Report from Dagstuhl Seminar 19061

Visual Analytics of Multilayer Networks Across Disciplines

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 19061 'Visual Analytics of Multilayer Networks Across Disciplines'.

Networks, used to understand systems, often contain multiple types of nodes and/or edges. They are often flattened to a single network, even though real-world systems are more accurately modelled as a set of interacting networks, or layers, with different node and edge types. These are so-called multilayer networks. These networks are studied by researchers both in network visualization and in complex systems – the domain from which the concept of multilayer networks has recently emerged. Moreover, researchers in various application domains study these systems, e.g. biology, digital humanities, sociology and journalism. These research areas have shown parallel individual developments. Therefore, one of the aims of the seminar was to bring together an interdisciplinary community of researchers and practitioners of different disciplines. This interdisciplinary community discussed existing solutions, open challenges and future research directions for visual analytics of multilayer networks across disciplines.

The seminar was attended by researchers from information visualization, visual analytics, complex systems and application domains. The application domains covered digital humanities, social sciences, biological sciences, and in public health research (25% of attendees were from these fields). The seminar not only provided multiple application domains for the visualization experts, but also also provided the domains experts with different groups of visualization experts in breakouts sessions, to expose them to multiple approaches to solving their problems. Building on this close working relationship between the visualization and domain experts, working groups were defined to determine which are the important challenges for multilayer network visualization. A number of sub-topics were identified that require further research: *A unifying visualization framework*, *Novel Visual Encodings*, *Analytic* and *Attributes*, *Interaction*, *Evaluation*, *Use Cases* and *Human Factors*. The outcomes of the seminar should stimulate collaborative research on these topics between our community, complex networks, and wide range of application domains for the visual analytics of multilayer networks

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1 Executive Summary

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Introduction

The topic of multilayer networks has recently emerged from the field of complex systems, however many of the of the fundamental concepts and ideas have existed for some time, in fields such as sociology, and often under different nomenclature, such as multimodal, heterogeneous or multiplex networks. The multilayer network framework of Kivelä *et al* [1] has collected many of these concepts and different labels, along with example data sets, allowing us to recognize the multi-disciplinary importance of multilayer networks as a topic. Despite the importance of this topic, it is only recently that the visualization community is beginning to consider approaches for the visual analytics of multilayer networks. This seminar was the first to bring together practitioners from multiple domains to discuss the visual analytics of multilayer networks. These fields included data visualization, complex systems, digital humanities, biological sciences, health informatics, and sociology. The primary goal of this seminar was to bring together these thinkers and practitioners from different disciplines to drive forward new advances on the topic. The seminar was designed to foster discussions between researchers and designers of visual analytics tools, those who define the underlying theory, and the the end-users of these tools. To push research further and produce significant impact in industry and general public practices, the research community needs to establish a deeper collaboration between data scientists and researchers from applications domains (e.g. biologists, social scientists, business analysts, journalists, physicists), who collect and analyze the data; and researchers in maths, physics and computer science who push the state-of-the-art, producing visualization and analysis models, algorithms and tools. This deeper collaboration starts with building an understanding of the needs and tasks of network analysts. This seminar was an important first step, leveraging cross domain synergies with the goal of identifying the shared underlying problems and helping to solve them. The domain experts presented their domain problems early on in the seminar, and then interacted with two different sets of visualization experts in two separate breakout sessions. The motivation for this was to expose the visualization experts to many different domain problems and to expose the domain experts to multiple approaches to their problems. Our goal was to not only to advance research in the field of visualization, but also to provide techniques to help the domain experts to advance research in their own field. Interdisciplinary intersection was a key part of the methodology of our seminar.

Seminar Topics

The seminar featured talks and working groups that discussed topics on visualization, analysis, theory and applications of multilayer networks (see Sections 3 and 4). The application domain focus was maintained throughout the seminar. Experts from application domains gave talks in the first day and a half highlighting the problems they encountered. Then there were two breakout sessions where each experts was assigned a different group of visualization experts, allowing the domain experts to brainstorm solutions to their problems with different sets of visualization experts.

Talks

The talks brought the interdisciplinary participants initial information on a) current application problems dealt with in the area of multilayer networks and b) current visualization, analysis and systems solutions.

The purpose of talks by application experts was to make sure that the potential solutions provided by the interactive visualizations and analytics fully meet the requirements of those who actually use them, i.e. the system biologists, social network analysts, historians, etc. Therefore, the talks provided understanding of the data and problems/tasks/goals when analyzing multilayer graphs by the domain experts. The talks covered application areas of social networks by A. Cottica and by M. Magnani, information circulation in an international organization by M. Grandjean, digital humanities by M. Düring , multi-omics data by S. Legay, population health by M. McCann, digital ethnography by A. Munk(see sections 3). These talks allowed the visualizations and complex systems theory experts to gain some insight into the domain experts problems. As we also wanted the domain experts to be exposed to multiple approaches to their problems, we had two breakout sessions after all of the domain experts presented their personal topics. In these breakout sessions, each domain experts was assigned a small group of visualization researchers to further brainstorm, mapping visualization problems to domain problems. Different researchers were assigned to each domain expert for each session. This exposed the domain experts to multiple visualization approaches, and allowed for synergies between application domain problems to be identified by the visualization researchers. At the end of each breakout session, each groups gave a short report back to other participants, allowing for further discussion and cross fertilization of ideas. This approach ensured that that both the domain experts and the visualization experts had a wide range of ideas to explore as part of the working groups in the later half of the seminar.

