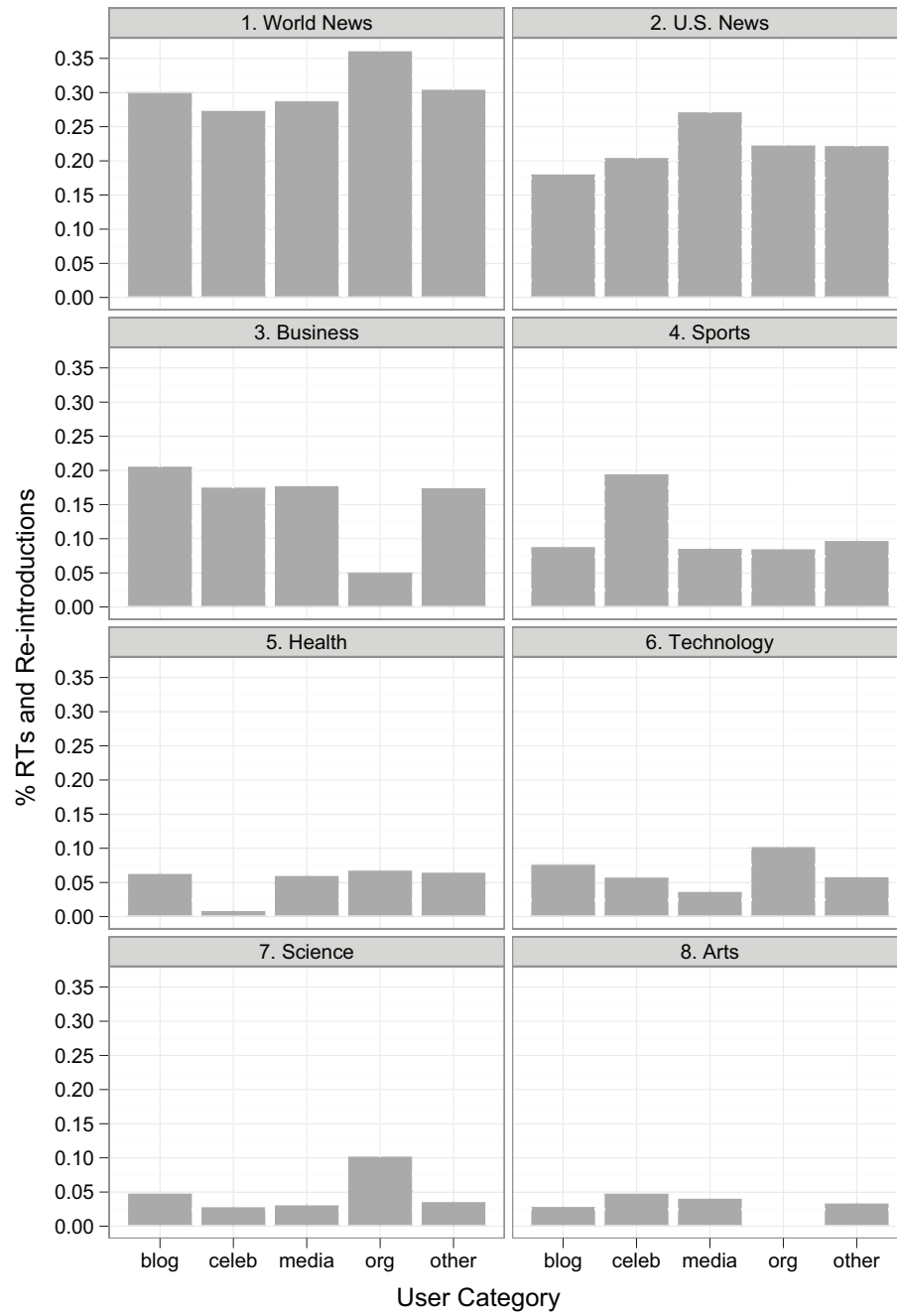


Figure 3.8: Number of RT's and Reintroductions of New York Times stories by content category

mostly by ordinary users, but in this case celebrities also reposted it. Although this analysis is far from systematic, it suggests that different categories of users respond to different sorts of content in ways that are consistent with our classification scheme.

3.5 Lifespan of content by category

In addition to different types of content, URLs introduced by different types of elite users or ordinary users may exhibit different lifespans, by which we mean the time lag between the first and last appearance of a given URL on Twitter.

Naively, measuring lifespan seems a trivial matter; however, a finite observation period—which results in censoring of our data—complicates this task. In other words, a URL that is last observed towards the end of the observation period may be retweeted or reintroduced after the period ends, while correspondingly, a URL that is first observed toward the beginning of the observation window may in fact have been introduced before the window began. What we observe as the lifespan of a URL, therefore, is in reality a lower bound on the lifespan. Although this limitation does not create much of a problem for short-lived URLs—which account for the vast majority of our observations—it does potentially create large biases for long lived URLs. In particular, URLs that appear towards the end of our observation period will be systematically classified as shorter-lived than URLs that appear towards the beginning.

To address the censoring problem, we seek to determine a buffer δ at both the beginning and the end of our 223-day period, and only count URLs as having a lifespan of τ if (a) they do not appear in the first δ days, (b) they first appear

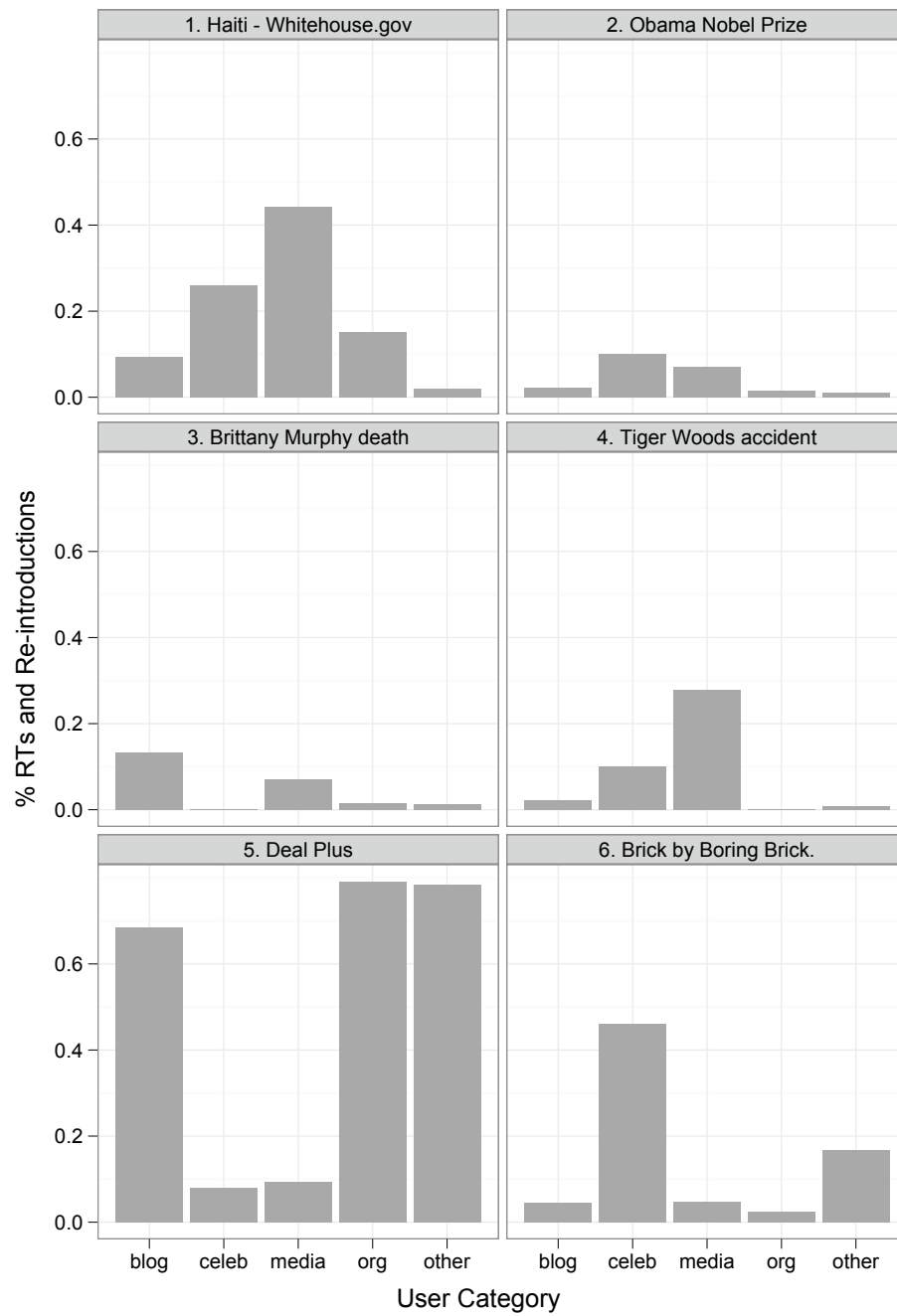


Figure 3.9: Number of RT's and Reintroductions of most popular URLs originating from media and other

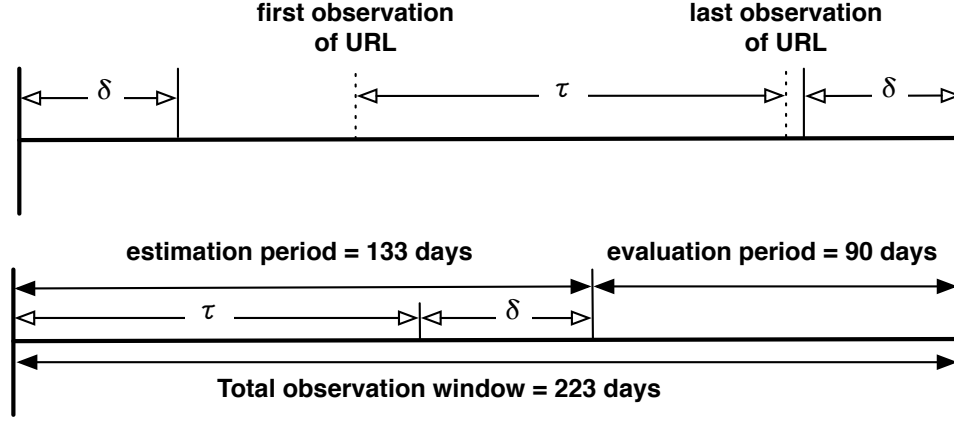
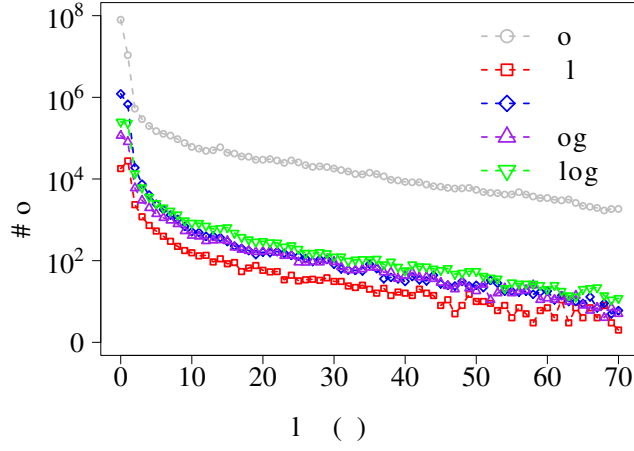


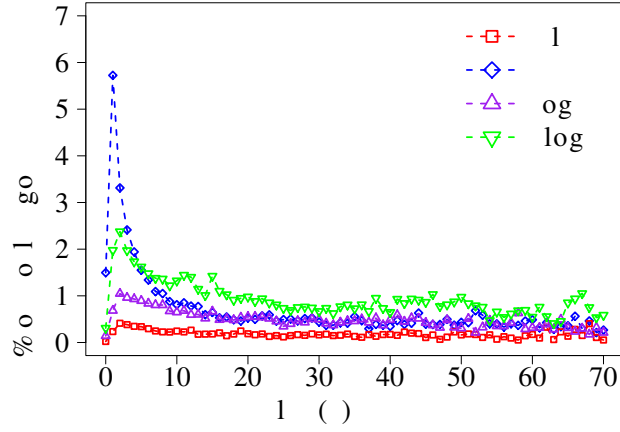
Figure 3.10: (a) Definition of URL lifespan τ (b) Schematic of lifespan estimation procedure

in the interval between the buffers, and (c) they do not appear in the last δ days, as illustrated in Figure 3.10(a). To determine δ we first split the 223 day period into two segments—the first 133 day estimation period and the last 90 day evaluation period (see Figure 3.10(b))—and then ask: if we (a) observe a URL first appear in the first $(133 - \delta)$ days and (b) do not see it in the δ days prior to the onset of the evaluation period, how likely are we see it in the last 90 days? Clearly this depends on the actual lifespan of the URL, as the longer a URL lives, the more likely it will re-appear in the future. Using this estimation/evaluation split, we find an upper-bound on lifespan for which we can determine the actual lifespan with 95% accuracy as a function of δ . Finally, because we require a beginning and ending buffer, and because we can only classify a URL as having lifespan τ if it appears at least τ days before the end of our window, we need to pick τ and δ such that $\tau + 2\delta \leq 223$. We determined that $\tau = 70$ and $\delta = 70$ sufficiently satisfied our constraints; thus for the following analysis, we consider only URLs that have a lifespan $\tau \leq 70$ ⁷.

