

Athena: Mining-based Interactive Management of Text Databases

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Abstract

We describe Athena: a system for creating, exploiting, and maintaining a hierarchical arrangement of textual documents through interactive mining-based operations. Requirements of any such system include speed and minimal end-user effort. Athena satisfies these requirements through linear-time classification and clustering engines which are applied interactively to speed the development of accurate models.

Naive Bayes classifiers are recognized to be among the best for classifying text. We show that our specialization of the Naive Bayes classifier is considerably more accurate (7 to 29% absolute increase in accuracy) than a standard implementation. Our enhancements include using Lidstone's law of succession instead of Laplace's law, under-weighting long documents, and over-weighting author and subject.

We also present a new interactive clustering algorithm, C-Evolve, for topic discovery. C-Evolve first finds highly accurate cluster digests (partial clusters), gets user feedback to merge and correct these digests, and then uses the classification algorithm to complete the partitioning of the data. By allowing this interactivity in the clustering process, C-Evolve achieves considerably higher clustering accuracy (10 to 20% absolute increase in our experiments) than the popular K-Means and agglomerative clustering methods.

1 Introduction

People and organizations are amassing more and more data in the form of unstructured or semi-structured textual documents, due mostly to the flourishing of e-mail and world-wide web usage. Systems that manage text databases typically provide support for keyword queries and manual arrangement of documents into a hierarchical ("folder") structure. Benefits of a folder hierarchy include the ability to quickly locate a document without having to remember the exact keywords contained in that document, and the ability to easily browse a set of related documents. Unfortunately, the task of maintaining coherent folders is time consuming, and often unused or under-used as a result. For example, many if not most e-mail users simply allow their messages to accumulate in the inbox where these messages remain until they are deleted. As a result, the benefits of a well-maintained folder hierarchy are never realized. Outside the e-mail context, web search engines such as Yahoo! [Yah] use hierarchical categories to allow browsing of related documents and to enhance the usability of search results.

In this paper, we present a system henceforth referred to as Athena¹ that simplifies the process of hierarchical document organization through text mining algorithms. Athena is currently implemented on top of Lotus Notes [Lot] to support the management of e-mail and discussion databases, though the concepts apply equally well to other document repositories including collections of web pages or text files. Important functionality of Athena includes:

- *Topic Discovery.* Decompose an unorganized collection of documents into groups so that each group consists of documents on the same topic.
- *Hierarchy Reorganization.* Reorganize a hierarchical collection of documents into another hierarchy.
- *Hierarchy Population.* Use the information contained in the current populated hierarchy to route incoming documents.
- *Hierarchy Maintenance.* Identify misfiled documents in a node of the hierarchy and detect concept drift within a node.

Classification and clustering are the two basic building blocks used for implementing the above functionality. These technologies have been studied extensively in the areas of statistics, data-mining, information retrieval, and machine learning. However, standard techniques performed poorly for our application. For example, Naive Bayes classifiers [Goo65] are recognized to be among the best for classifying text. We found that by specializing Naive Bayes for our application, we could reduce the number of errors by 30 to 60% (with 7 to 29% absolute increase in accuracy) when compared to a standard implementation. Our enhancements include using Lidstone's law of succession instead of Laplace's law, under-weighting long documents, and weighting author and subject.

Clustering algorithms applied in this domain must be fast to avoid taxing the patience of the user. We present a new linear-time interactive clustering algorithm, C-Evolve, for topic discovery. C-Evolve first finds highly accurate cluster digests (partial clusters), gets user feedback to merge/correct these digests, and then uses the classification algorithm to complete the partitioning of the data. By allowing interactivity in the clustering process, C-Evolve is considerably more accurate (10 to 20% absolute increase in accuracy in our experiments) than K-Means [Ras91] as well as agglomerative clustering methods [Ras91].

Paper Layout In the rest of this section, we discuss related work on systems for routing or clustering email or text documents. (We discuss related work in clustering or classification algorithms

¹Automated Text HiErarchy maNAGement

in Sections 3 and 4.) In Section 2, we give an overview of Athena's functionality from a user's perspective. We describe the technical details of the classification component in Section 3, along with experimental results justifying our design decisions. Section 4 goes into the technical details of the clustering component, and also provides an empirical evaluation of its efficacy. Section 5 concludes with a summary and directions for future work.

Related Work There have been at least three previous proposals on the development of classification models for the purpose of routing e-mail, either in general [Coh96],[SK99] or for the special case of junk-mail [SDHH98]. None of these proposals address the task of textual database organization outside of routing incoming documents for the purpose of maintaining an existing organization. Some systems provide agents that assist e-mail users by predicting an action the user is likely to take [Mae94] [PE97]. While these systems can assist with e-mail routing, they too do not address creation of the organizational structures, topic discovery, or visualization.

