# TEXT CLASSIFICATION THROUGH TIME:
## *Efficient Label Propagation in Time-Based Graphs*

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Abstract: One of the fundamental assumptions for machine-learning based text classification systems is that the underlying distribution from which the set of labeled-text is drawn is identical to the distribution from which the text-to-be-labeled is drawn. However, in live news aggregation sites, this assumption is rarely correct. Instead, the events and topics discussed in news stories dramatically change over time. Rather than ignoring this phenomenon, we attempt to explicitly model the transitions of news stories and classifications over time to label stories that may be acquired months after the initial examples are labeled. We test our system, based on efficiently propagating labels in time-based graphs, with recently published news stories collected over an eighty day period. Experiments presented in this paper include the use of training labels from each story within the first several days of gathering stories, to using a single story as a label.

## 1. INTRODUCTION

The writing, vocabulary, and topic of news stories rapidly shift within extremely small periods of time. In recent years, new events and breaking, “hot”, stories almost instantaneously dominate the majority of the press, while older topics just as quickly recede from popularity [19]. For typical automated news-classification systems, this can present severe challenges. For example, the ‘Political’ and ‘Entertainment’ breaking news stories of one week may have very little in common, in terms of subject or even vocabulary, with the news stories of the next week. An automated news classifier that is trained to accurately recognize the previous day/month/year’s stories may not have encountered the type of news story that will arise tomorrow.

Unlike previous work on topic detection and tracking, we are not attempting to follow a particular topic over time or to determine when a new topic has emerged [1][2][3]. Instead, we are addressing a related problem of immediate interest to live news aggregation sites: given that a news story has been published, in which of the site’s preset categories should it be placed?

The volume of news stories necessitates the use of an automated classifier. However, one of the fundamental assumptions in machine learning based approaches to news classification is that the underlying distribution from which the set of labeled-text is drawn is identical to the distribution from which the text-to-be-labeled is drawn. Because of the rapidly changing nature of news stories, this may not hold true. In this paper, we present a graph-based approach to address the problem of *explicitly* capturing both strong and weak similarities within news stories over time and to use these efficiently for categorization. Our approach combines the paradigm of *Min-Hashing* and *label propagation* in graphs in a novel way. While Min-Hashing is well-understood in information retrieval applications, our application of it to create a temporal similarity graph appears to be new. Label propagation is gaining popularity in the field of machine learning as a technique for semi-supervised learning. Our approach to label propagation follows our previous work [4], where equivalent views of a basic algorithm termed *Adsorption* were established, and the technique was successfully employed for propagating weak information in extremely large graphs to create a video recommendation system for YouTube.

The aims of this paper are to present the following techniques that we anticipate will have general applicability for data mining in industrial settings: formulation of temporal similarities via graphs created using Min-Hashes, and the application of label propagation as an off-the-shelf tool for classification tasks when very little ground truth is available.

The next section describes the data collected and presents a series of experiments to develop strong, realistic, baselines for performance. Section 3 gives a detailed description of the Adsorption algorithm. Section 4 presents the empirical results to establish the Adsorption baselines for this task. Section 5 presents extensive results with tiny amounts of labeled data (*e.g.,* a single labeled example). Section 6 concludes the paper and offers avenues for future exploration.