⁷We also performed our analysis with different values of τ , finding very similar results; thus our conclusions are robust with respect to the details of our estimation procedure.



(a) Count



(b) Percent

Figure 3.11: (a) Count and (b) percentage of URLs initiated by 4 categories, with different lifespans

Having established a method for estimating URL lifespan, we now explore the lifespan of URLs introduced by different categories of users, as shown in Figure 3.11(a). URLs initiated by the elite categories exhibit a similar distribution over lifespan to those initiated by ordinary users. As Figure 3.11(b) shows, however, when looking at the percentage of URLs of different lifespans initiated by each category, we see two additional results: first, URLs originated by media

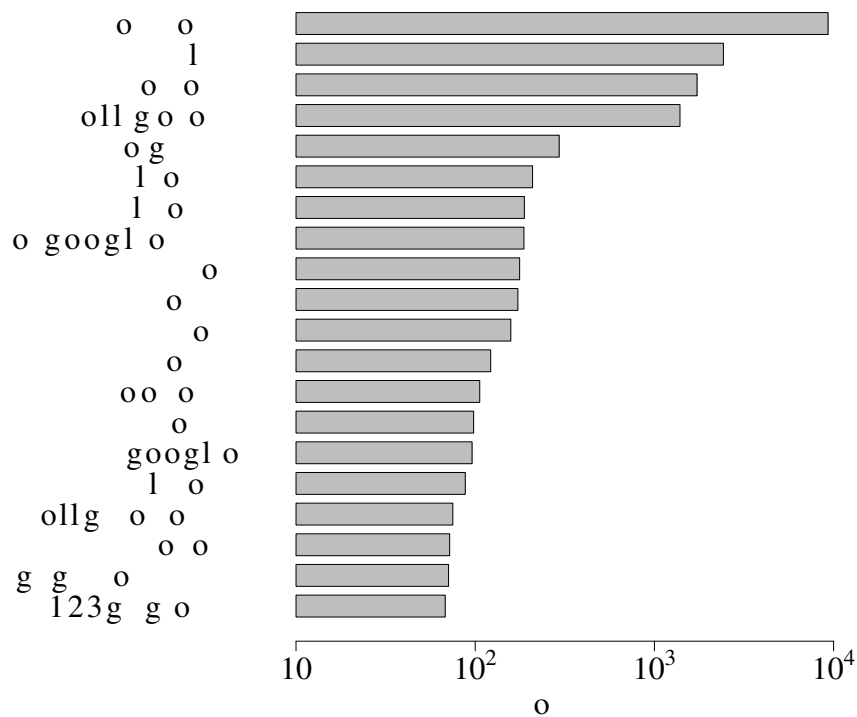


Figure 3.12: Top 20 domains for URLs that lived more than 200 days

actors generate a large portion of short-lived URLs (especially URLs with $\tau = 0$, those that only appeared once); and second, URLs originated by bloggers are overrepresented among the longer-lived content. Both of these results can be explained by the type of content that originates from different sources: whereas news stories tend to be replaced by updates on a daily or more frequent basis, the sorts of URLs that are picked up by bloggers are of more persistent interest, and so are more likely to be retweeted or reintroduced months or even years after their initial introduction. Twitter, in other words, should be viewed as a subset of a much larger media ecosystem in which content exists and is repeatedly rediscovered by Twitter users. Some of this content—such as daily news stories—has a relatively short period of relevance, after which a given story is unlikely to be reintroduced or rebroadcast. At the other extreme, classic mu-

sis videos, movie clips, and long-format magazine articles have lifespans that are effectively unbounded, and can seemingly be rediscovered by Twitter users indefinitely without losing relevance.

To shed more light on the nature of long-lived content on Twitter, we used the bit.ly API service to unshorten 35K of the most long-lived URLs (URLs that lived at least 200 days), and mapped them into 21034 web domains. As Figure 3.12 shows, the population of long-lived URLs is dominated by videos, music, and consumer goods. Two related points are illustrated by Figure 3.13, which shows the average RT rate (the proportion of tweets containing the URL that are retweets of another tweet) of URLs with different lifespans, grouped by the categories that introduced the URL⁸. First, for ordinary users, the majority of appearances of URLs after the initial introduction derives not from retweeting, but rather from reintroduction, where this result is especially pronounced for long-lived URLs. For the vast majority of URLs on Twitter, in other words, longevity is determined not by diffusion, but by many different users independently rediscovering the same content, consistent with our interpretation above. Second, however, for URLs introduced by elite users, the result is somewhat the opposite—that is, they are more likely to be retweeted than reintroduced, even for URLs that persist for weeks. Although it is unsurprising that elite users generate more retweets than ordinary users, the size of the difference is nevertheless striking, and suggests that in spite of the dominant result above that content lifespan is determined to a large extent by the type of content, the source of its origin also impacts its persistence, at least on average—a result that is consistent with previous findings [11].

⁸Note here that URLs with lifespan = 0 are those URLs that only appeared once in our dataset, thus the RT rate is zero.

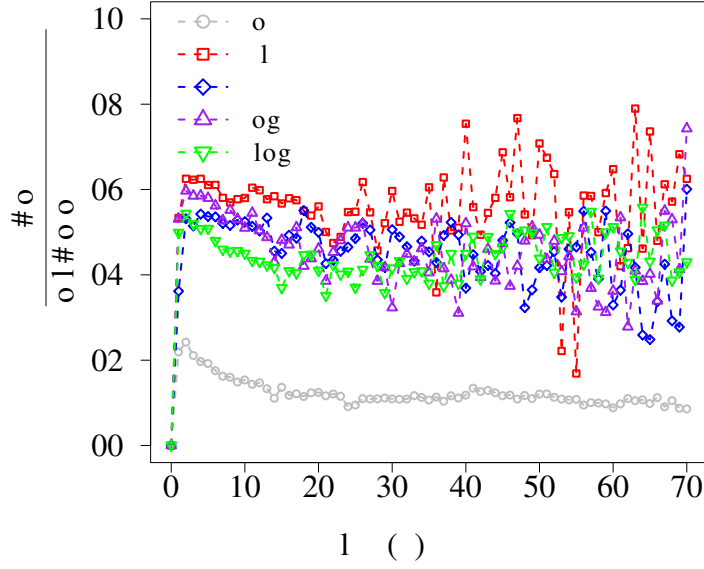


Figure 3.13: Average RT rate by lifespan for each of the originating categories

3.6 Conclusion

In this chapter, we investigated the influencer problem by incorporating exogenous influence into the context of Twitter. In particular, we find that although audience attention has indeed fragmented among a wider pool of content producers than classical models of mass media, attention remains highly concentrated, where roughly 0.05% of the population accounts for almost half of all posted URLs. Within this population of elite users, moreover, we find that attention is highly homophilous, with celebrities following celebrities, media following media, and bloggers following bloggers. Second, we find considerable support for the two-step flow of information—almost half the information that originates from the media passes to the masses indirectly via a diffuse intermediate layer of opinion leaders, who although classified as ordinary users, are

more connected and more exposed to the media than their followers. Third, we find that although all categories devote a roughly similar fraction of their attention to different categories of news (World, U.S., Business, etc), there are some differences—organizations, for example, devote a surprisingly small fraction of their attention to business-related news. We also find that different types of content exhibit very different lifespans: media-originated URLs are disproportionately represented among short-lived URLs while those originated by bloggers tend to be overrepresented among long-lived URLs. Finally, we find that the longest-lived URLs are dominated by content such as videos and music, which are continually being rediscovered by Twitter users and appear to persist indefinitely. We will further investigate the role of content in the diffusion process in next chapter.

By restricting our attention to URLs shared on Twitter, our conclusions are necessarily limited to one narrow cross-section of the media landscape. An interesting direction for future work would therefore be to apply similar methods to quantifying influence via more traditional channels, such as TV and radio on the one hand, and interpersonal interactions on the other hand. Moreover, although our approach of defining a limited set of predetermined user-categories allowed for relatively convenient analysis and straightforward interpretation, it would be interesting to explore automatic classification schemes from which additional user categories could emerge.

CHAPTER 4

THE ROLE OF CONTENT

As shown in previous chapter, the content originated by different people exhibit different lifespan. However, in practice, it is still quite difficult to predict to lifespan of content using the its author alone (think of that bloggers can write about a variety of things). In this chapter, we present a large scale empirical study centering at the textual characteristics of content, in relationship to the persistence of information. Our goal is to look for intrinsic qualities of the content that effectively affect the dissemination process, especially, resulting in different lifespans of information. We make two main contributions:

- We build a classifier that predicts the decay/persistence of information with textual features, providing one of the first empirical studies of the connection between content and temporal variations of information in on-line social media.
- We investigate the properties of the text that are associated with different temporal patterns, finding significant differences in word usage and sentiment between rapidly-fading and long-lasting information.

In the following sections of this chapter, we first provide an overview of the data we are using for this study, then present a binary classifier that predicts the persistence of URLs, using textual features from webpages pointed to by the URLs. We further examine and discuss different aspects of the content that are correlated with the difference in temporal patterns. In the end, we provide some additional insights about the quality of YouTube videos in relationship to the decay time.

This chapter is based on the joint work [89] with Chenhao Tan, Jon Kleinberg, and Michael Macy. Many thanks also go to the Social Dynamics Lab in Cornell University, for very inspiring feedback and conversations.

4.1 Data

4.1.1 Summary

In this study, we used the dataset publicly shared by the authors of [91]¹, consisting of approximately 20%-30% of all the tweets generated between June 1, 2009 and December 31, 2009. We only study the temporal patterns of bit.ly URLs for two reasons, following the arguments of [87]. First, shortened URLs have a unique token that is easily traceable in individual tweets. Second, the associated webpages provide a much richer source of content beyond the 140-character limit of tweets. From the total 476M tweets contained in the dataset, we find 118M distinct URLs embedded in 186M tweets. Among all the URLs, nearly half of them (56M) are bit.ly URLs (i.e., start with `http://bit.ly/`). For simplicity, we only extract the time series of bit.ly URLs and use them as a representative sample of all temporal patterns. Considering that a large portion of URLs mentioned in Twitter are spam and may not be able to provide meaningful content, we restrict our study to the bit.ly URLs that appeared more than 10 times in retweets², which gives us 131K bit.ly URLs. We are able to crawl 117K webpages pointed to by these bit.ly URLs, the remaining 14K URLs that we fail to crawl are mostly misspelled or linked to webpages that no longer exist.

¹<http://snap.stanford.edu/data/twitter7.html>

²We recognize a post as retweet when it contains “RT @” or “via @”.

We further restrict our study to URLs that are mentioned more than 50 times in order to remove spam and have sufficient observations to measure temporal dynamics, which leaves us with 21K URLs. In the rest of this chapter, when we talk about URLs and temporal patterns, we mean these 21K bit.ly URLs and the temporal pattern in their time series.

4.1.2 Persistence of URLs

After extracting the data of interest, we first propose a quantitative metric of persistence and present some insights on the overall temporal pattern of the URLs we study.

As the focus of this study is how fast URLs fade, we measure decay rates following peak attention. For each URL u , let the hour of maximum attention (also called the peak of attention) be hour 0. Then the *decay time* t_u is defined as the hour after the peak when the number of mentions first reaches 75% of the total. Instead of measuring the time lag between the first and last mention of a given URL [87], we intentionally choose to measure the time lag from the peak of attention to the point when the URL fades away, as given the limited observation window when the dataset was collected, it is not obvious to determine when exactly a URL was first introduced or last appeared on Twitter. The distribution of t_u shows a long tail(see Figure 4.1), as found previously in the distribution of URL lifespan [87]. Among all URLs we studied, the mean t_u is 217.3 hour and the median t_u is 19 hours.

We further examine the relationship between t_u and the overall popularity of URLs. Figure 4.2 shows the average number of tweets and retweets accu-

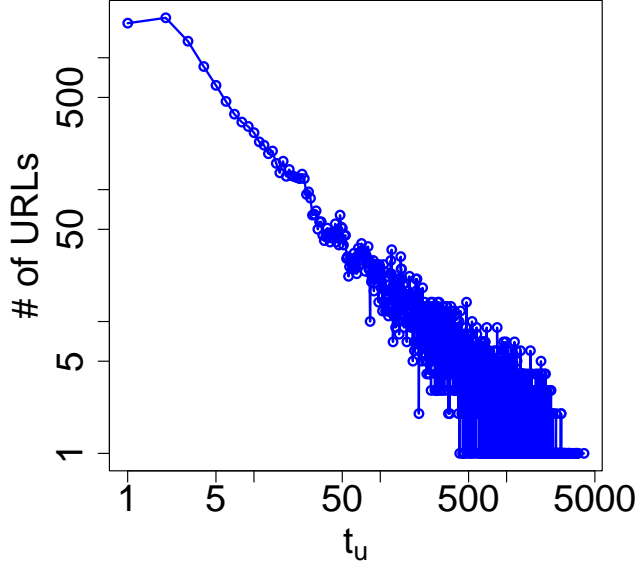


Figure 4.1: Distribution of URL decay time t_u

mulated by each URL as a function of t_u . Given the skewed distribution of t_u , we bin URLs by the integer part of $\log_2(t_u)$, and calculate the mean for each bin. Although the persistent URLs are mentioned in slightly more tweets, the rapidly-fading URLs do better at attracting retweets. This result is consistent with previous findings that the longevity of information is determined not by diffusion, but by independent generation of tweets of the same content over time [87].