Other related work includes the Scatter/Gather system [CDPT92], which uses on-line clustering to assist the user in browsing large collections of documents. While Scatter/Gather does not directly address the problem of document organization, many of the requirements of our systems are similar, such as the need for fast, on-line algorithms capable of extracting useful information from text, and the need to involve the user in the process of applying these algorithms. We make a more detailed comparison of our system to Scatter/Gather in a later section. SONIA [SYB98] uses agglomerative text clustering to organize the results of queries to networked information sources, and Naive Bayes classification to organize new documents within an existing categorization scheme.

2 Athena Functionality

Athena provides a complete suite of mining-based tools for automating the creation and maintenance of a hierarchical document organization. Athena is currently implemented on top of Lotus Notes and supports management of email and discussion databases. We briefly describe the important functionality of Athena to motivate the requirements this domain places on classification and clustering technology.

Hierarchy Reorganization Athena provides functionality for reorganizing the contents of a document collection into new collections given a small number of examples provided by the user. This functionality is useful when the user can easily identify several salient topics covered by the documents, but would rather not manually segregate every document according to these topics. In this scenario, Athena has the user create a new folder for each of these topics, position the new folders anywhere in the existing hierarchy, and populate each of these folders with a small number of

example documents from the original collection. Athena then creates an initial classification model from these examples for the purpose of automatically filing the remaining documents. Because a classifier developed with a very few examples can lead to poor results, Athena first presents the user with additional examples which the user is requested to properly classify. To minimize user effort, these documents are positioned in the folders which the classifier has identified as the most probable destination. As corrections are made, Athena updates its model appropriately. This interaction continues until the classifier has reached a point where the remaining documents can be accurately routed without user intervention, as determined either by the system or the end-user.

Topic Discovery In some cases, the topics covered by documents within an unorganized collection are not easily identified by the user. In this scenario, Athena can be used by the user to identify topics that may be useful for decomposing the contents of the collection. This functionality initially presents the user with a cluster digest consisting of a perusable number of related documents from the collection. The user can continue to request additional cluster digests indefinitely, though usually the user finds a useful set of topics from these digests after only a small number of iterations. With each iteration, the user can correct any obvious mistakes in the cluster digests, combine any of previously identified cluster digests, as well as discard clusters entirely. This feedback is used by Athena in producing any subsequent results. Athena attempts to place documents that are likely to be on the same topic within the same cluster digest. It also attempts to identify documents on a topic that is different from those covered by previously discovered clusters.

Athena does not attempt to find a complete clustering of the input collection right away because we have found that a complete partitioning, as produced by several well-known clustering algorithms, typically contains too many mistakes to be useful for the purpose of document organization. Instead, Athena produces only highly accurate cluster digests as described above, and uses the Hierarchy Reorganization functionality to accurately segregate the remaining documents based on the topics the user has deemed relevant. In this case, the user is not required to manually populate the new collections with examples since they can be seeded with the documents from the selected cluster digests.

Hierarchy Population In the context of e-mail organization, the user often maintains a collection of documents that are of immediate importance within his or her Inbox. Even outside the e-mail domain, incoming documents should not necessarily get automatically routed to some destination in the hierarchy without user approval, in which case they might first accumulate in an Inbox-like view. In this situation, the hierarchical arrangement of existing documents still provides useful information which can be used to simplify viewing of the Inbox contents, as well as simplify

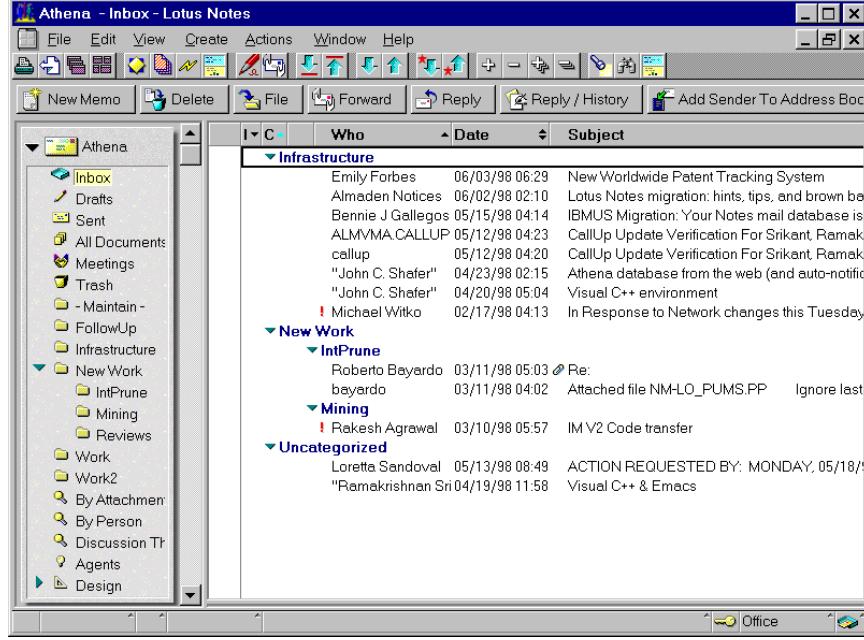


Figure 1: Inbox categorized by Topic

the task of positioning documents within the hierarchy when desired by the user.

