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STAR – State of The Art Report

Handling Complexity through Multilayer Network Visualization: STAR Sketch

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1. Topic Introduction

Usually networks (often referred to as graphs) are visualized and analyzed, as if the dataset is complete and independent. However, frequently real-world complex systems can be more accurately modeled as a set of interacting networks, or layers. This model can be applied to a wide range of real-world datasets. The concept of a multilayer network has recently emerged from the field of complex networks [GBSH12, KAB*14]. It builds on and encompasses many existing network definitions across many fields, some of which are much older, e.g. from the domain of sociology [Ver79, BS85].

Examples of multilayer network can be found in the domains of biology (the so-called "omics" layers), sociology (in a broad sense, including fields such as criminology, for instance) [BS85, LP99, FPSG10, GKL*13, CMF*14, BGRM15, DMR16], digital humanities [MDG16, DHRL*12, SGo16], civil infrastructure [CGGZ*13, Duc17] and more. Within the domain of network visualization there are many systems which visualize datasets having many characteristics of multilayer networks, albeit under a different title. Multi-label, multi-edge, multi-relational, multiplex [RMM15, CGGZ*13], heterogeneous [DHRL*12, SKB*14], and multimodal [GKL*13, HS09], multiple edge set networks [CMF*14], interdependent networks [GBSH12] are amongst the many names given to various types of data that are encapsulated by the Multilayer Networks definition of Kivelä et al. [KAB*14].

As an introductory illustrative example, consider a person's social networks. People frequently use more than one social network platform, e.g., Facebook for their personal social network or LinkedIn for their professional. Both of these networks can be considered independent, however they can also be considered as layers in a multilayer graph. The networks overlap as some people may be present in both layers. The relationship type (either personal or professional) characterizes the layers. A significant change in one network may also correlate with or cause changes in another. For example, a change of employer may cause immediate change in the professional network and a slower, more gradual, change in the personal social network.

2. Relevance for the Vis community

Complex Networks is a subdomain of the field of complex systems. The concept of a multilayer network has emerged from this rapidly growing research domain, and as such, is a fertile ground for novel visualization research. The number of papers focusing on "Complex Networks" (per Google scholar) shows a quite consistent rise from 1350 articles in 2000 up to 19,200 in 2016 . In recent years, the specific topic of multilayer networks has received prominence in top-level journals [GBSH12, RHB*14, Bia14]. It is clear that this field is growing, and will be able to provide interesting visualization challenges for many years to come.

Across all of the application domains described in Section 1, advances in sensors, scientific equipment, and technology mean that researchers have access to more data than ever. This wealth of complex data is often best understood as a multilayer network model. For instance, biologists have access to more proteomic, genomic and metabolomic data, allowing for the construction of complex multilayer models of real-world biological processes. The use of multiple online social networks allows for complex social multilayer networks to be built, that may help sociologists gain deeper insight [RMV14]. Digital access to source texts and processing techniques such as Named-Entity Recognition and Topic Modeling allow for vast Digital Humanities datasets to be built [MDG16]. Modern vehicles often provide a wealth of information about modern transportation networks. These networks can also be modeled as multilayer networks. For example, [HMB14] models the air and rail transportation networks of India as layers in a multilayer network. Another example can be seen in [GB15]. The Internet and associated infrastructure provide vast amounts of data about themselves and can be modeled as multilayer networks, as done by e.g., Reis et al. [RHB*14], who represent the power grid and the Internet as separate layers in a multilayer infrastructure network. The deluge of complex data produced across all these examples demands a visual approach to help understand it and in future that approach will often be multilayer network visualization.

An important finding for the community is how much the notion of *layers* incidentally appear as a crucial concept transversing the different levels in Munzner's nested model [Mun09]. Indeed, as the survey on application domains will reveal, experts most of the time frame questions using this exact term which obviously map to a clear concept – although often domain specific. Following Munzner, collecting and organizing data and at the same time forming relevant operations on data leads to precisely build a multilayer network. The challenge when designing a visualization system to support user tasks then is to come up with a set of relevant and sound graphical representations and interaction techniques – that our STAR will survey as well, while indicating possible directions for future research.