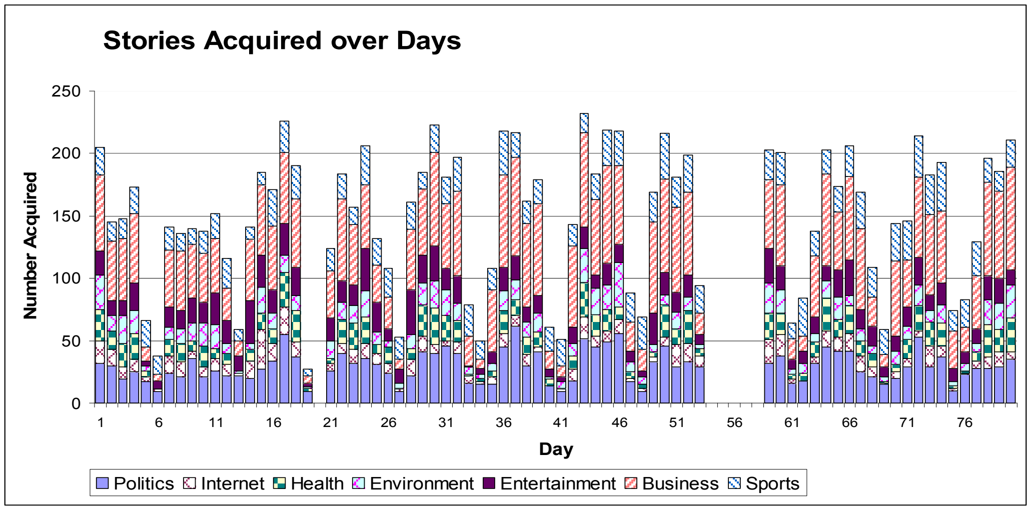


Figure 1: Distribution of Stories Acquired over Testing Period

## 2. DATA AND INITIAL EXPERIMENTS

For the experiments conducted in this paper, we examined 11,014 unique news stories published over an 80 day period in 2008. The news stories were manually placed into one of seven categories (% composition): "Politics" (19.8%), "Internet"(6.0%), "Health"(8.8%), "Environment"(8.3%), "Entertainment"(10.8%), "Business"(31.6%), or "Sports"(14.5%). Figure 1 shows the number of stories gathered each day from each class. Note that a few of the entries are 0; due to errors, no stories were gathered on those days. Although there are numerous methods to pre-process and represent text [5][6], we chose an extremely simple technique for reproducibility. Alternate, more sophisticated, pre-pre-processing techniques will improve all of the results obtained in this paper. For simplicity, we only generated a binary bag-of-words representation for each news story by determining the presence (or absence) of each word in the vocabulary. The vocabulary consisted of all words in the complete set of articles, except those words that occurred in less than 10 news stories (too infrequent) or those that occurred in more than 15% of the documents (too frequent); these words were simply discarded.

### 2.1 Initial Experiments

In the first set of experiments, we examine how two standard machine learning techniques, support vector machines [7][8] and *k*-nearest neighbor, perform on the standard task of classifying news stories into the 1-of-7 categories described earlier. This task is constructed as a standard machine learning classification task; a total of 3900 news stories are used (the first 3900 of the set described in Section 4).

In Table 1, we vary the number of labeled examples between 100 and 500, and label the examples 500-3900 using an SVM with linear kernel [8]. Additionally, a full set of experiments were conducted with non-linear kernels, such as Radial Basis Functions. The performance did not improve over using a linear kernel, this may be due to the little labeled data provided. Note that because the SVM is a binary classifier, we train 21 SVM models to distinguish each class from each other class. The performance of the SVM-system dramatically improved with more labeled samples. Additionally, if we continue to ignore the temporal nature of the task, we can use the test set as unlabeled data and take advantage of unlabeled-training methods. We attempted this in the training process for the SVM through the use of transductive learning (in SVM-Light [8][9]); however, that did not significantly impact the performance ([18] reported similar results).

Besides the overall performance, to view the effects of degradation of performance over time, we also examine the performance of the first (in time) 100 samples classified in the test set compared with the last 100 samples classified; these results are shown in the last two columns of Table 1. Note that, as expected, the unlabeled stories that are classified close to the period from which the labeled stories were taken are labeled more accurately than those that are labeled further away.

### 2.2 *k*-Nearest Neighbor

The experiments with *k*-nearest neighbor (*k*-NN) mirror those conducted with SVMs in the previous section. However, in order to make the *k*-NN process efficient, there must be a rapid method to find the nearest-neighbors. For this, we use a hashing scheme based on sparse sketches of the news stories. The sketches are created using a Min-Hash scheme [10] that is then looked up using an approximate hashing approach termed LSH. Previously, this technique has been successfully applied to the large-scale lookup of music and images [17]. Although a full discussion of these approaches is beyond the scope of this paper, both will be briefly described since the distance calculations are also used as the basis of the weights in the Adsorption graph.

Table 1: SVM Performance, measured with varying Labeled Samples

| Labeled Examples | **Overall** Performance (Samples 500-3900) | Initial Performance (Samples 500-600) | Later Performance (Samples 3800-3900) |
|---|---|---|---|
| 0-100 | 58.5 | 66 | 41 |
| 0-200 | 76.0 | 86 | 68 |
| 0-300 | 81.6 | 84 | 72 |
| 0-400 | 85.2 | 92 | 81 |
| 0-500 | 86.2 | 95 | 83 |

Min-Hash creates compact fingerprints of sparse binary vectors such that the similarity between the two fingerprints provides a reliable measure of the probability that the two original vectors were identical. Because of the sparseness of the bag-of-words presence vector that is used for the news stories, it is an ideal candidate for this procedure. Min-Hash works as follows: select a random, but known, reordering of all the vector positions. We call this a permutation reordering. Then for each story, (for a given permutation reordering) pick the minimum vector-element that is 'on' (in our application, 'on' refers to the representing a word that is present in the news story). It is important to note that the probability by which two news stories will have the same minimum vector-element is the same as its Jaccard coefficient value. Hence, to get better estimates of this value, we repeat this process $p$ times, with $p$ different permutations to get $p$ independent projections of the bit vector. Together, these $p$ values are the signature of the bit vector. Various values of $p$ were tried. For the remainder of this paper, we use $p$=500; this is the signature length of each vector, and is therefore the length of the representation of each news story.