Athena allows the user to switch between the standard inbox view and a new view that arranges documents in an outline format following the hierarchy structure, as displayed in Figure 1. Documents can, at any time, be selected and immediately routed to their respective destinations. If a document is misclassified by Athena, the user can instead drag the document to its appropriate location within the hierarchy or file it through the standard filing function. Since some incoming documents may not have an appropriate category, Athena puts documents whose classification is uncertain (as defined by a certainty threshold) into the Uncategorized section of this view. Athena can also suggest an appropriate location for just-composed documents such as outgoing mail.

Hierarchy Maintenance Mistakes are often made when a user manually files documents. Sometimes documents are inadvertently and unknowingly dropped into a folder other than their intended target; other times, the documents are dropped into a folder that the user mistakenly believed was appropriate. Athena solves these problems by identifying and presenting to the user documents which may be misfiled. Athena also suggests where each misfiled document actually belongs. This function identifies obvious mistakes as well as concept drift within a folder. Concept drift arises when, over time, the general subject matter of documents within a given folder is no longer the same as the subject that best described documents within the folder when it was originally created. In such cases, the user is encouraged to reorganize the folder using the reorganize by example and topic identification scenarios from above.

3 Classification Component

Athena's classification component is used for hierarchy reorganization, document routing/Inbox visualization, and identification of misfiled documents. We decided to base our classifier on the Naive-Bayes model [Goo65] for the following reasons:

- Naive-Bayes classifiers are very competitive with other techniques for text classification [CDAR97] [LR94] [Lan95] [PB97] [MN98].²
- They stabilize quickly [Koh96], which is useful for hierarchy reorganization.
- They are fast. They can be constructed quickly with a single pass over the documents, making them suitable for on-line model creation; they also quickly classify incoming documents [CDAR97].
- They are simple to update in the presence of document additions or deletions, making them easy to maintain.

The basic Naive-Bayes classifier estimates the posterior probability of class C_i given a document d via Bayes' rule:

$$\Pr(C_i|d) = \frac{\Pr(d|C_i) \times \Pr(C_i)}{\Pr(d)}$$

We ignore $\Pr(d)$ (the denominator) since it is the same for all classes. $\Pr(C_i)$ is estimated by:

$$\Pr(C_i) = \frac{\text{Number of documents in class } C_i}{\text{Total number of documents in the dataset}}$$

To estimate $\Pr(d|C_i)$, we “naively” assume that all the words in the document occur independently to get

$$\Pr(d|C_i) = \prod_{w \in d} \Pr(w|C_i)$$

Let $n(C_i, w)$ be the number of occurrences of word w in class C_i (counting multiple occurrences), and $n(C_i) = \sum_w n(C_i, w)$ the total number of words in class C_i . Then the maximum likelihood estimate for $\Pr(w|C_i)$ is simply $n(C_i, w)/n(C_i)$. However, using this estimate would give a probability of zero for any word that does not occur in the class, and thus result in $\Pr(d|C_i)$ being zero for any document d that contained a word not present in class C_i . The standard approach to address this problem (e.g. [CDAR97] [Mit97] [KMST98]) is to smooth the maximum likelihood estimate with Laplace's law of succession [Goo65] to get

$$\Pr(w|C_i) = \frac{n(C_i, w) + 1}{n(C_i) + |V|} \tag{1}$$

²We tried using the SPRINT decision-tree classifier [SAM96], but got low accuracy since our datasets typically had a very small number of examples per class and a very large feature space.

	Small Class	Large Class
Vocabulary	10,000	10,000
Number of Words	1000	100,000
Number of occurrences of word w	10	1000
$\Pr(w c)$ w/o correction	1%	1%
$\Pr(w c)$ with correction	0.1%	0.91%

Figure 2: Skew due to Laplace Correction

where $|V|$ is the size of the vocabulary (i.e., the number of distinct words in the dataset). The above formula is the result of assuming that all possible words are *a priori* equally likely (see [Ris95] for details).

Following [MN98], we use the multinomial form of the Naive Bayes classifier where each document is treated as a bag of words rather than a set of words to yield better accuracy.

3.1 Enhancing the Naive-Bayes Classifier

We first specialized the standard Naive-Bayes classifier by applying techniques such as under-weighting long documents and over-weighting author and subject [ADW94]. The weights were determined by using a part of the training set as a validation set. These enhancements yielded upto 3% accuracy improvements in our experiments.