4.2 Predicting temporal patterns based on content

In this section, we formally define the temporal pattern classification task and present our findings.

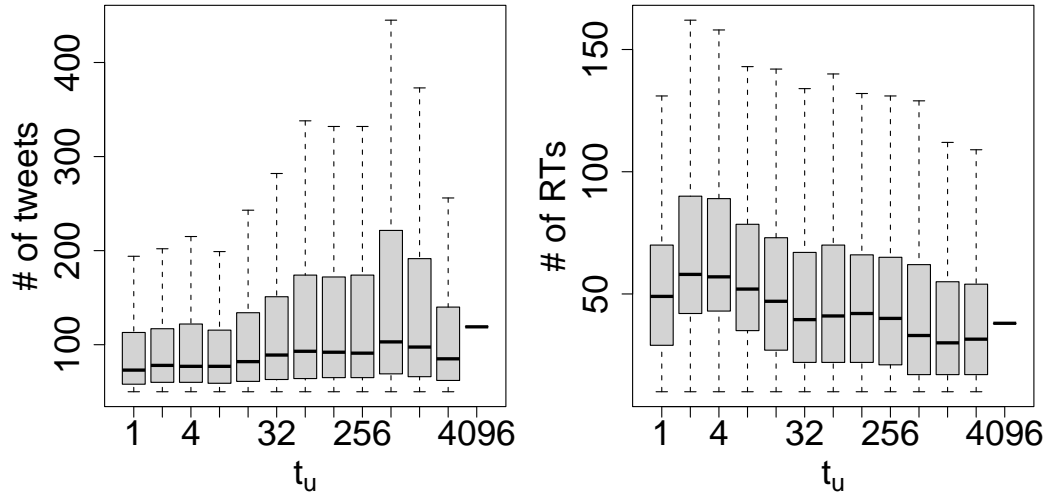


Figure 4.2: URL overall popularity as a function of t_u

4.2.1 Identifying information with two distinct temporal patterns

We start by casting our question into a binary classification problem in which class 1 is defined as consisting of those URLs with $t_u < 6$ and class 0 is defined as consisting of those URLs with $t_u > 24$. In this way we get a positive class with 7042 examples and a negative class with 6185 examples. We exclude the 7K examples in the middle, as the data is much noisier and the persistence of these URLs is ambiguous — our goal in this first exploration of persistence prediction is to construct a well-defined and tractable task from which we can understand whether there are features that meaningfully separate rapidly-fading URLs from long-lasting ones.

To better illustrate our classification scheme, we apply the time series normalization method introduced in [91] and calculate the centroid of time series for each class, as shown in Figure 4.3. The two classes we define do in fact collec-

tively exhibit very different temporal patterns: URLs of the positive class fade away slowly, with periodic, multiple peaks of attention; URLs of the negative class have a single spike and a rapid decay afterwards.

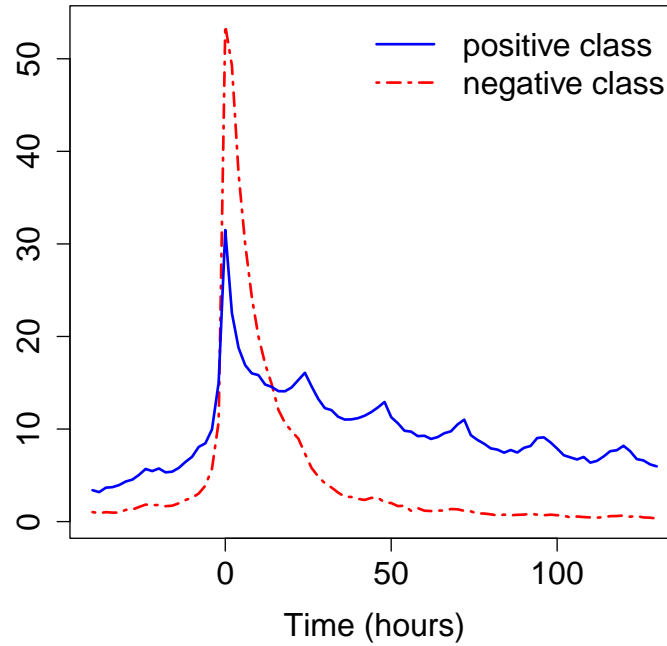


Figure 4.3: Normalized time series centroids for two classes

4.2.2 Features

To predict the temporal class of URLs, we extract and experiment with the following four incremental sets of unigram features from the HTML webpages linked by the URLs (one-character tokens and those that consist only of numbers are filtered out):

- Header. The text in the header of HTML, within tags “<title>”, “<description>”,

Table 4.1: Feature size

<i>Feature</i>	<i># of unique unigram terms</i>
Header	18471
Header + URL	27433
Header + Body	59475
Header + Body + URL	76487

and “<keywords>”.

- Header + URL. In addition to Header, this feature set also uses the terms tokenized from the URL links embedded in the HTML (i.e., within “<href>”).
- Header + Body. In addition to Header, this feature set includes all the text in the body of HTML.
- Header + URL + Body. This feature set combines all the features mentioned above.

As mentioned above, to get more meaningful unigram features, after tokenizing all the textual content into word terms, we filter the terms with length 1 (e.g., “s”, “t”) and the terms consisting of only numbers. As the dimension increases tremendously in the last 3 sets of features, we also filter the infrequent terms (i.e., terms with total frequency less than 20). Table 4.1 gives a summary of the number of features in each set.

Table 4.2: Results for predicting lastingness of information

<i>Feature</i>	<i>Accuracy</i>	<i>Pos F1</i>	<i>Neg F1</i>
Header	0.6909	0.7399	0.6186
Header + URL	0.7177	0.7666	0.6423
Header + Body	0.7136	0.7664	0.6296
Header + Body + URL	0.7224	0.7708	0.6478

4.2.3 Classifier performance

To predict the persistence of webpages, we employ a Support Vector Machine (SVM)³ classifier with a binary representation of unigram features (if a term appears in a webpage, the corresponding coordinate has value 1, and value 0 otherwise). To work with high-dimensional features, we use the linear SVM kernel for efficiency. We also apply the default parameters for SVM classifier for a fair comparison among different sets of features. Table 4.2 gives the performance of classifiers with different sets of features using 10-fold cross validation.

Table 4.2 shows that in general, the simple linear-kernel SVM classifier can predict the persistent/rapidly-fading category of URLs with impressively high accuracy (around 70%), as compared to 53% for always predicting positive. Also, the F1 score for positive class is around 75%, which shows a remarkable balance of precision and recall at identifying the persistent content. This result provides strong evidences for the connection between the content of HTML pages and the persistence of the associated URLs. Moreover, comparing across 4 feature sets, we see that the more information we have about the content, the better the classifier performs. This finding further confirms the relationship be-

³The SVM package we use is SVMLight, <http://svmlight.joachims.org/>

tween textual content and the persistence of attention of the information.

4.3 How temporal patterns vary with types of content

The SVM classifier shows that the content provides enough information to predict persistence reasonably well. However, SVMs are not as effective at providing a readily comprehensible sense for which properties of the text are the most related to the variations in temporal patterns. Here we address this question, by looking more closely at the textual content and identifying the aspects that exhibit the most significant difference across temporal classes.

4.3.1 LIWC analysis

Linguistic Inquiry and Word Count (LIWC) [68] is a widely used text analysis tool that maps words onto 60 pre-defined categories, covering linguistic, psychological, and social dimensions. Using LIWC categories, we start by comparing the distribution of words across two classes.

We say a LIWC category occurs in a URL when we find at least one word under that category from the header of the associated HTML page.⁴ Figure 4.4 shows the percentage of occurrence for all LIWC categories in webpages from

⁴We also conduct the same analysis with text from the other 3 feature sets, however, since the number of words increases markedly in these feature sets, and LIWC dictionary many times maps a word into multiple categories, the binary vector for each URL is easily saturated and the $f_w(t)$ curve becomes too flat to show interesting difference.

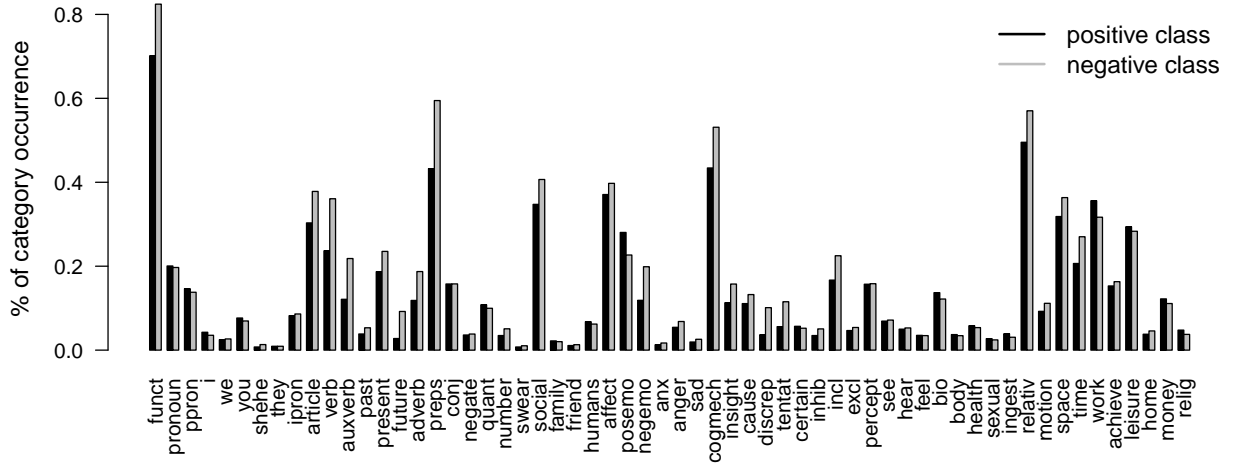


Figure 4.4: Class distribution in 60 LIWC dimensions, using words from HTML header

two classes. As illustrated by Figure 4.4, the two classes differ the most in the following three groups of LIWC categories,

- Emotion: *posemo* (positive emotion), *negemo* (negative emotion).
- Cognitive process: *cogmech* (cognitive process), *insight* (words like *think*, *know*, *consider*), *incl* (inclusive, words like *and*, *with*, *include*), *discrep* (discrepancy, words like *should*, *would*, *count*).
- Part of speech: *verb* (common verbs), *auxverb* (auxiliary verbs), *preps* (prepositions), *present* (present tense, words like *is*, *does*, *hear*), *future* (future tense, words like *will*, *gonna*).

To better see the trend in the frequency of specific categories as a function of t_u , for each category w , we define $f_w(t)$ as the fraction of occurrences of w in all URLs u for which $t_u = t$, and plot $y = f_w(t)$ for different groups of LIWC categories in Figure 4.5.

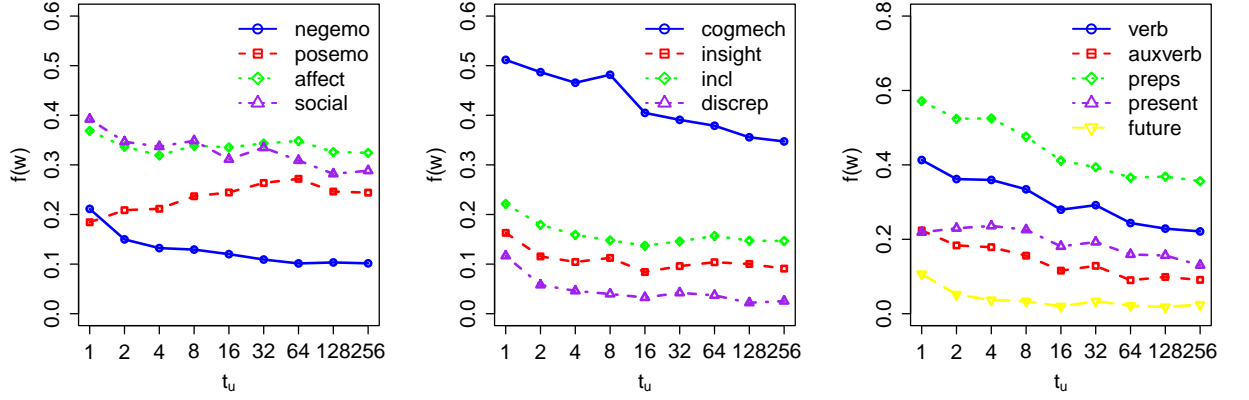


Figure 4.5: Trending LIWC categories

Again, to balance the skewed distribution of t_u , we bin t_u by integer part of $\log_2(t_u)$, and plot the value $f_x(w)$ for each bin x (instead of hour x). In this way, the later bins would still contain a substantial number of URLs so that the probabilistic curve is smoother. Similar as in [13, 42] we find the sentiment of content plays an important role in its dynamics: there is a clear trend of words with positive emotion rising in the persistent content, and the opposite for words with negative emotion. However, the amount of words related to affect stays more or less constant across t_u . We also see a drop of words related to cognitive process when t_u increases, suggesting that, content associated with more complicated cognitive process can be more viral [13], yet not so persistent. Not surprisingly, we find that rapidly-fading content with more words related to actions (verb, auxverb, preps) and tense (present, future), presumably because these webpages contain more action-demanding, time-critical information that expires after a certain event or time.

