

Visual Analysis of Multilayer Networks

Synthesis Lectures on Visualization

Editors

Niklas Elmqvist, *University of Maryland*

David S. Ebert, *University of Oklahoma*

Synthesis Lectures on Visualization publishes 50- to 100-page publications on topics pertaining to scientific visualization, information visualization, and visual analytics. Potential topics include, but are not limited to: scientific, information, and medical visualization; visual analytics, applications of visualization and analysis; mathematical foundations of visualization and analytics; interaction, cognition, and perception related to visualization and analytics; data integration, analysis, and visualization; new applications of visualization and analysis; knowledge discovery management and representation; systems, and evaluation; distributed and collaborative visualization and analysis.

Visual Analysis of Multilayer Networks

Fintan McGee, Benjamin Renoust, Daniel Archambault, Mohammad Ghoniem, Andreas Kerren, Bruno Pinaud, Margit Pohl, Benoît Otjacques, Guy Melançon, and Tatiana von Landesberger
2021

Adaptive and Personalized Visualization

Alvitta Ottley
2020

Diversity in Visualization

Ron Metoyer and Kelly Gaither
2019

User-Centered Evaluation of Visual Analytics

Jean Scholtz
2017

Interactive GPU-based Visualization of Large Dynamic Particle Data

Martin Falk, Sebastian Grottel, Michael Krone, and Guido Reina
2016

Semantic Interaction for Visual Analytics: Inferring Analytical Reasoning for Model Steering

Alexander Endert
2016

Design of Visualizations for Human-Information Interaction: A Pattern-Based Framework

Kamran Sedig and Paul Parsons

2016

Image-Based Visualization: Interactive Multidimensional Data Exploration

Christophe Hurter

2015

Interaction for Visualization

Christian Tominski

2015

Data Representations, Transformations, and Statistics for Visual Reasoning

Ross Maciejewski

2011

A Guide to Visual Multi-Level Interface Design From Synthesis of Empirical Study Evidence

Heidi Lam and Tamara Munzner

2010

© Springer Nature Switzerland AG 2022
Reprint of original edition © Morgan & Claypool 2021

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Visual Analysis of Multilayer Networks

Fintan McGee, Benjamin Renoust, Daniel Archambault, Mohammad Ghoniem, Andreas Kerren,
Bruno Pinaud, Margit Pohl, Benoît Otjacques, Guy Melançon, and Tatiana von Landesberger

ISBN: 978-3-031-01480-2	paperback
ISBN: 978-3-031-02608-9	ebook
ISBN: 978-3-031-00352-3	hardcover

DOI 10.1007/978-3-031-02608-9

A Publication in the Springer series
SYNTHESIS LECTURES ON VISUALIZATION

Lecture #12

Series Editors: Niklas Elmqvist, *University of Maryland*
David S. Ebert, *University of Oklahoma*

Series ISSN

Print 2159-516X Electronic 2159-5178

Visual Analysis of Multilayer Networks

Fintan McGee

Luxembourg Institute of Science and Technology (LIST), Luxembourg

Benjamin Renoust

University of Osaka, Japan

Daniel Archambault

Swansea University, United Kingdom

Mohammad Ghoniem

Luxembourg Institute of Science and Technology (LIST), Luxembourg

Andreas Kerren

Linköping University, Sweden

Bruno Pinaud

University of Bordeaux, France

Margit Pohl

Vienna University of Technology, Austria

Benoît Otjacques

Luxembourg Institute of Science and Technology (LIST), Luxembourg

Guy Melançon

University of Bordeaux, France

Tatiana von Landesberger

University of Rostok, Germany

University of Cologne, Germany

SYNTHESIS LECTURES ON VISUALIZATION #12

ABSTRACT

The emergence of multilayer networks as a concept from the field of complex systems provides many new opportunities for the visualization of network complexity, and has also raised many new exciting challenges. The multilayer network model recognizes that the complexity of relationships between entities in real-world systems is better embraced as several interdependent subsystems (or layers) rather than a simple graph approach. Despite only recently being formalized and defined, this model can be applied to problems in the domains of life sciences, sociology, digital humanities, and more. Within the domain of network visualization there already are many existing systems, which visualize data sets having many characteristics of multilayer networks, and many techniques, which are applicable to their visualization. In this Synthesis Lecture, we provide an overview and structured analysis of contemporary multilayer network visualization. This is 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 solving problems within application domains. We have explored the visualization literature to survey visualization techniques suitable for multilayer network visualization, as well as tools, tasks, and analytic techniques from within application domains. We also identify the research opportunities and examine outstanding challenges for multilayer network visualization along with potential solutions and future research directions for addressing them.

