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14. ABSTRACT In many real-world applications, the data are naturally multi-modal, in the sense that they are represented by multiple sets of features. In general, with the availability of multiple information sources, it is a challenging problem to conduct integrated exploratory analysis with the aim of extracting more information than what is possible from only a single source.  <i>In this project, building upon the foundations of NMF for unsupervised learning that the DI and collaborators</i>					
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## Report Title

Final Report: Unsupervised Learning from Multiple Information Sources Based on Non-negative Matrix Factorization (NMF)

### ABSTRACT

In many real-world applications, the data are naturally multi-modal, in the sense that they are represented by multiple sets of features. In general, with the availability of multiple information sources, it is a challenging problem to conduct integrated exploratory analysis with the aim of extracting more information than what is possible from only a single source.

In this project, building upon the foundations of NMF for unsupervised learning that the PI and collaborators discovered recently, aided with a substantial body of work by PI and other researchers, we propose to establish a comprehensive framework for unsupervised learning from multiple information sources based on NMF.

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**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

<u>Received</u>	<u>Paper</u>
01/16/2015 12.00	Wenting Lu, Jingxuan Li, Tao Li, Weidong Guo, Honggang Zhang, Jun Guo. Web Multimedia Object Classification Using Cross-Domain Correlation Knowledge, IEEE Transactions on Multimedia, (12 2013): 0. doi: 10.1109/TMM.2013.2280895
01/16/2015 13.00	Li Zheng, Tao Li, Chris Ding. A Framework for Hierarchical Ensemble Clustering, ACM Transactions on Knowledge Discovery from Data, (09 2014): 0. doi: 10.1145/2611380
01/16/2015 14.00	Zhong-Yuan Zhang, Tao Li, Chris Ding, Jie Tang. An NMF-framework for Unifying Posterior Probabilistic Clustering and Probabilistic Latent Semantic Indexing, Communications in Statistics - Theory and Methods, (05 2014): 4011. doi: 10.1080/03610926.2012.714034
08/24/2012 4.00	Wenting Lu, Lei Li, Jingxuan Li, Tao Li, Honggang Zhang, Jun Guo. A multimedia information fusion framework for web image categorization, Multimedia Tools and Applications, (07 2012): 1. doi: 10.1007/s11042-012-1165-2
08/24/2012 6.00	Tao Li, Zhongyuan Zhang, Chris Ding, Jie Tang. A NMF-framework for Unifying Posterior Probabilistic Clustering and Probabilistic Latent Semantic Indexing, Communications in Statistics: Theory and Methods, (12 2012): 0. doi:
<b>TOTAL:</b>	<b>5</b>

Number of Papers published in peer-reviewed journals:

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**(b) Papers published in non-peer-reviewed journals (N/A for none)**

Received      Paper

**TOTAL:**

Number of Papers published in non peer-reviewed journals:

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**(c) Presentations**

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**Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

Received      Paper

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**Peer-Reviewed Conference Proceeding publications (other than abstracts):**