In search for ideas for larger improvements in accuracy, we examined the words that had the maximum impact on the classification of a document. These words can be found by looking at the ratio of $\Pr(w|c)/\Pr(w|c')$, where c is the class Athena chose and c' the class for which $\Pr(w|c')$ is highest. Investigation of some misclassified documents revealed that the probability estimate of some words was being highly skewed by the Laplace correction. Figure 2 explains this skew with an example. Word w has a maximum likelihood estimate of 1% in both classes. However, after applying the Laplace correction, it is considered 9 times more likely to appear in the large class as in the small class. Hence we suspected that the Laplace correction was creating a strong bias towards larger classes.

Lidstone's law of succession We then replaced Laplace's law of succession with Lidstone's law of succession. For positive λ , we estimate $\Pr(w|C_i)$ to be

$$\Pr(w|C_i) = \frac{n(C_i, w) + \lambda}{n(C_i) + \lambda|V|} \quad (2)$$

This class of probability estimates is due to the actuaries G.F. Hardy [Har89] and G.J. Lidstone [Lid20] at the turn of the century. The above estimate is a linear interpolation of the maximum likelihood estimate $n(C_i, w)/n(C_i)$ and the uniform prior $1/|V|$. This can be seen by rewriting (2)

Dataset	#Folders	#Docs	#Docs/Folder Avg \pm Std. Dev.	#Words/Folder Avg \pm Std. Dev.	Vocabulary
A	53	768	14 \pm 25	4K \pm 4K	15K
B	38	1,039	25 \pm 34	10K \pm 17K	23K
H	204	2,995	15 \pm 23	5K \pm 9K	39K
S	15	964	64 \pm 47	18K \pm 13K	15K
Reuters	82	11,367	138 \pm 517	15K \pm 36K	24K

Table 1: Dataset Characteristics

with the substitution $\mu = n(C_i)/(n(C_i) + \lambda|V|)$:

$$\Pr(w|C_i) = \mu \frac{n(C_i, w)}{n(C_i)} + (1 - \mu) \frac{1}{|V|}$$

Note that if $\lambda = 1$, the Lidstone correction is identical to the Laplace correction. In their attempt to improve the accuracy of Naive Bayes, Kohavi et al [KBS97] also experimented with Lidstone correction using the datasets available in the UCI repository. None of these datasets consists of textual data. They found that using $\lambda = 1/\text{total records}$, they could slightly reduce the average absolute error (by 1%, from 19.59% to 18.58%) compared to Laplace correction.

We ran experiments on the datasets shown in Table 1. A, B, H and S refer to four email datasets, while Reuters is the single-category version of Distribution 1.0 of Reuters-21578³. Notice that three of the four email datasets have a very large number of classes, ranging from 38 to 53, and a very few examples per class, ranging from 25 to just 14 documents. All our accuracy numbers were computed using 10-fold cross-validation.

Figure 3(a) shows the change in accuracy as we vary λ in the Lidstone correction, relative to the accuracy for the Laplace correction ($\lambda = 1$). The results were dramatic: accuracy improved by 4% to 26%, with the largest gains on those datasets where the accuracy numbers were low. The number of errors was reduced by between 25% and 60% on these datasets (details given later in Table 2). The optimal value of λ varied between 0.2 and 0.01, depending on the dataset.

Recall our hypothesis that the reason for the improvement in accuracy due to decreasing λ is the bias towards large classes produced by the Laplace correction. To verify this hypothesis, we need to measure the size bias of the classifier. For any misclassified documents d , let C_m be the misclassified class and C_r the right class. We use the geometric mean of $n(C_m)/n(C_r)$ over all misclassified documents as a measure of the size bias of the classifier. Figure 3(b) shows that the size bias decreases dramatically with decreasing λ , confirming our hypothesis. At $\lambda = 1$, the misclassified class is between 2 and 9 times larger than the right class. At the optimal λ values for the datasets, the ratio is between 1 and 2.5. Note that dataset H, for which decreasing λ gave the

³ Available from <http://www.research.att.com/~lewis>

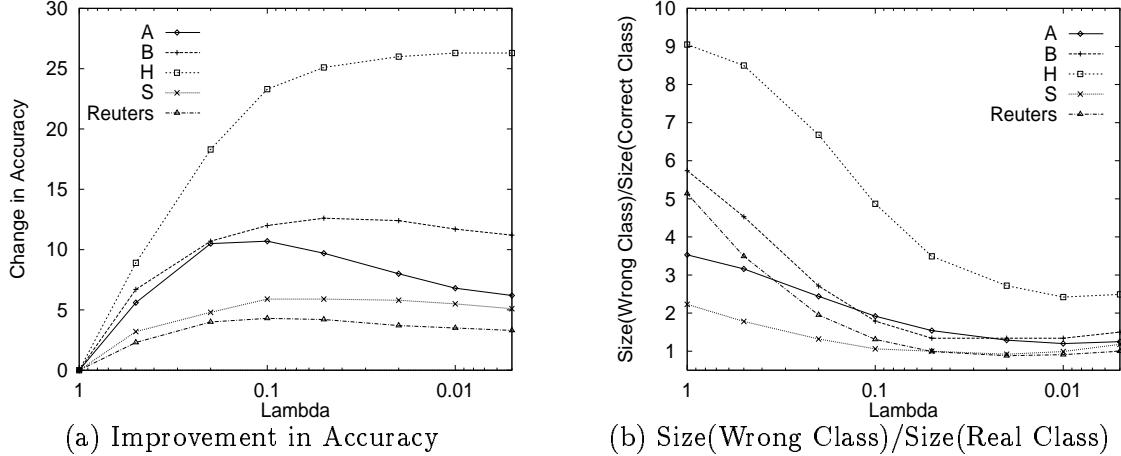


Figure 3: Lidstone Correction

most dramatic gains, also has the largest change in the size bias, decreasing from 9 to 2.5.