KEYWORDS

multilayer networks, visualization, network visualization, visual analytics, interaction, task taxonomy, attribute visualization, multivariate network visualization, evaluation

Contents

Preface	xi
Figure Credits	xiii
1 Introduction and Overview	1
1.1 Introduction	1
1.2 An Introduction to Multilayer Network Concepts	1
1.2.1 A More Formal Definition of Multilayer Networks	3
1.2.2 More Advanced Multilayer Network Concepts	3
1.3 Why the Visualization of Multilayer Networks is Important	6
1.3.1 The Ubiquity of Multilayer Networks	6
1.3.2 Handling Additional Complexity	7
1.3.3 New Challenges and Opportunities in Visualization	7
1.4 Book Motivation and Structure	8
1.4.1 Who is This Book for?	8
1.4.2 The Goals of This Book	8
1.4.3 Book Structure	8
2 Multilayer Networks Across Domains	11
2.1 The Emergence of Multilayer Networks	11
2.2 Related Network Visualization Concepts	13
2.2.1 k -Partite Graphs	13
2.2.2 Multivariate Graphs	14
2.2.3 Dynamic Graphs	16
2.3 Multilayer Networks in Application Domains	16
2.3.1 Life Sciences	17
2.3.2 Social Sciences	17
2.3.3 Economics and Finance	18
2.3.4 Sustainability	19
2.3.5 Digital Humanities and Multimedia	19
2.3.6 Infrastructure and Engineering	20
2.4 Data Sets Across Domains	21

2.5	Chapter Summary	21
3	The Layer as an Entity	23
3.1	Modeling Layers	23
3.1.1	Layers as Real Entities of the Network	24
3.1.2	Defining Layers	25
3.1.3	Aspects	26
3.2	Visualizing and Manipulating Layers	27
3.2.1	Layer Analysis and Visualization	28
3.2.2	Models of Layers	29
3.2.3	Layer Comparison and Overview	31
3.3	Challenges and Opportunities	33
3.3.1	Modeling of Real-World Concepts from the Data	33
3.3.2	Creative Definition of Layers	33
3.3.3	Analytical Generation of Layers	34
3.3.4	Summary Visual Comparison Across Layers	34
3.3.5	The Aspect as an Entity	34
4	Task Taxonomy for Multilayer Networks	37
4.1	Taxonomy of Multilayer Network Tasks	38
4.1.1	Task Category A – <i>Entity Connectivity Across Layers</i>	39
4.1.2	Task Category B – <i>Entity Comparison Across Layers</i>	39
4.1.3	Task Category C – <i>Layer Structure Manipulations</i>	40
4.1.4	Task Category D – <i>Layer Comparisons</i>	41
4.2	Related Tasks Taxonomies in Visualization	41
4.3	Challenges and Opportunities	43
4.3.1	Tasks for Defining an Initial Layering	43
4.3.2	Consideration of Other Taxonomies	44
5	Visualization of Nodes and Relationships Across Layers	45
5.1	Matrix-Based Visualizations	46
5.2	1D Node-Link Representations	48
5.2.1	Linear Node-Link Representations	48
5.2.2	Circular Representations	51
5.3	2D Layers with Node-Link Representations	52
5.4	Juxtaposition vs. Superposition of 2D Visualizations	54
5.5	3D and Immersive Node-Link Representations	57

5.6	Edge Visualization	57
5.7	Challenges and Opportunities	61
5.7.1	Matrix Visualization Approaches	61
5.7.2	Hybrid Approaches	61
5.7.3	Immersive Visualization	62
5.7.4	Edge Routing	63
5.7.5	Encoding of Entities	63
5.7.6	Other Complex Network Visualization Approaches	64
5.7.7	Dynamic and Temporal Layering	64
6	Interacting with and Analyzing Multilayer Networks	65
6.1	Interaction Approaches	66
6.1.1	Layer-Level Interactions	67
6.1.2	Node-Level and Link-Level Interactions	69
6.2	Multilayer Analytics	71
6.3	Challenges and Opportunities	72
6.3.1	Interactive Querying and Layer Definition	73
6.3.2	Merging, Splitting, Projecting, and Transforming Layers as Interactions	74
6.3.3	Interactive Layer Comparison	74
6.3.4	Exploitation of Existing Multilayer Analysis Techniques	75
7	Attribute Visualization and Multilayer Networks	77
7.1	Numeric Attributes	78
7.2	Categorical Attributes	80
7.3	Temporal Attributes	81
7.4	Network-Associated Metrics as Attributes	83
7.5	Challenges and Opportunities	83
7.5.1	Mixed Attributes Across Multiple Layers	83
7.5.2	Multilayer Network Centralities as Attributes	83
7.5.3	Novel Alternative Representations	84
7.5.4	Multilayer Network Embeddings	85
8	Evaluation of Multilayer Network Visualization Systems and Techniques . . .	87
8.1	Overview of Existing Evaluation Studies	89
8.2	Overview of Relevant Psychological Research	92
8.3	Recommendations for the Design of Multilayer Networks Visualizations . . .	93
8.4	Challenges and Opportunities	94