The purpose of talks by visualization, analysis and systems experts was to present currently available solutions to multilayer network visualization and analysis (see also Section 3). These talks were dispersed throughout out the week. The talk topics were: an introduction to multilayer networks by F. McGee, a complex systems perspective on the concept of multilayer network by M. Kivelä, survey of multilayer visualizations by G. Melançon, Py3plex library for visualization by B. Škrlj, interaction with multilayer network visualization by B. Renoust. This allowed application experts to get to know the advantages and limitations of existing solutions. The talk schedule was flexible, for example, due to a high level of interest form all attendees M. Kivelä gave a second question and answers session to his talk the following day.

Working Groups

At the midpoint of the week we defined the working groups. The breakout session stimulated a large amount of discussion and ideas across participants of all disciplines. Following on the breakout sessions discussions, all seminar participants wrote down topics and ideas that were that were of interest to them of pieces of paper, which were affixed to a board. Similar topics were re-positioned closer together on the board, until all participants reached a consensus of five topic areas for discussion within working groups. The resulting working groups were as follows:

- *Unifying Terminology and visual analytic approaches*: One open problem of multilayer network analysis and visualization is the inconsistent terminology across disciplines. There are many different names given to networks with such characteristics, outlining the current lack of consistent definitions between disciplines, such as heterogeneous, multi-faceted, multi-modal, or multi-relational networks, amongst others (see [1]) and in the vast majority of cases it is possible to model them as multilayer networks. The discussion group assessed various types of networks from visualization, application and systems perspective. It discussed possible unification of these perspectives in one visual analytics framework and identified open challenges (see Section 4.3).

- *Analytics, Communities Comparison and attributes*: Visual analysis of multilayer networks is also concerned with the exhibition of salient properties and patterns in data. Salience in networks is often captured through metrics (networks statistics) while patterns most often correspond to particular subsets of entities (nodes and edges). Layers bring additional complexity to the computation of these metrics and patterns, as metrics and patterns may need to be computed across several layers. The visualization of the computed metrics and patterns needs to consider also these layers, thus, posing challenges to the data presentation. This working group analyzed the current network metrics and proposed novel metrics specifically for multilayer networks (see Section 4.4).
- *Interaction (and Layer Creation)*: (see Section 4.2) This topic concentrated on interactive creation of layers in networks. While the input multilayer network may have predefined layers, in many use cases, the layers need to be adapted to the analytical task during network exploration. This working group has gathered requirements for interaction with layers, surveyed current solutions and their limitations. They have proposed novel approaches that will be pursued after the seminar.
- *Visual Encodings* The complex relationships between complex structures mean that traditional interactive visualizations need to be enhanced. Researchers from the various domains can exchange their ideas and thus start novel avenues in interactive visualization. The discussion of this working group focused on the visualization design – encodings. The group identified main requirements for visualization: aggregations, interactive layer editing, overview of all layers, details of an individual layer and exploration paths – top-down versus bottom up (see Section 4.5). These requirements are used to derive a design space of possible visualization approaches in future.
- *Human Factors and Multilayer Networks* This topic focused on the user's point of view in the design of multilayer network visualization. This is a challenge as the complexity of multilayer networks results in a significant amount of cognitive load on the users. The group collected results from related work that can be used as guidelines for designing multilayer visualizations. It also identified gaps in literature for future research (see Section 4.1).

Seminar Outcomes

During the seminar, a number of sub-topics were identified that require further research: *A unifying visualization framework*, *Novel Visual Encodings*, *Analytics* and *Attributes*, *Interaction*, *Evaluation*, *Use Cases* and *Human Factors*.

- **A unifying visualization framework for multilayer networks:** Currently, multilayer networks are referred to across communities using various names and concepts. A novel unified conceptual framework for multilayer network is needed that would be used for visualization, interaction and analytics purposes. It should extend the underlying mathematical framework [1] to meet the needs of the data and tasks associated with the various use cases, as well as existing visualization and interaction concepts.

- **Novel visual encodings:** The existing visualization techniques have limited scope for the broad range of data and tasks in the applications of multilayer networks. Therefore, novel visual encodings need to be researched that to enable data exploration across layers.
- **Interaction:** Visual exploration and analysis of multilayer networks requires novel interaction techniques that would allow to browse across layers and also to create new layers during the exploration process.
- **Interdisciplinarity:** The wide range of application domain problems sets novel problems that may be best addressed by new visualization approaches. The development of novel solutions for visual analysis of multilayer networks requires joined forces of application, visualization and analysis experts.
- **Multiple layers and attributes:** The complexity of multilayer networks often includes an additional dimension: The multivariate nature of node and edge attributes. This information needs to be encoded in the visualization and supported in analytical functions. This raises novel challenges.
- **Network Analytics:** Visual network analysis also covers the understanding the analytical relationship between layers (with respect to structure and/or attributes) and the layer comparison. The limitations of current analytical approaches and network metrics raises many interesting challenges and opportunities for developing new metrics for the multilayer use case.
- **Evaluation & Human Factors:** The human perspective on the complexity of the network structure and its visualization needs to be assessed. It covers a) the perceptual and cognitive aspects when interactively exploring the networks and b) a thorough empirical evaluation of the analytical paths and insights. The existing methodologies for such research should be adapted for the multilayer network case.

