proposed such as Jaccard coefficient, Pearson correlation coefficient [1], and random walks [20, 30, 34]. However, none of these similarity measures consider the multiple relations exist in the data. Recent advances in heterogeneous information networks [6, 32] have offered several similarity measures for heterogeneous relations, such as meta-path and relation path [24, 26]. However, these methods cannot deal with domain variety problems.

6 CONCLUSION

In this paper, we introduce an important and challenging problem of transfer learning on invariant networks. We propose **TINET**, a transfer learning framework for accelerating invariant network learning. By leveraging entity embedding and constrained optimization techniques, **TINET** can effectively extract useful knowledge (*e.g.*, entity and dependency relations) from the source domain, and transfer it to the target network. We evaluate the proposed algorithm using extensive experiments on both synthetic and real-world datasets. The experiment results convince us of the effectiveness and efficiency of our approach. We also apply **TINET** to a real enterprise security system for intrusion detection. Our method can achieve superior detection performance at least 20 days lead-lag time in advance with more than 75% accuracy.

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REFERENCES

[1] John Adrian Bondy and Uppaluri Siva Ramachandra Murty. 1976. *Graph theory with applications*. Vol. 290. New York: Elsevier.
[2] Bin Cao, Nathan N Liu, and Qiang Yang. 2010. Transfer learning for collective link prediction in multiple heterogenous domains. In *Proceedings of the 27th International Conference on Machine Learning*. 159–166.
[3] Rita Chattopadhyay, Wei Fan, Ian Davidson, Sethuraman Panchanathan, and Jieping Ye. 2013. Joint transfer and batch-mode active learning. In *International Conference on Machine Learning*. 253–261.
[4] Tianqi Chen, Ian Goodfellow, and Jonathon Shlens. 2016. Net2net: Accelerating learning via knowledge transfer. In *Proceedings of the 4th International Conference on Learning Representations*.
[5] Ting Chen and Yizhou Sun. 2017. Task-Guided and Path-Augmented Heterogeneous Network Embedding for Author Identification. In *Proceedings of the Tenth ACM International Conference on Web Search and Data Mining*. ACM, 295–304.
[6] Ting Chen, Lu An Tang, Yizhou Sun, Zhengzhang Chen, Haifeng Chen, and Guofei Jiang. 2016. Integrating community and role detection in information networks. In *Proceedings of the 2016 SIAM International Conference on Data Mining*. SIAM, 72–80.
[7] Wei Cheng, Kai Zhang, Haifeng Chen, Guofei Jiang, Zhengzhang Chen, and Wei Wang. 2016. Ranking causal anomalies via temporal and dynamical analysis on vanishing correlations. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. ACM, 805–814.
[8] Wenyuan Dai, Qiang Yang, Gui-Rong Xue, and Yong Yu. 2007. Boosting for transfer learning. In *Proceedings of the 24th International Conference on Machine Learning*. ACM, 193–200.
[9] Boxiang Dong, Zhengzhang Chen, Hui (Wendy) Wang, Lu-An Tang, Kai Zhang, Ying Lin, Zhichun Li, and Haifeng Chen. 2017. Efficient discovery of abnormal event sequences in enterprise security systems. In *Proceedings of the 2017 ACM on Conference on Information and Knowledge Management (CIKM'17)*. 707–715.
[10] Meng Fang, Jie Yin, and Xingquan Zhu. 2013. Transfer learning across networks for collective classification. In *2013 IEEE 13th International Conference on Data Mining*. IEEE, 161–170.
[11] Meng Fang, Jie Yin, Xingquan Zhu, and Chengqi Zhang. 2015. TrGraph: Cross-network transfer learning via common signature subgraphs. *IEEE Transactions on Knowledge and Data Engineering* 27, 9 (2015), 2536–2549.
[12] Jiawei Han, Jian Pei, and Micheline Kamber. 2011. *Data mining: concepts and techniques*. Elsevier.
[13] Jingrui He, Yan Liu, and Richard Lawrence. 2009. Graph-based transfer learning. In *Proceedings of the 18th ACM Conference on Information and Knowledge Management*. ACM, 937–946.
[14] Miao He and Junshan Zhang. 2011. A dependency graph approach for fault detection and localization towards secure smart grid. *IEEE Transactions on Smart Grid* 2, 2 (2011), 342–351.
[15] Jake M Hofman, Amit Sharma, and Duncan J Watts. 2017. Prediction and explanation in social systems. *Science* 355, 6324 (2017), 486–488.
[16] Guofei Jiang, Haifeng Chen, and Kenji Yoshihira. 2006. Discovering likely invariants of distributed transaction systems for autonomic system management. In *IEEE International Conference on Autonomic Computing*. IEEE, 199–208.
