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Information spread in online social media

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The goal of this research was to study viral information spread occurring in social media sites. This phenomenon is referred to as information cascades. This research investigated properties of massive network of users of a social media site VK.com, studied networks of adviser-advisee relationships in mathematics, networks formed by word2vec word embeddings, and networks of causal relationships in the U.S. stock market. In addition this research investigated how deep neural networks can be applied for prediction of cascades in social media sites VK.com and Weibo, developed multitask machine learning methods for native language identification, and applied transfer learning for novel recommender system algorithms. Finally, this grant supported the investigation of how difference of convex functions (DC) programming may be used for solving network optimization problems. This project resulted in five published papers in peer-reviewed journals, five peer-reviewed conference proceedings, and three submitted papers.

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Abstract

The goal of the present research is to study viral information spread occurring in social media sites. This phenomenon is referred to as information cascades. In this research we investigated properties of massive network of users of a social media site VK.com, studied networks of adviser-advisee relationships in mathematics, networks formed by word2vec word embeddings, and networks of causal relationships in the U.S. stock market. We studied how deep neural networks can be applied for prediction of cascades in social media sites VK.com and Weibo, developed multitask machine learning methods for native language identification, and applied transfer learning for novel recommender system algorithms. Further, we investigated how difference of convex functions (DC) programming may be used for solving network optimization problems. This project resulted in five published papers in peer-reviewed journals, five peer-reviewed conference proceedings, and three submitted papers. Also, the grant supported multiple research visits and collaborations.

Introduction

Social media sites play very important role in information dissemination. Nowadays, largest social media sites have more than 2B monthly active users. Users

of social media sites and connections between them may be represented as a graph, where users are the nodes of the graph, and connections between users are the edges of the graph. Social media sites allow to its users to post information on their feeds, and their peers are able to see this information and repost it to their own pages. As a result, messages are spread over social network graph. Understanding how the information propagates is essential for successful applications in viral marketing and cyber security in social media networks.

The ultimate goal of the present research is to study information spread occurring in social media sites. In order to understand characteristics of this spread, it is important to a) conduct descriptive study of the social network graphs, as the medium for spreading the information, and b) investigate the cascades occurring at social media sites.

In order to understand properties of information propagation, it is important to analyze data from real social media sites. One specific aim of this work was to perform investigation of the social network from the site VK.com, which at this moment has around 70M monthly active users, and is the largest social media site at "Post-Soviet" space. Before this work, there were no studies that analyze the entire VK social network from a global perspective.

Another aim is to investigate cascades at VK.com; specifically, to find, whether reposting behavior can be predicted. Next, the goal was to investigate engagement of users at social media sites, and analyze whether network effects play a role in growth of social media sites.

Social media sites allow users to add and remove peers from their friendship circles. Thus, topology of social network graph changes based on users' decisions to add or remove "friends". Also, in reality each user has an array of different interests: two users may be in agreement on the appeal of certain topics, while at the same time disagreeing on others. For instance, if two users support the same football team, but discover they do not like each other's posts about politics, should they stay friends a social media site? If they decide to unfollow each other, they still may keep receiving unwanted information through their other followees. In such cases it is important to find such a network configuration that would result in the best utility for all users combined. This can be formulated as an optimization problem. However, as many other network optimization problems, it has vast solution space, and it is important to develop efficient heuristics for solving network optimization problems.

Social media sites contain a lot of user generated content, and large portion of this content is in the textual form. Because of that, effective methodologies for text data analysis are very important for analyzing information propagation. Another aim of this study was to find, whether native language of the person can be identified by her text written in English, and whether multitask machine learning would be efficient for this problem. Results of this study could potentially contribute to such areas of research as authorship profiling, authorship attribution, and authorship identification; methodologies from these fields can be applied to social media analysis; for example, authorship identification may be employed to understand, whether multiple user accounts participating in information exchange are controlled by one person. Later, these user accounts

may be combined into one entity using data integration methods.

