Information Diffusion Through Blogspace*

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Abstract

We study the dynamics of information propagation in environments of low-overhead personal publishing, using a large collection of weblogs over time as our example domain. We characterize and model this collection at two levels. First, we present a macroscopic characterization of topic propagation through our corpus, formalizing the notion of long-running "chatter" topics consisting recursively of "spike" topics generated by outside world events, or more rarely, by resonances within the community. Second, we present a microscopic characterization of propagation from individual to individual, drawing on the theory of infectious diseases to model the flow. We propose, validate, and employ an algorithm to induce the underlying propagation network from a sequence of posts, and report on the results.

1 Introduction

Over the course of history, the structure of societies and the relations between different societies have been shaped to a great extent by the flow of information in them [9]. More recently, over the last fifteen to twenty years, there has been interest not just in observing these flows, but also in influencing and creating them. Doing this requires a deep understanding of the macro- and micro-level structures involved, and this in turn has focused attention on modeling and predicting these flows. This paper studies the propagation of discussion topics from person to person through the social network represented by the space of all weblogs.

The mainstream adoption of the Internet and Web has changed the physics of information diffusion. Until a few years ago, the major barrier for someone who wanted a piece of information to spread through a community was the cost of the technical infrastructure required to reach a large number of people. Today, with widespread access to the Internet, this bottleneck has largely been

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removed. In this context, *personal publishing* modalities such as weblogs have become prevalent. Weblogs, or "blogs," are personal online diaries managed by easy-to-use software packages that allow single-click publishing of daily entries. The contents are observations and discussions ranging from the mainstream to the startlingly personal. There are several million weblogs in existence today. Unlike earlier mechanisms for spreading information at the grassroots level, weblogs are open to frequent widespread observation, and thus offer an inexpensive opportunity to capture large volumes of information flows at the individual level. Furthermore, recent electronic publication standards allow us to gather dated news articles from sources such as Reuters and the AP Newswire in order to analyze weblogs in the context of current affairs; these sources have enormous influence on the content of weblogs.

Weblogs typically manifest significant interlinking, both within entries, and in boilerplate matter used to situate the weblog in a neighborhood of other weblogs that participate in the same distributed conversation. Kumar et al. [19] analyze the "burstiness" of blogs, capturing bursts of activity within blog communities based on an analysis of the evolving link structure. Here, we focus instead on the propagation of topics from one blog to the next, based on the text of the weblog rather than its hyperlinks. Using this information, we seek to characterize information diffusion along two dimensions:

Topics: We are interested in first identifying the set of postings that are *about* some topic, and then characterizing the different patterns into which the collection of postings about the topic may fall. We propose that topics are mostly composed of a union of *chatter* (ongoing discussion whose subtopic flow is largely determined by decisions of the authors) and *spikes* (short-term, high-intensity discussion of real-world events that are relevant to the topic). We develop a model to capture this observed structure.

Individuals: Though the advent of personal publication gives everyone the same reach, individual behavior differs dramatically. We begin by characterizing four categories of individuals based on their typical posting behavior within the life cycle of a topic. We then develop a model for information diffusion based on the theory of the spread of infectious diseases; the parameters of the model capture how a new topic spreads from blog to blog. We give an algorithm to learn the parameters of the model based on real data, and apply the algorithm to real (and synthetic) blog data. As a result, we are able to identify particular individuals who are highly effective at contributing to the spread of "infectious" topics.

2 Related Work

There is a rich literature around propagation through networks that is relevant to our work, from a variety of fields ranging from thermodynamics to epidemiology to marketing. We provide here a broad survey of the area, with pointers to more detailed survey works where possible, and give some details around recent work in disease propagation that is closest in spirit to the models we present.

2.1 Information Propagation and Epidemics

Much previous research investigating the flow of information through networks has been based upon the analogy between the spread of disease and the spread of information in networks. This analogy brings centuries of study of epidemiology to bear on questions of information diffusion. (See, for example, the book of Bailey [4] for some of the extensive work in this field.)

Classical disease-propagation models in epidemiology are based upon the cycle of disease in a host: a person is first *susceptible (S)* to the disease. If then exposed to the disease by an infectious contact, the person becomes *infected (I)* (and *infectious*) with some probability. The disease then runs its course in that host, who is subsequently *recovered (R)* (or *removed*, depending on the virulence of the disease). A recovered individual is immune to the disease for some period of time, but the immunity may eventually wear off. Thus *SIR* models diseases in which recovered hosts are never again susceptible to the disease—as with a disease conferring lifetime immunity, like chicken pox, or a highly virulent disease from which the host does not recover—while *SIRS* models the situation in which a recovered host eventually becomes susceptible again, as with influenza. In blogspace, one might interpret the SIRS model as follows: a blogger who has not yet written about a topic is exposed to the topic by reading the blog of a friend. She decides to write about the topic, becoming infected. The topic may then spread to readers of her blog. Later, she may revisit the topic from a different perspective, and write about it again.

Girvan et al. [11] study a SIR model *with mutation*, in which a node u is immune to any strain of the disease which is sufficiently close to a strain with which u was previously infected. They observe that for certain parameters it is possible to generate periodic outbreaks, in which the disease oscillates between periods of epidemic outbreak and periods of calm while it mutates into a new form. In blogspace, one could imagine the mutation of Arnold *qua* movie star into Arnold *qua* governor. (We observe this kind of ebb and flow in the popularity of various "spiky chatter"-type memes. See Section 4.2.1.)

Early studies of propagation took place on "fully mixed" or "homogeneous" networks in which a node's contacts are chosen randomly from the entire network. Recent work, however, focuses on more realistic models based on social networks. In a model of small-world networks defined by Watts and Strogatz [28], Moore and Newman [21] are able to calculate the minimum transmission probability for which a disease will spread from one seed node to infect a constant fraction of the entire network (known as the *epidemic threshold*).

We now review some previous research on epidemic spreading on networks that follow a *power law*, in which the probability that the degree of a node is k is proportional to $k^{-\alpha}$, for a constant α typically between 2 and 3. Many real-world networks have this property [20], including the social network defined by blog-to-blog links [19]. Pastor-Satorras and Vespignani [25] analyze an SIS model of computer virus propagation in power-law networks, showing that—in stark contrast to random or regular networks—the epidemic threshold is *zero*, so an epidemic will always occur. These results can be interpreted in terms of the robustness of the network to random edge failure, as follows. Suppose that each edge in the network is deleted independently with probability $(1-\varepsilon)$; we consider the network "robust" if most of the nodes are still connected. It is easy to see that nodes that remain in the same component as some initiator v_0 after the edge deletion process are exactly the same nodes that v_0 infects according to the disease transmission model above. This question has been considered from the perspective of *error tolerance* of networks like the Internet: what happens to the network if a random $(1-\varepsilon)$-fraction of the links in the Internet fail? Many researchers have observed that power-law networks exhibit extremely high error tolerance [2, 6].