9	Conclusions	97
	Bibliography	101
	Authors' Biographies	129
	List of Figures	133

Preface

Although not presented using the concept of multilayer networks, the 1985 paper “Relational contents in multiple network systems” by Burt and Schøtt [1985] clearly brings it into play. The ideas they laid out in their seminal paper were generalized, further examined and extended in a series of papers by Renoust et al. [2013, 2014, 2015]. Renoust transferred the notion of relation multiplexity to document collections, and later applied his approach to any collection of homophily relations in any context. At the same time, Kivelä et al. [2014] were developing a formal framework unifying all preceding efforts to deal with heterogeneous, multi-source networks.

Many of the ideas, concepts, definitions, and overall content of this book were given a decisive boost within the FR-LUX bilateral research project BLIZAAR¹ between its writing early 2015 to its official end in 2019. Incidentally, the writing of a survey on the visualization of multilayer networks [McGee et al., 2019a] was a deliverable of this project. Other projects² involving the Bordeaux team with sociologists and law researchers investigating human-trafficking [Lavaud-Legendre et al., 2017] definitely contributed to mature the concept of multilayer network and some of its intimate requirements when it comes to building systems supporting their visualization and navigation.

The authors would also like to thank Schloss Dagstuhl and the participants of seminar #19061 on the “Visualization of Multilayer Networks across Domains” [Kivelä et al., 2019]. The seminar was a unique event gathering both researchers of the visualization field, complex systems theory, and a significantly large group of domain experts all familiar with the concepts and in demand of the visualization of multilayer networks. Without the support of Schloss Dagstuhl and the commitment of its participants, this book would have never come to be.

In October 2019, all authors of this book participated to the “Multilayer Network Visualization” workshop organized on the occasion of the IEEE VIS’19 week conferences held in Vancouver. We would like to thank the organizers of IEEE VIS’19 for their support for the workshop. One of the results of the workshop was to gather the authors around the project of writing this book.

¹BLIZAAR was funded by the French national research agency (ANR), grant ANR-15-CE23-0002-01, and the Luxembourg National Research Fund (FNR), grant INTER/ANR/14/9909176. The project involved the Luxembourg Institute of Science and Technology (LIST), the University of Bordeaux, the center for Digital Research in European Studies (CVCE <https://www.cvce.eu/>), and EISTI (<https://eisti.fr/>).

²We acknowledge the support from University of Bordeaux through the 2015–2016 TETRUM grant, and from the GIP Justice for their financial support of the 2017–2019 AVRES grant number 217.03.30.05.

Finally, we would like to thank Niklas Elmqvist and all at Morgan & Claypool for supporting us in the production of this book.

Fintan McGee, Benjamin Renoust, Daniel Archambault, Mohammad Ghoniem,
Andreas Kerren, Bruno Pinaud, Margit Pohl, Benoît Otjacques, Guy Melançon,
and Tatiana von Landesberger
April 2021

Figure Credits

- Figure 3.1** From B. Renoust, G. Melançon, and T. Munzner. Detangler: Visual analytics for multiplex networks. *Computer Graphics Forum*, 34(3):321–330, 2015. John Wiley and Sons. Used with permission.
- Figure 3.2** From Renoust et al., 2015. John Wiley and Sons. Used with permission.
- Figure 3.3** From Renoust et al., 2015. John Wiley and Sons. Used with permission.
- Figure 3.4** From V. Yoghourdjian, T. Dwyer, K. Klein, K. Marriott, and M. Wybrow. Graph thumbnails: Identifying and comparing multiple graphs at a glance. *IEEE Transactions on Visualization and Computer Graphics*, 24(12):3081–3095, 2018. IEEE. Used with permission.
- Figure 3.5** From M. Freire, C. Plaisant, B. Shneiderman, and J. Golbeck. ManyNets: An interface for multiple network analysis and visualization. In *Proc. of the SIGCHI Conference on Human Factors in Computing Systems, CHI'10*, pages 213–222, 2010. Association for Computing Machinery, Inc. Reprinted by permission.
- Figure 3.6** From M. Rosvall and C. T. Bergstrom. Mapping change in large networks. *PloS One*, 5(1), 2010. Used with permission under Creative Commons license Attribution 4.0 International (CC BY 4.0).
- Figure 5.5** From S. Ghani, B. C. Kwon, S. Lee, J. S. Yi, and N. Elmqvist. Visual analytics for multimodal social network analysis: A design study with social scientists. *Transactions on Visualization and Computer Graphics*, 19(12):2032–2041, 2013. IEEE. Used with permission.
- Figure 5.6** From H. Yang, K. Tang, X. Liu, L. Xiao, R. Xu, and S. Kumara. A user-centred approach to information visualisation in nano-health. *International Journal of Bioinformatics Research and Applications*, 12(2):95–115, 2016. Inderscience Enterprises Ltd. Used with permission.