Experiments and Theory

There are many social media sites, the largest of which have billions of monthly active users. For example, Facebook had around 2.3B monthly active users, and Twitter had 330M monthly active users. The largest social media site at Post-Soviet space is called VK.com, in 2019 it had around 70M monthly active users. VK.com provides convenient API interface for extraction of their data, we used data collected from VK.com for analyzing graphs and information propagation principles. In the project we modelled social networks as graphs, and studied properties of these graphs, and properties of cascades spreading over these graphs. Also, we studied how machine learning methods may be used for analysis of information spread.

Social Network Analysis

Social network of users of a social media site may be modeled as a graph $G = (V, E)$ with a set of n vertices nodes $V = \{1, ..., n\}$ and a set of m edges $E \subset V \times V$, $|V| = n$ and $|E| = m$.

If $(i, j) \in E$, then vertices i, and j are called adjacent. If every of two vertices are adjacent, the graph is called complete. Neighborhood $\mathcal{N}(v)$ of a vertex v is a set of all nodes v' adjacent to v, i.e. $v' \in \mathcal{N}(v)$ for all $(v, v') \in E$. Then, the *degree* of v, $deg(V) = |\mathcal{N}(v)|$. Path $\mathcal{P}_{ij}$ between vertices i and j is a set of vertices $\{v_0, ..., v_d\} \subseteq V$ such that $v_0 = i$, $v_d = j$, and $(v_k, v_{k+1}) \in E$, $\forall k = 0, ..., d-1$. Such path is called a path of length $d-1$. Two vertices i and j are connected, if there is a path between them. Graph G is connected, if all of its vertices are pairwise connected, and disconnected otherwise. Shortest path between vertices i and j is the path containing of least number of edges among all paths between i and j. The length of the shortest path between i and j in G is referred to as the distance between i and j in G and is denoted by $d(i, j)$. The largest distance between any two vertices in G is referred to as the graph diameter.

Betweenness centrality $C_B(v)$ of v is the fraction of shortest paths connecting any two other vertices i and j that pass through v, $C_B(v) = \sum_{i,j \in V} \frac{\sigma_{ij}(v)}{\sigma_{ij}}$, where σ_{ij} is total number of shortest paths, and $\sigma_{ij}(v)$ is the number of shortest paths that pass through vertex v.

Machine Learning Approaches for Social Media Analysis

Consider a dataset $\mathcal{D}_t = \{(x_i, y_i)\}_{i=1}^n$, where $x_i \in \mathcal{X}$ is the ith observed variable, and $y_i \in \mathcal{Y}$ is the corresponding ith label. In machine learning tasks, performed in this project, the goal was to to learn a function $\hat{y}_j = f(x_j, \theta)$, where $\hat{y}_j$ is predicted class, and θ is a vector of parameters. In order to find vector of optimal parameters θ, we need to minimize loss function $\mathcal{L}(y, \hat{y})$ between actual

and predicted classes. In our research for prediction of cascades, we designed a neural network to solve binary classification problem; observed variables x_i were represented by features of social media users who participated in social media spread. In our research on native language identification, $\mathcal{X}$ contained essays written by non-native English speakers, and $\mathcal{Y}$ contained their native languages. We propose multiple architectures to find optimal θ.

Results and Discussion

In this section I will describe the summaries of the contribution of research articles, that were published during this project and acknowledged with grant number, and discuss what future research may be performed as follow on projects.

Summary of the Results, Social Network Analysis

This section contains summaries of the articles that investigate descriptive properties of the networks formed by users of social media sites. During this project we also studied networks formed by word embeddings, and network of causal relationships in the U.S. Stock Market.