In blogspace, however, many topics propagate without becoming epidemics, so such a model would be inappropriate. One refinement is to consider a more accurate model of power-law networks. Eguíluz and Klemm [10] have demonstrated a non-zero epidemic threshold under the SIS model in power-law networks produced by a certain generative model that takes into account the high *clustering coefficient*—the probability that two neighbors of a node are themselves neighbors—found in real social networks [28]. Another refinement is to modify the transmission model. Wu et al. [30] consider the flow of information through real and synthetic email networks under a model in which the probability of infection decays as the distance to the initiator v_0 increases. They observe that meme outbreaks under their model are typically limited in scope—unlike in the corresponding model without decay, where the epidemic threshold is zero—exactly as one observes in real data. Newman et al. [24] have also empirically examined the simulated spread of email viruses by examining the network defined by the email address books of a user community. Finally, Newman [23] is able to calculate properties of disease outbreaks, including the distribution of outbreak sizes and the epidemic threshold, for an SIR model of disease propagation.

2.2 The Diffusion of Innovation

The spread of a piece of information through a social network can also be viewed as the propagation of an *innovation* through the network. (For example, the URL of a website that provides an new, valuable service is such a piece of information.) In the field of sociology, there has been extensive study of the *diffusion of innovation* in social networks, examining the role of *word of mouth* in spreading innovations. At a particular point in time, some nodes in the network have adopted the innovation, and others have not. Two fundamental models for the process by which nodes adopt new ideas have been considered in the literature:

- *Threshold models [14].* Each node u in the network chooses a *threshold* $t_u \in [0, 1]$, typically drawn from some probability distribution. Every neighbor v of u has a nonnegative *connection weight* $w_{u,v}$ so that $\sum_{v \in \Gamma(u)} w_{u,v} \leq 1$, and u adopts if and only if $t_u \leq \sum_{\mathsf{adopters}\ v \in \Gamma(u)} w_{u,v}$.
- *Cascade models [13].* Whenever a social contact $v \in \Gamma(u)$ of a node u adopts, then u adopts with some probability $p_{v,u}$. (In other words, every time a person close to a person u adopts, there is a chance that u will decide to "follow" v and adopt as well.)

In the *Independent Cascade model* of Goldenberg, Eitan, and Muller [13], we are given a set of N nodes, some of which have already adopted. At the initial state, some non-empty set of nodes are "activated." At each successive step, some (possibly empty) set of nodes become activated. The episode is considered to be over when no new activations occur. The set of nodes are connected in a directed graph with each edge (u, v) labeled with a probability $p_{u,v}$. When node u is activated in step t, each node v that has an arc (u, v) is activated with probability $p_{u,v}$. This influence is independent of the history of all other node activations. (If v is not activated in that time step, then u will never activate v.) The *General Cascade model* of Kempe, Kleinberg, and Tardos [17] generalizes the Independent Cascade model—and also simultaneously generalizes the threshold models described above—by discharging the independence assumption.

Kempe et al. are interested in a related problem on social networks with a marketing motivation: assuming that innovations propagate according to such a model, and given a number k, find the k "seed" nodes S^*_k that maximize the expected number of adopters of the innovation if S^*_k adopt initially. (One can then give free samples of a product to S^*_k, for example.)

2.3 Game-Theoretic Approaches

The propagation of information through a social network has also been studied from a game-theoretic perspective, in which one postulates an increase in utility for players who adopt the new innovation or learn the new information if enough of their friends have also adopted. (For example, each player chooses whether to switch from video tape to DVDs; a person with friends who have made the same choice can benefit by borrowing movies.) In blogspace, sharing discussion of a new and interesting topic with others in one's immediate social circle may bring pleasure or even increased status.

Morris [22] and Young [31] consider a setting like the following coordination game: in every time step, each node in a social network chooses a *type* $\{0, 1\}$. Here we interpret players of type one to have adopted the meme. Each player i receives a positive payoff for each of its neighbors that has the same type as i, in addition to an intrinsic benefit that i derives from its type. (Each player may have a distinct utility for adopting, depending on his inherent interest in the topic.) Suppose that all but a small number of players initially have type 0. Morris and Young explore the question of whether type 1's can "take over" the graph if every node chooses to switch to type 0 with probability increasing as the number of i's neighbors that are of type 0 increases.

There has also been work in the economics community on models of the growth of social networks when an agent u can selfishly decide to form a link with another agent v, who may have information that u desires to learn. There is a *cost* borne by u to establishing such a link, and a *profit* for the information which u learns through this link. This research explores properties of the social network which forms under this scenario [5, 16].

3 Corpus Details

One of the challenges in any study involving tens of thousands of publishers is the tracking of individual publications. Fortunately for us, most of the publishers, including the major media sources, now provide descriptions of their publications using *RSS* (*rich site summary*, or, occasionally, *really simple syndication*) [18]. RSS, which was originally developed to support the personalization of the Netcenter portal, has now been adopted by the weblog community as a simple mechanism for syndication. In the present work, we focus on RSS because of its consistent presentation of dates—a key feature for this type of temporal tracking.

Our corpus was collected by daily crawls of 11,804 RSS blog feeds. We collected 2K–10K blog postings per day—Sundays were low, Wednesdays high—across these blogs, for a total of 401,021 postings in our data set. (Each posting corresponds to an "item" entry in RSS.) Complementing this, we also crawled fourteen RSS channels from `rss.news.yahoo.com` hourly, to identify when topics were being driven by major media or real-world events, as opposed to arising within blogspace itself. The blog entries were stored as parent/child entities in WebFountain [29] and analyzed with a half-dozen special-purpose blog annotators to extract the various date formats popular in RSS, convert to UTF8, detag, etc.

See Figure 1 for the profile of blog postings within a day and from day-to-day, normalized by the poster's time zone. The most frequent posting is at 10AM. There is a pronounced dip at 6 and 7PM (the commute home? dinner? Must-See-TV?), an odd plateau between 2 and 3AM and a global minimum at 5AM. Posting seems to peak midweek, and dips considerably on weekends.

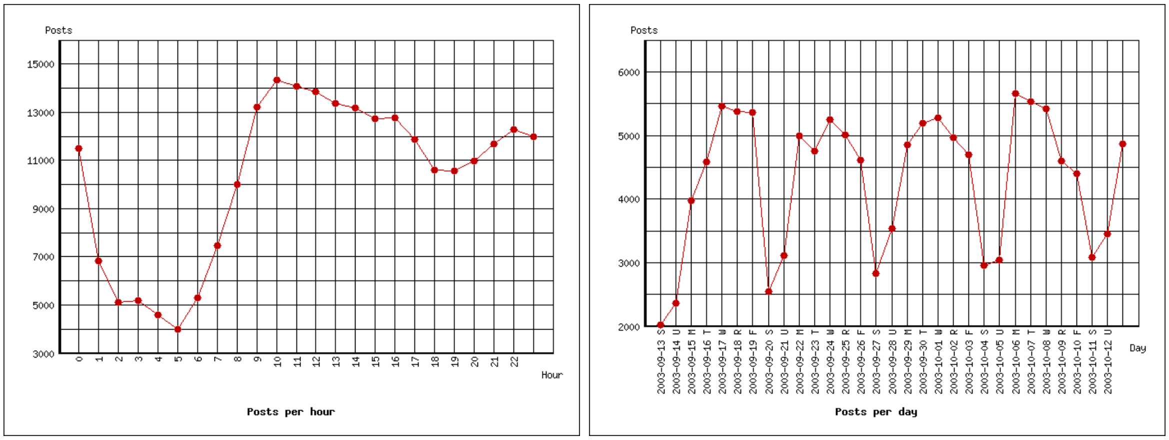

Figure 1: Number of blog postings (a) by time of day and (b) by day of week, normalized to the local time of the poster.