Given the sensitivity of accuracy to the value of λ , Athena uses an automatic procedure to select the optimal value of λ on a per-dataset basis. We use a portion of the training set as a validation set, and compute the accuracy of the classifier over this validation set for various values of λ to obtain the optimal value.

Recent work by McCallum et al. [MRMN98] uses both the uniform prior and a global prior (the frequency distribution over the entire dataset) to smooth the maximum likelihood estimate. Their algorithm uses expectation maximization to assign weights to each of these distributions on a per-class basis. This procedure typically requires a dozen or so iterations over the data, which can be very expensive.

Summary of Results Table 2 shows the accuracy of the classifier for several versions:

- *Standard*: Standard Naive Bayes classifier with Laplace correction
- *Lidstone*: Classifier using Lidstone correction instead of Laplace correction, with the optimal value of λ determined automatically using part of the training set as a validation set.
- *Final*: Classifier additionally over-weights author and subject, and under-weights long documents.
- *Reduction in Errors* between the Standard version and the Final version.
- *Top 3 classes*: Accuracy of the classifier with the classifier considered accurate if any of the top 3 choices were correct.

We observe dramatic gains in accuracy due to using Lidstone's correction, and small (but useful) gains in accuracy due to over-weighting author and subject, and under-weighting long documents.

Dataset	Number of Classes	Standard	Lidstone	Final	Reduction in Errors	Top 3 classes
A	53	60.5 \pm 5.7	71.5 \pm 6.3	72.4 \pm 5.4	30%	84.4 \pm 5.5
B	38	66.2 \pm 5.4	84.8 \pm 1.7	86.9 \pm 2.4	61%	95.1 \pm 2.0
H	204	47.0 \pm 3.0	74.4 \pm 1.9	76.1 \pm 2.3	55%	88.1 \pm 2.7
S	15	81.6 \pm 4.2	88.6 \pm 3.2	88.9 \pm 1.8	40%	98.1 \pm 1.6
Reuters	82	79.9 \pm 1.3	84.8 \pm 1.0	85.2 \pm 1.2	26%	94.8 \pm 0.7

Table 2: Accuracy \pm Standard Deviation

The increase in absolute accuracy ranged from 7 to 29% for the email datasets, with a 30 to 61% reduction in the number of errors. We also note that the classifier accuracy for predicting the top three classes is very high, especially given the large number of classes. In this application domain, many documents can naturally belong to multiple classes. Having multiple classifications for a document is therefore quite useful. Additionally, applications can be designed to propose to the user multiple recommendations for document routing (e.g. [SK99]) and let the user make the final selection. High accuracy over the top 3 or top 5 recommendations is very important for these applications.

4 Clustering Component

The clustering component is responsible for topic discovery within an unorganized collection of documents. We have developed an interactive approach to clustering which involves iteratively presenting the user with a perusable number of related documents that suggest how a specified folder might be decomposed. We call such a set of documents a cluster digest. This term is borrowed from the Scatter/Gather system [CDPT92] which uses on-line text clustering to assist the user in browsing a document collection. In this system, documents are clustered and cluster digests are presented to the user to determine which documents in the collection are worth browsing. Unlike Scatter/Gather, Athena does not produce a complete clustering before forming the cluster digests. Instead, it applies a novel algorithm that produces the digests directly. This results in response times suitable for on-line application with equivalent or better results. The algorithm can also produce clusters incrementally, allowing the incorporation of feedback from the user into the clustering model before producing additional results, and avoiding any need for the user to specify a desired number of clusters apriori.

There are multiple proposals for text clustering, with many of the most popular and effective belonging to the agglomerative class [Ras91]. A serious drawback of this class of algorithms is they are at best of quadratic runtime complexity, limiting their usefulness in on-line applications

Input variables:

- A set D of input documents.
- A set P of previously-discovered cluster digests (possibly empty).
- An integer n specifying the number of clusters to evolve simultaneously.
- An integer DIGEST_SIZE bounding the number of documents in a cluster.

Return value:

- A cluster digest consisting of at most DIGEST_SIZE documents from D .