Network-based indices of individual and collective advising impacts in mathematics (1.1) We define and interpret a family of metrics (collectively referred to as "a-indices") that can potentially be applied to "ranking academic advisors" using the academic genealogical records of scientists, with the emphasis on taking into account not only the number of students advised by an individual, but also subsequent academic advising records of those students. We also define and calculate the extensions of the proposed indices that account for student co-advising (referred to as "adjusted a-indices"). In addition, we extend some of the proposed metrics to ranking universities and countries with respect to their "collective" advising impacts, as well as track the evolution of these metrics over the past several decades. To illustrate the proposed metrics, we consider the social network of over 200,000 mathematicians (as of July 2018) constructed using the Mathematics Genealogy Project data. This journal paper is an extension of the conference paper **2.3**

Exploration and Clustering Analysis of Semantic Spaces (1.2) The goal of this study is to demonstrate how network science and graph theory tools and concepts can be effectively used for exploring and comparing semantic spaces of word embeddings and lexical databases. Specifically, we construct semantic networks based on word2vec representation of words, which is "learnt" from large text corpora (Google news, Amazon reviews), and "human built" word networks derived from the well-known lexical databases: WordNet and Moby Thesaurus. We compare "global" (e.g., degrees, distances, clustering coefficients) and "local" (e.g., most central nodes and community-type dense clusters) characteristics of considered networks. Our observations suggest that human built networks possess more intuitive global connectivity patterns, whereas local characteristics

(in particular, dense clusters) of the machine built networks provide much richer information on the contextual usage and perceived meanings of words, which reveals interesting structural differences between human built and machine built semantic networks.

Exploring social media network landscape of post-Soviet space (1.3) The "post-Soviet space" consists of countries with a substantial fraction of the world's population; however, unlike many other regions, its social media network landscape is still somewhat underexplored. This study aims at filling this gap. To this purpose, we use anonymized data on user friendships at VK.com, which is the largest and most popular social media portal in the post-Soviet space with hundreds of millions of user accounts. Using the VK network snapshots from October 2015 and December 2016, we conduct a "multiscale" empirical study of this network by considering connections between individual users, cities, and countries. Our findings indicate that VK users form a small-world network with basic characteristics consistent with Facebook and other social media networks. In addition, the analysis of modularity-based communities within the user scale network reveals a pattern of geographical separation of the identified communities mostly along the borders between countries.

Establishing Engagement as a Driver of Growth of Online Health Communities (1.5) The emerging research on nurturing the growth of online communities posits that it is in part attributed to network effects, wherein every increase in the volume of user-generated content increases the value of the community in the eyes of its potential new members. This study supports the claim that network effects play an important role in accelerating OHF growth, opening the door to exploiting these effects in calculated ways. In such efforts, engagement metrics can be used to monitor the "health" of an OHF and to identify the users most important to its success.

The Network of Causal Relationships in the U.S. Stock Market (2.4) We propose a network-based framework to study causal relationships in financial markets and demonstrate the proposed approach by applying it to the entire U.S. stock market. Directed networks (referred to as causal market graphs) are constructed based on stock return time series data during 2001-2019 using Granger causality as a measure of pairwise causal relationships between all stocks. We consider the dynamics of structural properties of the constructed network snapshots, group stocks into network-based clusters, as well as identify the most "influential" stocks via a PageRank algorithm. The proposed approaches offer a new angle for analyzing global characteristics and trends of the stock market using network-based techniques.

Summary of the results, Optimization and Machine Learning

This section contains summaries of the articles that investigate machine learning and optimization algorithms, that are relevant for social media analysis tasks.
A DC programming approach for solving multicast network design problems via the Nesterov smoothing technique (1.4) This paper describes application of continuous optimization techniques to study optimal multicast communication networks modeled as bilevel hierarchical clustering problems. Given a finite number of nodes, we consider two different models of multicast networks by identifying a certain number of nodes as cluster centers, and at the same time, locating a particular node that serves as a total center so as to minimize the total transportation cost throughout the network. The fact that the cluster centers and the total center have to be among the given nodes makes these problems discrete optimization problems. Our approach is to reformulate the discrete problems as continuous ones and to apply Nesterov's smoothing approximation techniques on the Minkowski gauges that are used as distance measures. This approach enables us to propose two implementable DCA-based algorithms for solving the problems.

Neural Networks with Multidimensional Cross-Entropy Loss Functions (2.1) Deep neural networks have emerged as an effective machine learning tool successfully applied for many tasks, such as misinformation detection, natural language processing, image recognition, machine translation, etc. Neural networks are often applied to binary or multi-class classification problems. In these settings, cross-entropy is used as a loss function for neural network training. In this short note, we propose an extension of the concept of cross-entropy, referred to as multidimensional cross-entropy, and its application as a loss function for classification using neural networks.