4 Characterization and Modeling of Topics

In this section, we explore the *topics* discussed in our data. We differentiate between two families of models: (i) *horizon* models, which aim to capture the long-term changes (over the course of months, years, or even decades) in the primary focus of discussion even as large chatter topics (like Iraq and Microsoft, as of this writing) wax and wane; and (ii) *snapshot* models, which focus on short-term behavior (weeks or months) while the background "chatter" topics are assumed to remain fixed. This paper explores snapshot models; we do not address horizon models, but instead raise the issue as an interesting open problem.

4.1 Topic Identification and Tracking

To support our goal of characterizing topic activity, we must first find and track topics through our corpus. The field of *topic detection and tracking* has studied this problem in depth for a number of years—NIST has run a series of workshops and open evaluation challenges [27]; see also, for example, [3]. Our requirements are somewhat different from theirs; we require schemes that provide views into a number of important topics at different levels (very focused to very broad), but rather than either high precision or high recall, we instead require that our detected set contain good representatives of all classes of topics. We have thus evaluated a range of simple techniques, chosen the ones that were most effective given our goals, and then manually validated different subsets of this broader set for use in particular experiments.

Our evaluations of these different techniques revealed some unexpected gaps in our intuition regarding blogspace; we give a brief walk-through here. First, we treated references to particular websites as topics, in the sense that bloggers would read about these "interesting" sites in another blog and then choose to write about them. However, while there are over 100K distinct links in our corpus, under 700 of them appear 10 times or more—not enough to chart statistically significant information flows. Next, we considered recurring sequences of words using sequential pattern mining [1]. We discovered under 500 such recurrent sequences, many of which represented automatically generated server text, or common phrases such as "I don't think I will" and "I don't understand why." We then turned to references to entities defined in the TAP ontology [15]. This

apple	arianna	ashcroft	astronaut
blair	boykin	bustamante	chibi
china	davis	diana	farfarello
guantanamo	harvard	kazaa	longhorn
schwarzenegger	udell	siegfried	wildfires
zidane	gizmodo	microsoft	saddam

Table 1: Example topics identified during manual scan.

provided around 50K instances of references to 3700 distinct entities, but fewer than 700 of these entities occurred more than 10 times. The next two broader sets provided us with most of the fodder for our experiments. We began with a naive formulation of proper nouns: all repeated sequences of uppercase words surrounded by lowercase text. This provided us with 11K such features, of which more than half occurred at least 10 times. Finally, we considered individual terms under a ranking designed to discover "interesting" terms. We rank a term t by the ratio of the number of times that t is mentioned on a particular day i (the term frequency $tf(i)$) to the average number of times t was mentioned on previous days (the cumulative inverse document frequency). More formally, $tfcidf(i) = (i-1)tf(i)/\sum_{j=0}^{i-1} tf(j)$. Using a threshold of $tf(i) > 10$ and $tfcidf(i) > 3$ we generate roughly 20,000 relevant terms.

All features extracted using any of these methods are then spotted wherever they occur in the corpus, and extracted with metadata indicating the date and blog of occurrence.

4.2 Characterization of Topic Structure

To understand the structure and composition of topics, we manually studied the daily frequency pattern of postings containing a large number of particular phrases. We analyzed the 12K individual words most highly ranked under the tfcidf ranking described above. Most of these graphs do not represent topics in a classical sense, but many do. We hand-identified 340 classical topics, a sample of which is shown in Table 1.

Next, based on our observations, we attempt to understand the structure and dynamics of topics by decomposing them along two orthogonal axes: internally driven, sustained discussion we call *chatter*; and externally induced sharp rises in postings we call *spikes*. We then refine our model by exploring the decomposition of these spikes into subtopics, so that a topic can be seen as the union of chatter and spikes about a variety of subtopics.

4.2.1 Topic = Chatter + Spikes

There is a community of bloggers interested in any topic that appears in postings. On any given day, some of the bloggers express new thoughts on the topic, or react to topical postings by other bloggers. This constitutes the *chatter* on that topic.

Occasionally, an event occurring in the real world induces a reaction from bloggers, and we see a *spike* in the number of postings on a topic. Spikes do not typically propagate through blogspace, in the sense that bloggers typically learn about spikes not from other blogs, but instead from a broad range of channels including mainstream media. Thus, we can assume all informed authors are aware of the topical event and have an opportunity to write about it.

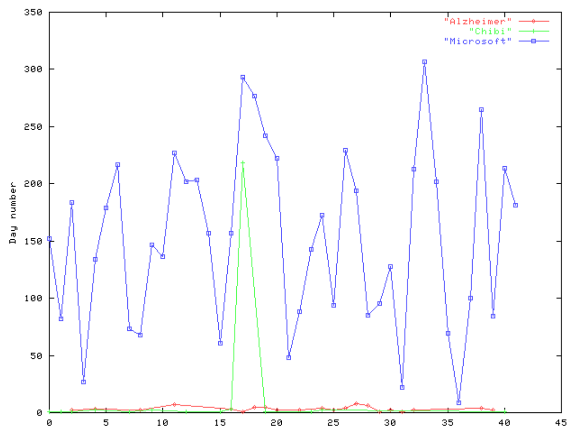

Figure 2: Three types of topic patterns: the topic "Chibi" (green line with single spike in center of graph) is *Just Spike*; "Microsoft" (blue line with peaks and valleys throughout graph) is *Spiky Chatter*; and "Alzheimer's" (red line with relatively flat content) is *Mostly Chatter*.

On rare occasions, the chatter reaches *resonance*, i.e., someone makes a posting to which everyone reacts sharply, thereby causing a spike. The main characteristic of resonance is that a spike arises from either no external input or a very small external input. The formation of order (a spike) out of chaos (chatter) has been observed in a variety of situations [26], though observation of our data reveals that this happens very rarely in blogspace. In fact, the only sustained block re-posting meme that we observed in our data consisted of the "aoccdrnig to rscheearch at an elingsh uinervtisy it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is taht the frist and lsat ltteer is at the rghit pclae" story which came out of nowhere, spiked and died in about 2 weeks (with most postings over a four-day period).

Depending on the average chatter level and pertinence of the topic to the real world, topics can be roughly placed into one of the following three categories, with examples shown in Figure 2:

Just Spike: Topics which at some point during our collection window went from inactive to very active, then back to inactive. These topics have a very low chatter level. E.g., Chibi.