These topics will be discussed in the follow-up VIS 2019 Workshop 'Challenges in Multilayer Network Visualization and Analysis'. The workshop is co-organized by Dagstuhl Seminar organizers and participants: Fintan McGee, Tatiana von Landesberger, Daniel Archambault and Mohammad Ghoniem. The seminar will feature keynote, paper and poster sessions as well as discussion rounds on the above-mentioned topics.

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3 Overview of Talks

3.1 Visualizing multilayer networks with Py3plex

Blaž Škrlj (Jozef Stefan Institute – Ljubljana, SI)

Joint work of Blaž Škrlj, Jan Kralj, Nada Lavrač
Main reference Blaz Skrlj, Jan Kralj, Nada Lavrac: "Py3plex: A Library for Scalable Multilayer Network Analysis and Visualization", in Proc. of the Complex Networks and Their Applications VII – Volume 1 Proceedings The 7th International Conference on Complex Networks and Their Applications COMPLEX NETWORKS 2018, Cambridge, UK, December 11-13, 2018., Studies in Computational Intelligence, Vol. 812, pp. 757–768, Springer, 2018.
URL https://doi.org/10.1007/978-3-030-05411-3_60

Real-world complex networks frequently consist of separate layers, representing either the same entity in different contexts (multiplex), or interacting, entirely different entities (multilayer). In this talk we first describe how multilayer networks are visualized currently along with the main drawbacks of such approaches. Next, we discuss Py3plex, a python library offering a novel multilayer visualization layout. It first projects individual layers across a diagonal. Here, each layer can have a unique layout. Next, inter-layer edges are drawn as curves between layers. We have identified layout algorithms as one of the main bottlenecks in graph drawing. We propose an embedding-based layout computation, where the network is first embedded to a high dimension (e.g., 512) and next compressed to two dimensions. The obtained projections are used as the starting (initial) positions for only a handful of iterations of the Barnes-Hut force-directed layout. The proposed approach scales to networks with hundreds of thousands of nodes and millions of edges on an of-the-shelf laptop.

3.2 Semantic social networks: a multilayer interpretation

Alberto Cottica (Edgeryders – Brüssel, BE)

Joint work of Alberto Cottica, Guy Melançon, Amelia Hassoun, Jason Vallet, Benjamin Renoust
Main reference Alberto Cottica, Amelia Hassoun, Jason Vallet, Guy Melançon: "Semantic Social Networks: A New Approach to Scaling Digital Ethnography", in Proc. of the Internet Science – 4th International Conference, INSCI 2017, Thessaloniki, Greece, November 22-24, 2017, Proceedings, Lecture Notes in Computer Science, Vol. 10673, pp. 412–420, Springer, 2017.
URL http://dx.doi.org/10.1007/978-3-319-70284-1_32

Semantic social networks are a method to treat large ethnographic corpora. Starting from a conversational medium, like an online forum, semantic social networks are built by ethnographic coding of the utterances in the conversation. The result is a social network of interaction, where the edges encode meaning.

Semantic social networks can be interpreted as multiplayer networks. A social layer encodes interaction between key informants in the ethnography; a semantic layer encodes co-occurrence between ethnographic codes. I discuss how best to interrogate each layer to address questions relevant to ethnographic research.

3.3 Digital Humanities Data

Marten Düring (University of Luxembourg, LU)

This talk stressed the interpretative nature and purpose of data encountered in the Digital Humanities (DH) sphere, especially data which is collected by humanities researchers from either unstructured text, serial sources, such as membership lists, or existing databases. The DH community has three main expectations when collaborating with Visual Analytics scholars: the joint development of custom-fit visualisation solutions, trustworthy representations of their data as well as insights of actual significance for their own work. Differences arise with regard to the strong interpretative aspect in DH data collection, the common absence of a testable ground truths as well as more interpretative research practices such as close reading as opposed to quantifications. The talk pointed out potential tensions in the relationship between DH and Visual Analytics scholars which arise from the goal to develop highly original contributions in VA and the need for robust tools in DH. These tensions can be overcome by fostering close relations between the fields which are based on the early definition of success criteria, ease of integration into DH workflows, sufficient time for skill development, and the acknowledgment of DH data particularities.