Even with the compression afforded with Min-Hash, efficiently finding near-neighbors in a 500 dimensional space is not a trivial task; naïve comparisons are not practical. Instead, we use Locality-Sensitive Hashing (LSH) [11]. In contrast to standard hashing, LSH performs a series of hashes, each of which examines only a portion of the sub-fingerprint. The goal is to partition the feature vectors (in this case the Min-Hash signatures) into sub-vectors and to hash each sub-vector into separate hash tables. Each hash table uses only a single sub-vector as input to the hash function. Candidate neighbors are those vectors that have collisions in at least one of the sub-fingerprint hashes; the more collisions the more similar. Together with Min-Hash, LSH provides an effective way to represent and lookup nearest neighbors of large, sparse binary vectors. The results with the $k$-NN system are given in Table 2. In order to make the baselines as competitive as possible, we searched over a large range of possible $k$-values for each trial to find the best answer; it is given below. Note that for smaller number of training examples, $k$-NN outperformed SVMs; as the number of training examples increased, the performance of $k$-NN dropped below SVMs.

Table 2: $k$-Nearest Neighbor, with Varying Labeled Samples, Best Value for $k$ given in Column 1.

| Labeled Examples (best value of $k$ shown) | **Overall** Performance (Samples 500-3900) | Initial Performance (Samples 500-600) | Later Performance (Samples 3800-3900) |
|---|---|---|---|
| 0-100 (10) | 81.3 | 85 | 79 |
| 0-200 (1) | 80.9 | 86 | 78 |
| 0-300 (10) | 82.2 | 90 | 76 |
| 0-400 (10) | 83.3 | 90 | 79 |
| 0-500 (10) | 83.4 | 92 | 80 |

## 3. ADSORPTION

The genesis of the family of algorithms that we collectively call ***Adsorption*** [4] is the following question: assuming we wish to classify a node in a graph in terms of class-labels present on some of the other nodes, what is a principled way to do it? Perhaps the easiest answer to this question is to impose a metric on the underlying graph and classify the label by adopting the labels present on its nearest neighbor. There are a variety of metrics to choose from (e.g., shortest distance, commute time or electrical resistance, etc.), but most of these are expensive to compute, especially for large graphs. Furthermore, conceptually simple ones like shortest distance have undesirable properties; for example, they do not take into account the number of paths between the labeled and unlabeled nodes. Adsorption provides an intuitive, iterative, manner in which to propagate labels in a graph.

The first step is setting up the problem in terms of a graph. For the news story classification task, the embedding is straightforward: each story is a node in the graph, and the weights of the edges between nodes represent the similarity between two news stories. The similarity is computed via the MIN-HASH/LSH distance described previously; if there is a collision via the LSH procedure, then an edge exists and the weights is non-zero and positive. In the simplest version of the algorithm, the stories that are labeled, are labeled with a single category. The remaining nodes, those to be labeled, will gather evidence of belonging to each of the seven classes as Adsorption is run. At the end of the algorithm, for each node, the class with the largest accumulated evidence is assigned to the node (and therefore the news story). When designing a label propagation algorithm in this framework, there are several overarching, intuitive, desiderata we would like to maintain. First, node *v* should be labeled *l* only when there are short paths, with high weight, to other nodes labeled *l*. Second, the more short paths with high weight that exist, the more evidence there is for *l*. Third, paths that go through high-degree nodes may not be as important as those that do not (intuitively, if a node is similar to many other nodes, then it being similar to any particular node may not be as meaningful). Adsorption is able to capture these desiderata effectively.

Next, we present Adsorption in its simplest form: iterated label passing and averaging. We will also present an equivalent algorithm, termed Adsorption-RW, that computes the same values, but is based on random walks in the graphs. Although not presented in this paper, Adsorption can also be defined as a system of linear equations in which we can express the label distribution at each vertex as a convex combination of the other vertices. Our presentation follows our prior work [4], which also includes additional details. These three interpretations of the Adsorption algorithm provide insights into the computation and direct us to important practical findings; a few will be briefly described in Section 3.3.