4.3.2 Topic analysis

Although LIWC offers the most straightforward insights from the text, as a manually-generated, pre-defined category system, it is limited by the underlying psycholinguistic concepts. To extend the dimensions of text described in LIWC, we also build topic models that represent mixtures of words, and see how these topics vary across our temporally-defined classes. For this we use Latent Dirichlet Allocation (LDA)⁵, a flexible generative model for collections of discrete data [16]. Here, we use it to find proper underlying generative probabilistic semantics from content. We use the corpus consisting of the unigrams in the two classes. With the topic distribution for each document, we try to study whether the temporal patterns are correlated with “topics”. First, we will show the probability of topics in the two classes and find those topics with significant differences across different topics. Then we interpret these topics to find some differences between persistent webpages and rapidly-fading webpages. As for the details of running LDA, we use the features in “header+body” because we find that when using features from URLs, the results will include some irregular words, while with only “header”, it cannot include enough words in detail.

First, since the output of LDA provides a continuous value of topic weight for each document, we cast it into binary by assigning 1 when the weight is above the default value. For each topic, we compute the probability that one document contains this topic in the positive class and in the negative class respectively. More specifically, we conduct a paired t-test between the two classes on each topic and find that, on 39 topics, the two classes are different at significance level $\alpha = 5\%$. 24 of them are with p-value 0. This shows that these two

⁵We use the software from <http://www.cs.princeton.edu/~blei/lda-c/index.html> with the number of topics set to 50.

classes differ significantly in the space of topics. Figure 4.6 shows topics distribution in all 50 topics. We notice that the most significant differences occur at topics 18, 25 (with a high probability in rapidly-fading webpages), and topics 32, 37 (with a high probability in persistent webpages).

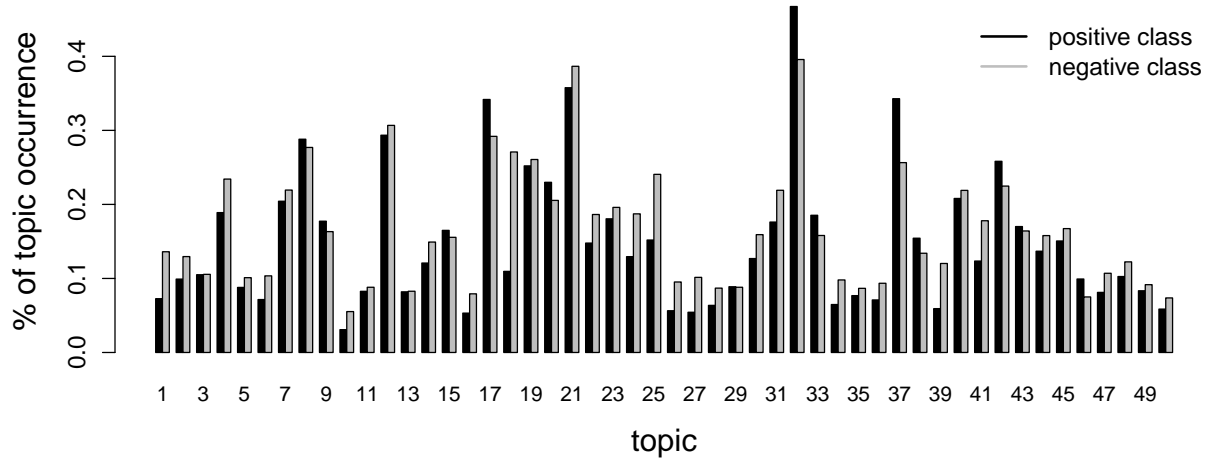


Figure 4.6: Class distribution in 50 LDA topics, using words from HTML header and body

Providing a closer look at those topics, Table 4.3 shows top 20 words given by the topic model. We see some similar phenomena as in previous section: words related to strong - and mostly negative - emotions tend to appear more in the topics highly weighted in rapidly-fading webpages. For example, negative words, such as “die”, “freaking”, “incredibly”, “incredible” and “destroy”, show up in topic 18 and 25. In the topics associated with persistent webpages, interestingly, we notice an increase of nouns.

Table 4.3: LDA Topics

<i>Topic 32</i>	<i>Topic 37</i>	<i>Topic 18</i>	<i>Topic 25</i>
fred	incident	net	die
net	website	dan	gov
care	subscriber	fred	fields
produce	clean	pack	static
incident	rates	gov	say
mas	net	impressed	expensive
office	considering	read	read
hello	potentially	native	york
julian	die	worm	freaking
teen	gov	user	seek
red	money	attempts	destroy
democratic	donation	treatment	dear
boy	dennis	august	supporters
tagging	seek	incredibly	tagged
ways	read	incident	office
opinion	dislike	potentially	microwave
read	il	talented	challenges
different	challenges	die	fred
british	posted	placed	british
heads	kind	busy	august

4.3.3 Trending words analysis

After measuring the content in LIWC categories and latent topics, in this part, we examine the content with more details, trying to discover the nuance between classes at the word level. We calculate and compare the most represen-

tative words in the two classes. Picking the words to describe a collection of documents can be turned into a trend detection problem: let the webpages of negative class be the corpus of early period and the webpages of positive class be the later period, negative class can thus be described by the most significant “falling words” whereas the positive class can be described by the most significant “rising words”. To do so, we apply the methods as presented in [49] on the Header feature set, and generate the top 20 trending words for each class (see Table 4.4)⁶.

To get the words that are most meaningful, we filter all the numbers, and the words with frequency less than 20 (mostly specific names) or greater than 400 (mostly stopwords and website names). As discussed in [49], trending words identified by the three metrics have different bias. Words based on *normalized absolute change* are biased towards words that are frequent in both classes. Words selected by *relative change* are biased towards words frequent in one class but not the other. Words selected by *probabilistic change* are the ones that based on the frequency of occurrence in one class, most unlikely to be seen in the other class. Although [49] recommends the probabilistic change as a metric that gives the cleanest results, we find the selected words in all three categories highlight interesting points that reinforce, and provide some intuitive basis for, the results to emerge from the LIWC analysis earlier in this section.

- normalized absolute/relative change. First of all, we again find the persistent content most represented by positive words (e.g. *good, best, love*).

In terms of the semantics of content, the persistent webpages are more re-

⁶We also tried the same method on the other three feature sets, but as the number of terms largely increases, the data becomes too noisy to be described with a few words, and the results are difficult to interpret.

Table 4.4: Representative words for two temporal classes

<i>Absolute change</i>		<i>Relative change</i>		<i>Prob. change</i>	
<i>pos</i>	<i>neg</i>	<i>pos</i>	<i>neg</i>	<i>pos</i>	<i>neg</i>
twibbon	cnn	twibbon	cnn	small	plan
marketing	google	marketing	blogs	mp3	net
support	iphone	contest	source	creative	better
giveaway	blogs	trailer	finest	open	girl
quot	america	review	onion	view	file
free	source	support	apple	vs	touch
best	apple	vote	house	story	smashing
contest	onion	giveaway	iphone	kids	pictures
win	finest	big	white	ipod	using
review	app	movie	guardian	american	organizing
design	house	design	google	know	cancer
trailer	white	quot	users	party	game
vote	jackson	win	app	dj	technology
big	live	good	download	use	want
amp	official	best	america	star	page
movie	uk	love	jackson	things	single
good	obama	green	public	daily	don
home	iran	week	myspace	care	action
music	michael	funny	today	life	watch
love	guardian	version	uk	song	need

lated to art (e.g. *music, movie*), advertisement, and online marketing (e.g. *twibbon, marketing, giveaway, free, win, review*), whereas the rapidly-fading webpages contain more news (e.g. *cnn, google, onion, guardian, blogs*), and names (e.g. *michael jackson, white house, obama, iran, america, uk*).

- probabilistic change. By this metric, we find the trending words for persistent content are more associated with lifestyle (e.g. *party, dj, care, life, song*) and family (e.g. *kids, care, life*), whereas the short-lived content again has a higher portion of words related to time critical concepts (e.g. *technology, game*), or action (e.g., *plan, touch, using, want, action, watch, need*).

These results are mostly consistent with the findings from the previous parts, confirming the prominence of positive emotion in the persistent content, and the fleetingness of content with many action and time-critical terms. The distinct existence of news and art content of two classes supports the claim by authors of [87] that the persistent content - although not as viral as news - exhibits more association with art.

4.4 The quality and persistence of YouTube videos

In our dataset of 20K bit.ly URLs, there is a significant portion (15%) of them linked to YouTube videos. Among these linked videos, 707 are already removed by the user and 2304 are still available online. Noting that the *content* of videos may not be accurately represented by the text of the YouTube page, we conduct a separate study of the persistence of YouTube videos, leveraging the user rating feature YouTube provides - namely, *likes* and *dislikes* - to assess the content from the quality perspective.

First, Figure 4.7 shows the distribution of decay time t_u for the 2304 available YouTube videos. In contrast to the overall distribution of t_u for all URLs (see Figure 4.1), YouTube videos in general receive a longer span of attention.

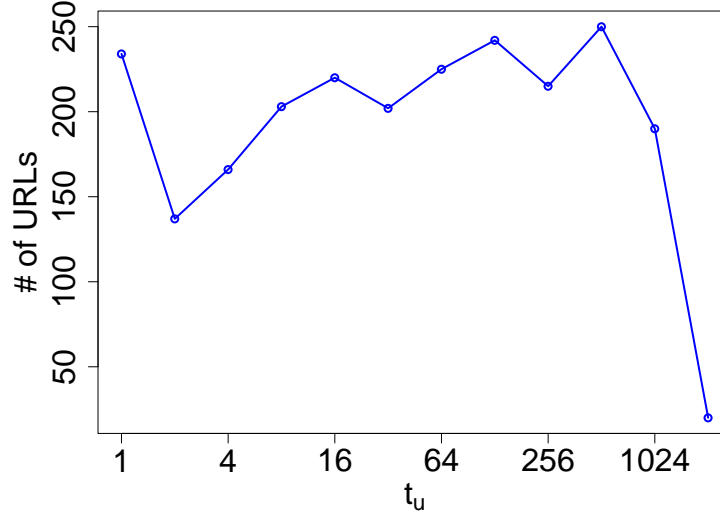


Figure 4.7: Distribution of t_u for YouTube videos

We also study the user-rated quality of these 2304 videos as a function of t_u . Figure 8 shows two indicators of the quality (a) the average likes/dislikes rate, (b) the ratio of *bad* videos, for videos in each bin of t_u (the binning method is the same as in previous sections). Interestingly, we find that although the quality of video overall increases with t_u , there is a drop of quality in the middle - videos with medium persistence seem to be of the worst quality.

Sampling videos with different t_u values suggests a further way to break the YouTube videos in our set into categories. We find that the most persistent videos are mostly music videos, again underscoring the increasing appearance of art-related topics in this class. On the other hand, many home-recorded video clips have very small value of t_u ; as seen in Figure 4.2, content that fades away quickly might not have lasting value, but in general is more viral.

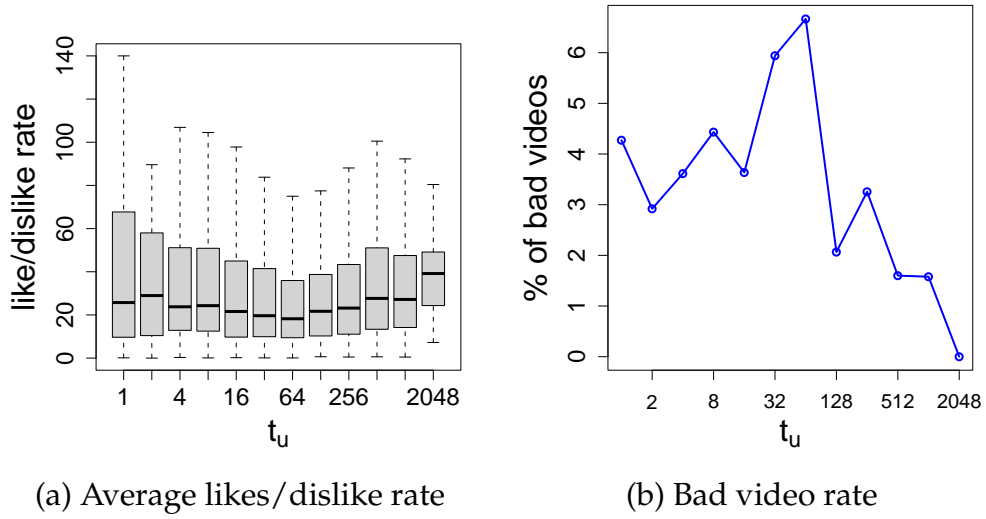


Figure 4.8: The quality of videos as a function of decay time t_u . *Like/dislike rate* is the number of likes divided by the number of dislikes. *Bad videos* are those with the number of dislikes greater than half of the number of likes. There are in total 83 out of 2304 “bad” videos by our definition.