Sampled Fictitious Play on Networks (2.2) We formulate and solve the problem of optimizing the structure of an information propagation network between multiple agents. In a given space of *interests* (e.g., information on certain targets), each agent is defined by a vector of their desirable information, and a vector of available information. The agents seek to build a directed network that maximizes the value of the desirable source-information that reaches each agent having been filtered *en route*, less the expense that each agent incurs in filtering any information of no interest to them. We frame this optimization problem as a game of common interest, where the Nash equilibria can be attained as limit points of Sampled Fictitious Play (SFP), offering a method that turns out computationally effective in traversing the huge space of feasible networks on a given node set.

Recommending Serendipitous Items using Transfer Learning (2.5) Most recommender algorithms are designed to suggest relevant items, but suggesting these items does not always result in user satisfaction. Therefore, the

efforts in recommender systems recently shifted towards serendipity, but generating serendipitous recommendations is difficult due to the lack of training data. We introduce transfer learning method to recommend serendipitou sitems. It uses transfer learning to firstly train a deep neural network for relevance scores using a large dataset and then tunes it for serendipity scores using a smaller dataset.

Multidimensional Assignment Problem for multipartite entity resolution (3.1) Multipartite entity resolution aims at integrating records from multiple datasets into one entity. We derive a mathematical formulation for a general class of record linkage problems in multipartite entity resolution across many datasets as a combinatorial optimization problem known as the multidimensional assignment problem. As a motivation for our approach, we illustrate the advantage of multipartite entity resolution over sequential bipartite matching. Because the optimization problem is NP-hard, we apply two heuristic procedures, a Greedy algorithm and very large scale neighborhood search, to solve the assignment problem and find the most likely matching of records from multiple datasets into a single entity. We evaluate and compare the performance of these algorithms and their modifications on synthetically generated data.

Multitask learning for native language identification (3.2) Identification of a native language of the person by her text written in English (L1 identification) plays an important role in such tasks as authorship profiling and identification. With the current proliferation of misinformation in the social media, these methods are especially topical. Most studies in this field have focused on development of supervised classification algorithms, that are trained on a single L1 dataset. Although, multiple labeled datasets are available for L1 identification, they contain texts authored by speakers of different languages, and do not fully overlap. Current approaches achieve high accuracy on available datasets, but it is attained by training individual classifier for each dataset. Studies show that joint training of multiple classifiers on different datasets can result in sharing information between the classifiers, leading to increase in accuracy of both tasks. In this study we develop a novel deep neural network (DNN) architecture for L1 classification; it is based on adversarial multitask learning method, that integrates shared knowledge from multiple L1 datasets. We propose several variants of the architectures, and perform rigorous evaluations of their performance on multiple datasets. Our results indicate that proposed multitask architecture is more efficient in terms of classification accuracy, than previously proposed methods.

Information Diffusion Prediction via Deep Learning Considering Neighborhood Influence in Social Media Networks (3.3) Predicting information diffusion within social media networks plays an important role in human activities analysis and influence maximization decision making. Traditional methods for information diffusion prediction can be categorized into stochastic diffusion models based and user profile or content features based machine

learning models. In this paper, we propose a new framework combining user profile, content similarity and the neighborhood information around each target link as input features to make the prediction. Here neighborhood information can be interpreted as the propagation of neighbors' user profile. Two different kinds of graph based propagation models are introduced in the article. After collecting the input features, we implement deep neural network to predict the information diffusion probability. We evaluate our model on two real datasets: Weibo and VK to compare the performance with state-of-the-art methods.