3.4 Mapping information circulation within an international organisation in the 1920s – An example of historical multilayer analysis

Martin Grandjean (Université de Lausanne, CH)

Main reference Grandjean Martin: "Les réseaux de la coopération intellectuelle, la Société des Nations comme actrice des échanges scientifiques et culturels dans l'entre-deux-guerres", University of Lausanne, 2018, 600 p.
URL https://halshs.archives-ouvertes.fr/tel-01853903

We propose to analyse the activity and connectivity of the International Committee on Intellectual Cooperation (ICIC) of the League of Nations through a fine indexing of its correspondance archives. Created in 1922, this committee brought together leading scientists such as Henri Bergson, Albert Einstein, Marie Sklodowska-Curie and Hendrik Lorentz and laid the foundations of UNESCO after the Second World War. The rise and bureaucratization of this organization during the 1920s is accompanied by a rapid increase of the number of documents produced and received as well as a complexification of information flows. By mapping this circulation in a network composed of more than 3.000 individuals involved in intellectual cooperation during its early years (approx. 30.000 documents), this method reveals the main organizational trends while highlighting the situation of actors that are so far little studied in this context. This exploratory "datafication" of the archives of the League of Nations leads us to reconsider and recontextualize the personal commitment of the individuals who made up the ICIC.

The development of a multilayer model that allows a comparison between the official institutional framework of the international organizations of this time and the structuring of information exchanges at an individual level helps to highlight the discrepancy from a

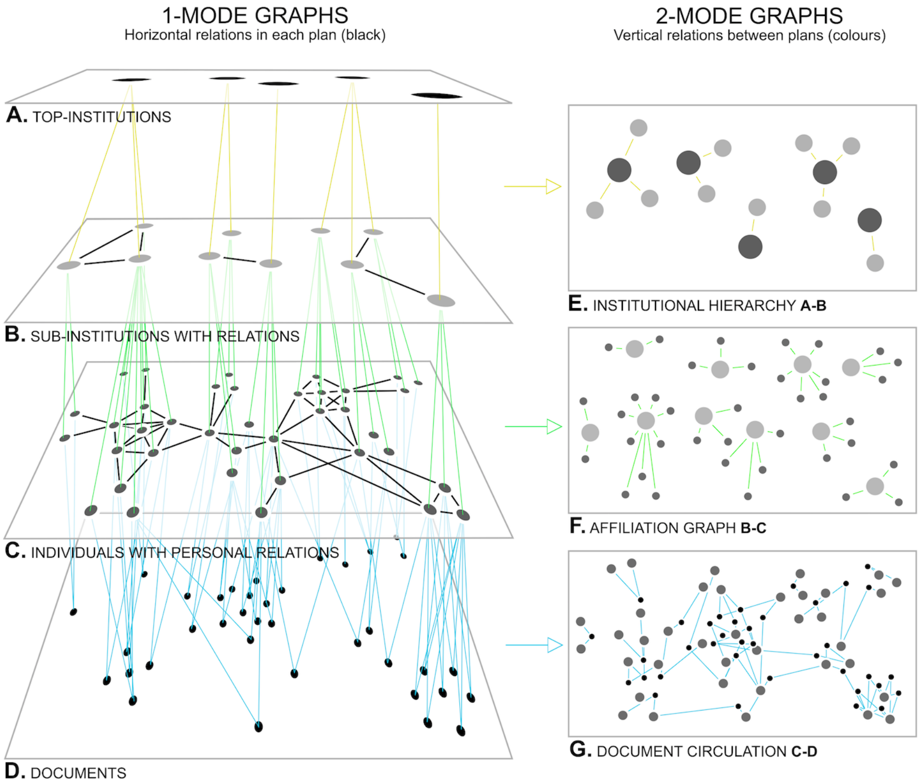

Figure 1 Example of a multilayer model.

hierarchical level to another. In our example, we propose to use this multilayer model to flatten the hierarchical structure of the two upper levels so that they contain the individual nodes. Creating such a stable visualisation is the condition for a comparative analysis of the edges connecting groups in time of based on a thematic filtering of the data.

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3 Martin Grandjean. *Multimode and Multilevel: Vertical Dimension in Historical and Literary Networks*. Digital Humanities 2017, Montreal.

3.5 Multilayer Networks

Mikko Kivelä (Aalto University, FI)

Main reference Mikko Kivelä, Alex Arenas, Marc Barthelemy, James P. Gleeson, Yamir Moreno, Mason A. Porter: "Multilayer networks", J. Complex Networks, Vol. 2(3), pp. 203–271, 2014.
URL https://doi.org/10.1093/comnet/cnu016

Network science has been very successful in investigations of a wide variety of applications from biology and the social sciences to physics, technology, and more. In many situations, it is already insightful to use a simple (and typically naive) representation as a simple, binary graph in which nodes are entities and unweighted edges encapsulate the interactions between those entities. This allows one to use the powerful methods and concepts for example from graph theory, and numerous advances have been made in this way. However, as network science has matured and (especially) as ever more complicated data has become available, it has become increasingly important to develop tools to analyse more complicated structures. For example, many systems that were typically initially studied as simple graphs are now often represented as time-dependent networks, networks with multiple types of connections, or interdependent networks. This has allowed deeper and more realistic analyses of complex networked systems, but it has simultaneously introduced mathematical constructions, jargon, and methodology that are specific to research in each type of system. Recently, the concept of "multilayer networks" was developed in order to unify the aforementioned disparate language (and disparate notation) and to bring together the different generalised network concepts that included layered graphical structures. In this talk, I will introduce multilayer networks and discuss how they have been studied and visualised in the complex networks literature.