<u>Received</u>	<u>Paper</u>
01/16/2015 15.00	Liang Tang, Yexi Jiang, Lei Li, Tao Li. Ensemble contextual bandits for personalized recommendation, the 8th ACM Conference on Recommender systems . 06-OCT-14, Foster City, Silicon Valley, California, USA. : ,
01/16/2015 16.00	Yexi Jiang, Charles Perng, Tao Li. META: Multi-resolution Framework for Event Summarization, Proceedings of the 2014 SIAM International Conference on Data Mining . 01-MAY-14, . : ,
08/24/2012 5.00	Wenting Lu, Lei Li, Tao Li, Honggang Zhang, Jun Guo. Web Multimedia Object Clustering via Information Fusion, 2011 International Conference on Document Analysis and Recognition (ICDAR). 18-SEP-11, Beijing, China. : ,
08/24/2012 7.00	Chen Lin, Runquan Xie, Lei Li, Zhenhua Huang, Tao Li. PRemiSE: Personalized News Recommendation via Implicit Social Experts, ACM CIKM International Conference. 29-OCT-12, . : ,
08/30/2011 2.00	Wenting Lu, Lei Li, Tao Li , Honggang Zhang , Jun Guo. Web Multimedia Object Clustering via Information Fusion, the 11th International Conference on Document Analysis and Recognition (ICDAR 2011). 18-SEP-11, . : ,
08/30/2011 3.00	Wenting Lu, Jingxuan Li, Tao Li, Honggang Zhang, Lei Li, Jun Guo. Exploring Interaction Between Images and Texts for Web Image Categorization, The 24th Florida Artificial Intelligence Research Society Conference (FLAIRS-24) . 18-MAY-11, . : ,
09/11/2013 9.00	Yimin Yang, Wenting Lu, Jesse Domack, Tao Li, Shu-Ching Chen, Steven Luis, and Jainendra K. Navlakha. MADIS: A Multimedia-Aided Disaster Information Integration System for Emergency Management, Proceedings of 8th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing (CollaborateCom 2012). 14-OCT-12, . : ,
09/11/2013 10.00	Dingding Wang, Tao Li and Mitsunori Ogihara. Generating Pictorial Storylines via Minimum-Weight Connected Dominating Set Approximation in Multi-view Graphs, Proceedings of the Twenty-Sixth AAAI Conference on Artificial Intelligence. 22-JUL-12, . : ,
<b>TOTAL:</b>	<b>8</b>

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

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**(d) Manuscripts**

Received

Paper

09/11/2013 11.00 Wenting Lu, Jingxuan Li, Tao Li, Weidong Guo, Honggang Zhang, and Jun Guo. Web Multimedia Object Classification using Cross-Domain Correlation Knowledge, IEEE TRANSACTIONS ON Multimedia (01 2013)

**TOTAL: 1**

**Number of Manuscripts:**

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**Books**

Received

Book

**TOTAL:**

Received

Book Chapter

09/11/2013 8.00 . Nonnegative Matrix Factorizations for Clustering: A Survey, : , ( )

**TOTAL: 1**

**Patents Submitted**

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**Patents Awarded**

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## Awards

1. One student supported by Florida International University Presidential Fellowship and one student supported by China Council

Scholarship have involved in the project.

2. Dr. Tao Li has won Xerox University Affairs Committee (UAC) Award, 2011-2014 (This is an award from Xerox Research to support

research project on mining social media)

3. Dr. Tao Li has won FIU College of Engineering and Computing Mentorship Award for 2011 (This is an award given to one faculty

member at College of Engineering for excellence in student mentorship)

4. Dr. Tao Li has won FIU School of Computer Science Excellence in Research Award for 2011 (This is an award given to one faculty

member at FIU School of Computer Science for excellence in research)

5. Dr. Tao Li has won FIU College of Engineering and Computing Excellence in Research Award in 2012 (This is an award given to one faculty member at College of Engineering for excellence in research)

6. Dr. Tao Li has won FIU School of Computer Science Excellence in Mentorship Award for 2014 (This is an award given to one faculty

member at FIU School of Computer Science for excellence in mentorship)

## Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Lei Li	0.50	
Wenting Lu	0.10	
Li Zheng	0.33	
Longhui Zhang	1.00	
Yexi Jiang	0.50	
<b>FTE Equivalent:</b>	<b>2.43</b>	
<b>Total Number:</b>	<b>5</b>	

## Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
<b>FTE Equivalent:</b>	
<b>Total Number:</b>	

## Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Tao Li	0.11	
<b>FTE Equivalent:</b>	<b>0.11</b>	
<b>Total Number:</b>	<b>1</b>	

## Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Jesse Domach	0.20	B.S.in Computer Science
Yahya Benhadda	0.30	B.S. in Computer Science
<b>FTE Equivalent:</b>	<b>0.50</b>	
<b>Total Number:</b>	<b>2</b>	

**Student Metrics**

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 2.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 2.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