Spiky Chatter: Topics which have a significant chatter level and which are very sensitive to external world events. They react quickly and strongly to external events, and therefore have many spikes. E.g., Microsoft.

Mostly Chatter: Topics which were continuously discussed at relatively moderate levels through the entire period of our discussion window, with small variation from the mean. E.g., Alzheimer's.

Spiky Chatter topics typically have a fairly high level of chatter, with the community responding to external world events with a spike; their persistent existence is what differentiates Spiky Chatter from spikes. They consist of a superposition of multiple spikes, plus a set of background discussion unrelated to any particular current event. For example, the Microsoft topic contains numerous spikes (for example, a spike towards the end of our window around a major announcement about Longhorn, a forthcoming version of Windows) plus ongoing chatter of people expressing opinions or offering diatribes regarding the company and its products.

windows	server	services	longhorn
exchange	ie	office	msdn
outlook	msn	gates	redmond
eolas	xp	netscape	powerpoint
scoble	pdc	motorola	avalon
ms	vb	acrobat	xaml

Table 2: Top coverage terms for Microsoft spikes.

4.2.2 Topic = Chatter + Spiky Subtopics

In this section, we refine our model of Topic = Chatter + Spikes by examining whether the spikes themselves are decomposable. Intuitively, the community associated with a topic can be seen as randomly choosing a subtopic and posting about it. When an external world event occurs, it is often particular to something very specific—that is, a subtopic—especially for complex topics. In this section, we consider a subtopic-based analysis using the spikes in the complex, highly posted topic "Microsoft" as a case study. Microsoft was especially appropriate for this analysis, as several Microsoft-related events occurred during the collection of our data set, including the announcement of blog support in Longhorn.

We used a multi-step process to identify some key terms for this experiment. First, we looked at every proper noun x that co-occurred with the target term "Microsoft" in the data. For each we compute the support s (the number of times that x co-occurred with the target) and the reverse confidence $c_r := P(\mathit{target}|x)$.

Thresholds for s and c_r were manipulated to generate rational term sets. As is common with these cases, we do not have a hard-and-fast support and confidence algorithm, but found that s in the range of 10 to 20 and c_r in the range of 0.10 to 0.25 worked well. For the target "Microsoft," this generates the terms found in Table 2. Of course, this is not a complete list of relevant subtopics, but serves rather as a test set. For these terms, we looked at their occurrences, and defined a spike as an area where the posts in a given day exceeded $\mu + 2\sigma$. We then extended the area to either side until a local minimum less than the mean was reached. We refer to posts during these intervals as *spike posts*.

Now, having identified the top coverage terms, we deleted spike posts related to one of the identified terms from the Microsoft topic. The results are plotted in Figure 3. The de-spiked posts line shows a considerable reduction in the spikes of the Microsoft graph, with minor reduction elsewhere. Note that even in the spiky area we are not getting a complete reduction, suggesting we may not have found all the synonymous terms for those spike events, or that subtopic spikes may be correlated with a latent general topic spike as well.

This analysis in no way implies that the topics in Table 2 are atomic. We also explored the subtopic "Windows"—one of the subtopics with better coverage—and looked at its decomposition. The proper noun selection was performed as before, generating the term set in Table 3. There is some duplication of terms from Table 2, as the topics "Microsoft" and "Windows" overlap significantly. However, some terms unique to Windows appear, especially the comparison to Apple (Apple, Steve Jobs, Quicktime, Mac, Macs, Macintosh).

Applying these terms to the Windows posting frequency, we see the results in Figure 4. Again, we see a similar reduction in spikes, indicating that we have found much of the spiky behavior of this topic. As might be expected with a more focused topic, the top 24 spike terms have better

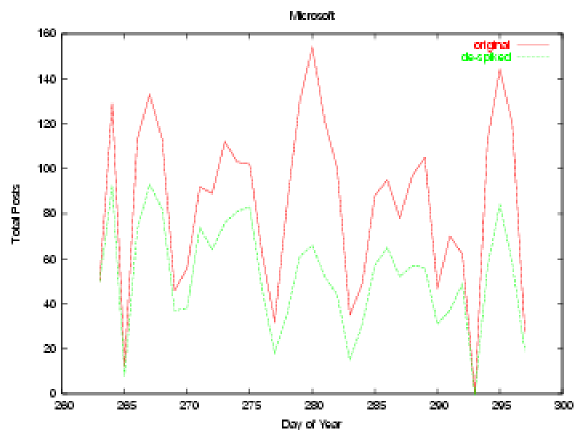

Figure 3: The topic density for posts on Microsoft, both before and after spike removal.

series	server	os	longhorn
pc	ie	mac	gui
apple	jobs	dell	ui
ram	xp	explorer	drm
unix	pcs	linux	apples
ms	macs	quicktime	macintosh

Table 3: Top coverage spike terms for Windows. Terms on a grey background are also spike terms for Microsoft (Table 2).

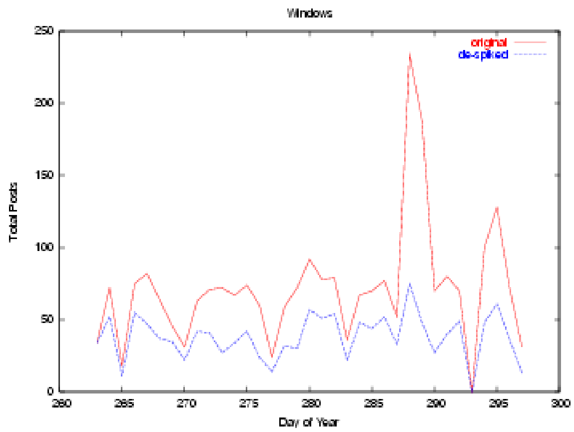

Figure 4: The topic density for posts on Windows, both before and after spike removal.

coverage for "Windows" than for "Microsoft," leaving a fairly uniform chatter.

This case study strongly supports our notion of a spike and chatter model of blog posting. While not presented here, similar behavior was observed in a number of other topics (terrorism, Linux, the California recall election, etc.).

4.2.3 Characterization of Spikes

Having presented a qualitative decomposition of topics into chatter and spikes, we now present measurements to quantify the nature of these spikes. Each chatter topic can be characterized by two parameters corresponding to the chatter level (distribution of the number of posts per day) and the spike pattern (distribution of the frequency, volume, and shape of spikes).

To perform these evaluations, we hand-tagged a large number of topics into the categories given in Section 4.2.1. Of those hand-tagged topics, 118 fell into the chatter category; we performed this characterization study on those topics. We used the simple spike definition of Section 4.2.2 to determine where the spikes occurred in each chatter topic; an examination of the spikes found by this algorithm led us to believe that, while simple, it indeed captures our intuition for the spikes in the graph.

To begin, the average number of posts per day for non-spike regions of our collection of chatter topics ranges between 1.6 to 106. The distribution of non-spike daily average is well-approximated by Pr[average number of posts per day $> x$] $\sim ce^{-x}$.