3.6 Multi-omics Data in Non-model Plants. Treatment, Integration and Visualization

Sylvain Legay (Luxembourg Inst. of Science & Technology, LU)

These last decades, the progress in plant sciences has vastly increased the amount of data that researchers must deal with. The recent high-throughput technologies offer extremely powerful tools, but also raise many issues linked to big data management, as well as visualization of complex biological processes. The realm of living organisms constitutes a natural multilayer system with multiple type of driven/non-driven, intra/inter-network and time-dependent interactions. Currently, integrative sciences usually focused on the "holy trinity": Gene expression, protein expression and metabolites. In order to simplify the investigation of these three heavily complex networks and to connect them to concrete biological meanings, scientists developed new layers (networks and/or databases) considering metabolic pathways, biological processes or molecular function to name a few. This strategy offered the scientific community useful tools to deeply investigate their topic of interest but it also increased the number of inter/intra network interactions. By the time, the visualization and investigation of these interconnected networks became a challenge. This is even more of an issue for scientists from applied research, which are dealing with non-model plants with species-specific metabolic pathways. In such cases, knowledge repositories are more incomplete due to lower efforts engaged to build them. As research topics are more and more turned to technology transfer and because biological networks are growing exponentially, the need of highly efficient, user-friendly visualisation tools to investigate complex biological processes is a crucial challenge for years to come.

3.7 Multilayer Social Networks

Matteo Magnani (Uppsala University, SE)

Joint work of Matteo Magnani, Luca Rossi
Main reference Mark E. Dickison, Matteo Magnani, Luca Rossi: "Multilayer Social Networks", Cambridge University Press, 2016.
URL https://doi.org/10.1017/CBO9781139941907

The objective of this talk is to introduce some of the main types of multilayer networks used to analyse social networks. We first give a historical presentation of early examples of multilayer networks /multiplex, multi-mode, etc.) leading to the proposal of a unified model (by Kivela et al.). Then, we present two concrete examples of multilayer social networks extracted from online social media, including different types of vertices (users and messages), different types of edges (communication, following, etc.), and attributes such as text and time. We also provide a list of open questions that would require advanced visualization methods to be addressed.

3.8 Multilayer Networks and Population Health

Mark McCann (University of Glasgow, GB)

Modern population health science has had a predominantly medical focus. Analysis often relies on the assumption of "no interference" – meaning that the health risk exposure of one individual does not affect the outcomes of other individuals.

Such an assumption is untenable in social systems. There are many relational features of experience, attitude formation and behaviours that relate to health outcomes. Network science, and thus information visualisation have important roles to play in population health.

Conceptualising population health as a feature of a complex system has been identified as a priority for the discipline. A key task is thus moving from conceptualisation, to practical application of complex systems science methods. Adopting a multilayer network approach may help to advance population health applications.

The complex system of a school may comprise pupil interaction: 'friends', 'foes', and 'prestigious' peers; co-participation of pupils in school events; the causal connections between health behaviours, and symptoms of poor physical and mental health; as well as the social transmission of health behaviours and outcomes.

Considering each of the elements above as multiple aspects of a multilayer network makes it easier to study the interactions within and between layers; for example, change in pupil interactions over time, or across levels of 'friend' and 'prestige' networks, or across levels of the social-ecological model of health. Layering a school social system may provide a relational equivalent of conditioning in causal inference, where statistical associations are layered by conditioning variables.

The sharing of ideas around visualising multilayer systems at Dagstuhl shows promise for the development of systems methods for population health science; and I strongly encourage continued collaborative work on visualising population health systems.

3.9 Multilayer Networks Overview and Examples across Domains

Fintan McGee (Luxembourg Inst. of Science & Technology, LU)

Joint work of Mohammad Ghoniem, Fintan McGee, Guy Melançon, Benoît Otjacques, Bruno Pinaud
Main reference Mohammad Ghoniem, Fintan McGee, Guy Melançon, Benoît Otjacques, Bruno Pinaud: "The State of the Art in Multilayer Network Visualization", Computer Graphics Forum, 2019.
URL https://doi.org/10.1111/cgf.13610

Multilayer networks may be a new term to some in the field of visualization, however there are many related concepts and ideas that will be familiar to those with experience in network visualization. The goal of this talk was to provide a gentle introduction from a network visualization perspective, justifying the use of multilayer networks and differentiating their visualization from related approaches. Multilayer network visualization is required as complex systems are often not accurately described by a single network, and modelling it as such means making many simplifying assumptions. Real life is better modelled as several interdependent subsystems or layers, as real-world systems are not general 100% closed and independent. For example, the professional and personal social networks of an individual can be considered independent networks, but in reality one may interact with the other. A dramatic changes in a professional network (resulting perhaps from a change of job) may precede a more gradual change of personal social network. Within biological networks interactions at different "omics" levels (e.g. proteomic, metabolomics and genomics) are best considered multiple layers rather than individual networks.

Multilayer networks often crop up under different nomenclature (see Kivela *et al.* [1]), and there some similarities to existing visualization approaches. Scheiber *et al.* [3] describe "heterogeneous networks" as a class of multivariate network, however multilayer networks as described by Kivela *et al.* are more complex, allowing multiple aspects to be defined characterising layers. While layer information can be reflected in an attribute it is important to remember that layers are based on a physical or conceptual reality related to the system being modelled, and is not just an arbitrary slicing of data.