Score Function: See algorithm description.**Algorithm:**

1. Remove documents within the digests of P from D .
2. Initialize a cluster C_1 with a random document from D .
3. For $i = 2 \dots n$
 - Initialize a cluster C_i with the document d in D that minimizes the following:

$$\max(\forall_{j=1 \dots i-1} \text{sim}(d, C_j))$$
4. For $i = 2 \dots n$
 - Let cluster C'_i contain the top $\min(|C_i| + 1, \text{DIGEST_SIZE})$ scoring documents d according to $\text{score}(d, C_i, P)$
5. If there exists some $i = 1 \dots n$ such that $C_i \neq C'_i$,
 - (a) $C_i := C'_i$ for all $i = 1 \dots n$
 - (b) goto step 4.
6. Return the cluster C_i out of $C_1 \dots C_n$ that maximizes the following:

$$\min(\forall_{d \in C_i} \text{score}(d, C_i, P))$$

Figure 4: The C-Evolve(n) algorithm for evolving a cluster digest.

such as ours. To overcome this limitation, Scatter/Gather uses a complex intermixing of iterative partitional clustering algorithms (e.g. K-Means) and an agglomerative scheme. The basic idea is to apply the inferior but fast partitional clustering algorithm until the document set has been decomposed to a point where agglomerative clustering can be used efficiently. Because we found that a complete clustering typically contains too many errors to be useful for reorganizing a document collection, we instead opted to develop a new algorithm that very quickly produces only the cluster digests for topic discovery, and leaves further document partitioning to the classifier. Our experiments reveal that this method is considerably more accurate.

Our algorithm can be thought of as “evolving” one cluster digest at a time. After evolving a new digest, it is presented to the user who can discard irrelevant documents, move documents between the digests, and even discard a digest entirely. After these modifications are made, additional digests can be mined from the remaining documents at the user’s request. In implementing clustering in this manner, the user need not specify up-front an exact number of clusters to discover.

4.1 Algorithm Details

The pseudo-code for the digest evolution routine appears in Figure 4. We call the algorithm C-Evolve(n), where the variable n specifies the number of cluster digests to evolve simultaneously. (Only the best of this set is returned.) This algorithm is called once for each cluster desired by the user.

The pseudo-code makes use of a similarity function denoted by $\text{sim}()$ that returns a floating point value between 0 and 1, with 1 indicating maximum similarity. This function must accept either a single document or a set of documents as argument. We use the cosine distance function on term frequencies, with term frequencies damped by the square root function exactly as is done by Scatter/Gather. Also like Scatter/Gather, for similarity computations involving document sets, we compute the average pair-wise similarity between documents.

Another function used by the pseudo-code is denoted by $\text{score}()$. This function accepts a document, a cluster digest C , and a set of cluster digests P . The return value of this function is maximized when the document is highly similar to cluster C , and highly dissimilar to those clusters within P . We use the method below for computing such a value, though C-Evolve can use other scoring functions with these properties.

$$\text{score}(d, C, P) = \begin{cases} \min(\forall_{C_p \in P} [\text{sim}(d, C) - \text{sim}(d, C_p)]) & \text{if } P \text{ non-empty,} \\ \text{sim}(d, C) & \text{otherwise} \end{cases}$$

The first three steps of the algorithm perform initialization which involves removing documents from the input set that already belong to previously-discovered cluster digests, and seeding the n clusters with documents that are dissimilar to each other. This seeding policy spreads the search for a good cluster digest across the document space.

Step 4 grows the clusters one document at a time until the maximum size is reached and clusters stop changing. By virtue of the scoring function, this step not only attempts to maximize similarity between documents within a given cluster, but also dissimilarity between the evolving cluster and previously discovered clusters. This ensures that, even though the algorithm is not performing a complete partitioning of the input documents, the evolving digests are likely to discover a topic that is not already represented by the existing ones. Note that this scheme is not entirely greedy – that is, a document added to the cluster may disappear from it in a later iteration. Even though a document may score highly during an early iteration, as the cluster evolves it may no longer score so highly. This feature ensures such documents are removed to improve the final result.

Athena employs C-Evolve with the parameter n set to 6. This setting was chosen because it yielded good results, and it is small enough to guarantee response times of a few seconds given a document collection of a thousand documents, a cluster digest size of 10-20, and a Java based implementation.

There is no simple way to obtain a tight bound on the iterations performed by C-Evolve(n) since the clusters can continue to evolve after reaching the desired size. In practice, however, the number of iterations performed after the cluster digest has reached the desired size is typically small, usually well under 5. This amounts to a linear average-case complexity assuming the cluster digest size and the value of n are bounded by constants. If desired, the number of iterations can be hard-bounded by a small constant to guarantee linear complexity in the worst-case. If the user desires a larger cluster digest, e.g. one that is proportional to the collection size instead of bounded by a constant, the procedure can be modified to grow the cluster more than a single document at a time. We have found that slow cluster growth is most helpful during the early iterations of the procedure, so growth can be accelerated during later iterations in order to guarantee linear complexity without significantly compromising the results.