**Names of Personnel receiving masters degrees**

NAME

Long Wang

**Total Number:**

1

**Names of personnel receiving PHDs**

NAME

Lei Li

Li Zheng

**Total Number:**

2

**Names of other research staff**

NAME

PERCENT SUPPORTED

**FTE Equivalent:**

**Total Number:**

**Sub Contractors (DD882)**

**Inventions (DD882)**

**Scientific Progress**

**Technology Transfer**

See attachement

See attachment



## **Unsupervised Learning from Multiple Information Sources Based on Non-negative Matrix Factorization (NMF)**

**PI: Tao Li,**

**School of Computing and Information Sciences, Florida International University**

### **Project Objective**

In many real-world applications, the data are naturally multi-modal, in the sense that they are represented by multiple sets of features. For example, in image classification, we may have features directly extracted from the images and the keywords or contextual information in the environments. For target identification, we may have images taken from the same sensor with different viewpoints or images taken by different types of sensors. In general, with the availability of multiple information sources, it is a challenging problem to conduct integrated exploratory analysis with the aim of extracting more information than what is possible from only a single source.

Nonnegative matrix factorization (NMF) factorizes an input nonnegative matrix into two nonnegative matrices of lower rank. Recent studies show that NMF provides a principled framework for unsupervised learning. In this proposal, building upon the foundations of NMF for unsupervised learning that the PI and collaborators discovered recently, aided with a substantial body of work by PI and other researchers, we propose to establish a comprehensive framework for unsupervised learning from multiple information sources based on NMF.

### **Project Approach**

The proposed framework is based on Nonnegative matrix factorization (NMF). It has been shown that NMF with the sum of squared error cost function is equivalent to a relaxed K-means clustering, the most widely unsupervised learning algorithm. In addition, NMF with the I-divergence cost function is equivalent to probabilistic latent semantic indexing, another unsupervised learning method popularly used in text analysis. These results established the theoretical foundation for NMF to solve unsupervised learning problems.

The framework has several advantages. First, NMF-based approaches are amenable to vigorous analysis and benefits from the well-established knowledge in linear algebra accumulated through centuries. Second, NMF-based methods can be efficiently computed thanks to the mature software packages developed by scientific computing communities. Third, NMF-based algorithms are simple to implement and easy to understand, comparing with the probabilistic, information-theoretic and graph-theoretic methods.

The successful developments of the NMF-based framework utilize the established computational mathematics tools, solve challenging data fusion problems, and have a variety of real-world applications. This new framework complements the existing statistics and information theory based approaches.

### **Scientific Barriers**

The first challenge is on extending the NMF framework from one data source to multiple data sources. In particular, we need to develop NMF-based algorithms for clustering by similarity fusion; for ensemble clustering; for semi-supervised clustering from multiple information sources; and for semi-supervised learning from multiple information sources with limited supervision. Another challenge is how to scale the NMF-based framework for large-scale datasets

### **Scientific Significance**

Fusing multiple information sources can yield significant benefits to successfully accomplish learning tasks. The successful developments of the NMF-based framework utilize the established computational mathematics tools, solve challenging data fusion problems, and have a variety of real-world applications critical to the Army's mission such as automated target recognition (e.g., for smart weapons), guidance for autonomous vehicles, battlefield surveillance, and automated threat recognition. The NMF-based framework is amenable to vigorous analysis, simple to implement, and efficient. This framework also complements the existing statistics and information theory based approaches.

### **Scientific Accomplishments**

In traditional soft clustering, a data point may be assigned to multiple clusters and the probabilities of a point belonging to different clusters are directly normalized. In [1], we show that a form of Nonnegative Matrix Factorization (NMF) based clustering has the nice property that posterior cluster probabilities are directly normalized. If we use class conditional probability normalization, the NMF-based reduces to Probabilistic Latent Semantic Indexing (PLSI). We also provide a NMF based framework for unifying posterior probabilistic clustering and probabilistic latent semantic Indexing. Figure 1 shows an example for illustrating the proposed posterior NMF. In a recent book chapter [4], we provide a comprehensive review of non-negative matrix factorization methods for clustering. In particular, we outline the theoretical foundations on NMF for clustering, provide an overview of different variants on NMF formulations, and examine several practical issues in NMF algorithms. We also summarize recent advances on using NMF-based methods for solving many other clustering problems

including co-clustering, semi-supervised clustering, and consensus clustering and discuss some future research directions.