[17] Guofei Jiang, Haifeng Chen, and Kenji Yoshihira. 2006. Modeling and tracking of transaction flow dynamics for fault detection in complex systems. *IEEE Transactions on Dependable and Secure Computing* 3, 4 (2006), 312–326.
[18] Guofei Jiang, Haifeng Chen, and Kenji Yoshihira. 2007. Efficient and scalable algorithms for inferring likely invariants in distributed systems. *IEEE Transactions on Knowledge and Data Engineering* 19, 11 (2007).
[19] Anita K Jones and Robert S Sielken. 2000. Computer system intrusion detection: A survey. *Computer Science Technical Report* (2000), 1–25.
[20] U Kang, Hanghang Tong, and Jimeng Sun. 2012. Fast random walk graph kernel. In *Proceedings of the 2012 SIAM International Conference on Data Mining*. SIAM, 828–838.
[21] Samuel T King, Z Morley Mao, Dominic G Lucchetti, and Peter M Chen. 2005. Enriching intrusion alerts through multi-host causality. In *Proceedings of the 2005 Network and Distributed System Security Symposium (NDSS)*.
[22] Ronald L Krutz and Russell Dean Vines. 2010. *Cloud security: A comprehensive guide to secure cloud computing*. Wiley Publishing.
[23] David Liben-Nowell and Jon Kleinberg. 2007. The link-prediction problem for social networks. *Journal of the Association for Information Science and Technology* 58, 7 (2007), 1019–1031.
[24] Chen Luo, Renchu Guan, Zhe Wang, and Chenghua Lin. 2014. HetPathMine: A novel transductive classification algorithm on heterogeneous information networks. In *Proceedings of the 36th European Conference on Information Retrieval*. Springer, 210–221.
[25] Chen Luo, Jian-Guang Lou, Qingwei Lin, Qiang Fu, Rui Ding, Dongmei Zhang, and Zhe Wang. 2014. Correlating events with time series for incident diagnosis. In *Proceedings of the 20th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. ACM, 1583–1592.
[26] Chen Luo, Wei Pang, Zhe Wang, and Chenghua Lin. 2014. Hete-cf: Social-based collaborative filtering recommendation using heterogeneous relations. In *2014 IEEE International Conference on Data Mining*. IEEE, 917–922.
[27] Jingchao Ni, Wei Cheng, Kai Zhang, Dongjin Song, Tan Yan, Haifeng Chen, and Xiang Zhang. 2017. Ranking causal anomalies by modeling local propagations on networked systems. In *2017 IEEE International Conference on Data Mining (ICDM)*. IEEE, 1003–1008.
[28] Sinno Jialin Pan and Qiang Yang. 2010. A survey on transfer learning. *IEEE Transactions on Knowledge and Data Engineering* 22, 10 (2010), 1345–1359.
[29] Ajit P Singh and Geoffrey J Gordon. 2008. Relational learning via collective matrix factorization. In *Proceedings of the 14th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. ACM, 650–658.
[30] Jimeng Sun, Huiming Qu, Deepayan Chakrabarti, and Christos Faloutsos. 2005. Relevance search and anomaly detection in bipartite graphs. *ACM SIGKDD Explorations Newsletter* 7, 2 (2005), 48–55.
[31] Qian Sun, Mohammad Amin, Baoshi Yan, Craig Martell, Vita Markman, Anmol Bhasin, and Jieping Ye. 2015. Transfer learning for bilingual content classification. In *Proceedings of the 21st ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*. ACM, 2147–2156.
[32] Yizhou Sun and Jiawei Han. 2012. Mining heterogeneous information networks: principles and methodologies. *Synthesis Lectures on Data Mining and Knowledge Discovery* 3, 2 (2012), 1–159.
[33] Douglas Brent West. 2001. *Introduction to graph theory*. Vol. 2. Prentice hall Upper Saddle River.
[34] Yusheng Xie, Zhengzhang Chen, Lu Liu, Ankit Agrawal, and Alok Choudhary. 2013. Random walk-based graphical sampling in unbalanced heterogeneous bipartite social graphs. In *Proceedings of the 22nd ACM International Conference on Information and Knowledge Management*. 1473–1476.
[35] Zhang Xu, Zhenyu Wu, Zhichun Li, Kangkook Jee, Junghwan Rhee, Xusheng Xiao, Fengyuan Xu, Haining Wang, and Guofei Jiang. 2016. High fidelity data reduction for big data security dependency analyses. In *Proceedings of ACM SIGSAC Conference on Computer and Communications Security*. ACM, 504–516.
[36] Jihang Ye, Hong Cheng, Zhe Zhu, and Minghua Chen. 2013. Predicting positive and negative links in signed social networks by transfer learning. In *Proceedings of the 22nd International Conference on World Wide Web*. ACM, 1477–1488.
[37] Kai Zhang, Qiaojun Wang, Zhengzhang Chen, Ivan Marsic, Vipin Kumar, Guofei Jiang, and Jie Zhang. 2015. From categorical to numerical: Multiple transitive distance learning and embedding. In *Proceedings of the 2015 SIAM International Conference on Data Mining*. SIAM, 46–54.