The facets of faceted data visualization (see Hadlak *et al.*, [2]) may seem superficially similar to layers, however facets are more focused on visualization semantics (relating to the type of data) rather than a structure within the data, layers can interact with each other and are entities within their own right. There is also some overlap with dynamic graph visualization as time can be considered an aspect of a multilayer networks, characterising different layers. Multilayer networks visualization are of course more general however integrating time among other aspects may also raise other challenges. A bipartite graph may also be considered a type of multilayer network, albeit one without edges within the layers. However, some bi-partite analytics may be of interest for understanding the relationships between layers. For more detail on visualization approaches related to multilayer network visualization see [4].

The application domains for multilayer network visualization are numerous, and include infrastructure, biology, sociology and digital humanities, among many others. In this talk we briefly discussed these fields as well as giving examples of data sources available on line:

- CoMuNe Lab : https://comunelab.fbk.eu/data.php
- Queen Mary, University of London http://www.maths.qmul.ac.uk/~vnicosia/sw.html
- The Colorado Index of Complex Networks (ICON): https://icon.colorado.edu/

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3.10 Survey on visualization of multilayer networks – Towards a tasks taxonomy

Guy Melançon (University of Bordeaux, FR)

Joint work of Mohammad Ghoniem, Fintan McGee, Guy Melançon, Benoît Otjacques, Bruno Pinaud
Main reference Mohammad Ghoniem, Fintan McGee, Guy Melançon, Benoît Otjacques, Bruno Pinaud: "The State of the Art in Multilayer Network Visualization", Computer Graphics Forum, 2019.
URL https://doi.org/10.1111/cgf.13610

The talk briefly presented a survey work accomplished in parallel with the organization of the workshop, as a teaser of the paper that has been published since then [3].

The talk focused on the task taxonomy part developed in the paper. Tasks on multilayer networks share specificities with those conducted on "ordinary", single layer graphs. However many tasks revolve around the notion of layers as a central device to explore and query the data. Tasks are organized into different categories emerging from existing literature.

- Task category A – Cross layer entity connectivity (e.g., inter-layer path) definitely is one. Numerous papers indeed propose generalization of path-based metrics to multilayer networks, for instance.
- Task category B – Cross layer entity comparison. Being able to observe whether a same node or gorup of nodes have simialr position on different layers (or layer subsets) is a natural question that can be asked.
- Task category C – Layer manipulation, reconfiguration (split, merge, clone, project) allows users to combine layers according to domain questions.
- Task category D1 – Layer comparison based on numerical attributes. Comparing layers is a fundamental task that can either rely on numerical attributes reflecting layer structure. A typical task is to form the distribution of some node or edge statistics and look at correlation values to infer layer similarities.

- Task category D2 – Layer comparison based on topological, connectivity patterns, layer interaction. Layer coparison can also be performed using network topology (link structure), typically looking at how network communities compare for instance.

While we focus here on tasks, it is important to note that layers do not reduce to some operational apparatus. The concept goes far beyond a simple intent to capture data heterogeneity. While it is true this notion is most of the time embodied as nodes and edges of a network being of different "types", its roots lie deeply in sociology [4, 6, 5]. The concept of a multilayer network builds on and encompasses many existing network definitions across many fields, some of which are much older, e.g., from the domain of sociology [1, 2]. Examples of multilayer networks can be found in the domains of biology (the so-called "omics" layers), epidemiology, sociology (in a broad sense, including fields such as criminology, for instance), digital humanities, civil infrastructure and more. Multilayer networks have been explicitly recognised as promising for biological analysis. See [3] for and expanded dicussion and extended references.

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3.11 Digital Ethnography

Anders Kristian Munk (Aalborg University, DK)

URL https://docs.google.com/presentation/d/1BElobz_X7W3l5gze83KY96YpODlHJdf43_–NKmnQu0/edit?usp=sharing

In this talk I map the potential overlaps between ethnography, as a conventionally qualiative and situated field practice born in anthropology, and network analysis of big social data typically associated with computational social science. I argue that data science approahces to ethnographic work raise questions about the interface between qualitative and quantiative modes of reasoning, about the way in which findings are grounded, and about the potential effects of media platforms and algorithmic environments. I then provide a case example to illustrate these challenges, namely the contruction and analysis of the the Atlas of Danish Facebook Culture and suggest ways in which multi-layered network analysis might be a solution to some of them.

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3.12 Interacting with multilayer networks

Benjamin Renoust (Osaka University, JP)

Joint work of Benjamin Renoust, Guy Melançon, Tamara Munzner, Haolin Ren, Marie-Luce Viaud, Shin'Ichi Satoh, Youssef Mourchid, Hocine Cherifi, Mohammed El Hassouni
Main reference Benjamin Renoust, Guy Melançon, Tamara Munzner: "Detangler: Visual Analytics for Multiplex Networks", Comput. Graph. Forum, Vol. 34(3), pp. 321–330, 2015.
URL http://dx.doi.org/10.1111/cgf.12644

In this presentation we introduce three types of interactive visualization with multilayer networks. Through Detangler [1], we introduce the visualization of multilayer networks without displaying a network with multiple layers, all based on careful interaction design and linked highlighting. With the Visual Clouds [2] we introduce the visualization of multilayer networks without displaying actual network. We present different facets captured through different networks with an advanced and coordinated tag-cloud-inspired viusalization that is designed for multimedia search engines. We finally introduce an animated drag-and-drop interaction [3] for the tracking of communities in dynamic multilayer networks. In addition, this paper presents a dataset that combines many characteristics of multilayer networks built on top of movie scripts, though both NLP and computer vision processing [4].

