

# Construction of Story Telling Graphs

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## Abstract

Stream-like data sources, such as a collection of RSS feeds, can be challenging to summarize as the corpus is ever growing and the nature of the data evolves over time. This project implements an intelligent RSS reader that leverages topic modeling to provide a high-level view of the document stream. LDA Topic modeling is performed at daily intervals and linkages between learned topics from different days are computed to form the edges in what can be considered a “Story Graph”. This story graph can be used to answer a number of contextual questions from both the perspective of a topic and a document.

## 1 Introduction

Stream-like data sources are a common fixture of the current technological landscape. Well known examples of streaming data sources include news content from major media outlets (i.e. through RSS feeds), the collective musings of Twitter’s user base (i.e. the Twitter Firehose), and the click-stream generated from surfing internet (i.e. from network logging). Summarizing and contextualizing information in a data stream is a natural and important problem that arises.

The most popular form of summarization on a data stream is mining for trending topics, typically through an unsupervised learning process. Trending topics provide a high level view of the prominent themes present in a data stream during a window of time. A set of trending topic sets, or even multi-

ple sets from different windows of time, can provide insight in isolation. However, contextual questions about a topic’s origin, lifetime, momentum, and evolution cannot be addressed. To answer these more advanced questions, topics must be linked beyond the window in time they were discovered. This set of time sensitive topics and the linkages between them is referred to in this report as a “Story Graph”.

Given a set of topics, the construction of a story graph is only slightly more complicated than the discovery of the topics themselves. However, not all approaches to topic discovery result in representations where computing linkages between topics is straight forward. Further, the topic modeling should be sufficiently powerful to accommodate complicated real-world mixtures of topics. For both of the above reasons, Latent Dirichlet Allocation (LDA) is used on the bag of word representation of documents to mine for topics.

Queries on a story graph may start and end from both the perspective of a topic and a document. Starting from a topic, the story graph can be traced to another topic or down to a document through the topic weights. Likewise, starting from a document, the story graph can be traced through the topic weights to another topic or again down to a neighboring document. Features of a trace through the graph, such as the length in time covered or the number of topics or documents traversed, serve as the basis for the answers to the contextual questions posed above.

This project investigates story graphs, their construction process, and their relevant queries by implementing a system that digests a stream of documents exposed from a collection of RSS feeds and generates

a summary view of the data through a web portal. Three different datasets are explored from different categories: General news, Business, and Sports. Data was collected by the system for 60 days.

## 2 Background

Unsupervised methods for discovery and summarization of a corpus have a rich history rooted in information retrieval. Before the more abstract task of a topic discovery became widely known, document clustering was a well studied problem. Document clustering is used to find inter-document similarities and partitions of similar documents in a corpus.

The vector space representation of a document is a common place to begin document clustering. The vector space representation of a document holds term counts by assigning a unique dimension to each term that exists in the corpus. Various term weighting schemes can be applied to the document vectors such as tf-idf weighting. These schemes enhance the similarity measures by reducing the contribution of unimportant words such as stop words. Similarity between two documents in vector space can be measured with a geometric interpretation either, by the angle between them (cosign similarity) or the distance apart (euclidean distance).

A good first step towards topic discovery is the K-means algorithm applied to corpus of tf-idf weighted documents in the vector space representation. K-means attempts to find a partitioning of the corpus into K groups such that the euclidean distance of a cluster's members is minimized. Iterative refinement from randomly initialized means can be used to approximate this hard problem. The most highly weighted term indices of the resulting K mean vectors from a clustering job loosely represent the topics present within the corpus. The approach is advantageous for streaming data because the learned mean vectors can be compared across clustering jobs from different time windows easily (using either cosign similarity or euclidean distance between the means). The approach is also desirable because it is simple and fast. However, the technique lacks the richness of topic mixtures by assuming each document can be

long to only one mean vector.

Another early approach that improves upon the vector space representation is Latent Semantic Analysis (LSA). LSA computes the singular value decomposition of a document-term matrix to find low-rank approximations of the latent document and term matrices. The resulting matrix factorization has the property that when a pair of documents or a pair of terms are similar, they will be near (using cosign similarity or euclidean distance) in their respective vector spaces. LSA is good step towards finding a representation that can capture synonymy and polysemy, but is not suitable in the streaming paradigm where the process repeats and regular intervals. The resulting matrix factorizations are unique to the document-term matrix they were derived from. There is no straight forward way to compare either the learned term or the document representations from different time windows.