Next, we focus on characteristics of spike activity. Figure 5 shows the distribution of the duration of spikes, as well as their *period*, the interval from the center of one spike to the next. Most spikes in our hand-labeled chatter topics last about 5–10 days. The median period between spike centers is about two weeks.

Figure 6 shows the distribution of average daily volume for spike periods. In addition to the distribution shown in the figure, we observed that the median spike among our chatter topics peaks at 2.7 times the mean, and rises and falls with an average change of 2.14 times the mean in daily volume.

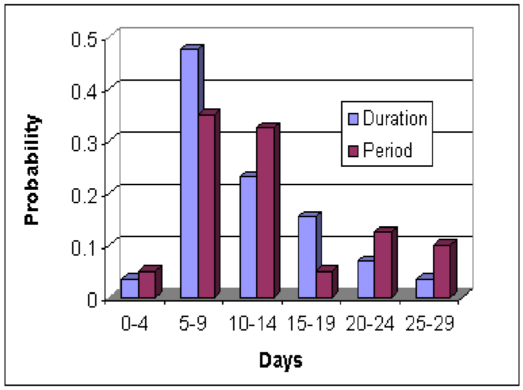

Figure 5: Distribution of spike duration and period (spacing between two consecutive spike centers) within chatter topics.

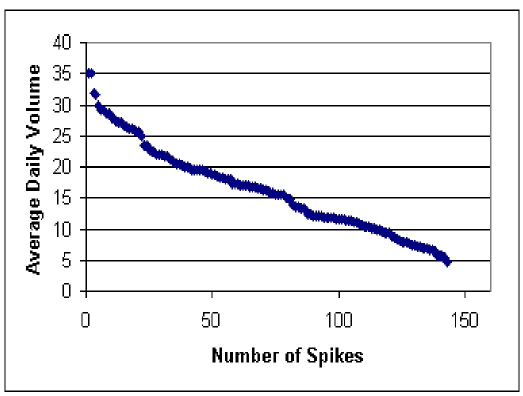

Figure 6: Average daily volume of spikes within chatter topics.

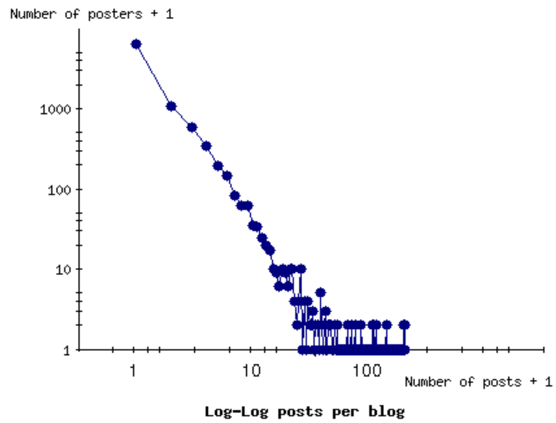

Figure 7: Distribution of number of posts by user.

5 Characterization and Modeling of Individuals

We have covered the high-level statistical "thermodynamic" view of the data in terms of aggregates of posts at the topic level; now we turn to a view more akin to particle dynamics, in which we attempt to uncover the path of particular topics through the various *individuals* who make up blogspace. We begin in Section 5.1 by categorizing individuals into a small number of classes, just as we did for topics in the previous section. Next, in Section 5.2 we formulate a model for propagation of topics from person to person through blogspace, and we present and validate an algorithm for inducing the model. Finally, we apply the model to real data, and give some preliminary applications.

Our model is akin to traditional models of disease propagation, in which individuals become "infected" by a topic, and may then pass that topic along to others with whom they have close contact. In our arena, close contact is a directed concept, since a may read the blog of b, but not vice versa. Such a model gives a thorough understanding of how topics may travel from person to person. Unfortunately, we do not have access to direct information about the source that inspired an author to post a message. Instead, we have access only to the surface form of the information: the sequence in which hundreds, thousands, or tens of thousands of topics spread across blogspace. Our algorithm processes these sequences and extracts the most likely communication channels to explain the propagation, based on the underlying model.

5.1 Characterizing Individuals

We begin with a quick sense of the textual output of our users. Figure 7 shows the distribution of the number of posts per user for the duration of our data-collection window. The distribution closely approximates the expected power law [20].

We now wish to classify these users. We adopt a simple set of predicates on topics that will allow us to associate particular posts with parts of the life cycle of the topic. Given this information, we will ask whether particular individuals are correlated with each section of the life cycle. The predicates are defined in the context of a particular time window, so a topic observed during a different time window might trigger different predicates. See Table 4 for the definitions of these predicates, and the fraction of topics that evince each of these regions.

Predicate	Algorithm	Region	% of topics
RampUp	All days in first 20% of post mass below mean, and average day during this period below $\mu - \sigma/2$.	First 20% of post mass.	3.7%
Ramp-Down	All days in last 20% of post mass below mean, and average day during this period below $\mu - \sigma/2$.	Last 20% of post mass.	5.1%
Mid-High	All days during middle 25% of post mass above mean, and average day during this period above $\mu + \sigma/2$.	Middle 25% of post mass.	9.4%
Spike	For some day, number of posts exceeds $\mu + 2\sigma$.	From spike to inflection point below μ, both directions.	18.2%

Table 4: Life-cycle predicates on topics, and the fraction of topics containing each region type.

We can then attempt to locate users whose posts tend to appear in RampUp, RampDown, MidHigh, or Spike regions of topics. However, we must exercise caution in tracking this correspondence: for example, we wish to avoid capturing users who simply happened to post more frequently during the early part of our data-collection window, and thus are more likely to post during regions identified as RampUp by our predicates. We therefore consider the probability p_i that a post on day i falls into a given category (e.g., RampUp). For any given user, we then consider the pair (t_i, c_i) of total posts on day i and posts in the category on day i, respectively. The total number of posts in the category is $C = \sum_i c_i$. We can then define a "random" user who contributes the same number of posts each day, but does so without bias for or against the category. The expected number of posts in the category for the random user is then $\sum_i p_i t_i$. Because the random user produces a sum of independent random variables, each of which is simply a series of Bernoulli trials with some bias depending on the day, we can determine the probability that the random user would produce C or more posts in the category, and therefore determine the extent to which we should be surprised by the behavior of the given user. We set our threshold for surprise when the number of occurrences is more than three standard deviations beyond the mean of the random user.

Using this technique, we give the number of users who are unusually strong contributors to each region in Table 5. In some cases, as for the Up region, the numbers are relatively low, but the total number of posts in the region is also quite small. The correlation is quite strong, leading us to suggest that evaluating broader definitions of a "ramp up" phase in the discussion of a topic may identify a larger set of users correlated with this region. For regions such as Mid or Spike, the number of associated users is quite substantial, indicating that there are significant differing roles played by individuals in the life cycle of a topic.