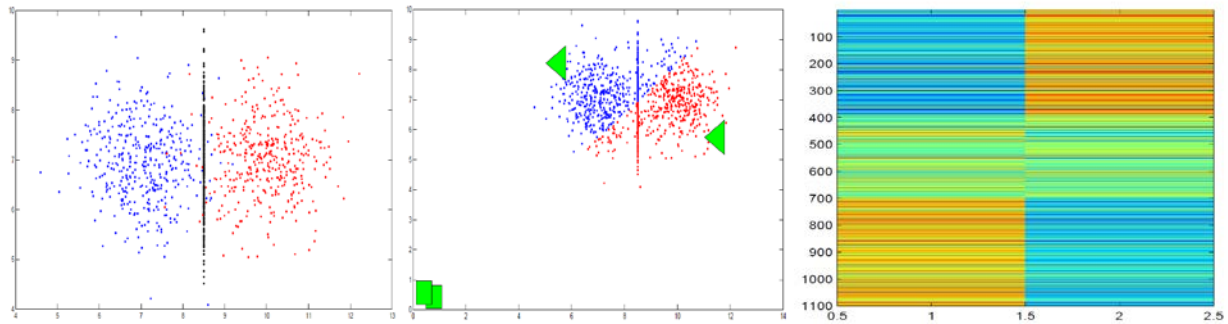


Figure 1: The original data, shown on the left, contains two clusters; the black points are in the middle of two clusters. Result of running the proposed posterior NMF is placed in the middle. “ $\triangleleft$ ” is the matrix factor obtained from the proposed NMF. As reference, matrix factor  $F$  obtained from traditional NMF is also given by “ $\square$ ”. The heat map of  $G$  of the posterior NMF, shown on the right, indicates that the black points belong to multiple clusters with almost similar degrees of membership (best viewed in color).

The team has developed a novel multimedia information fusion framework, in which two multi-view classification approaches – (Dynamic Weighting and Region-based Semantic Concept Integration) for categorizing the images under the “supervision” of topic-related textual descriptions, are seamlessly integrated by analyzing the special characteristics of different images [2]. Notice that, the proposed framework is a generic multimedia information fusion framework which is not limited to the aforementioned approaches, and it can also be used to integrate other existing multi-view classification methods or models. Also, our proposed framework is capable of handling the large scale image categorization. Specifically, the proposed framework can automatically choose an appropriate classification model for each testing image according to its special characteristics and consequently achieve better classification performance with relatively less computation time for large scale datasets; Moreover, it is able to categorize images without any textual description in real world applications. Empirical experiments on two different types of web image datasets demonstrate the efficacy and efficiency of our proposed classification framework. An overview of our proposed framework is depicted as in Figure 2.

In [3], we have applied our developed multimedia fusion framework in disaster management to semantically associate situation reports with disaster-related multimedia data. We have designed and developed a Multimedia-Aided Disaster information Integration System (MADIS) within an iPad-specific application that conveys all such information via a unified and intuitive graphical interface. The mobility of the iPad device provides the EM personnel with free and fast interaction in communicating between both the command centers and the actual disaster sites. Figure 2 shows the overview of the MADIS system.