3. Proposed Structure with Key References

Our STAR report will explore the visualization literature to survey visualization techniques, tools and tasks suitable for multilayer network visualization. However, a key feature is that we will not be just examining literature for the visualization domain, we will also be exploring tools, tasks, and analytic techniques from within the application domains' literature.

3.1. Multilayer Network Definition and Scope

In this section we will contextualize the definition of multilayer networks introduced by Kivelä for the visualization audience [KAB*14]. As part of this we will be clarifying the nomenclature and all network types that are encompassed by Kivelä *et al.*'s work and contextualizing it in the domain of visualization as well as examining the prevalence of multilayer graphs across the multiple domains described in section 1.

We will also compare and contrast other related network types and classifications to the multilayer model. This will include examining the relationship between multifaceted visualization [HSS15] and multilayer networks, particularly between facets and the aspects that characterize layers, as well as the relationship with multivariate networks [SKB*14]. Multilayer networks may have a temporal nature [BBC*14], therefore, we will examine their relationship with dynamic network visualization.

As part of this we will build on work of previous STAR reports such as [HSS15, KPW14, BBDW14]. We will explicitly highlight the differences from the definitions described in these previous reports, and discuss the idiosyncrasies of multilayer networks that require a new STAR. For example, [HSS15] discusses primarily four common facets of network structure considered in network visualization, and their composition. While multilayer networks may use notions similar to these facets to characterize layers, amongst others, multilayer network visualization also focuses on the interactions between layers, and the role of layers in the network as a whole.

3.2. Multilayer Network Visualization Survey

A key feature of our STAR is the inclusion of literature from the application and related domains outside of information visualization. For the domain of visualization we have compiled a list search terms (using the synonyms and variants of multilayer graphs), and searched the most prominent journals e.g. (IEEE TVCG, CGF) and conferences (IEEE Infovis, Pacific Vis, Eurovis, Graph Drawing and Network Visualization) in the field, resulting in 49 papers. Unfortunately, for the application domain journals this level of rigor is too inefficient, due to the range and size of the domains. Therefore, we search for articles based on the references to those in our existing set of visualization papers as well as the complex system papers concerning multilayer networks, e.g. [GBSH12, KAB*14, DDSRC*13]. This approach has already provided many relevant examples of applications across domains and insight into the approaches used for visualizing multilayer networks in other domains, e.g. [Duc17, ZB16, RHB*14, HMB14].

To support our survey, we have developed a categorization of the most important aspects of multilayer network visualization that are to be considered for each paper. We list them here in a manner consistent with Munzner's nested process model [Mun09]. **Tasks and Analysis:** Multilayer systems that address new problems and domains may expose tasks that do not fit in existing task taxonomies, such as [LPP*06, PPS14]. New analytics have been developed for multilayer networks, and new visualizations have been developed as a result, e.g. [DDPA15]. **Data Definition:** This aspect of the review looks at the nomenclature used for the dataset e.g., multiplex, heterogeneous, which aspects are used to define layers across the data, as well as the structure of the data. **Visualization Approach:** We will analyze and categorize the various visualization approaches described, identifying novel approaches and novel application of existing approaches e.g. [BISP16]. **Interaction Approach:** Interaction with multiple layers will often be more complex and requires innovative techniques, such as [RMM15, SLT*14]. **Attribute visualization:** Multilayer networks can also have multivariate data [SKB*14, DHRL*12]. Under this category we will examine the impact of multilayer structure on attribute visualization. **Empirical Evaluation:** Empirical evaluation is a challenge for information visualization [Pla04]. Within the domain there are many guides to evaluation such as [Pur12]. However, techniques developed in application domains may not have been exposed to the same level of rigor as those developed within the visualization domain. It is important to understand which novel techniques have been empirically validated.