Probabilistic Latent Semantic Analysis (PLSA) addresses the limitations above with LSA by stepping away from the vector space representation of LSA to a probabilistic representation of terms and document. PLSA represents documents in the bag-of-words format where term frequency is maintained but not order and no geometric interpretation is applied. PLSA introduces a hidden random variable to model topics and then learns document-topic and topic-term distributions through the Expectation Maximization (EM) algorithm. PLSA can also overcome issues such as synonymy and polysemy through the topic, and has the advantage of allowing mixtures of topic (or cluster) assignments. Lastly, PLSA is advantageous in the streaming paradigm because the resulting topic distributions are interpretable and comparable across different time windows.

PLSA is the predecessor to LDA, the model used in this project. LDA improves upon PLSA by modeling the document probabilities and word distributions as dependent on Dirichlet prior distributions. This dependence on prior distributions enhances the generality of the distributions learned. An LDA model is more complicated and the distributions are commonly estimated using Gibbs Sampling.

Summary of LDA Variables	
$i < N$	Number of Documents
$j < M$	Number of Terms
$k < K$	Number of Topics
$w_{i,j}$	Count of Term=j in Document=i
$z_k$	Topic k of K
$\alpha_k$	Document-Topic Prior Parameter
$\beta_j$	Topic-Term Prior Parameter
$\theta_{i,k}$	$P(\text{Topic}=z_k \mid \text{Document}=i)$
$\phi_{k,j}$	$P(\text{Word}=j \mid \text{Topic}=z_k)$

### 3 Method

#### 3.1 Graph Creation

The starting point of graph creation is corpus of documents partitioned by a time interval over an indefinite period. Formally, we may represent this by the following notation where the maximum interval  $T$  is ever increasing.

$$\begin{aligned} \mathbf{C} &= \{\mathbf{C}_0, \dots, \mathbf{C}_T\} \\ \mathbf{C}_t &= \{\mathbf{d}_0^t, \dots, \mathbf{d}_N^t\} \\ \mathbf{d}_i^t &= \{w_{i,0}, \dots, w_{i,M}\} \end{aligned}$$

For the purposes of this project, the partitions  $\mathbf{C}_t$  for  $t \leq T$  represent the documents partitioned by day. Each individual day's sub-corpus  $\mathbf{C}_t$  is a collection documents where each document  $\mathbf{d}_i^t$  is in the bag-of-word format. For the purposes of this document, superscripts are used to denote documents, topics, and distributions from a given day  $t$  except when describing running times. In this project LDA topic modeling is used to estimate from the daily corpus  $\mathbf{C}_t$  the probability distributions of the the document-topic distribution,  $\theta_{i,k}^t$ , and topic-term distribution,  $\phi_{j,k}^t$ .

The story graph constructed from the learned distributions follows the standard form:  $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ . A unique feature of the story graph is that the vertices in  $\mathbf{V}$  can include both the documents and the topics and follows directly from the conditional dependence graph of the LDA model. The edges in

$\mathbf{E}$  are undirected, as opposed to directed when representing conditional independence, so traversals in either direction may be performed.

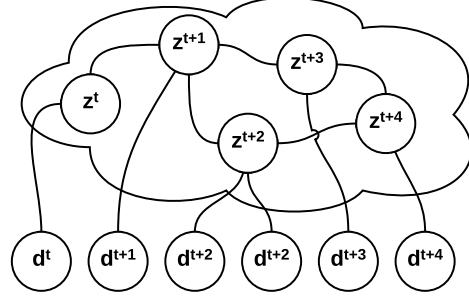


Figure 1: Story Graph: An example graph over  $t$  to  $t + 4$  days

Edges are weighted by floating point values ranging between  $[0, 1]$ . Edges between documents are always 0 (i.e. are not allowed). Topics may form edges with documents of the same day using the document-topic distribution. Edges between topics across different days are formed by computing the cosign similarity on the vector space interpretation of the topic-word distributions. Though blatantly not probabilistic, the cosign similarity between two probability distributions will at least always return a value between  $[0, 1]$ . These topic-topic edges are precomputed between the current days topics and all previous days topic within some limit (in this project, 15 days). The formal rules for constructing edge weights are as follows:

$$\begin{aligned} e(\mathbf{d}_i^t, \mathbf{d}_{i'}^{t'}) &= 0 \quad \forall \quad i, t, i', t' \\ e(\mathbf{z}_k^t, \mathbf{z}_{k'}^{t'}) &= \begin{cases} 0 & \text{if } t = t' \\ \frac{\phi_k^t \cdot \phi_{k'}^{t'}}{\|\phi_k^t\| \|\phi_{k'}^{t'}\|} & \text{if } t \neq t' \end{cases} \\ e(\mathbf{d}_i^t, \mathbf{z}_k^{t'}) &= \begin{cases} \theta_{i,k}^t & \text{if } t = t' \\ 0 & \text{if } t \neq t' \end{cases} \end{aligned}$$

### 3.2 Query by Topic

Starting from a topic  $\mathbf{z}_k^t$ , a natural query is to find the sub-graph of related topics across all time. This sub-graph can be thought of as the story a topic belongs to. This query performs a breadth first search of the neighboring topics from different days while the product of the edge weights along each path from starting to ending topic is above a threshold between  $[0,1]$ .

```

Define: Subgraph()
Input: Starting topic  $z_k^t$ ,
       Topic threshold  $thresh_z$ 
Output: Related topic set  $Z$ 
Begin:
  Initialize  $Z = \{\}$ ,
             $V = \{z_k^t\}$ ,
             $F = \langle z_k^t, 1 \rangle$ 
  While  $F \neq \{\}$ :
    Remove  $z$  from  $F$ 
    For  $z' \in \text{TopicNeighbors}(z)$ :
      Let  $w = e(z, z') * \text{weight}(z)$ 
      If  $z' \notin V$  and  $w > thresh_z$ :
         $Z = Z \cup \langle z', w \rangle$ 
         $F = F \cup \langle z', w \rangle$ 
       $V = V \cup z$ 
  return  $Z$ 
End
Algorithm topic sub-graph of topic  $z_k^t$ 

```

Querying the graph for a topic's sub-graph can, in the worse case, be somewhat expensive for long-lived stories. Breadth first search has a running time in the general case of  $O(|E|)$ . For a given day, there will be  $K^2W$  edges where  $K$  is the number of topics and  $W$  is the number of days compared. A long lived story can trace through  $T$  days. Therefore, the number of edges is  $O(TK^2W)$ , which is less than the possible  $O(T^2K^2)$  edges if windowing were not applied. Better yet, the edges are pre-computed and only edges above the threshold are added. Typically much less than  $K^2W$  edges per day are used in this query.

### 3.3 Query by Document

Another useful query on the story graph is the more classic problem of finding relevant neighboring documents given a starting document. Again a breadth first search is required. Recall that documents are connected to the graph only through their topic weights and that the interior of the graph is entirely edges between topics of different days. Therefore, the traversal of the graph from one document to another may reuse the **Subgraph()** routine presented in the previous subsection.

A similar approach is taken to querying by document as by topic in that again the paths from document to document will be pruned by the product of the edge weights. To make the algorithm more efficient, a modified version of the **Subgraph()** routine is assumed where a set of starting topics can be supplied instead of only a single one. This modification does not change the algorithm or the running time.

```

Define: Similar()
Input: Starting document  $d_i^t$ ,
       Topic-topic threshold  $thresh_z$ ,
       Document-topic threshold  $thresh_d$ 
Output: Related document set  $D$ 
Begin:
  Initialize  $D = \{\}$ ,
             $F = \{\}$ 
  For  $z \in \text{TopicNeighbors}(d_i^t)$ :
    If  $e(d_i^t, z) > thresh_d$ :
       $F = F \cup \langle z, 1 \rangle$ 

  For  $z \in \text{Subgraph}(F, thresh_z)$ :
    For  $d \in \text{DocumentNeighbors}(z)$ :
      Let  $w = e(d, z) * \text{weight}(z)$ 
      If  $w > thresh_d$ :
         $D = D \cup \langle d, z, w \rangle$ 
  Return  $D$ 
End
Algorithm for relevant documents  $d_i^t$ 

```

An interesting consequence of querying by document is that a document may be similar to another

document indirectly through multiple topics. The indirect nature of the query makes the running time of the algorithm slower than querying by document. For a given day  $t$ , the number of documents retrieved by any topic can be at most the number of documents that day  $|\mathbf{C}^t|$ . Therefore, over all time and all topic-topic edges, a factor of  $|\mathbf{C}|$  extra edges between documents need be explored. The total running time is  $O(TK^2W|C|)$ . Again, thresholding can be performed prior to updating the graph so many of the total possible edges do not exist.