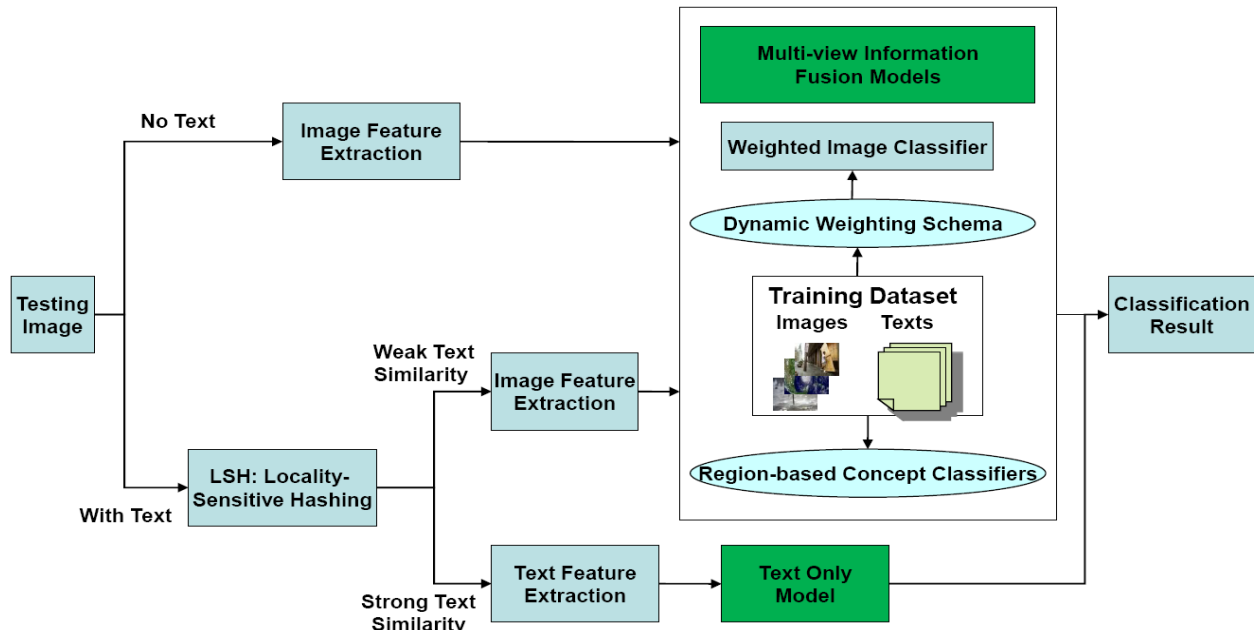


Figure 2. The Multimedia Information Fusion Framework for Web Image Categorization