3.3. Discussion and Contribution

Our discussion will first address the results of the survey presenting and analyzing potential gaps in terms of existing approaches. We will also compare and contrast the approaches taken within the information visualization domain and those published in the application domains. We will also be considering the various approaches from other areas of network visualization that may be promising for application to multilayer visualization problems, e.g., hybrid visualizations [RMF12] difference graphs [RM13b], hive-plots [KBJM11], and list based views [GKL*13, SGL08, vdCAvW14].

Following on from our discussion of the survey results, we will have a detailed analysis relating the tasks to the existing taxonomies such as [PPS14, BBDW14, MMF17, LPP*06], and highlighting any gaps revealed by our survey. We are particularly interested in tasks related to the layers themselves, and the impact of task on layers and vice-versa. These multilayer specific tasks are what will drive the need for novel techniques for multilayer network visualization and provide a basis for future work. Additionally, we will examine analytical approaches and specific statistical techniques which are underexploited in current multilayer networks systems.

This STAR will be providing an overview and analysis of contemporary multilayer network visualization, not only for researchers in visualization, but also for those who aim to visualize multilayer networks in the domain of complex systems, as well as those developing systems across all application domains. The final contribution of our STAR will consist of identifying the key challenges outstanding in the field, and providing a road map for future research developments on the topic.

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Short Biographies of Authors

The initiative for this STAR report came from the collaboration of all co-authors on the BLIZAAR bi-national France-Luxembourg funded research project (ANR grant BLIZAAR ANR-15-CE23-0002-01 and FNR grant BLIZAAR INTER/ANR/14/9909176). The project looks at developing multilayer network visual analytics techniques that can be applied in the domains of digital humanities and biological network analysis.

Fintan McGee

Dr. Fintan McGee is a researcher of information visualization, in the eScience Unit of the Environmental Research and Innovation department at the Luxembourg Institute of Science and Technology. He received his doctorate in computer science from Trinity College Dublin in 2013. His doctoral thesis was on the visualization of small world graphs. It focused on using a vertex centrality, clustering coefficient as an aid to network layout, as well as empirically evaluating the impact of edge routing techniques on user performance. In addition to multilayer network visualization his current areas of research include biological pathway visualization, multivariate data visualization, visualization evaluation, crowdsourcing for visualization, and applied visualization in the domain of bioinformatics. He is a work package leader on the BLIZAAR project.

Guy Melançon

Guy Melançon is a full professor at Université de Bordeaux, France. His primary research area is network visual analytics, focused on multilayer dynamic networks with a strong interest in multi-disciplinary research projects. The application domains of his work have included human trafficking networks, digital ethnography, historical archives, spatial geography, and technological intelligence. He was co-editor of the book "Methods for multilevel analysis and visualisation of geographical networks" [RM13a] and co-author of a Graph Visualization survey [HMM00] (part of the ten most cited TVCG papers, as of 2009). He is also a member of SIF (Société Informatique de France) and has institutional membership of Eurographics.

Sébastien Rufiange

Sébastien Rufiange received his Ph.D. degree in computer science at École de technologie supérieure (Canada) in 2013. During his thesis, he designed and empirically evaluated novel network visualization techniques, including hybrid techniques and taxonomies covering state-of-the-art advances. He was a postdoctoral researcher at INRIA Bordeaux Sud-Ouest (Bordeaux, France), and designed dynamic network visualizations. He is working as an associate professor at EISTI (France) since 2014 and is leading the computer science department of the Pau campus. His research interests include information visualization, graph visualization, software visualization and evolution. He has published in top conferences and journals in information visualization and is active in the community, reviewing journal papers and part of program committees.

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Bruno Pinaud received the Ph.D. degree in Computer Science in 2006 from the University of Nantes. Since September 2008, he is associate professor at the University of Bordeaux in the Computer Science Department. His current research interests are visual analytics, graph rewriting systems, graph visualization (especially dynamic graphs) and experimental evaluation in HCI. He is the lead developer of Porgy (http://porgy.labri.fr), a visual and interactive platform to model complex systems based on graph rewriting and an active developper of Tulip (http://tulip.labri.fr) on which Porgy is based. Dr. Pinaud has been recently involved as a PI in a research project on the visualization of dynamic graph. He is the PI for the French component of the BLIZAAR project.

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