Discussion and Future Research

Networks appear in many different problem domains, and analysis of social networks may produce valuable insights into health care, or public policy. During this project it was identified, that social media site VK.com has similar properties to other large social media sites such as Facebook, and thus, results of information diffusion analysis that may be obtained using VK.com data may be generalized to other social media sites. PI is interested in studying diffusion of information further. One potential direction is to continue studies of embeddings of users of social media sites based on the information that they post and repost (initial results were presented at the conference presentation 4.12). Further, it would be important to formulate and solve engaging team formation problem, based on the results of the paper 1.5. Initial results of this study were presented at the conference 4.2. It is important to note, that processes similar to cascading information transfer in the social media may occur also in networks of economic agents (input-output networks), but these networks may transfer cascading economic shocks, and it is important to prevent them. Initial results on this topic were presented at the conference talk 4.1. Further, studies of multitask and transfer learning for natural language processing, and their applications to social media data for identification of misinformation may lead to fruitful research results. PI is interested in continuation of these studies.

List of Publications and Significant Collaborations

1. Peer-reviewed journals:

    1.1. A. Semenov, A. Veremyev, A. Nikolaev, E.L. Pasiliao, V. Boginski. Network-based indices of individual and collective advising impacts in mathematics. Computational Social Networks, 2020, 7: 1. DOI: 10.1186/s40649-019-0075-0

    1.2. A. Veremyev, A. Semenov, E.L. Pasiliao, V. Boginski. Graph-Based Exploration and Clustering Analysis of Semantic Spaces. Applied Network Science, special issue on machine learning with graphs, 2019, DOI: 10.1007/s41109-019-0228-y

    1.3. A. Semenov, A.V. Mantzaris, A. Nikolaev, A. Veremyev, J. Veijalainen, E.L. Pasiliao, V. Boginski. Exploring social media network

landscape of post-Soviet space. IEEE Access, 7: p. 411–426, 2019. DOI: 10.1109/ACCESS.2018.2885479

1.4. W. Geremew, N.M. Nam, A. Semenov, V. Boginski, E.L. Pasiliao. A DC programming approach for solving multicast network design problems via the Nesterov smoothing technique. Journal of Global Optimization, 2018. DOI: 10.1007/s10898-018-0671-9

1.5. R. Gopalsamy, A. Semenov, E.L. Pasiliao, S. McIntosh, A. Nikolaev. Establishing Engagement as a Driver of Growth of Online Health Communities. Journal of Medical Internet Research. 19(8):e304, 2017, DOI: 10.2196/jmir.724

2. Peer-reviewed conference proceedings:

2.1. A. Semenov, V. Boginski , E. L. Pasiliao, "Neural Networks with Multidimensional Cross-Entropy Loss Functions", CSoNet 2019, International Conference on Computational Social Networks, pp. 57-62, 2019

2.2. A. Nikolaev, A. Semenov, E. L. Pasiliao, "Sampled Fictitious Play on Networks", CSoNet 2019, International Conference on Computational Social Networks, pp. 33-44, 2019

2.3. A. Semenov, A. Veremyev, A. Nikolaev, E. L. Pasiliao, V. Boginski, "Ranking Academic Advisors: Analyzing scientific advising impact using MathGenealogy social network", CSoNet 2018, International Conference on Computational Social Networks, pp. 437-449, 2018

2.4. O. Shirokikh, G. Pastukhov, A. Semenov, S. Butenko, A. Veremyev, E. L. Pasiliao, V. Boginski, "The Network of Causal Relationships in the U.S. Stock Market", CSoNet 2018 (short), LNCS 11280, pp. 541 - 542, 2018

2.5. G. Pandey, D. Kotkov, A. Semenov, "Recommending Serendipitous Items using Transfer Learning". In Proceedings of the 27th ACM International Conference on Information and Knowledge Management (CIKM '18). ACM, New York, NY, USA, pp. 1771-1774, 2018

3. Manuscripts submitted but not yet published:

3.1. A. Kammerdiner, A. Semenov, E.L. Pasiliao, Multidimensional Assignment Problem for multipartite entity resolution. Submitted to Journal of Global Optimization, 2020.

3.2. V. Habic, A. Semenov, E.L. Pasiliao. Multitask learning for native language identification. Major revision, journal of Knowledge-Based Systems, 2020

3.3. Z. Qiang, Q. Zheng, A. Semenov, E.L. Pasiliao. Information Diffusion Prediction via Deep Learning Considering Neighborhood Influence in Social Media Networks, Journal of Association of Information Science and Technology (rejected after 2nd review, will be resubmitted).