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4 Working groups

4.1 Human Factors and Multilayer Networks

Kathrin Ballweg (TU Darmstadt, DE), Margit Pohl (TU Wien, AT), and Helen C. Purchase (University of Glasgow, GB)

From the user's point of view the design of multilayer networks is a challenging task. Multilayer networks are very complex resulting in a significant amount of cognitive load on the users. It is an open question how to design such networks so that users can derive insights from such visualizations. The working group 6 on Human Factors and Multilayer Networks identified three main research areas in this context:

1. *Overview of existing evaluation studies on multilayer networks or other complex networks:* There are still very few studies doing evaluations of multilayer networks. In this context, it might be useful to look at studies of other complex networks and try to transfer the results of these studies to multilayer networks. The results of such studies can inform the design of multilayer networks.

2. *Overview of psychological research relevant for the evaluation of multilayer networks:* There are several areas in psychology that might be relevant for evaluation studies of multilayer networks, especially in the area of cognitive load. As mentioned above, increased cognitive load is probably the most serious challenge facing designers of multilayer network interfaces. It has been argued that restricting investigations of visualizations to simple tasks can be at times misleading. Cognitive load theory can form a theoretical foundation for getting a more comprehensive picture of cognitive processes users engage in when interacting with complex visualizations.

3. *Development of tentative recommendations for the design of multilayer networks based on the literature review.*

4.2 Interactive Layer Creation

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A multilayer graph may have predefined layers. However, in many practical applications – as it turned out in discussions with domain experts during the seminar – the definition of layers can and should be adapted according to the research question studied. For instance, a social media dataset might contain users, posts, comments, and tags with various possible types of connections between them; research questions related to the spread of information might require different network representations than others related to trending topics. Instead of creating an overarching multilayer network that considers all data entities and all possible relations in one complex structure, it might be more appropriate to let analysts derive appropriate network abstractions on the fly along with querying subsets of the data. Layers of a network can be a powerful abstraction in this process as they reflect different perspectives.

To support interactive layer creation, it is first important to acknowledge that there are different ways to define a layer and several interactive solutions to do so have been already suggested. A certain layer might contain only nodes of a specific type. Similarly, we can use edge types to discern layers. However, layers can also mix different types of nodes and edges. They can be derived from other layers by filtering, flattening, projection, partitioning, or applying set operations like union, intersection, difference, and exclusivity. The starting point of the process might be an overview visualization of the whole dataset but could also be a query interface. Existing querying approaches already provide support to visually define network structures. Both Orion (Heer and Perer, 2014) and Ploceus (Liu et al., 2014) introduce a visual query interface to derive various types of networks from tabular data; subdividing the network covers aspects of multilayer networks. While Orion focusses on diverse subdivision methods and recommending relationship types, Ploceus puts more emphasis on a visual network schema editor. In contrast to using a tabular basis, Cuenca et al. (2018) present a solution for visually querying of multilayer graphs and exploring the results. Although these approaches already support the interactive definition or querying of networks, they still lack that a multilayer network is interactively created, with sophisticated options to contrast different layers. Also, using existing layers to derive and combine new layers is not yet fully leveraged.

As it is difficult, in general, to display a multilayer graph of non-trivial size in a single view across all layers, we suggest using multiple views. In our mental model, imagining a multilayer graph as a vertical stack of planes where each plane represents a layer, we can describe the different views as cuts and aggregations of this stack. We discern the following types of views:

- Intra-layer view(s): A horizontal cut through the stack, i.e., a single layer of the graph.
- Inter-layer view(s): A vertical cut through the stack, i.e., a view that focuses on the edges that connect different layers rather the ones within the layers.
- Conceptual view: An overview of the stack, i.e., a representation of layers and their characteristics.

The intra- and inter-layer views can be borrowed from existing graph visualization research; especially, approaches for multilayer graph visualization as surveyed by McGee et al. (2019) might be used as a basis. However, the conceptual view introduces a novel aspect and forms one cornerstone of an interactive layer creation and management. Instead of directly showing the data, the conceptual view that we propose would abstract from the data and would visually represent the query that was used to define the layer. Statistics on the resulting network layer can augment this representation to provide a preview and make the layers easier to compare.