### 3.4 Graph Metrics

Given a topic’s sub-graph, there are a number of interesting metrics that can be used to analyze the story. The first query of interest is the lifetime of a story. The lifetime of a story is simply the maximum topic time window less the minimum. Knowing the total time a story has existed can then be used to estimate what can be interpreted as density or velocity. Story density or velocity is defined as the number of topics in the subgraph divided by a time range. This time range can be the lifetime if examining a story in isolation or an arbitrary range if comparing multiple stories.

The number of documents a given topic connects to in the sub-graph provides a notion of size. A threshold is required to ensure documents are truly relevant to the topic, which is described in the next section. The number of relevant documents over an entire sub-graph can be thought of as the story’s mass. Putting the velocity and mass together, the notion of momentum can be borrowed from physics to assess how enduring a story is.

An alternative measure of size of a topic is the hyper-parameter  $\alpha_k$ . In previous versions of LDA this parameter had to be supplied, but now can be estimated from the corpus using a burning period. The topic modeling software used in the project performs this estimation.

For notation, let  $\mathbf{S}$  be a topic’s sub-graph and let  $\mathbf{D_S}$  be the number of unique documents connected to the sub-graph with a path product above the threshold used in `Similar()`. The various metrics are stated below in these terms.

$$\text{Lifetime}(\mathbf{S}) = \max_{z \in \mathbf{S}} \text{time}(z) - \min_{z \in \mathbf{S}} \text{time}(z) \quad (1)$$

$$\text{Velocity}(\mathbf{S}) = \frac{|\mathbf{S}|}{\Delta \text{time}} \quad (2)$$

$$\text{Mass}(\mathbf{S}) = |\mathbf{D_S}| \quad (3)$$

$$\text{Mass2}(\mathbf{S}) = \sum_{z \in \mathbf{S}} \alpha_z \quad (4)$$

$$\text{Momentum}(\mathbf{S}) = \text{Mass}(\mathbf{S}) \times \text{Velocity}(\mathbf{S}) \quad (5)$$

## 4 Architecture

Processing the document stream is accomplished by a nightly process that downloads content from a collection of RSS feeds for the previous day. The entire process is composed a series of stages that happen sequentially. While the production environment schedules the process to handle a single day’s worth of data from a cron job, the process can also be run in batch mode to process all data over a provided time range. Importantly, each stage in the processing pipeline is dependent only on the output from the previous stage.

The process begins with the sync stage by gathering the list of URLs for unprocessed data in the stream using the Google Reader undocumented API (GRAPI). The GRAPI normalizes the many quirks and formatting issues present in a large set of RSS/Atom feeds and exposes a standard representation of a document stream. The output of the Sync stage is a mapping for URL to path on local storage the content should be downloaded to.

The fetch stage of the processing pipeline is run after the Sync stage generates output. This stage is responsible for downloading HTML content, extracting the relevant article content from the raw HTML, and saving the result to local disk. Content downloading is managed by through the Apache Commons libraries. Article extraction was originally handled by extracting text content with an HTML parser. However, the resulting saved documents included too many artifacts of the hosting site such as advertisements, comments, and boiler plate content. The artifacts present in the document made the topic

modeling perform poorly. To remedy this problem, a library known as “boilerpipe” was used to separate article content from artifact with an in-built decision tree classifier.

The next stage of the pipeline performs topic modeling on the daily corpus that was created locally from the Fetch stage. Topic modeling is handled by the ParallelTopicModel in the Mallet library. Documents are transformed into the bag-of-words format by converting characters to lower case, removing punctuation, and splitting on whitespace. A burn-in phase of 10 iterations is used to estimate the Dirichlet hyperparameters. The learned topics improve qualitatively when the content is boosted by appending the document’s title 5 times. The number of topics,  $K$ , is chosen to be half the corpus size. This allows space for redundant themes to cluster on a single topic, but also the common situation where a topic has no history and is new or one-time event.