## 3.1 Adsorption via Averaging

In Adsorption, given a graph where some nodes have labels, the nodes that carry some labels will forward the labels to their neighbors, who, in turn, will forward them to their neighbors, and so on, and all nodes collect the labels they receive. Thus each node has two roles, forwarding labels and collecting labels. The crucial detail is the choice of how to retain a synopsis that will both preserve the essential parts of this information as well as guarantee a stable (or convergent) set of label assignments.

Formally, we are given a graph $G = (V, E, w)$ where $V$ denotes the set of vertices (nodes), $E$ denotes the set of edges, and $w : E \to \mathbf{R}$ denotes a nonnegative weight function on the edges. Let $L$ denote a set of labels, and assume that each node $v$ in a subset $V_L \subseteq V$ carries a probability distribution $L_v$ on the label set $L$. We often refer to $V_L$ as the set of labeled nodes. For the sake of exposition, we will introduce a pre-processing step, where for each vertex $v \in V_L$, we create a "shadow" vertex $\widetilde{v}$ with exactly one out-neighbor, namely $v$, connected via an edge $(\widetilde{v}, v)$; furthermore, for each $v \in V_L$, we will re-locate the label distribution $L_v$ from $v$ to $\widetilde{v}$, leaving $v$ with no label distribution. Let $\widetilde{V}$ denote the set of shadow vertices, $\widetilde{V} = \{\widetilde{v} \mid v \in V_L\}$. From now on, we will assume that at the beginning of the algorithm, only vertices in $\widetilde{V}$ have non-vacuous label distributions. See Figure 2 for the full algorithm.

```
Algorithm Adsorption:
    Input: $G = (V, E, w),\ L,\ V_L$
    repeat
        for each $v \in V \bigcup \widetilde{V}$ do:
            Let $L_v = \sum_u w(u, v) L_u$
        end-for
        Normalize $L_v$ to have unit $L_1$ norm
    until convergence
    Output: Distributions $\{L_v \mid v \in V\}$
```

Figure 2: Basic adsorption algorithm

Some comments on Adsorption: (1) In the algorithm, we say that convergence has occurred if the label distribution of none of the nodes changes in a round. It can be shown that the algorithm converges to a unique set of label distributions. (2) Upon convergence, each node $v \in V \bigcup \widetilde{V}$ carries a label distribution, provided there is a path from $v$ to some node $u \in V_L$. (3) We do not update the label distribution in each round; rather, we recompute it entirely, based on the distributions delivered by the neighbors. (4) Adsorption has an efficient iterative computation (similar to PageRank [12]), where, in each iteration, a label distribution is passed along every edge.

Recalling that our goal was to maintain a synopsis of the labels that are reachable from a vertex, let us remark that the normalization step following the step of computing the weighted sum of the neighbors' label distribution is crucial to our algorithm. Labels that are received from multiple (or highly-weighted neighbors) will tend to have higher mass after this step, so this normalization step renders the Adsorption algorithm as a classifier in the traditional machine learning sense. The algorithm, as presented, is a modification of the label propagation algorithm of Zhu *et. al.* [13][14], where they considered the problem of semi-supervised classifier design using graphical models. They also note that their algorithm is different from a random-walk model proposed by Szummer and Jaakkola [15]; in the next section we will show that there is a very different random walk algorithm that coincides exactly with the Adsorption algorithm. The latter fact has also been noticed independently by Azran [16]. This aspect of the Adsorption algorithm distinguishes it from the prior works of Zhu et al; the enhanced random walk model we present generalizes the work of Zhu et al., and presents a broader class of optimization problems that we can address[1]. The approach of Zhu et al. is aimed at labeling the unlabeled nodes while preserving the labels on the initially labeled

[1] We thank P. Talukdar (personal communication, November 2008) for pointing this out.

nodes and minimizing the "error" across edges. In Adsorption, there is a subtle, but vital, difference, the importance attached to preserving the labels, as well as the importance of near vs. far neighbors is *explicitly* controlled through the use of the injection-label weights and abandonment probabilities. These will both be described in detail in Section 3.3. The random walk equivalence, under the mild conditions of ergodicity, immediately implies an efficient algorithm for the problem, a fact not obvious from a general formulation as minimizing a convex function. From a broader standpoint, it is interesting to note that this family of "repeated averaging" algorithms have a long history in the mathematical literature of differential equations, specifically in the context of boundary value problems (*i.e.,* estimating the heat at a point of a laminar surface, given the boundary temperatures).