5.2 Model of Individual Propagation

We derive our formal model from the Independent Cascade model of Goldenberg et al. [13], which has been generalized by the General Cascade Model of Kempe et al. [17]. We are given a set of N nodes, corresponding to the authors. At the initial state of each episode, some possibly empty set

Region	Up	Down	Mid	Spike
Users with > 4 posts and $> \mu + 3\sigma$	20	55	157	310
Total posts this region	1733	3300	12453	55624

Table 5: Number of users associated with each region.

of nodes have written about the topic. At each successive state, some possibly empty set of authors write about the topic. We present the model in the SIR framework, in which authors do not write multiple postings on the topic; then in Section 5.4 we consider an extension into the more accurate SIRS framework, allowing authors to write repeatedly on the same topic. We consider the episode to be over when no new articles appear for some number of time steps, the *timeout interval*.

Under the Independent Cascade Model, the authors are connected by a directed graph, where each edge (v, w) is labeled with a *copy probability* $\kappa_{v,w}$. When author v writes an article at time t, each node w that has an arc from v to w writes an article about the topic at time $t + 1$ with probability $\kappa_{v,w}$. This influence is independent of the history of whether any other neighbors of w have written on the topic. The General Cascade Model can be seen as generalizing this by eliminating the assumption of independence.

We introduce the notion that a user may visit certain blogs frequently, and other blogs infrequently. We capture this with an additional edge parameter $r_{u,v}$, denoting the probability that u reads v's blog on any given day.

Formally, propagation in our model occurs as follows. If a topic exists at vertex u on a given day—i.e., u has previously written about the topic—then we compute the probability that the topic will propagate from u to a neighboring vertex v as follows. Node v reads the topic from node u on any given day with reading probability $r_{u,v}$, so we choose a delay from an exponential distribution with parameter $r_{u,v}$. Then, with probability $\kappa_{u,v}$, the author of v will choose to write about it. If v reads the topic and chooses not to copy it, then v will never copy that topic from u; there is only a single opportunity for a topic to propagate along any given edge.

Alternatively, one may imagine that once u is infected, node v will become infected with probability $\kappa_{u,v} r_{u,v}$ on any given day, but once the $r_{u,v}$ coin comes up heads, no further trials are made. See Section 5.4 for some extensions to the model.

Thus, given the transmission graph (and, in particular, each edge's reading frequency r and copy probability κ), the distribution of propagation patterns is now fully established. Given a community and a timeout interval, our goal is therefore to learn the arcs and associated probabilities from a set of episodes. Using these probabilities, given the initial fragment of a new episode, we would like to be able to predict the propagation pattern of the episode.

5.3 Induction of the Transmission Graph

In the following, we make a *closed world assumption* that all occurrences of a topic except the first are the result of communication via edges in the network. In Section 5.4, we discuss weakening this assumption by introducing an "outside world" node into the model.

A *topic* in the following is a URL, phrase, name, or any other representation of a meme that can be tracked from page to page. We gather all blog entries that contain a particular topic into a list $[(u_1, t_1), (u_2, t_2), \ldots, (u_k, t_k)]$ sorted by publication date of the blog, where u_i is the universal identifier for blog i, and t_i is the first time at which blog u_i contained a reference to the topic. We refer to this list as the *traversal sequence* for the topic.

We wish to induce the relevant edges among a candidate set of $\Theta(n^2)$ edges, but we have only limited data. We shall make critical use of the following observation: the fact that blog a appears in a traversal sequence, and blog b *does not* appear later in the same sequence gives us evidence about the (a, b) edge—that is, if b were a regular reader of a's blog with a reasonable copy probability, then sometimes memes discussed by a should appear in b's blog. Thus, we gain information from both the presence and absence of entries in the traversal sequence.

We present an EM-like algorithm to induce the parameters of the transmission graph [8], in which we first compute a "soft assignment" of each new infection to the edges that may have caused it, and then update the edge parameters to increase the likelihood of the assigned infections. Assume that we have an initial guess at the value of r and κ for each edge, and we wish to improve our estimate of these values. We adopt a two-stage process:

Soft-Assignment Step: Using the current version of the transmission graph, compute for each topic and each pair (u, v) the probability that the topic traversed the (u, v) edge.

Parameter-Update Step: For fixed u and v, recompute $r_{u,v}$ and $\kappa_{u,v}$ based on the posterior probabilities computed above.

5.3.1 Soft-Assignment Step

We are given as input the traversal sequence for a particular topic j. For each v in the sequence, we consider all previous vertices u in the sequence, and compute the probability $p_{u,v}$ that topic j would have been copied from u to v, given the delay between u and v in the sequence. We then normalize by the sum of these probabilities to compute posteriors of the probability that each node u was v's source of inspiration. That is, setting $r = r_{u,v}$, $\kappa = \kappa_{u,v}$, and δ to be the delay in days between u and v in topic j:

$$p_{u,v} := \frac{r(1-r)^{\delta}\kappa}{\sum_{w<v} r_{w,v}(1-r_{w,v})^{\delta_{w,v}}\kappa_{w,v}}.$$

In practice, for efficiency reasons, we consider only the 20 values of w closest to v, and require propagation to occur within 30 days.

5.3.2 Parameter-Update Step

We perform the following operation for each fixed u and v.

Let S_1 denote the set of topics j such that topic j appeared first at node u and subsequently at node v, and let S_2 denote the set of topics j such that u was infected with topic j but v was never infected with the topic.

For each topic $j \in S_1$, we require as input the pair (p_j, δ_j), where p_j is the posterior probability computed above that u infected v with topic j, and δ_j is the delay in days between the appearance of the topic in u and in v. For every topic $j \in S_2$, we require as input the value δ_j, where δ_j days elapsed between the appearance of topic j at node u and the end of our snapshot.

We can then estimate an updated version of r and κ as follows:

$$r := \frac{\sum_{j\in S_1} p_j}{\sum_{j\in S_1} p_j\delta_j} \qquad\qquad \kappa := \frac{\sum_{j\in S_1} p_j}{\sum_{j\in S_1\cup S_2} \Pr[r \le \delta_j]}$$

where $\Pr[a \leq b] = (1-a)(1-(1-a)^b)$ is the probability that a geometric distribution with parameter a has value $\leq b$. (Given the p_j's, the updated $1/r$ is the expected delay in topics copied from u to v, and the updated κ is the ratio of the expected number of topics at u copied by v to the expected number of such topics read by v.)

5.3.3 Iteration and Convergence

We now have an improved guess at the transmission graph, so we can return to the soft-assignment step and recompute posteriors, iterating until convergence. In the first step, we use our model of the graph to guess how data traveled; in the second, we use our guess about how data traveled to improve our model of the graph.

For our data sets, the values of r and κ converge within 2–5 iterations, depending on the data, to a vector of values within 1% of the limiting value under the L_2 norm.

5.4 Extensions to the Model

The real world. Most blog topics do not travel exclusively through blogspace; rather, they are real-world events that are covered to some extent in traditional media. During online coverage of the topic, certain bloggers may read about the topic in other blogs and respond, while others may read about the topic in the newspaper and write without reference to other blogs. Our model can be extended by introducing a "real world" node, which we view as writing about a topic whenever that the topic is covered sufficiently in the media. Transmission probabilities and delays are handled just as before, though we assume that essentially all bloggers will receive input from this "real world" node.