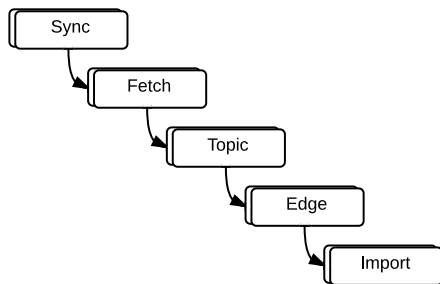


Figure 2: Architecture Diagram: Sequential Stages

After the topic modeling has completed for the current day, edges are computed between topics of the previous days within a given window of time. As time progresses, the total time frame a similar topic can be detected is the window of days before and after the topic date. Similarity between topics is computed by treating the topic-term distribution as a vector space representation and computing the cosign-similarity.

Lastly, after all the previous stages have completed the downloaded document data, topic distributions, and similarity measures are imported into a database. After the import process completes the max date is updated so that queries may be performed against the new, fully imported day’s worth of information. The database contains all information required by the web portal to let a user explore the data stream and answer relevant story graph queries.

## 5 Evaluation

### 5.1 Popular Topics

The first item to confirm is that the topic modeling is effective at summarizing the relevant topics for a given day. Because LDA is an unsupervised method, the learned topics are already the best fit possible according to the optimization criteria (marginal likelihood). Therefore, this evaluation is more qualitative than quantitative and a judgement call must be made.

As mentioned previously, the first article extraction simply removed HTML content and returned text. This naive approach left many artifacts present in the document and the learned topics matched the raw content better than the thematic content. Examples of “artifact” topics include topics dominated by numbers, topics dominated by terms that related to the hosting sites (such as “CNN”, “Fox” or “ABC”), topics related to advertisements, and topics related to comments sections.

These “artifact” topics can be removed for the most part with more data cleaning using the “boilerpipe” article extraction library. However, content problems persist for new reasons such as expired links and sites hosting video content with very little content. These ambiguous topics remain somewhat prominent. However, in the middle range of prominence the topics learned are in fact informative and effective at summarizing a topic. A few such examples of informative topics for a day are provided.

One basic approach to further improve the learned topics is filtering by manual inspection. The ambiguous topics reappear from day to day regularly and

Prominent “Artifact” Topics		
1	comments	fox
5	usa	news
3	today	twitter
2	news	facebook
4	life	report
6	comment	home
7	blog	world
8	travel	friends
9	sports	air
romney	contact	email
10	stories	article

Top terms for “artifact” topics using naive article extraction.

Ambiguous Topics		
page	video	external
search	watch	internet
close	2012	sites
missing	1	2012
found	july	network
center	full	provided
report	images	content
visit	photo	purposes
links	aug	responsible
find	size	copyright
public	news	ventures

Top terms for ambiguous topics even after improved article extraction.

share almost identical distributions. By identifying a sample of individual topics that should be excluded from display and edge creation, the same method of similarity comparison used to link topics across days can be used to suppress future topics.

## 5.2 Query by Topic

The next component to evaluate is the effectiveness of computing topic similarities. Querying the story graph by topic requires a threshold for similarity that not straightforward to set. Again, because the method is unsupervised there are no explicit labels for when two topics should be joined that would allow the threshold to be optimized for accuracy. Instead the threshold must be set by a qualitative feel.

Plotting the density of the cosign similarity values for one day’s topics with the neighboring topics provides some clues about where to search for a threshold. The density plot of the all topic similarities for one day reveal that the vast majority are near 0. Zooming in further to only similarities above .3 reveals a slightly more interesting structure. To get a sense of how topic distributions become less similar, this zoomed in threshold space is sampled by comparing a starting prominent topic to a neighboring topic for each similarity range: [.9, 1], [.8, .9], [.6, .8], [.4, .6], and [.3, .4].

Informative Toics		
romney	gaza	syrian
obama	benghazi	rebels
ohio	hamas	assad
campaign	walk	syria
president	trust	aleppo
ad	missiles	military
state	obama	battle
mitt	dome	forces
romneys	live	regime
auto	holiday	weapons
democratic	rohrabacher	city

Top terms for informative topics that succinctly capture a topic.