## 3.2 Adsorption via Random Walks

The memoryless property of the Adsorption algorithm that we alluded to earlier immediately leads to a closely related interpretation. Let us "unwind" the execution of the algorithm from the final round, tracing it backwards. For a vertex $v \in V$ , denote by $N_v$ the probability distribution on the set of neighbors of $v$ described by $N_v(u) = w(u,v)/(\sum_u w(u,v))$ that is, the probability of $u$ is proportional to the weight on the edge $(u,v)$. The label distribution of a vertex $v$ is simply a convex combination of the label distributions at its neighbors, that is, $L_v = \sum_u N_v(u) L_u$ ; therefore, if we pick an in-neighbor $u$ of $v$ .at random according to $N_v$ and sample a label according to the distribution $L_u$ , then for each label $l \in L$ , $L_v(l)$ is precisely equal to $\mathrm{Exp}_u[L_u(l)]$, where the expectation arises from the process of picking a neighbor $u$ according to $N_v$ . Extending this to neighbors at distance 2, it is easy to see that for each label $l \in L, \quad L_v(l) = \mathrm{Exp_w Exp_u}[L_w(l)]$ where an in-neighbor $u$ of $v$ is chosen according to $N_v$ and an in-neighbor $w$ of $u$ is chosen according to $N_u$ . Expanding this out, we see that $L_v(l) = \sum_w \sum_u N_v(u) N_u(w) L_w(l)$ .

Notice that $N_v(u)$ is the probability of reaching $u$ from $v$ in one step of a random walk starting from $v$ and picking a neighbor according to $N_v$ , and similarly, $N_u(w)$ is the probability of picking a neighbor $w$ of $u$ according to $N_u$ . Notice also the crucial use of the Markov property (memorylessness) here: conditioned on the random walk having reached $u$ , the only information used in picking $w$ is $N_u$ , which depends only on $u$ , and not on where we initiated the random walk from. Finally, note that if the random walk ever reaches one of the shadow vertices $\tilde{z}$ where $z \in V_L$ , then there is no in-edge into $z$ , so the random walks stops. Thus vertices in $\tilde{V}$ are "absorbing states" of the Markov chain defined by the random walk. A simple induction now establishes that the Adsorption algorithm is equivalent to the following variation, described in terms of random walks on the ***reverse*** of the graph $G$ together with the edges from $\tilde{V}$ to $V$ . See Figure 3. Here, pick-neighbor $(v, E, w)$ returns a node $u$ such that $(u,v) \in E$ (so that there is an edge from $v$ to $u$ in the reversed graph) with probability $w(u,v)/(\sum_u w(u,v))$ .

In our exposition below, the algorithm takes a starting vertex $v$ for the random walk, and outputs a label distribution $L_v$ for it when it reaches an absorbing state. Thus, the label distribution for each node is a random variable, whose expectation yields the final label distribution for that vertex. To obtain label distributions for all vertices, this procedure needs to be repeated many times for every vertex, and the average distributions calculated. This yields a very inefficient algorithm; therefore, in practice, we exploit the equivalence of this algorithm to the averaging Adsorption algorithm in Section 2.2, which has very efficient implementations.

```
Algorithm Adsorption-RW
Input: $G = (V, E, w), L, V_L$, distinguished vertex $v$
Let $\tilde{G} = (V \cup \tilde{V}, E \cup \{(v, \tilde{v}) \mid v \in V_L\}, w\}$
Define $w(v, \tilde{v}) = 1$ for all $v \in V_L$
done := false
vertex := $v$
while (not done) do:
    vertex := pick-neighbor $(v, E, w)$
    if (neighbor $\in \tilde{V}$ )
            done := true
end-while
$u$ := vertex
Output label according to $L_u$ .
```

Figure 3: Adsorption in terms of random walks.

It is instructive to compare algorithm Adsorption-RW with typical uses of stationary distributions of random walks on graphs, such as the PageRank algorithm [12]. In the case of PageRank, a fixed Markov random walk is considered; therefore, the stationary probability distribution gives, for each node of the graph, the probability that the walk visits that node. In the absence of any absorbing node (and assuming the walk is ergodic), the initial choice of the node from which the random walk starts is irrelevant in determining the probability of reaching any particular node in the long run. Consequently, these methods do not allow us to measure the influence of nodes on each other. In our situation, labeled nodes *are* absorbing states of the random walk; therefore, the starting point of the walk determines the probability with which we will stop the walk at any of the absorbing states. This implies that we may use these probabilities as a measure of the influence of nodes on each other.