4.2 Evaluation

In this section, we compare C-Evolve with more traditional clustering methods including K-Means and Hierarchical Agglomerative Clustering [Ras91]. Our first suite of experiments evaluates how well C-Evolve works at finding cluster digests compared to these other (appropriately modified) techniques. Because agglomerative and K-Means clustering fully partition the input documents, in order to produce cluster digests, we modified them to return the most central documents of each cluster. The second suite of experiments evaluates how well C-Evolve, when applied interactively with the classifier from the previous section, compares to these other clustering methods when fully partitioning the input documents.

Agglomerative clustering algorithms work by placing each document in its own cluster, and then iteratively merging the pair of most similar clusters until the desired number of clusters remain. In our implementation, cluster similarity is given by average pair-wise similarity between the documents from each cluster. We use the same document similarity function (cosine distance) and document representation (term frequencies damped by the square-root function) for all clustering algorithms to ensure a fair comparison. This algorithm is exactly the “reference” clustering algorithm used in Scatter/Gather [CDPT92].

K-Means clustering seeds each initial cluster (the number of which equals the number of desired clusters) with a single randomly chosen document. A pass is made over the input documents and each document is placed moved into the cluster that is most similar to it. This process repeats until the clusters stop changing, at which point they are returned.

We used real e-mail collections to evaluate these algorithms, obtained from co-workers who diligently file their e-mail, along with the standard Reuters-21578 benchmark data⁴ in order to

⁴Available at <http://www.research.att.com/~lewis/reuters21578.html>

show the results apply more generally. (Table 1 shows some of the characteristics of these datasets.) For each data-set, we selected at most 100 documents from each folder/category to prevent folders with many documents (e.g. those compiled from an active mailing list) from excessively slowing the agglomerative algorithms⁵ and overly skewing the input distribution. For the Reuters data, each document was placed into a “folder” corresponding to the first topic to which it is assigned.

4.2.1 Evaluating Topic Discovery

We assume that the organization provided by the folder hierarchy from each data-set is the “true” clustering of the data. For each data-set, fifty trials were performed, where for each trial, six folders were selected at random from a given data-set and the documents intermixed. Each clustering algorithm was then run on the resulting document collection and made to identify three cluster digests containing 11 documents each.

We chose to identify a smaller number of cluster digests than the number of true clusters in order to determine the sensitivity of agglomerative and K-Means clustering to the number of clusters identified – in real world applications, the true number of clusters is unknown, so the number of clusters the user chooses to identify will unlikely be the same as the true number of clusters. To demonstrate that knowledge of the true number of clusters does not necessarily improve the results, we also have agglomerative and K-Means clustering identify six cluster digests and return the best three of the result. (The best cluster digests are those which maximize average pair-wise similarity).

For each set of cluster digests provided by an algorithm for a given run, we compute two “goodness” metrics. The first is digest purity: we want each digest to contain only documents from a single one of the true clusters. Purity of a digest is therefore defined as the maximum number of documents within the digest that belong to the same true cluster, divided by the total number of documents within the digest. Another metric is digest diversity: we want each digest to present a topic that is distinct from the others. Cluster diversity is therefore the number of true clusters covered by the dominant class from each cluster digest. This implies the maximum diversity score is 3 since we apply the algorithms to find only 3 digests in this experiment.

The results of the experiment appear in Figure 5. As can be seen, C-Evolve is superior to all other schemes with respect to the purity metric. With respect to diversity, it is superior to all but the agglomerative algorithm which identifies three clusters before returning the digests of each. Surprisingly, the algorithms which attempt to identify the true number of clusters do not fare any better than their counterparts which identify only three clusters.

⁵Experiments were run by e-mail database owners on their personal machines in order to maintain their privacy. This required our experiments to complete over a single evening so that their machines were free for regular work during the day.