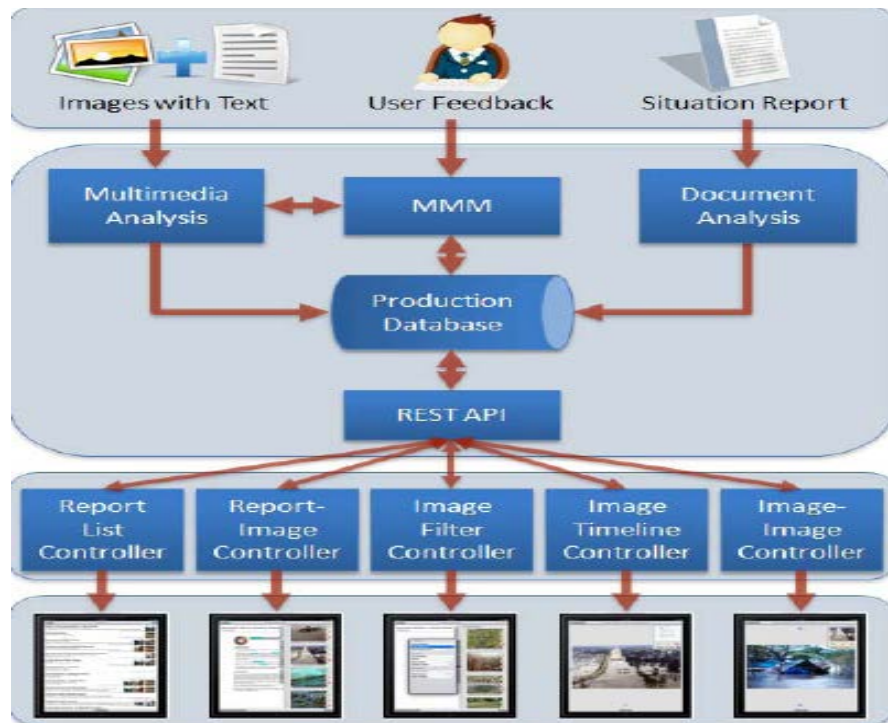
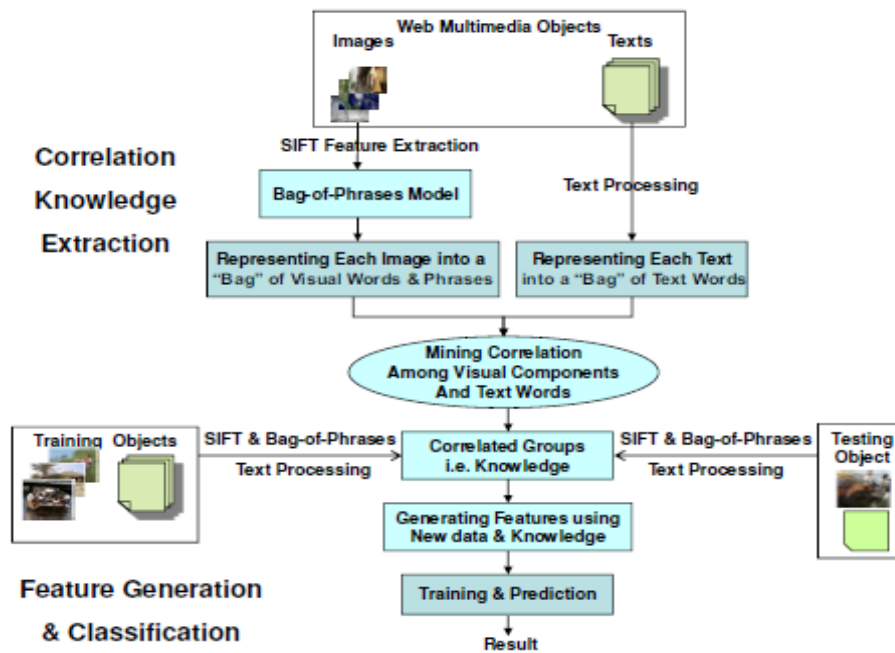


Figure 3. The Overview of the MADIS System

In [5], we propose a novel cross-domain learning method (shown in Figure 4) to classify these web multimedia objects by transferring the correlation knowledge among different information sources. Here, the knowledge is extracted from unlabeled objects through unsupervised learning and applied to perform supervised classification tasks. To mine more meaningful correlation knowledge, instead of using commonly used visual words in the traditional bag-of-visual-words (BoW) model, we discover higher level visual components (words and phrases) to incorporate the spatial and semantic information into our image representation model, i.e., bag-of-visual-phrases (BoP). By combining the enriched visual components with the textual words, we calculate the frequently co-occurring pairs among them to construct a cross-domain correlated graph in which the correlation knowledge is mined. After that, we investigate two different strategies to apply such knowledge to enrich the feature space where the supervised classification is performed. By transferring such knowledge, our cross-domain transfer learning method can not only handle large scale web multimedia objects, but also deal with the situation that the textual descriptions of a small portion of web images are missing. In [6], we introduce a novel framework for generating pictorial storylines for given topics from text and image data on the Internet. Unlike traditional text summarization and timeline generation systems, the proposed framework combines text and image analysis and delivers a storyline containing textual, pictorial, and structural information to provide a sketch of the topic evolution.



**Figure 4. The Framework of the cross-domain transfer**

Ensemble clustering refers to the problem of combining different (input) clusterings of a given dataset to generate a final (consensus) clustering that is a better fit in some sense than existing clusterings. Over the past few years, many ensemble clustering approaches have been developed. However, most of them are designed for partitional clustering methods, and few research efforts

have been reported for ensemble hierarchical clustering methods. In [7], a hierarchical ensemble clustering framework that can naturally combine both partitional clustering and hierarchical clustering results is proposed. In addition, a novel method for learning the ultra-metric distance from the aggregated distance matrices and generating final hierarchical clustering with enhanced cluster separation is developed based on the ultra-metric distance for hierarchical clustering.