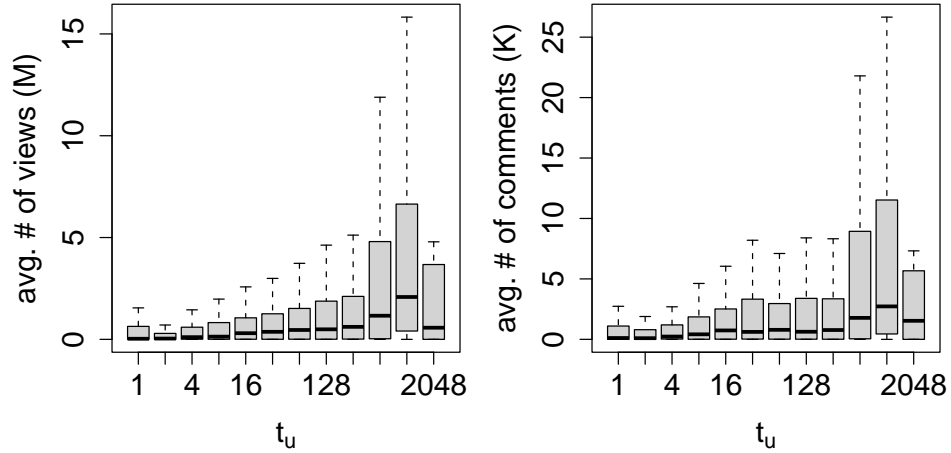


Figure 4.9: Average number of views and comments as a function of t_u

Finally, in Figure 4.9, we consider the number of views and comments on the videos in our set. We find an increase in views and comments particularly for very large values of t_u , in a way that is more extreme than the variation in the number of tweets from Figure 4.2, and that also forms an intriguing contrast

with the trend in the number of RTs from that figure. Understanding how persistence translates into these secondary popularity measures such as view count is an interesting question.

4.5 Conclusion

In this chapter, we explore the relationship between content and the temporal dynamics of information in the context of Twitter. In particular, we find that using the textual features extracted from the content, we can predict the persistence of information with high accuracy. Second, we employ different text analysis techniques to understand the nature of content that contributes to persistence. We examine and compare the fleeting and lasting content on three aspects, including the psycholinguistic characteristics, trending words, and latent topics distribution. We find that the persistent information is more related to content with long-term value, such as positive emotions, life, family, and art. On the other hand, the rapidly-fading content contains mostly time-critical information that carries relatively more negative sentiments, demanding more cognitive effort, or is associated with quick action.

By restricting our scope of study to the time series of bit.ly URLs mentioned on Twitter, our findings can be limited to the types of social media and the dynamics of information they support. An interesting direction for future work could be studying the content and temporal patterns of information across systems. One possibility is to use the transcribed content of TV, radio, together with materials from online social media. Also, since we only predicted the persistence of content for two extreme cases, it would be interesting to further inves-

tigate the connection between content and persistence as a continuous variable.

CHAPTER 5

NETWORK STRUCTURE AND THE SPREAD OF DISENGAGEMENT

There has been significant focus on the dynamics of propagation in social networks, especially, with the local and global structure involved [66, 33, 11, 57, 9, 73, 61, 41]. In many cases, such as the decision to become a member or use a product, the story does not end at adoption. Instead, the user may decide at any point to cease using the product, or to depart the community. It is not clear that a decision of this type, to “reverse” a prior socially-mediated decision to adopt, will follow the same dynamics as the original decision to adopt. In this chapter, we study this question in the context of arrivals and departures within online social networks.

A natural place to look for models of arrivals and departures is the existing literature on the spread of infectious physical disease. These models often include a recovery component [66, 33], which is akin to a reversal of the decision to become infected. Typically, however, this component assumes that an infected user recovers based on properties of the immune system, without reference to any social process. In our case, we are motivated by the metaphor of a user at a party with friends. The user is more likely to attend upon discovering that some number of friends will also attend. If some or all of the friends then opt to depart, whether for a new party or to just go home, then the original user is much more likely to follow suit. Hence, we anticipate to see the network effect in both arrivals and departures.

We begin to address this question with a basic study of the temporal correlation of arrivals and departures, and show that both processes introduce significant correlation; in fact, we show that time intervals between the departure

of friends are more tightly distributed than the equivalent distribution of gaps between arrival of friends.

Assuming part of the temporal correlation is induced by social influence, we might consider arrival as the propagation of a “join” virus, and departure as simply the propagation of a new virus, in this case representing the decision to cease usage. However, this formulation is at odds in reality. It is plausible that seeing one friend join a social network, then two, then three, might impel a user to join, as we see in prior work [9]. However, once a user has two hundred friends, will the departure of one, then two, then three friends have a qualitatively different impact on the user’s likelihood to depart? Perhaps like the decision to join, the decision to depart depends more on the number of active friends than the number of inactive friends. Or perhaps departure is a fundamentally different decision that depends on an assessment of the pulse of the neighborhood, captured more accurately by the fraction of friends who remain active. At last, departure can be merely a symptom of some external process that is driven mostly by exogenous factors rather than social forces.

We study this question in the context of the DBLP co-authorship graph and a large social network, and argue that a hybrid of the social influence models could characterize the observed temporal clustering rather accurately. While number of active friends is known to be a strong predictor of joining a group, for users with twenty or more friends, overall neighborhood activity, measured by the fraction of friends who remain active, is by far the best predictor of likelihood to depart. Surprisingly, this likelihood is linear in the fraction of active friends throughout almost its entire range, and the linear form is identical in both slope and intercept for several different buckets of neighborhood size. Raw

counts of inactive friends have low predictive power, and raw counts of active friends, while stronger, remain weak compared to the overall fraction of active friends. On the other hand, for users with fewer than twenty neighbors, the actual count of active friends remains a strong predictor of likelihood to depart. An intuitive interpretation of these findings is that users with few friends rely heavily on the presence of individual friends, while users with more friends stay for the neighborhood atmosphere - they are pushed one unit closer to departure by each successive fraction of existing friends observed to depart (this phenomena is particularly relevant for the DBLP dataset where many nodes have very small degree).

From this emerging local picture of behavior, we may then ask how arrival and departure dynamics interact with the global structure of the graph. In particular, we seek to understand where departures happen in the graph. It is possible, for example, that departures tend to occur as high-status users in the core of the graph choose to depart in search of the next big thing. Alternately, it is possible that departure happens first at the “fringes” of the graph, and then spreads inwards from there. We study this problem by computing the average induced degree (or density) and conductance of the subgraphs of active and inactive users through time, and comparing these results to thought experiments in which each node decides independently whether to remain active. These experiments allow us to conclude that a core of active nodes remains at much higher internal density than the set of inactive nodes. We also compare the densities observed against the expected density and conductance under a planted degree constraint model. The results suggest that although the inactive set of nodes densifies, its densification is not just a consequence of the degree distribution, but really a consequence of well-connected cluster of nodes from the

fringes departing. We reach the picture that departures happen from the fringes and spread to their immediate neighborhoods, while an internal dense core of active nodes survives.

Most of the content in this chapter is adapted from the joint work [88] with Atish Das Sarma, Alex Fabrikant, Silvio Lattanzi, and Andrew Tomkins. Many thanks also to Google Research for providing data and computing resources.

5.1 Data

In this chapter, we study the dynamics of arrival and departure using a snapshot of the DBLP co-authorship graph and a well-known social network. As previous research [9] showed that the co-author network largely reassembles the dynamics of online social networks in forming individual communities, we are interested at testing whether this similarity persists in the forming and degenerating of the entire social graph. The DBLP snapshot that we consider contains 1 million nodes and around 1.8 millions edges, for each author we store his/her co-authors and the year of the last publication. Furthermore for each author to author edge we also store the year of the first publication. In the rest of the paper we will refer to it as DBLP. The social network dataset we study contains 260 millions of users and 17 billion edges (as observed by August, 2011). For each user, we have the timestamp of signup and last login, and for each edge, we have the timestamp of edge creation. In the rest of the paper we will refer to this network as SN.

To study the pattern of user arrivals and departures, we first describe each user at each timestamp as either active or inactive, based on his most recent ac-

tivity time. Given a snapshot of the SN network at time t , we consider a user *inactive* if his last login time is earlier than two months prior to t , and consider a user *active* otherwise¹. Given a snapshot of the DBLP network at time t , we consider a user *inactive* if he/she has not published any paper in the earlier than five year prior to t , and consider a user *active* otherwise. Note that our results do not depend on the time frame that we used. In fact, they hold for two quite different networks and time frames. Considering all the possible exogenous factors that may affect people’s activities in these two networks, the consistency of our results suggests that there might be some internal process that is fundamental to human social interactions and gives rise to the dynamics of arrivals and departures observed and studied in this chapter.

5.2 Arrival and departure correlation among friends

In this section, we study the basic properties of arrival and departure. We wish to understand whether users typically arrive and/or depart together in social networks. However, we cannot directly compare gaps between arrivals and departures of friends, as networks are not stationary—consider for example the case of a network that grows very rapidly during a brief period, resulting in a flurry of temporally-proximate arrivals, leading to a mistaken conclusion that arrivals tend to be tightly clustered in time.

We must therefore normalize in some way against global rates of arrival and departure, which we do by the following technique. Given a snapshot of the

¹As most online social network or social game sites use Monthly-Active-Users(MAU) as a standard way to measure the number of engaged users, we double the cutoff window to 2-month for a more conservative threshold to determine a user has departed.

network at time t , we consider two samples of user-pairs, one in which the pair of users are friends, and another in which the pair of users is chosen uniformly from all possible pairs². We then consider the distribution of the gap in arrival time between pairs in the two cases. Differences in these distributions will then highlight temporal correlation of arrivals of friends compared to strangers.

To study departures, we adopt the same technique. We consider only inactive users, and generate again a set of pairs of friends, and another set of pairs chosen uniformly at random. For a fixed time t , we define the last login time of inactive users as their departure time. We pick 1M pairs for each of these four sample groups, and compute the Cumulative Distribution Function (CDF) for these distributions. In Figure 5.1, we plot the CDF curves, showing the percentage of friends(co-authors)/strangers who joined and left the SN(DBLP) within n days(years) of each other.

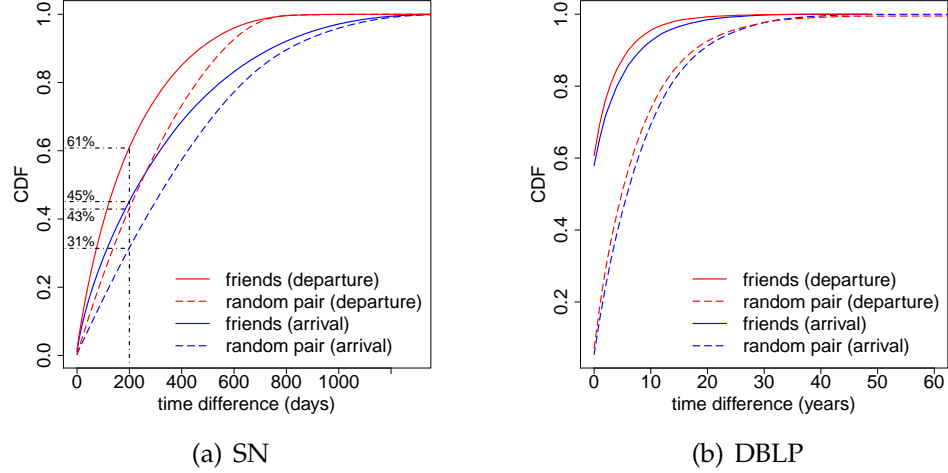


Figure 5.1: The CDF curve for the difference in arrival and departure time between friends and random pairs of users.

The CDF for both arrivals and departures of friends lies significantly above

²Technically, it is possible for a random pair to be a pair of friends, however, given the service policy that each user has a rather small upper-bound for the number of friends, the chance of a random pair being friends is negligible.

the CDF for random pairs, indicating that friends both arrive and depart together, in comparison to the control group of random pairs. As the figure shows, in the case of SN, 43% of random pairs depart within 200 days of one another, while 61% of friends depart within the same period. We find similar pattern in the time interval of arrival - only 31% of random pairs arrive within 200 days, but 45% of friends arrive within the same period. This observation is even more evident in DBLP, where the solid and dashed lines show stronger separation.

To quantify the differences, we plot in Figure 5.2 the distribution of absolute difference in the CDF values at each time, for arrivals and departures. The correlation of departures in SN is seen to be stronger than the correlation of arrivals, although the two gaps peak around roughly the same value. However, arrivals and departures behave almost identically in DBLP, suggesting the dynamics of arrival and departure are more similar in collaboration networks than in social networks.

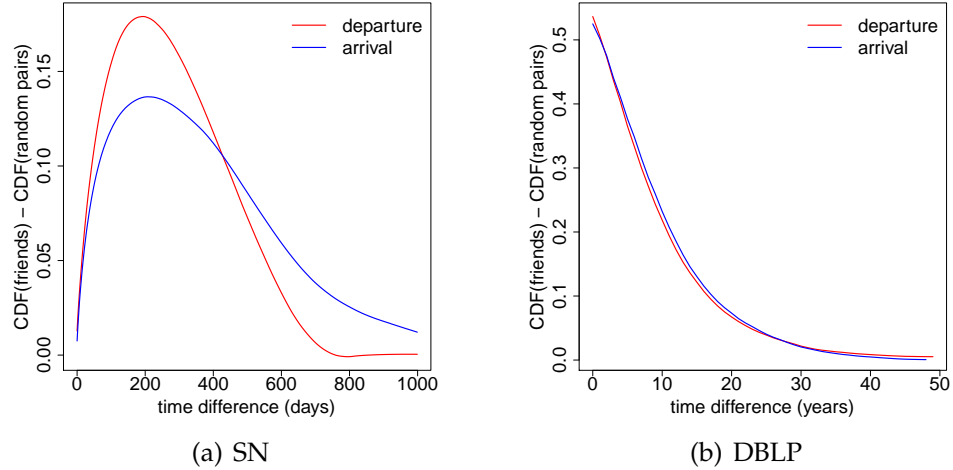


Figure 5.2: Gap between CDF curves.