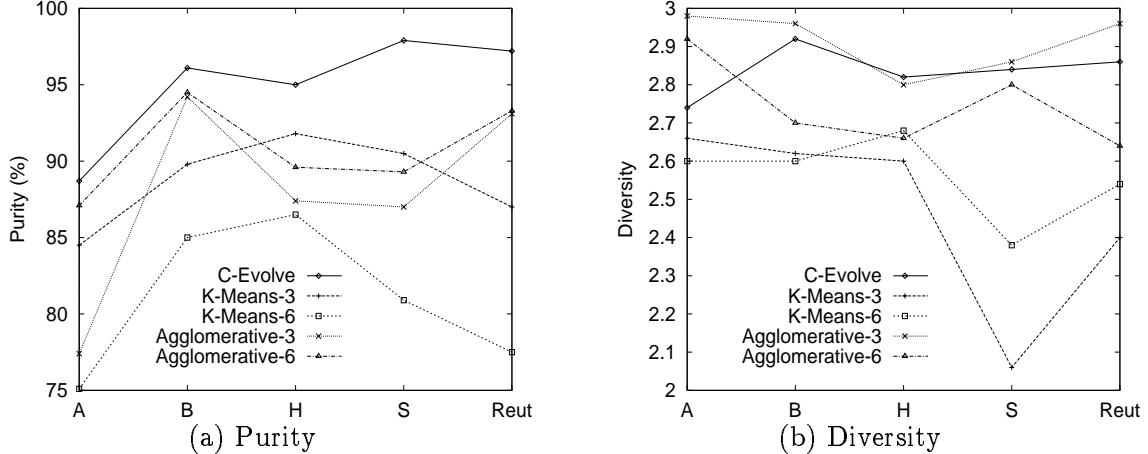


Figure 5: Purity and Diversity Results for the Cluster Digests

4.2.2 Evaluating Interactive Clustering

After a set of topics is discovered, Athena allows the user to populate these topics with additional documents by applying the classifier from the previous section. We evaluate how well this technique works when attempting to fully recover the true clustering by completely partitioning the input documents. For these experiments, we select 5 folders at random from each data-set and intermix the documents to form the algorithm input. Once again, fifty trials are performed on each data-set and the results averaged.

For this experiment, we have the K-Means and Agglomerative clustering algorithms attempt to identify the true number of clusters (5 in this case). For each cluster identified, each document is considered an “error” if its class does not match the dominant class of the cluster. Following [SYB98], we compute the accuracy of a given clustering as one minus the error rate.

We apply C-Evolve repeatedly until each folder is discovered (a folder is said to be discovered by a digest if the dominant class of the digest matches that of the folder). Typically, the number of digests identified in order to discover all folders exceeds the true number of clusters by only one or two. We compute errors for this approach by first summing up the total number of documents in each digest that do not belong to the dominant class of the digest. This error value is then added to the number of errors produced by the classifier in populating the clusters with the remaining documents. To simulate user-corrections, before applying the classifier, we remove any errors from the cluster digests and merge cluster digests that discover the same folder. We also evaluate the effect of having the system present the user with a small number of randomly-selected examples for manual classification before the classifier is applied in order to broaden the training set. We tried both 5 documents per folder and 10 documents per folder. Each document presented to the user by Athena is counted as an error if the suggested class is not the folder to which the document

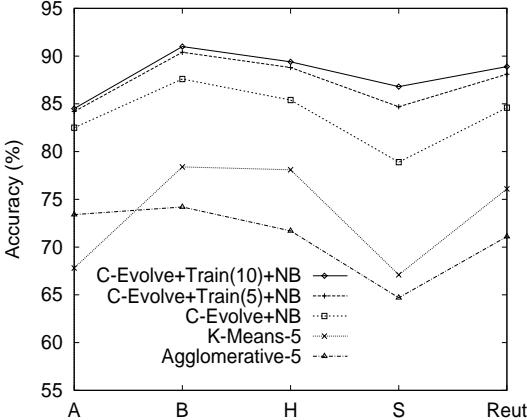


Figure 6: Accuracy Results

actually belongs.

As can be seen in Figure 6, our interactive approach to clustering leads to substantial improvements in accuracy over standard clustering techniques. Manual classification of a small number of randomly-selected examples before applying the classifier leads to further improvement. Note that we obtain these results even though we provide the traditional clustering techniques with knowledge of the true number of clusters. The fact that such improvements are possible suggests that a “true” clustering as envisioned by an end-user who organizes documents rarely matches the true clustering as defined by any statistical technique. By allowing interactivity in the clustering process, our approach allows the user to guide the algorithm towards a more desirable partitioning of the input documents.

5 Conclusions and Future Work

We addressed the problem of simplifying the process of hierarchical document organization and management through text mining algorithms. Using classification and clustering as the basic building blocks, our Athena system provides rich functionality for automatic creation and maintenance of hierarchical text databases. Using Athena, users can discover topics in their unorganized collection of documents and partition the documents according to these topics. They can reorganize a hierarchical collection into a different hierarchy by giving only few documents as examples. They can exploit the information contained in their current hierarchy to route new documents. They can also find misfiled documents and identify when some node in a hierarchy may need reorganization due to concept drift within a node.

The implementation of this application placed new requirements on the classification and clustering technology, making the use of standard solutions inadequate. For classification, we enhanced

the basic Naive-Baye's algorithm with several features including the use of Lidstone's law of succession, under-weighting long documents, and over-weighting author and subject. These enhancements led to 7 to 29% absolute increase in accuracy on our real-life test data sets.

We also developed a new interactive clustering algorithm. This algorithm first finds highly accurate cluster digests (partial clusters), obtains user feedback to merge/correct these digests, and then uses the classification algorithm to complete the partitioning of the data. In our experiments, this new algorithm resulted in 10-20% increase in absolute accuracy over k-means and agglomerative clustering. While strict classification and clustering algorithms have been well-studied in previous work, this interactivity dimension has received comparably little attention. We feel further research directed towards cooperation between on-line data-mining algorithms and the end-user will prove fruitful.

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