Span of attention. Blogging communities can become quite large, and most people do not have the time to read more than a few blogs on any regular basis. This phenomenon can be modeled either by limiting the in-degree of nodes, or by allowing only some small number of in-edges to influence a particular node at any time step. We can extend the model to support this phenomenon by adding an *attention threshold* parameter. More sophisticated models can capture the fact that the attention threshold is a function of the other episodes that are occurring at the same time—the more concurrent episodes, the lower the attention threshold for each episode. This can explain the phenomenon that during high-chatter events like the Iraq war or the California elections, many other topics that would otherwise have received a lot of attention in fact received little. The algorithm to learn the graph would require significant modification to incorporate these changes.

Stickiness. As described above, the probability that a node v will be infected with topic j by a node u in our model depends only on the parameters $r_{u,v}$ and $\kappa_{u,v}$, and is independent of the topic itself. Realistically, certain topics are inherently more interesting than others, and thus are more likely to be copied. To extend the model, we introduce the *stickiness* S_j of each topic j that controls the probability that the topic will "stick" with v. The probability of infection when v reads u's blog now becomes $\kappa_{u,v}S_j$ instead of just $\kappa_{u,v}$. (Stickiness of a topic is analogous to *virulence* of a disease.) Our algorithm for inducing parameters of the induction graph requires only minor modification for the updating of p, r, and κ if we knew the S_j's, but we still must compute or induce the stickiness values. Often we can employ outside information, such as empirical data on the popularity of a particular topic. Stickiness can also be learned from the model using a

Topics per node	μ_r	σ_r	μ_κ	σ_κ
2	0.718	0.175	0.141	0.455
4	0.703	0.157	0.107	0.039
6	0.694	0.134	0.103	0.034

Table 6: Mean and standard deviation for r and κ in low-traffic synthetic benchmark. Correct values: $r = 0.66, \kappa = 0.1$.

maximum likelihood estimation. However, the likelihood equations appear quite complicated, and the estimation would be computationally expensive. We have not pursued this direction.

Multiple Posts. In our domain, authors routinely write multiple posts on the same topic. The framework presented above extends naturally to this case, except that traversal sequences of the form $[(u_1, t_1), (u_1, t_2), (u_3, t_3), \ldots]$ are possible. Thus, in estimating copy probabilities κ and delays r, we must consider the disjoint events that u_3 received the information from the first instance of u_1, or the second instance. The relevant expectations must now be taken over multiple instances of u, but the equations are otherwise unchanged. The experiments described below, however, simply assume that the reader of a blog will respond to the most recent post on a particular topic, rather than to a prior post.

5.5 Validation of the Algorithm

5.5.1 Validation for Synthetic Data

In order to validate the algorithm, we created a synthetic series of propagation networks, ran each synthetic network to generate observable sequences of infection by particular topics, and then ran our mining algorithm to extract the underlying propagation network. The synthetic graphs are modified Erdös-Renyi random graphs: a number of vertices n is fixed, as is a target degree d.[1] Each vertex selects d out-neighbors uniformly with replacement from the vertex set; all parallel edges and self-loops are then removed. Each edge is then given an (r, κ) value; we used $r = 2/3$ and $\kappa = 1/10$ for our tests.

We began with a synthetic graph with $n = 1000$ and $d = 3$. For this graph, we performed multiple trials of a synthetic benchmark in which a topic begins at a single vertex, and then propagates according to a model. The number of trials per vertex ranged from 20 to 60. We refer to this benchmark below as the "impulse response topics." Due to the small value of κ, between 2 and 6 topics originating from each vertex propagate to at least one other vertex, on average. We considered only edges that were traversed by at least three topics with probability at least 0.1. We then compared the resulting edge set against the edge set from the original propagation network. An edge was counted as erroneous if it appeared in only one of those two graphs—i.e., we penalize for both missing edges and unnecessary edges. The algorithm requires little data to infer the correct edges: once it saw 6 topics per node on average, it correctly inferred 2663 of the 3000 edges, plus 4 erroneous additional edges. For this benchmark, the algorithm converges in two iterations. The mean and standard deviation of the inferred values of r and κ for this experiment are shown in Table 6.

[1] We validate the model on these simple graphs; future work involves validation on other graph types, such as synthetic power-law graphs.

Next, we turn to a propagation model with higher degrees in which topics tend to take off and propagate throughout the graph, making it more difficult to learn exactly how the information had traveled. The parameters are $n = 500$, $d = 9$, and we take 20 topics per node. Topic sizes range from 1 to slightly over 200. The estimated r values have mean 0.73 and standard deviation 0.12; the κ values have mean 0.08 and standard deviation 0.03. The system identifies almost all relevant edges (to within 1%), and identifies a further almost 9% spurious edges due to the more complex structure of this task. Thus, both the edges and the estimated parameters of the edges are very close to the underlying model.

5.5.2 Validation and Analysis for Real Data

Now that we have validated the algorithm on synthetic data, we validate the model itself against our data. We run the graph induction algorithm as described above on all the ProperName sequences in our dataset. As we have seen, roughly 20% of these sequences contain spikes, and fewer than 10% contain RampUp and RampDown areas. So the dataset consists of both signal and noise. Rather than introducing a "real world" node to modeling communication through the general media, we restrict our attention to topics for which at least 90% of the occurrences are in blogspace, rather than in our RSS media content. This focuses on about 7K topics.

To validate that the model has in fact discovered the correct edges, we performed two experiments. First, we downloaded the top 100 blogs as reported by `http://blogstreet.com`. Of the 100 blogs, 70 of them were in our RSS-generated dataset. We then used the model to rank individual nodes of the network based on the amount of traffic flowing through those nodes. Of the 70 nodes in our dataset, 49 were in the top 10% of blogs in our analysis; 40 were in the top 5%, and 24 were in the top 1.2%.

As a second validation, we ranked all edges in the final model by the expected number of topics that flowed down the edge, and produced the top 200. We hand-examined a random sample of this set, and in 90% of the cases were able to find a link between the two blogs. Note that we were able to make use of the structure of blogspace in the discovery of these links (i.e., blogrolls, and userids appearing inline), while the algorithm did not have access to these mechanisms, and made its determinations based on topics alone.

Figure 8 shows the distributions of r and κ as learned by the algorithm on the approximately 7K topics described above. Most edges have an expected propagation delay $(1/r)$ of fewer than 5 days; the mean r is 0.28 and the standard deviation is 0.22. Copy probabilities are quite low, with mean 0.04 and standard deviation 0.07, indicating that even bloggers who commonly read from another source are selective in the topics they choose to write about.

Figure 9 shows the distribution of expected traffic along each edge; i.e., over the set of 7K given topics, for a particular edge (a, b), how many times does b read about something on a and consequently write about it? The iteration converges to about 4000 edges with traffic. Popular edges might have 50 expected copies; the median edge has 1–2 total expected messages that traverse it.