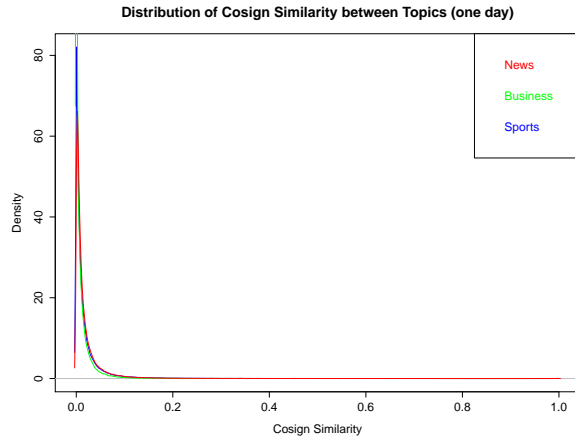


Figure 3: Density of Topic Similarity by dataset

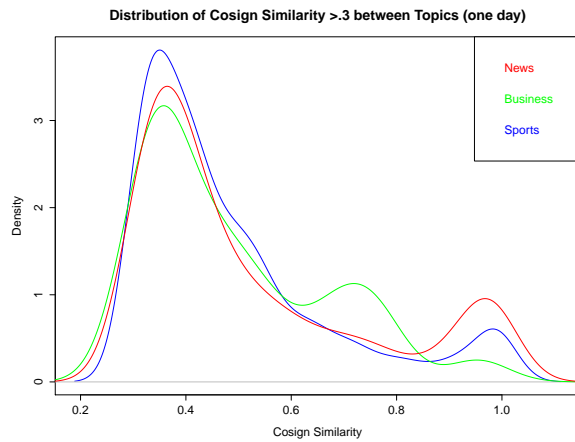


Figure 4: Density of Topic Similarity > .3 by dataset

Impact of Topic Similarity Top ten terms of similar distributions		
start	.9	.8
isaac	isaac	isaac
louisiana	louisiana	lousiana
hurricane	hurricane	hurricane
orleans	storm	flooded
storm	orleans	baithwaite
home	residents	home
braithwaite	home	street
residents	parish	residents
plaquemines	flooded	pontchartrain
flooded	mississippi	floodwaters

Examination of topic similarity thresholds.

Impact of Topic Similarity (continued) Top ten terms of similar distributions		
.6	.4	.3
storm	haiti	fire
isaac	isaac	storm
hurricane	crisis	friday
national	hits	officials
gulf	portauprince	wednesday
orleans	storm	winds
coast	earthquake	center
tropical	people	rain
rain	topical	house
winds	city	damaged

Examination of topic similarity thresholds.



The sampled distributions of increasingly lower similarity show qualitatively that a good threshold is likely somewhere between .6 and .4. Though only one example of many possible is shown, similar behavior is observed generally. At the lowest value in this range the neighboring topic begins to really diverge.

### 5.3 Query by Document

Show examples of querying by document. Given metrics of similarity on returned documents for the 3 datasets.

### 5.4 Graph Metrics

Using the estimated thresholds of .6 for the topic similarity threshold and .15 for document-topic threshold, three prominent stories found during the middle of the corpus (2012-09-01) are queried with the resulting subgraphs' documents plotted by day. These stories happen to be related to President Obama's reelection campaign, turmoil in Gaza, and Hurricane Irene. The Obama and Gaza topics are fairly enduring in this dataset so they remain steady. The hurricane, however, was a more isolated event which began August 21, 2012 and ended September 1, 2012. The story graph accurately captures this lifetime.

How useful are topic metrics? Show samples/summary plots of topic lifetime, velocity, and momentum

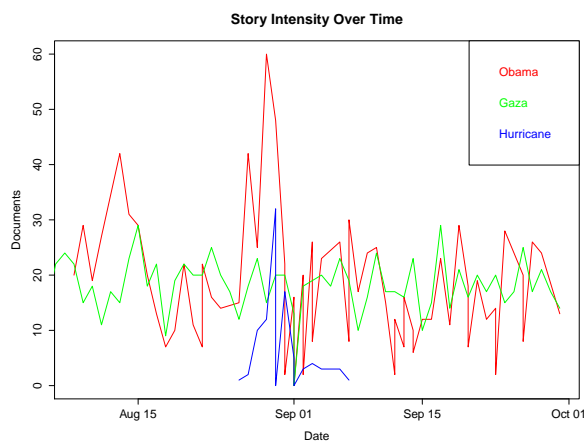


Figure 5: Prominent topic sub-graphs by document count over time

## 6 Future Work

Talk about how given more time, the world could be saved.