The temporally correlated activities between friends have been observed and modeled before [9, 64, 5], mostly in the form of adopting a new behavior or

product within an existing social network. However, given that there is not a single underlying social network that might be accountable for the joining of new users, are those models still applicable in the scenarios of arrival? To answer this question, we will now focus on individual users, and study one's arrival in position of his local neighborhood.

Since we have no information on friendship outside the networks we are studying, we use the eventual set of friends acquired by a user at the snapshot time t to approximate the set of friends he had before arrival, and ask whether those friends join before or after the user. For DBLP, we see the “diminishing returning” curve (Figure 5.3(c)) as found in previous research [9]. In SN (Figure 5.3(a)), however, the probability of a user signup increases near-linearly as the number of adopted friends increases. The expected fraction of friends joining before the user is 0.5, as the friend network is undirected and each edge contributes one pair in which a joins before b , and one pair with b before a . Thus, for regular graphs (of constant degree), the mean fraction of friends already signed up will be 0.5. The results are shown in Figure 5.3. True social networks are of course non-regular, and while the distribution of plot (Figure 5.3(b)) appears largely symmetrical, there are some outliers. In particular, in SN there are more than 20 times as many users who signed up after all of their eventual friends did, compared to users who signed up before any of their friends. This follows from the many low-degree nodes who join in response to an invitation but do not subsequently engage with the network. In DBLP, the peaks at 0%, 25%, $\frac{1}{3}$, 50%, ..., 100% (Figure 5.3(d)) can be explained by the substantial number of authors with only one publication, as they have a very small set of co-authors. Although the plot in Figure 5.3(d) is largely symmetrical but is slightly skewed to the left. This shows that there are more authors whose collaboration networks

grow than ones who stay with their early collaborators. Overall, we posit a weak network effect for new users in both networks, which may not be enough to actively engage users after they sign up.

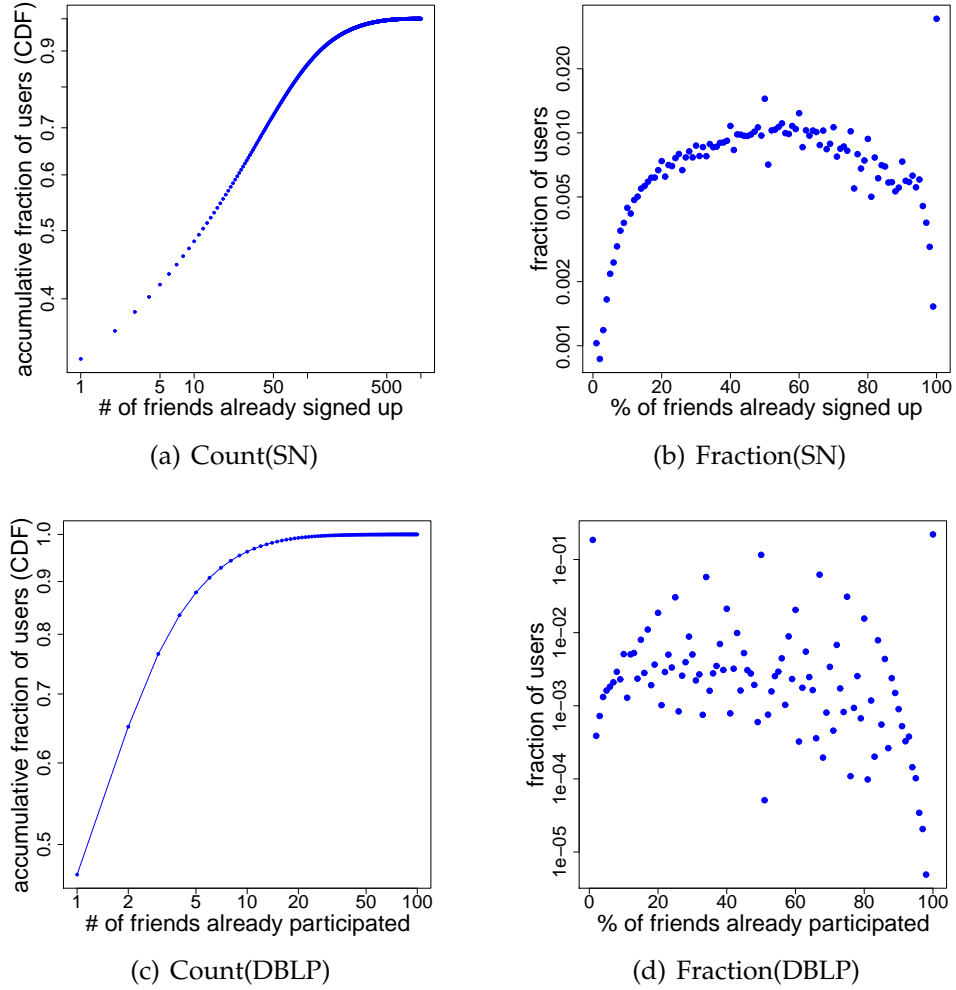


Figure 5.3: Count and Fraction of friends already signed-up when user signs up.

Our conclusion from these graphs is that friends tend to arrive and depart together, but at least for SN, departures are more tightly clustered than arrivals. We also find interesting nuances in the dynamics of arrivals, in comparison to previous research. In the next section, we will look more closely at departures, learning the how neighborhood activities affect one's likelihood to depart.

5.3 Local Neighborhoods

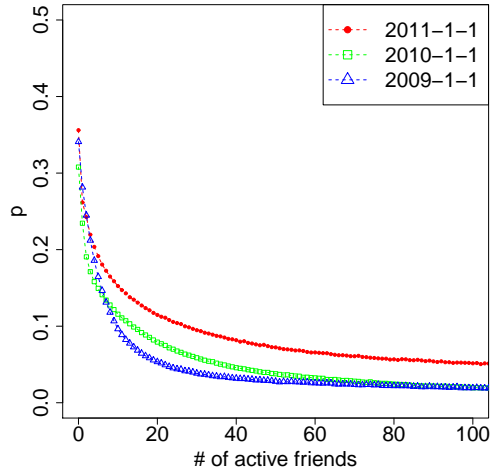
Figure 5.1 shows a strong correlation in arrivals and departures for friends; now we will go beyond single-edges and study how such correlation is presented in the entire neighborhood of a node.

5.3.1 Dependence on local properties

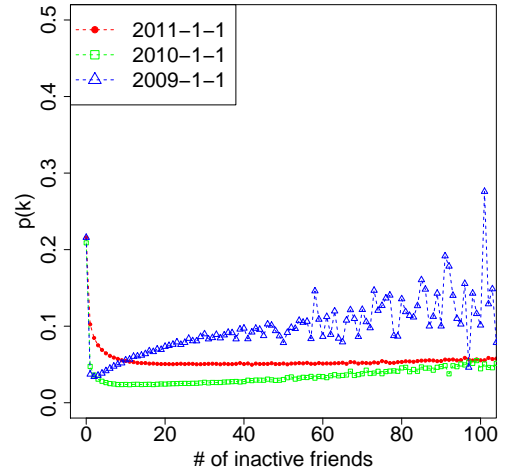
To better understand how a user's departure corresponds to his local community, we look at the probability of a user's departure in relation to the following four properties of the user's neighborhood.

- number of active friends;
- fraction of active friends;
- number of inactive friends;
- number of inactive friends who left in the past 6 months;

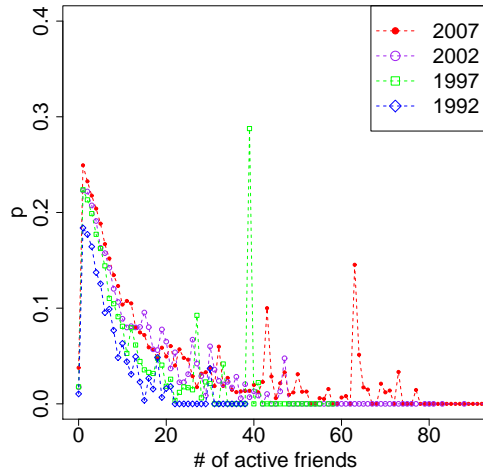
We use a similar method as in [9] to calculate the probability of a user becoming inactive, as a function of the number of active friends: we first take two snapshots (t_0, t_1) of the network, three months apart in SN and three years apart in DBLP; we then find all pairs (u, k) such that u is active at the time of first snapshot t_0 , and has k friends who are also active at t_0 ; $p(k)$ is calculated as the fraction of such pairs (u, k) for a given k such that u had left the network at the time of second snapshot t_1 . In other words, $p(k)$ is the fraction of active users who left the network in the next three months, given that k friends were active at the first snapshot time. Figure 5.4(a) and Figure 5.4(c) shows the curves of $p(k)$



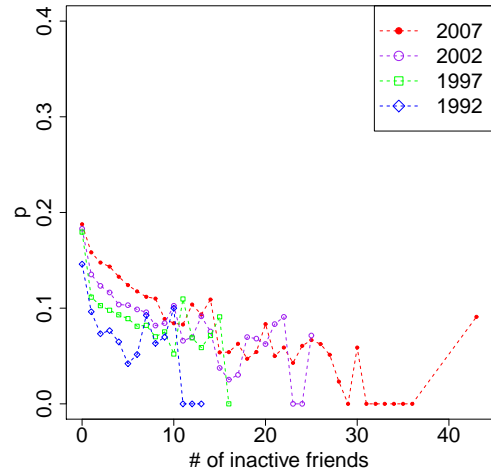
(a) p as $f(\text{active friend count})$ in SN



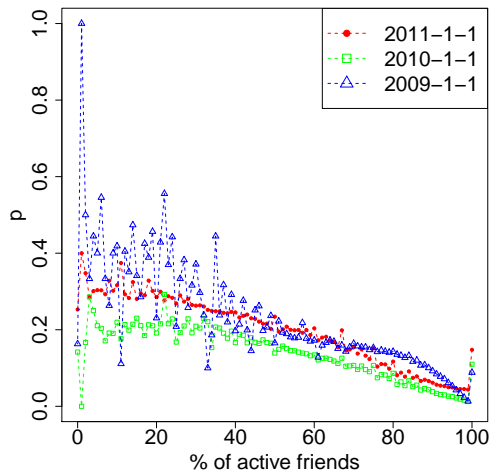
(b) p as $f(\text{inactive friend count})$ in SN



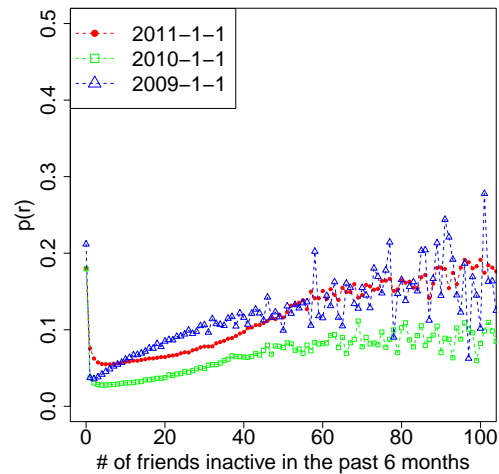
(c) p as $f(\text{active friend count})$ in Dblp



(d) p as $f(\text{inactive friend count})$ in Dblp



(e) p as $f(\text{active friend fraction})$ in SN



(f) p as $f(\text{inactive friends who left in the past 6 months})$ in SN

Figure 5.4: Probability of departure (between 0 and 1) as function of different local properties.

at three different t_0 . In a similar way, we can fix the fraction of friends f who are active at time t_0 , and calculate the probability $p(f)$ of an active user leaving the network as function of f (see Figure 5.4(e)). Note that in all figures involving the fraction of active/inactive friends, we exclude all nodes with no friends in SN (around 10% of all active users as of 2011/1/1). Among those users, 35% of them left within three months.

Not surprisingly, Figure 5.4(a), Figure 5.4(c) and Figure 5.4(e) show that as more and more friends stay active, a user is less and less likely to be inactive. The curve of $p(k)$ (see Figure 5.4(a)) also matches very well with what has been seen in other domains [9], exhibiting the “diminishing returns” property. This observation indicates that the marginal gain of having each additional active friend is quite significant for users with a small number of active friends, but rather negligible when a user already has many, say more than 50, active friends. In contrast, in Figure 5.4(e), we do not see such a “diminishing returns” trend, but a steeper, and almost constant rate of decrease in the probability of departure throughout the course when the fraction of active friends increases. This is an interesting observation that has not been previously seen (specifically in various positive influence studies).

To see how the inactivity of the neighborhood determines the departure of a user, we also plot the probability of departure as a function of number of inactive friends, in Figure 5.4(b) and Figure 5.4(d). The curves in Figure 5.4(b) and Figure 5.4(d) show an interesting trend of decreasing slope through time: while the probability of a user departing increases with the growth in the number of inactive friends initially, it becomes more and more insensitive to the value of k in the later curves. This phenomenon is quite intriguing to us: if the depar-

ture of friends do have certain predictive power on the departure of the user, as shown in the earlier curves, why is such predictive power diminished so much in the latest years? To answer this question, we note that we are counting the number of inactive friends as prior to the time of each snapshot, but many of them could have been inactive for a long time thus could hardly account for the dynamics of the network at the snapshot time. Figure 5.4(f) confirms this idea, showing that the curves we see in Figure 5.4(b) are somewhat misleading - in general, the probability of user's departure constantly grows with the number of friends r who *recently* became inactive (when r is not too small).