5.6 Nature of the Induced Transmission Graph

Now that we have learned the transmission graph from real data, we consider two quick analyses of its nature.

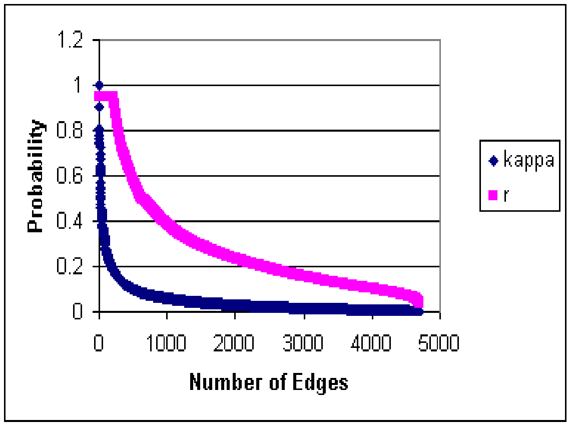

Figure 8: Distribution of Inverse Mean Propagation Delay (r) and Copy Probability (κ) for RSS data.

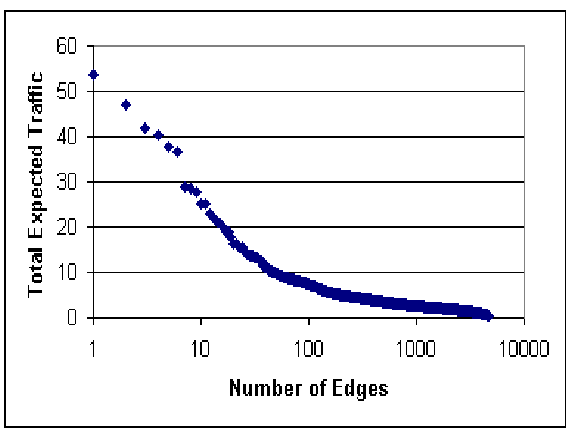

Figure 9: Expected Traffic over 7K episodes for RSS data.

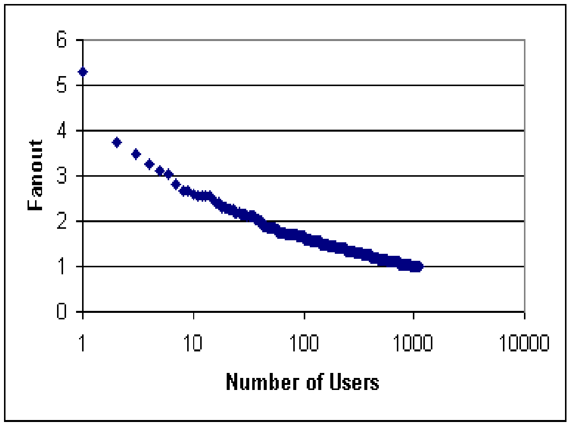

Figure 10: Fanout per individual.

5.6.1 Fanout by individual

Certain individuals are likely to pass topics on to many friends, while others never see a follow-on response. We can measure the expected number of follow-on infections generated by each person in the graph; we refer to this number as the *fanout*. Most users leave the topic with less energy than it arrived, transmitting to an expected less than one additional person, as we would expect; thus, very few topics reach resonance and cover blogspace through grassroots channels. Some users, however, provide a boost to every topic they post about—over time, these are the users who can have significant impact on a community, or even on blogspace overall. The fanout results are shown in Figure 10. The point to the very left of the graph with fanout 5.3 is a standout; she is a classic "connector" in the sense of *The Tipping Point* [12] with a huge collection of friends, a broad set of interests, and an intelligent and up-to-date blog.

5.6.2 Critical Linkages

We may ask further whether any individuals tend to be more strongly associated with topics that begin to take off. If we consider the random set of "impulse response" topics from the previous section, there are 357 of them that reach more four or more users. Although the topics have been started at all possible start points in the graph, and on average hit only 5 users, there is nonetheless a single user who is present in 42 of the 357 episodes. Similarly, there are 18 users present in at least 20 of the 357 episodes—as has often been pointed out, marketers would do well to understand these 18 users.

6 Future Work and Applications

In this section, we adopt a broader perspective and sketch some possible domains in which a better understanding of the flow of information through networks might be a powerful tool.

6.1 News Services

Over the past few years, we have seen the launch of a number of alert-based news services, which attempt to filter the large volume of online news items and identify a small number of important, high-impact stories relevant to a given topic. The explosion in the volume of news items poses a significant challenge for making these services useful. Weblogs compound this problem: while some blog postings may be sufficiently important to merit notification, it can be difficult to identify the crucial posts in high-chatter topics. (Corporate press releases pose a similar problem: while some press releases are important and newsworthy, the vast majority are comparatively irrelevant marketing propaganda.) Sites like DayPop [7] attempt to track spikes, but the lack of a topic structure reduces their value. Our topic model contributes to a solution for this problem by enabling us to identify subtopics that are experiencing spikes. Such an approach leverages the blogging community's reaction to external world events, as manifested by spikes in blog postings, to identify news events that are worthy of attention. We believe that this view of the blogging community—as a giant collaborative filtering mechanism built around an implicit web of trust, as manifested in propagation patterns between individuals—offers great potential.

6.2 Marketing

Weblogs offer an excellent, inexpensive, and nearly real-time tool for evaluating the effectiveness and health of a company's image and image-affecting activities. The ability to perform such evaluations in the real world (and not in experimental focus groups) can be a powerful and—given the substantial marketing expenditures of many organizations—important tool.

For example, a company launching a new advertising campaign can gain significant value from being able to judge (and thus, hopefully, increase through tuning) the effectiveness of the campaign. To the extent that the blogging community is representative of the target audience for such a campaign, marketers can measure uptake of key messages by defining and tracking the appropriate topics.

The topic model might be used in the development of public relations campaigns, as well. Typically a company has a wide variety of distinct possible emphases for an advertisement or a press release, and must select one of these directions. As discussed previously, high-chatter topics tend to exhibit larger spikes; thus choosing to emphasize a high-chatter (sub)topic can increase the likelihood of the message eliciting a large reaction.

The chatter level on a topic can potentially also be used for keeping tabs on the "mindshare" that a company has. As illustrated in our examples and case studies, high visibility companies such as Microsoft and Apple exhibit a high chatter level; tracking this chatter could provide an early view of trends in share and perception.

6.3 Resonance

Resonance is the fascinating phenomenon in which a massive response in the community is triggered by a minute event in the real world. It is an extremely rare phenomenon; we were surprised to find even a few instances of resonance in our data set. Understanding what causes resonance in networks like blogspace is an interesting future direction for research, from both the computational and the sociological perspective. The observation of the spontaneous generation of order from chaos is not new [26], but perhaps the access to blog data can shed new insight on this type of phenomenon.

Resonance is the marketeers' Holy Grail [12]; a better understanding of the cause of resonance would have massive implications for marketing.

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