Table 3: Adsorption, with Varying Number of Connections Per Node, 200 Labeled Nodes

| | Maximum Number of Connections per Node | **Overall** Performance (Samples 500-3900) | Initial Performance (Samples 500-600) | Later Performance (Samples 3800-3900) |
|---|---|---|---|---|
| Adsorption | 10 | 80.1 | 90 | 72 |
| | 100 | 88.1 | 92 | 83 |
| | 500 | 86.6 | 91 | 84 |
| | 1000 | 85.8 | 91 | 82 |
| | unlimited | 82.4 | 94 | 80 |

## 3.3 Injection and Abandonment Probabilities in Adsorption

The three equivalent renditions of the algorithm (averaging, random walk, system of linear equations) lead to a number of interesting variations that one may employ. For example, in the viewpoint of a linear system of equations, it is easy to see how we can restrict which labels are allowed for a given node. In another variation, we can model the "amount of membership" of a node to a class. Recall the notion of a "shadow" node $\widetilde{v}$ that act as a "labelbearer" for $v$. A judicious choice of edge weight along the edge to the label-bearer, or equivalently the *label injection probability*, helps us control how the random walk behaves (this is equivalent to choosing the transition probability from $v$ to $\widetilde{v}$ in the reversed graph). For example, lower transition probabilities to the shadow nodes may indicate lower membership in the label class (e.g. a news story is ½ in politics as it is only tangentially related, etc). Note that indicating ½ politics label *does not* imply that the other ½ must be assigned to another class. This will be used in experiments described in Section 5.

Another important insight is realized when examining Adsorption in terms of random walks. Instead of considering the standard random walk on an edge-weighted graph, one may consider a "hobbled walk," where at each step, with some probability, which we call the *abandonment probability*; the algorithm abandons the random walk without producing any output label. Our experiments (here and in other applications) have confirmed that abandoning the random walk with a small probability at each iteration is a very useful feature. It slows down the random walk in a quantifiable way: the influence of a label $l$ on a node $u$ falls off exponentially in the number of nodes along the paths from nodes that carry $l$ to $u$. This strengthens the effect of nearby nodes; this has proven crucial to obtaining good results in large graphs.

## 4. INITIAL EXPERIMENTS WITH ADSORPTION

In the experiments presented in this section, we use the same data that was presented in Section 2, and apply the Adsorption algorithm. Given the similarity measurements that were computed via the MIN-HASH & LSH combination described earlier, the graph and weights are constructed by simply setting each story as a node in the graph, and the weights of the edges between stories as the distance as specified by the distance computation mentioned above. The stories that are in the labeled set have shadow nodes attached to them with the correct label; stories outside of the labeled set do not have shadow nodes. Adsorption computes a label distribution at each node; the label with the maximum value at the end of the Adsorption run is considered the node's (and therefore story's) classification. In constructing the graph to use with Adsorption, a number of options are available. Encoding domain-specific information into the graph topology may be a powerful way to express any *a priori* or expert knowledge of the task. For example, knowing that the most accurate classifications are likely to happen in stories temporally close to the labeled stories, connections to nodes representing earlier news stories may receive a higher weighting; or connections to the labeled set may be prioritized over other connections, etc. Nonetheless, to avoid confusing the causes of the performance numbers and introducing ad-hoc, domain specific, heuristics, we experimented with only domain-independent parameters. One of the most salient is when we construct the graph, we can limit the number of the closest neighbors that we connect with each node. In Table 3, we experiment with connecting each neighbor only with, at most[2], its S=10, 100, 500, 1000 most similar stories[3]. Perhaps the most

[2] Because there may be fewer than S collisions for a news story in the LSH hash-tables that are used to rapidly estimate similarity, every node may not have the maximum S connections.

[3] Recall that since the connections are undirected, a node may have more than S connections. The total number of *undirected* connections will not exceed $S * |V|$.

Table 4: Adsorption Performance, with Varying Labeled Samples, 500 connections per node

| | Labeled Examples | **Overall** Performance (Samples 500-3900) | Initial Performance (Samples 500-600) | Later Performance (Samples 3800-3900) |
|---|---|---|---|---|
| Adsorption | 0-100 | 86.4 | 91 | 84 |
| | 0-200 | 86.6 | 91 | 84 |
| | 0-300 | 86.4 | 91 | 82 |
| | 0-400 | 86.8 | 92 | 84 |
| | 0-500 | 86.5 | 93 | 83 |

interesting observation is that increasing the number of connections does not necessarily increase the performance. As the number of maximum connections is increased, eventually the connections encode such weak similarities between the news stories that it better not to use them. Currently, we set the maximum number of connections empirically (to 500); in the future, other methods will be explored.