5.3.2 Interaction between local properties

The results of the previous section provide qualitative evidence that an individual's probability of departure is related to the activeness of his neighborhood. However, does that apply to all users? Do the highly connected users act differently than the more marginally connected ones? Is the probability of departure sensitive to the degeneration of neighborhood, or is it a step function that will only drop once there are less than k active friends, as modeled in [15]? To address these questions, we compute the probability of user's departure in SN in relation to the interaction between local properties, such as neighborhood degree and the fraction of active friends in the neighborhood. More specifically, we control the degree and the fraction of active friends separately, and look at how the probability of departure changes under each condition.

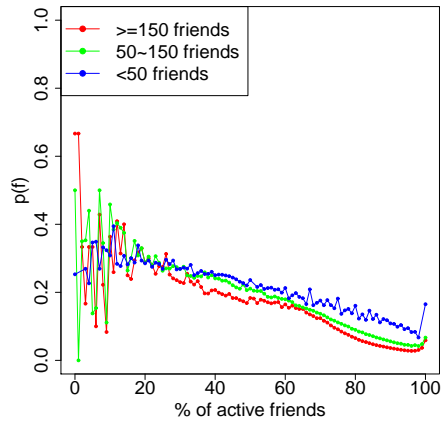
In Figure 5.5(a), we divide users into three groups based on their degrees, and plot the probability of departure as a function of the number/fraction of

active friends, for each group separately. We note that for users with different levels of connectivity in the network, the curves of $p(f)$ (Figure 5.5(a)) are qualitatively identical. This result demonstrates again that the fraction of friends who are active has a stronger effect on the probability of an individual's departure, regardless of the size of the user's neighborhood.

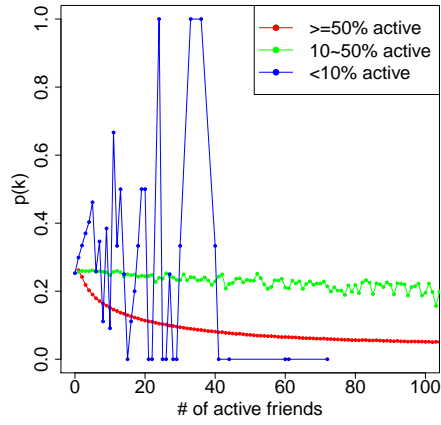
We also aggregate users by the fraction of active/inactive friends, and show how the probability of departure depends on the number of active/inactive friends for each group (see Figure 5.5). There are two things we note from Figure 5.5: First, for users with different fractions of inactive friends, there is a big gap between their probabilities of departure - for example, compared to users with less than 10% friends left (blue line in Figure 5.5(c)), users who have more than 50% friends left (red line in Figure 5.5(c)) are 10 times more likely to leave as well. Second, once the user is in an inactive part of the neighborhood, the raw count of inactive friends has little effect in determining the probability of the user's departure (green line in Figure 5.5(b)). Note that the blue line in Figure 5.5(b) is very noisy because there are very few people in a highly obsolete neighborhood but still with a substantial amount of active friends. We still plot it just to be symmetric with Figure 5.5(c).

5.3.3 Predict the departure of user

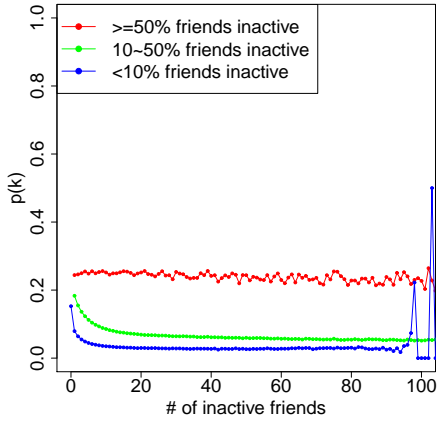
Given a strong correlation between the probability of a user becoming inactive and the inactivity of his friends, the next question is, can we actually predict individuals's departures based on local properties? In this section, we model the departure of users using simple linear regression models and decision tree



(a) SN



(b) SN



(c) SN

Figure 5.5: Probability of departure as function of local properties, at different levels of active/inactive friend fraction and friend count (snapshot taken at time $t = 2011/1/1$). All measured in SN

classifiers. In particular, we will focus exclusively on SN because we have a richer set of features available.

To start, we formalize our problem as a binary classification task in which class 1 is defined as consisting of those users who were active as of Jan 1st, 2011 (t_0) and departed within two months after t_0 , and class 0 is defined as consisting of those who stayed active for two months after t_0 . We then randomly sample 500K examples for each class, from all the users who were active at t . Note that in our data, there are 90% negative and only 10% positive cases; our sampling scheme provides a more balanced distribution of examples of both classes.

We extract two sets of local features for each user:

- Neighborhood features. The local structural properties of the user's direct neighborhood, including the number of friends who already departed, the number of friends who are active, the number of friends who departed recently (six months prior to t_0), and the fraction of friends who departed recently.
- Activity features. The properties reflecting user's participation to activities in the network, including the number of contents he received, the number of contents he sent, and the number of status updates.

To predict the departure of users, we train a simple decision tree (REPTree) classifier on our examples. Table 5.1 gives the performance of the classifier with different sets of features under 10-fold cross validation.

Table 4.2 shows that relying on only local features of individuals, the simple decision tree classifier can predict the departure of user with high accuracy (75% with all features, as compared to 50% for always predicting one class). This

Table 5.1: Predict user departure with decision tree

<i>Feature</i>	<i>Accuracy</i>	<i>F1 pos</i>	<i>ROC area</i>
Neighborhood	0.694	0.694	0.755
Activity	0.730	0.735	0.801
All	0.755	0.761	0.833

result demonstrates a strong connection between user’s local properties and the propensity of departure. Moreover, comparing across 3 sets of features, we see that although the activity features are most effective, neighborhood features can also provide rather accurate insights on the departure of users.

5.4 Structural trends in network topology

In this section, we explore the overall structural changes that occur in the network as a result of the departure of existing users, as well as the steady arrival of new users. Topological changes have been studied in the context of new nodes arriving but here we pay specific attention to how the global structure changes in the process of the departure or decline of user activities.

To get a sense of the how the structure of the network evolves over time, we first study the distribution of nodes (Figure 5.6) and edges (Figure 5.7) among active and inactive parts of the network. For nodes, we notice that although the total number of users keeps on increasing steadily, the number of active users has stopped growing for a long time (see Figure 5.6). For edges, we look at the edges between active nodes (Figure 5.7(a) and Figure 5.7(d)), edges between inactive nodes (Figure 5.7(b) and Figure 5.7(e)), and the edges across active and

inactive nodes (Figure 5.7(c) and Figure 5.7(f)), and plot the ratio between the actual number of edges over the expected value over time.

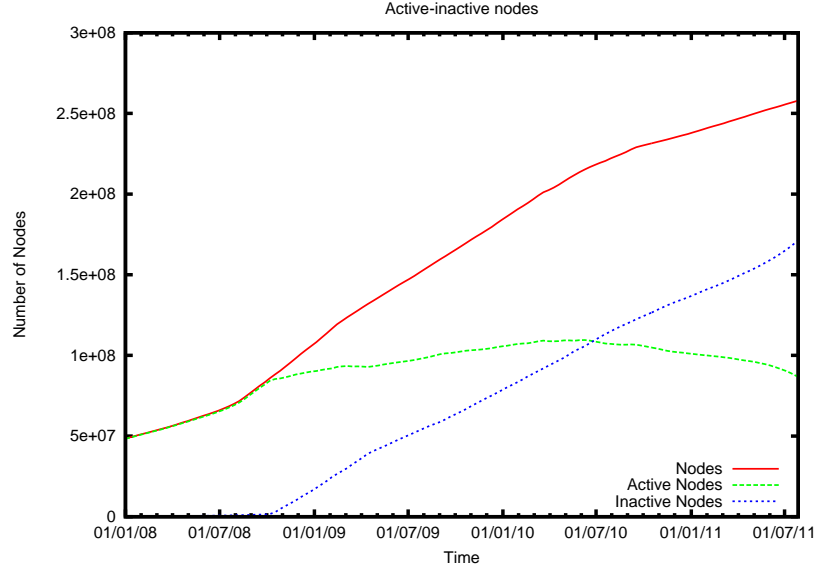


Figure 5.6: Distribution of nodes in active and inactive sub-networks

Here, the expected number of edges is computed based on the total number of edges, $|E|$, in the network and the number of nodes in each of the active and inactive sets. The expected number of edges of any type is the expected number of edges if the the total $|E|$ edges are placed between randomly chosen pairs of nodes.

To understand the overall structure among the sets of active and inactive nodes, we also study the density and conductance of these two sub-networks in the rest of this section. Here the active sub-network consists of the active nodes and the edges among them, and the inactive sub-network is similarly defined.

Figure 5.8 and plots the overall density of the active (5.8(a) and 5.8(c)) and inactive (5.8(b) and 5.8(d)) set of nodes, as a function of time. For comparison, we also plot the *expected* densities of the respective sets, as determined by the

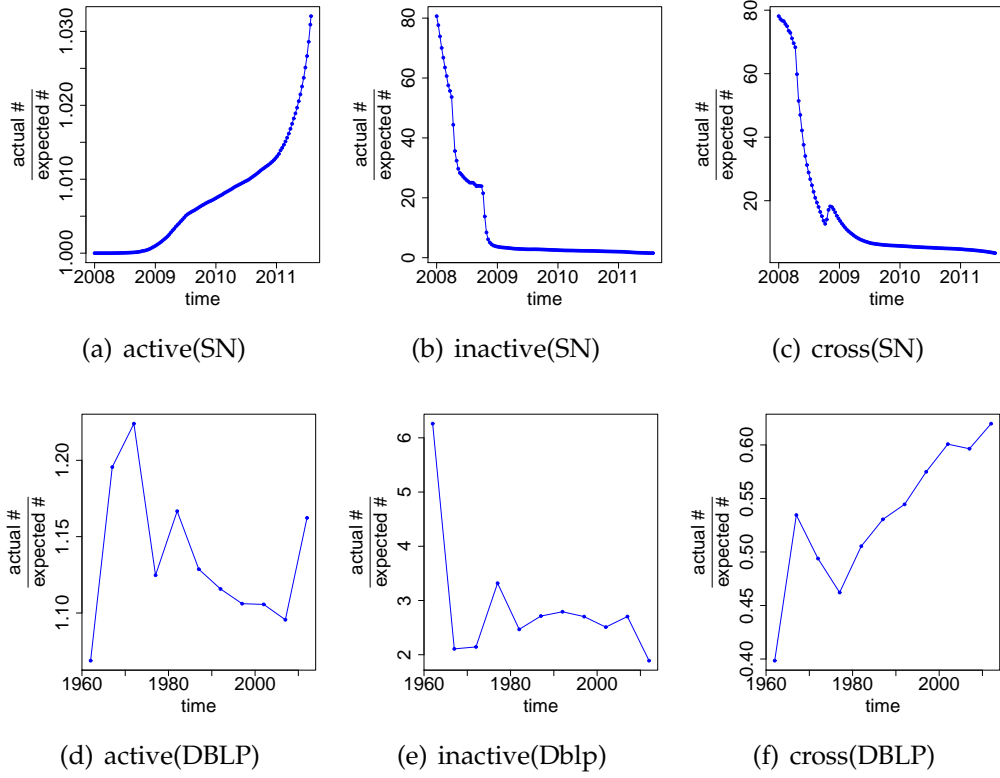


Figure 5.7: Distribution of edges, indicated by the ratio of actual number of edges over the expected number of edges (formed in random process).

number of active and inactive nodes and edges and the degree distributions.

We use the definition density of a set of nodes (or average induced degree) used in [23], where the density of a set of nodes is the number of edges between the nodes divided by the number of nodes; i.e. for a set of nodes S , $density(S) = \frac{|E(S,S)|}{|S|}$ (here $E(S,S)$ contains all edges (u,v) such that $u,v \in S$). Therefore, the density of set S is half of the average induced degree of the set of nodes in S . In order to compare the the density we observe for the set of active nodes and the set of inactive nodes, we define an *expected* density for each sub-network. The expected density of the inactive set of nodes could be computed simply as the density of the entire graph times the fraction of inactive nodes.

However, we even use a stronger baseline to see if the trends we observe are a result of a trend more than just that of degrees. Therefore, we compute expected density subject to the overall degree constraints on active and inactive nodes as follows.

Consider each edge as occupying two slots (end points), each slot being in either S_a (the active set of nodes), or S_i (the inactive set of nodes); therefore $S_a \cup S_i = V(G)$. Let the fraction of all these slots that are in S_i be P_i (which is the number of edges going across the active and inactive sub-network plus twice the number of edges in the inactive sub-network); therefore the number of such slots occupied in S_a is $P_a = (1 - P_i)$. Suppose that all the $|E|$ edges were randomly placed in two slots each, with probabilities determined such that in expectation we respect P_i and P_a , then we consider the induced density of this process as the expected density (for respective sub-networks). Notice that this is a more stringent baseline for our comparison. Therefore, an edge is contained in the inactive sub-network with probability P_i^2 and so the expected density of the inactive set is $(|E|P_i^2)/|S_i|$. Similarly the expected density of the active sub-network can be computed.