- Figure 5.7** L. Angori, W. Didimo, F. Montecchiani, D. Pagliuca, and A. Tappini. Hybrid graph visualizations with ChordLink: Algorithms, experiments, and applications. *IEEE Transactions on Visualization and Computer Graphics*, 2020. IEEE. Used with permission.
- Figure 5.9** From C. Ducruet. Multilayer dynamics of complex spatial networks: The case of global maritime flows (1977–2008). *Journal of Transport Geography*, 60:47–58, 2017. Elsevier. Used with permission.
- Figure 5.11** From M. Müller, K. Ballweg, T. von Landesberger, S. Yimam, U. Fahrner, C. Biemann, M. Rosenbach, M. Regneri, and H. Ulrich. Guidance for multi-type entity graphs from text collections. In *Proc. of the EuroVis Workshop on Visual Analytics, EuroVA'17*, pages 1–6, 2017. The Eurographics Association. Used with permission.
- Figure 5.12** From R. Bourqui, D. Ienco, A. Sallaberry, and P. Poncelet. Multilayer graph edge bundling. In *IEEE Pacific Visualization Symposium (PacificVis)*, pages 184–188, 2016. IEEE. Used with permission.
- Figure 5.13** From T. Crnovrsanin, C. W. Muelder, R. Faris, D. Felmlee, and K.-L. Ma. Visualization techniques for categorical analysis of social networks with multiple edge sets. *Social Networks*, 37(Supplement C):56–64, 2014. Elsevier. Used with permission.
- Figure 6.1** From M. Hascoët and P. Dragicevic. Interactive graph matching and visual comparison of graphs and clustered graphs. In *Proc. of the International Working Conference on Advanced Visual Interfaces, AVI'12*, pages 522–529, 2012. Association for Computing Machinery, Inc. Reprinted by permission.
- Figure 6.2** From L. Shi, Q. Liao, H. Tong, Y. Hu, C. Wang, C. Lin, and W. Qian. OnionGraph: Hierarchical topology+attribute multivariate network visualization. *Visual Informatics*, 2020. Elsevier. Used with permission.
- Figure 6.3** From Renoust et al., 2015. John Wiley and Sons. Used with permission.
- Figure 6.4** From B. Renoust, H. Ren, and G. Melançon. Animated drag and drop interaction for dynamic multidimensional graphs. *ArXiv Preprint ArXiv:1902.01564*, 2019. Used with permission.

- Figure 7.1** From S. Grottel, J. Heinrich, D. Weiskopf, and S. Gumhold. Visual analysis of trajectories in multi-dimensional state spaces. *Computer Graphics Forum*, 33(6):310–321, 2014. John Wiley and Sons. Used with permission.
- Figure 7.2** From A. J. Pretorius and J. J. Van Wijk. Visual inspection of multivariate graphs. *Computer Graphics Forum*, 27(3):967–974, 2008. John Wiley and Sons. Used with permission.
- Figure 7.3** From M. Burch, M. Höferlin, and D. Weiskopf. Layered TimeRadarTrees. In *Proc. of the 15th International Conference on Information Visualisation, IV*, pages 18–25, 2011. IEEE. Used with permission.
- Figure 7.4** From M. De Domenico, M. A. Porter, and A. Arenas. MuxViz: A tool for multilayer analysis and visualization of networks. *Journal of Complex Networks*, 3(2):159–176, 2015. Oxford University Press. Used with permission.
- Figure 7.5** From I. Jusufi, A. Kerren, and B. Zimmer. Multivariate network exploration with JauntyNets. In *17th International Conference on Information Visualisation*, pages 19–27, 2013. IEEE. Used with permission.
- Figure 8.1** From F. Schreiber, A. Kerren, K. Börner, H. Hagen, and D. Zeckzer. Heterogeneous networks on multiple levels. In A. Kerren, H. C. Purchase, and M. O. Ward, Eds., *Multivariate Network Visualization: Dagstuhl Seminar #13201*, Dagstuhl Castle, Germany, May 12–17, 2013, Revised Discussions, pages 175–206, 2014. Springer International Publishing. Used with permission.