Having set the connection count, we examine the effects of the number of labeled training samples. The Adsorption algorithm reveals performance with 100 labeled examples that is comparable or exceeds in overall and long-term performance to the best *k*-NN and SVM performance with 500 labeled examples. Results are shown in Table 4.

In the next section, we continue the empirical evaluation by looking at larger numbers of news stories, and the effects of even fewer labels.

## 5. FULL-SCALE EXPERIMENTS

The first full-scale experiment parallels the experiments presented to this point. We assume that we have 100 labeled examples and that we would like to categorize examples that appear up to 80 days later after the labeled examples were classified. The performance is shown in Figure 4, each day in which a news story was gathered is shown in the graph. In Figure 4 (right), the comparative results for *k*-NN are given. The average performance for Adsorption is 87.8%, *k*-NN: 82.5%. Other techniques such as Naïve-Bayes and SVMs were also tried; of these other techniques, *k*-NNs performed the best. Specifically, Naïve-Bayes performed worse than both SVMs and *k*-NNs, and SVMs performed worse than *k*-NNs.

In our second experiment, we explore the ramifications of having two orders of magnitude ***less*** training data. Only a single example is labeled on day 1. The goal is to examine the articles in the last three days (days 78-81), and to rank them according to the probability of being in the *same class as the single labeled example from the first day*. This scenario is a proxy for a very common scenario encountered in practice in sites like news.google.com and other news aggregation sites. A user may read only a small number of articles one day, and then come back to the site many days later. Although there is not much evidence of the user's preferences, we know simply that of all the articles the user could have chosen to read on day 1, (s)he read a single one. In this case, the labels from the first day's article are simply **0:** article was not read or **1:** the article was read. For Adsorption, we weighted the examples with label 0 with an injection probability of 0.1 to

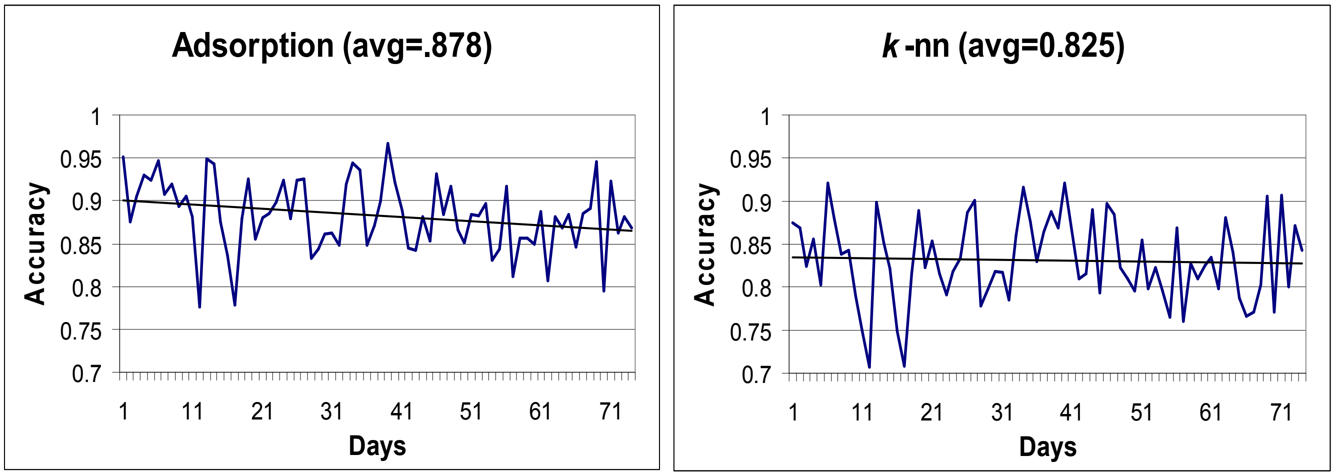
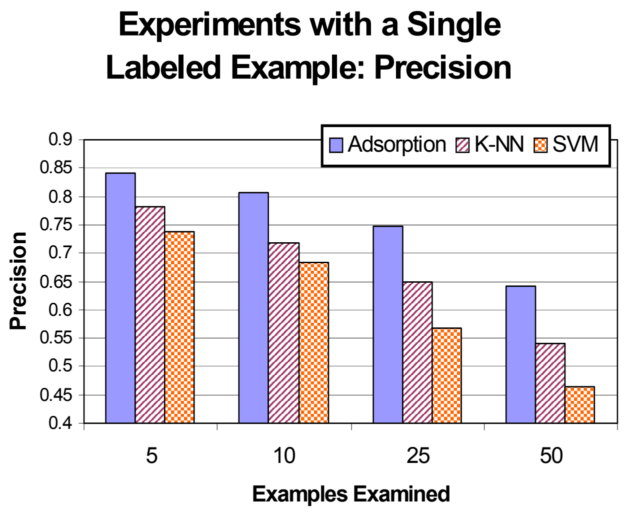