The plots on these densities in Figure 5.8 shows that the density of the active set $density(S_a)$ increases rapidly with increase in time. However, as shown in the plot on distribution of edges in Figures 5.7, as the number of edges in the active sub-network continue growing, the density of the active sub-network is only marginally higher than its expected density. On contrast, the density of inactive sub-network is significantly higher than the expected density, even conditioned on the degree distribution. This further confirms the fact that departure is correlated across edges, as shown in our local analysis. The nodes that are

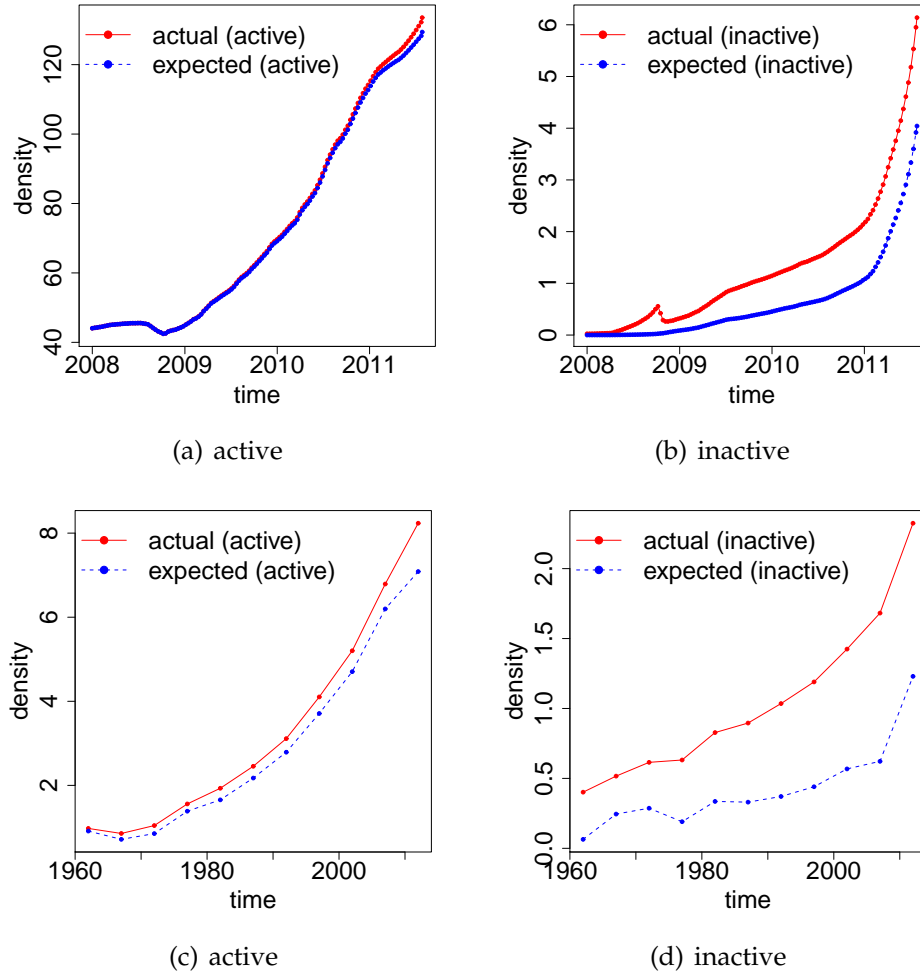


Figure 5.8: Density of the active and inactive sub-networks

departing are still probably at the periphery of the network (since the inactive set has much lower density than the active set), but these inactive nodes continue to be internally well-connected because of a higher-than-expected density. This strengthens the evidence from previous sections that a node's likelihood to become inactive is strongly associated with neighboring inactivity.

After studying the connectedness within the active/inactive sub-network separately, we now look at the connection of each sub-network to the rest of social graph, to get a more complete picture about where departures happen

and spread in the network. We use conductance to measure the amount of possible connections between different sets of nodes in a network.

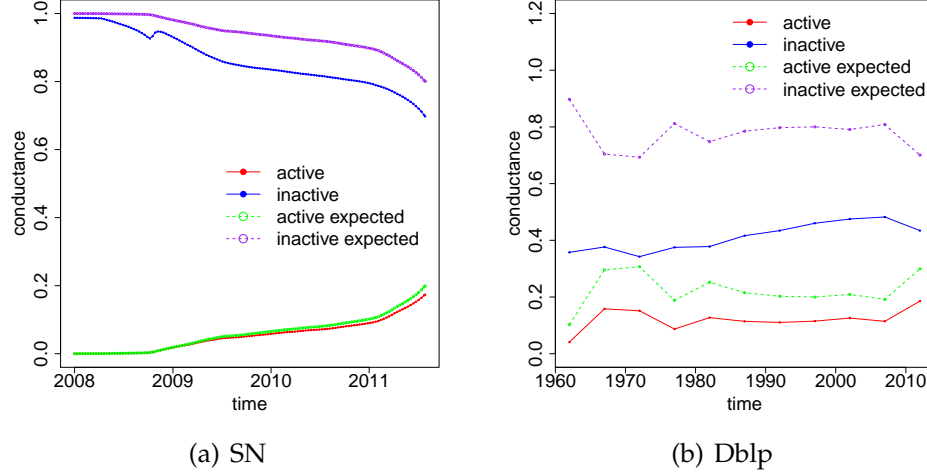


Figure 5.9: Conductance of the active and inactive sets

Conductance of a set of nodes S , $\phi(s)$, first defined in [44], is measured as $\phi(S) = \frac{|E(S, V(G) \setminus S)|}{|E(S)|}$. Here $E(S, V(G) \setminus S)$ contains all edges (u, v) such that $u \in S, v \notin S$, and $|E(S)| = 2|E(S, S)| + |E(S, V(G) \setminus S)|$. So notice that conductance is always less than 1, and any set with more than half its edges going across to the complement set has a conductance of more than $\frac{1}{3}$. We again measure the conductance of sets S_a and S_i through time and compare with their expected conductances (see Figure 5.9). The computation of expected conductance is also performed in a similar manner to as described previously for expected density.

We see a similar trend in conductance (Figure 5.9) as seen for densities. The conductance of the active set of nodes S_a , $\phi(S_a)$ remains less than the conductance expected for this set. This suggests that there are fewer edges going across from S_a to the inactive set S_i and far more edges within S_a itself, than would be expected. The conductance plots for the set of inactive nodes however is again more contrasting. $\phi(S_i)$ remains far lower than the expected conductance.

Nodes that are becoming inactive continue to have many more edges within, than one would expect. This clearly suggests that the inactive set of nodes are influencing neighbors to inactivity. Yet again, the absolute conductance value still suggests that nodes at the periphery of the network are more susceptible to becoming inactive.

The takeaway from these plots are two fold. Firstly, of course, these trends corroborate our findings from the previous sections suggesting that there is a strong correlation among inactivity in neighboring nodes . However, these plots on global measures such as density and conductance also suggest a picture of the evolving network. With the active sub-network's density being much higher than the inactive, and the inactive set showing higher than expected density and lower than average conductance, we are led to believe that nodes in the *core* of the network are much more likely to survive, while nodes at the periphery are more susceptible to departure, probably by a combination of external forces and the neighborhood inactivity.

5.5 Conclusion

We have studied the dynamics of user departure from online social networks and collaboration networks, from the perspectives of local and global network structure. We considered the predictive power of local neighborhoods on the behavior of nodes as well as studied global changes in the network topology. At the local level, we studied individuals and the dynamics in their local neighborhood, measured the probability of user arrival and departure in relation to the activity of their friends. Our findings are threefold: first, there is a strong

clustered effect in the timing of departure among friends while this is not as visible in arrivals; second, although both numbers and fractions of neighborhood (in)activity are correlated to the probability of the individual's departure, the fraction of inactive friends has arguably the better predictive power on the departure probability, providing an interesting complement to literature on arrivals which shows number of active friends as the most predictive of these measures; third, once a significant fraction of friends depart, the overall connectivity of individuals in the entire network does not have predictive power as to whether the user will leave the network. At the global level, we looked at the trend of network topological properties over the past few years, showing that as the network evolves, users at the peripheral region of the network are more likely to depart in groups; yet an internal core of the network survives and densifies over time.

We want to emphasize that our results do not prove a causal relationship between the departure of friends and the departure of a user. What we have observed and modeled is only correlated actions among neighbors, and we are aware of the possible factors that can contribute to, or actually lead to, the departure of users. For example, internally, users with similar personal traits may tend to leave the network altogether; externally, the emergence of competing services may draw users away from the original network. Our model provides *one* possible explanation on the emergence of observed pattern, but does not exclude other explanations. Our goal is to offer a space for building better models of how people tune out of social networks, in addition to how they sign up.

CHAPTER 6

CONCLUSION

This thesis explored three major aspects of information diffusion process: influencers, content, and network structure. In Chapter 3, we revisited the influencer problem by incorporating exogenous influence into the context of Twitter, and showed a very high concentration of attention on a small number of “elites” identified by their role in the global communication environment. We also noticed that there is a significant amount of long-lived content on Twitter, and longevity of information is related to both the type of initiator and the nature of content. In Chapter 4, we further studied the longevity of information, explored the relationship between content and the temporal dynamics of information on Twitter. We demonstrated the strong connection between content and the persistency of information, and found some unique characteristics for rapid-fading content and long-lasting content, respectively. In Chapter 5, we studied the local and global structure of several social networks to understand the spread of inactivity. We found that, departures, more than arrivals, are highly correlated among neighboring nodes. Also, the decay of activity first happens in the fringe of networks, then spreads to neighbors in tightly-knit communities, leaving a very well-connected central active core that survives and densifies through time.

Building on top of current research, our exploration on these aspects of diffusion process highlights the following three contributions.

First, we study the “virality” of diffusion with new aspects.

Instead of bursty events, we focus on the longevity of information, studying

lifespan of information in social media. We notice that, although both skewed, the distribution of lifespan has a much heavier tail, than the distribution of cascade scale. In Chapter 3 and Chapter 4, we compare the lifespan of information by its initiator and content, and ask what makes certain things so persistently eye-catching in a world where information is overly rich and attention is remarkably scarce [76]. Our major findings include:

- The longevity of information is determined to a large extent by the exogenous qualities of the information, not by social contagion.
- Content picked up by certain group of users (e.g., bloggers) are in general of more persistent interest, as these users actively perform the role of “information filter” on online social media.
- There is a strong correlation between the content and the temporal dynamics of information. Content with cultural/intelligent value are more likely to persist. At the text level, rapidly-fading information contains significantly more words related to negative emotion, actions, and more complicated cognitive processes, whereas the persistent information contains more words related to positive emotion, leisure, and lifestyle.
- The decay of attention, although much less visible, also has a network effect that coordinates the disengagement in online social networks among friends.

On the other hand, we also look at the “negative” virality - the virality of “inactivity”. In Chapter 5, we study the arrival and departure dynamics of large social networks, and show that user disengagement — similar to user engagement — is correlated among neighbors, but operates slightly differently.

Second, we examine the exogenous properties of actors and artifacts beyond the closed, single-medium communication network. For example, by looking in-depth at the textual characteristics, we find that the persistent attention to certain content can be better explained by the innate quality of the content, independent from the mechanism of how it spreads in the network. We also find that, despite the connectivity and demographics, certain users are more influential on social media because of their established role (and fame) from the world outside social media. These results suggest that, diffusion process should be studied in context, considering the socio-cultural factors that constantly interact with the information cascade.

Third, we study different components of diffusion not only by themselves, but also the interaction between them. As information diffusion is an interactive process between people and content, mediated by the communication networks, different components of diffusion do not exist in isolation. People with high influence tend to cluster together [7], and the location in the network can tell us a lot about a person's status [48, 9]. In our work, we show that different people have different preference of content and individual's influence is topic-dependent.

Besides these findings, this thesis is also an attempt to demonstrate the interdisciplinary research methodology. Although most of the results are quantitative and are drawn from analysis on large online datasets, I have worked closely with experts from various fields including sociologists, computer scientists, psychologists, communication scholars, and political scientists. During this process, I try to conduct my research with not only computational methods but also theories and insights from different fields. As a result, I hope our

findings are not limited to online social networks, but can also help uncover the nature of information diffusion process across online and off-line spaces.

In the future, I would like to extend my research cross media platforms, networks, and even between on-line and off-line spaces. Joining social media data with real world events, I will look forward to studying the effect of information, in a broad socio-cultural context. One of my ongoing projects is to study the role of social media in social movements, for better understanding on how the propagation of information leads (or reflects) societal changes. To do so, we have collected a large number of tweets and twitter networks related to big social movements (i.e., Middle East Revolution, Occupy WallStreet Movement). Using effective algorithms for community detection, hub detection, trend detection, and opinion mining, we will be able to identify the informal structure of massive communication networks for social movements and study the diffusion of ideology and behaviors across organizational/geographical boundaries.

In summary, I am deeply intrigued by the developing characteristics of information diffusion in online social media. Thanks to the Internet and social media technologies, I believe that we are heading towards a more democratic era where revolutions can be started by ordinary people and the power to change is in the hands of the masses. As part of this process, social media sites such as Facebook and Twitter have also evolved from friendship networks to a much broader platform for organizing social/political changes and communicating with various communities. I hope my work can help understand this movement and foster the effective flow of information in the society.

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