4. Conference presentations without papers:

   4.1. Identifying important nodes in input-output networks, 13th Conference on Computational and Financial Econometrics, session "Robustness to shocks and dependence in networks and financial data", London, UK, December 14 - 16, 2019

   4.2. Engaging Team Formation Problem for Reach Maximization of Online Health Communities, INFORMS 2019 conference, Seattle, USA, October 24, 2019

   4.3. Application of Transfer and Multitask Learning to Native Language Identification, 7th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida Research Engineering Education Facility (REEF), Shalimar, FL, July 31 - August 1, 2019

   4.4. Neural Networks with Multidimensional Cross Entropy Loss Function, 7th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida Research Engineering Education Facility (REEF), Shalimar, FL, July 31 - August 1, 2019

   4.5. Analysis of transactions of energy-related ERC20 tokens, talk at Blockchain Energy SysTems (BEST2019) Conference, Orlando, Florida, USA, January 18 - 19, 2019

   4.6. Blockchain based decentralized microgrid energy distribution system (with H. Heinonen), Blockchain Energy SysTems (BEST2019) Conference, Orlando, Florida, USA, January 18 - 19, 2019

   4.7. Analysis of dynamics of blockchain peer-to-peer network topologies. Invited speaker, IEEE Day 2018, Jyvaskyla, Finland, October 2, 2018

   4.8. Q-Learning on Networks with Attribute-Rich Nodes, 6th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida Research & Engineering Education Facility (REEF), Shalimar, FL, July 31 - August 2, 2018

   4.9. Sampled Fictitious Play on Networks (co-author), 6th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida Research & Engineering Education Facility (REEF), Shalimar, FL, July 31 - August 2, 2018

   4.10. Information Diffusion Prediction Based on Graph Neural Networks (co-author), 6th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida Research Engineering Education Facility (REEF), Shalimar, FL, July 31 - August 2, 2018

   4.11. Analysis of Dynamics of Blockchain Peer-to-Peer Network Topologies, 5th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida, Research Engineering Education Facility (REEF), Shalimar, FL, August 1 - 3, 2017

4.12. Cascade Prediction in Social Networks via Euclidean Embedding (co-author), 5th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida, Research Engineering Education Facility (REEF), Shalimar, FL, August 1 - 3, 2017

4.13. Network Analysis of Social Media Portal VK.com (co-author), 5th Annual Meeting of the AFRL Mathematical Modeling and Optimization Institute, University of Florida, Research Engineering Education Facility (REEF), Shalimar, FL, August 1 - 3, 2017

5. provide a list of significant collaborations that resulted from this work:

- This grant helped me to establish research collaboration with number of researchers from the US universities. Many of these researchers work in other AFOSR grants. Funded in part with this grant, four US professors were visiting the University of Jyvaskyla. Please see the details below.
  - I have established collaboration with the researchers who are funded by other AFOSR grants and are based at the University of Central Florida. They work closely with AFRL researchers from Eglin AFB, FL, USA. Three researchers were visiting University of Jyvaskyla:
  - Assoc. Prof. Vladimir Boginski (University of Central Florida), and Research. Assistant Prof. Alexander Veremyev (University of Central Florida) were visiting JYU in August 2017; we were working on the papers, and they were giving a course "IS2: Optimization Approaches to Analyzing Robustness of Complex Networks" at 2017 Summer school.
  - Research Assistant Prof. Alexander Veremyev (University of Central Florida) was also a guest visitor at the University of Jyvaskyla in August 2018, and 2019.
  - Associate Professor Qipeng Phil Zheng (University of Central Florida) was visiting the University of Jyvaskyla in September 2019.
  - I established collaboration with Prof. My Thai from the University of Florida; she was visiting the University of Jyvaskyla in August 2019, also she was giving a course "KYBS5593 Network and Information Security" at 2019 summer school.
  - I established collaboration with the researchers based at the Research and Engineering Educational Facility (REEF), at the University of Florida. The grant allowed me to visit it in summer 2017, 2019, and 2019.