We also studied some other related problems for information fusion. In [8], we proposed an extensible framework – META – to enable analysts to easily and selectively extract and summarize events from different views with different resolutions. In [9], we explored ensemble strategies of contextual bandit algorithms to obtain robust predicted click-through rate (CTR) of web objects. The ensemble is acquired by aggregating different pulling policies of bandit algorithms, rather than forcing the agreement of prediction results or learning a unified predictive model.

### **Collaborations and Leveraged Funding**

One student supported by Florida International University Presidential Fellowship and one student supported by China Council Scholarship have involved in the project. Recently, we received a grant from Purdue VACCINE Center/Department of Homeland Security (DHS) to develop a data mining framework for enhancing emergency response situation reports with multi-agency, multi-partner, multimedia data.

### **Technology Transfer**

We have been collaborating with the Emergency Management (EM) personnel at Miami-Dade Emergency Management (MDEM) and they showed strong interest in using the Multimedia-Aided Disaster information Integration System to perform daily operations. We are encouraged to further develop the system into an operational pilot and promote the commercialization of the system for benefitting the whole EM community.

### **Anticipated Scientific Accomplishments**

We will publish our research results in reputable conferences and journals. In addition, we will develop a versatile and user-friendly tool that implements our developed NMF algorithms in different analysis contexts to support the above-mentioned applications. The program components (as source code) will be made available to interested researchers through the project web pages. We will package our developed toolkits in a form that can be quickly deployed to an interested user.

## References:

- [1] Zhongyuan Zhang, Tao Li, Chris Ding and Jie Tang. **A NMF-framework for Unifying Posterior Probabilistic Clustering and Probabilistic Latent Semantic Indexing**. *Communications in Statistics-Theory and Methods*, 43:19, 4011-4024, 2014.
- [2] Wenting Lu, Lei Li, Jingxuan Li, Tao Li, Honggang Zhang, and Jun Guo. **A Multimedia Information Fusion Framework for Web Image Categorization**, *Multimedia Tools and Applications*, 1-34, July 2012.
- [3] Yimin Yang, Wenting Lu, Jesse Domack, Tao Li, Shu-Ching Chen, Steven Luis, Jainendra K Navlakha, **MADIS: A Multimedia-Aided Disaster Information Integration System for Emergency Management**, The 8th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing (IEEE CollaborateCom 2012), October 14-17 October, 2012, Pittsburgh, PA, USA.
- [4] Tao Li and Chris Ding. **Non-negative Matrix Factorizations for Clustering: A Survey**. In C. C. Aggarwal and C. K. Reddy, eds., *Data Clustering: Algorithms and Applications*, Chapman & Hall/CRC Data Mining and Knowledge Discovery Series, 2013.
- [5] Wenting Lu, Jingxuan Li, Tao Li, Honggang Zhang, and Jun Guo. **Web Multimedia Object Classification using Cross-Domain Correlation Knowledge**, *IEEE Transactions on Multimedia*, 15 (8): 1920-1929, 2013.
- [6] Dingding Wang, Tao Li, and Mitsunori Ogihara. **Generating Pictorial Storylines via Minimum-Weight Connected Dominating Set Approximation in Multi-view Graphs**. In *Proceedings of the Twenty-Sixth AAAI Conference on Artificial Intelligence (AAAI 2012)*.
- [7] Li Zheng, Tao Li, Chris Ding. **A Framework for Hierarchical Ensemble Clustering**, *ACM Transactions on Knowledge Discovery from Data (ACM TKDD)*, 9(2): 9, 2014.
- [8] Yexi Jiang, Chang-shing Perng, Tao Li. **META: Multi-resolution Framework for Event Summarization**. *SIAM International Conference on Data Mining (SDM)*, 2014.
- [8] Liang Tang, Yexi Jiang, Lei Li, Tao Li. **Ensemble Contextual Bandits for Personalized Recommendation**. *ACM Conference on Recommender Systems (RecSys)*, 2014