Figure 4: Performance of Adsorption and *k*-NN over 81 days



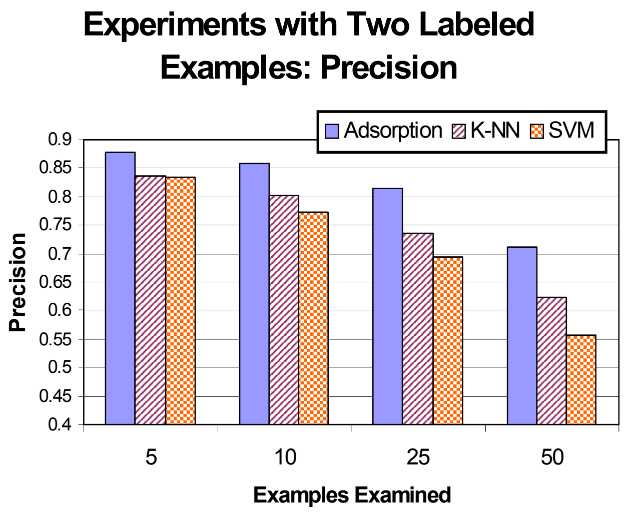


Figure 5: Experiments with 1 & 2 labeled examples. Precision at 5,10,25, and 50 results in retrieving examples from the same class as the single labeled example (left) or two labeled examples (right).

reflect uncertainty of why the user did not read the article, was it because of interest, time, or simply not noticing it? The articles labeled 1 ("read"), continued to have an injection probability of 1.0.

The performance was measured as follows. 500 articles from the last few days of the experiment were ranked according to their probability of being from the same class as the 'read' article. The full Adsorption connectivity graph was used, as described in the previous experiments, to propagate the label through time. In Figure 5, we examine the top-N (N = 5, 10, 25, 50) of the ranked articles, and give the percentage of the N that are from the same class. As can be seen, Figure 5 (Left), even with a single example, the average precision rate is approximately 84% with Adsorption for the top-5 examples, and over 80% for the top-10. In Figure 5(Right), the same experiment is performed, but measures the effect of having added a second labeled example (from the same class as the first). All algorithms improve dramatically over all ranges of N. Interestingly, a single additional labeled example provides information that all the algorithms effectively exploit. Adsorption continues to outperform K-NN and SVMs[4] in both tests, for all values of N.

## 6. CONCLUSIONS & FUTURE WORK

In this paper, we have presented an efficient and simple procedure in which to incorporate an often ignored signal into the task of news classification: time. Although the writing, vocabulary and topics of the news stories rapidly change over time, we are able to perform the classification of news stories with very little training data that is received only in the beginning of the testing period.

There are many avenues for future research, both in this task and in the development of Adsorption. First, a comparison with different unlabeled data learning systems is warranted. Although, in this study, we used transductive SVMs as means to incorporate unlabeled data, it did not improve performance significantly. Other methods, such as spectral clustering may do better. Although most other techniques do not incorporate a notion of time, perhaps combinations of the other methods with the ones presented here can be devised; this is potentially large area of interest. Second, we used a simple graph structure that did not incorporate all of the available domain information (*e.g.* all the labeled examples are at the beginning). Using the graph structure to encode domain knowledge will be very relevant in new domains as well. Further, graph pruning algorithms are of interest, especially in the cases in which domain knowledge may not be readily available; as was seen in the experiments, more connections do not imply improved performance. Finally, this test was conducted over a period of approximately 3 months with real examples of rapidly shifting news stories that exemplify current news-aggregation-site challenges; longer tests are forthcoming.

[4] The use of unlabeled samples through transductive learning for the SVM was again used here. It slightly improved performance in a few trials; the best of both is given here.

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