In addition to the conceptual view, interactions to create and combine the layers will be a second cornerstone of the approach. It is desirable to use direct manipulation as a natural way to interact with the visually represented objects directly (i.e., with the layers, nodes, edges, etc.). Dragging a layer and dropping it on another, for instance, may trigger a combination of the two layers. However, as discussed above, options for combining layers are versatile; hence, different drag-and-drop modes might need to be available. Projections specifically might also be described as a path through the layers. A path from layer A to layer B back to layer A can indicate that a new layer C should be formed that contains the nodes of layer A; two nodes are now connected if there exists an intra-layer path between the nodes from layer A through layer B. Some interactive relationship creation and projection methods are already contained in Orion and Ploceus. Other approaches that support interactive layer manipulation are also surveyed by McGee et al. (2019, Table 2, "C – Layer manip."). These approaches can be extended to integrate with the suggested conceptual view.

In conclusion, the challenges of designing a visualization system to support interactive layer creation and analysis comprise both the design of the conceptual view as well as corresponding interactions. Since the approach shall be used by domain experts (who are often not trained specifically in computer science and data analysis), the interactive layer creation should easy to apply – a general challenge will be to find a good balance between analytical power and ease of use.

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4.3 Unifying the framework of Multi-Layer Network and Visual Analytics

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The notion of multi-layer networks introduces a general framework and common vocabulary for existing ideas in complex network theory [4]. In doing so, it is possible to understand and compare these different ideas in a new and more fruitful manner. However, to make this operationalizable to the visualization and visual analytics community, we need more clarity. For example: What is a layer? What are the semantics of interlayer edges, and specifically, identity links between layers? Can different multilayered networks be expressed or implemented in the same way? And vice versa, can one multilayered network be expressed or implemented in different ways?

It seems it is difficult to agree on a unifying framework for Visual Analytics (VA) and multilayer networks (MLN). The complex notation and diverging conceptualizations of multilayer networks are hard to unify when starting with complex constructs, and they are not easily transferred to a VA domain. The existing framework are very powerful and general, but at the same time there are several aspects that make it difficult to utilize the models from a VA perspective. If we, as computer scientists, cannot agree on how to understand this framework, how can we enter into collaborations with domain experts that we are often involving as collaborators? While considering their use of MLNs might provide new and fruitful insights, it is necessary to agree on the fundamental aspects of the framework, and how to use it for VA. Further, in doing so, these collaborations might facilitate appropriation of the model by researchers with concrete analysis needs. Finally, not agreeing on the foundations makes it difficult to build systems and tools. If we do not understand the foundations, how might we implement software on top of it?

4.3.1 How might we consider MLN from VA?

We think it is possible to respond to the issues from different perspectives, which might in different ways help us approach a general answer to the question "how might we approach MLN for VA?" We offer three such perspectives in the following.

4.3.1.1 Faceting perspective

The faceting perspective very concretely considers the types of visualizations we can create by gradually introducing more and more complexity of MLN. Doing so, we can identify "facets" – visualization techniques – that characterize multilayer networks (see Figure 1).

Facets that might be considered include, those related to nodes of a multilayer network:

- No layers (baseline)
- Existence of layers plus non-layer nodes
- Overlap-free layers
- Sequenced layers
- Overlapping layers
- Nested (or hierarchical) layers

Facets related to edges of a multilayer network:

- No layers (baseline)
- Intra-layer edges
- Inter-layer edges
- Overlapping edges

These offer a starting point for discussion but are not the only possibilities. Further aspects might be considered, such as attributes (categorical or quantitative) at nodes and edges.

The illustrations in Figure 1 are deliberately kept simple. Obviously, dealing with more than two layers is more complicated than the simple depictions might suggests. For multiple overlapping layers there is a clear connection to Euler Diagrams. Yet, for understanding and communicating the framework, we think it is beneficial to provide simple illustrations.

The faceting perspective suggests dividing the complex problem of defining a unifying framework into simple conceptual units. One might describe them as a divide-and-conquer approach to the problem. The simple conceptual units may help in constructing a comprehensive model in a step-wise and modular fashion. Depending on which facets are present in a multilayer network, different complex underlying data structures, visual representations, and interaction facilities might be required. This allows for scalability in terms of the complexity of the domain problem.

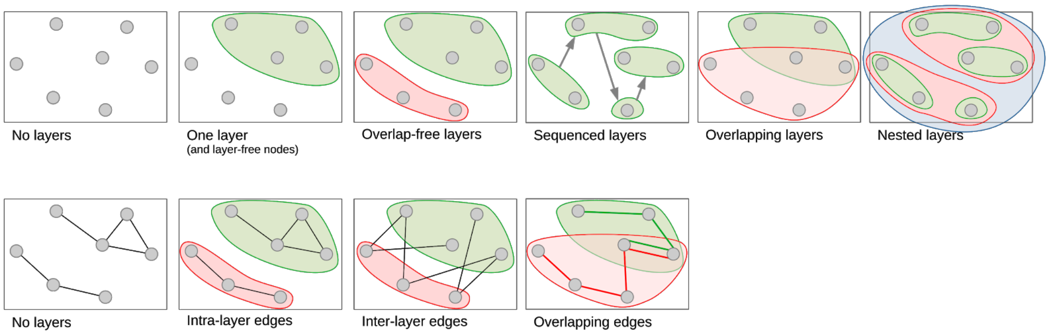

Figure 2 Faceting perspective. In this, we consider the types of visualizations we can create by gradually introducing more and more complexity of MLN.

4.3.1.2 Application perspective

The application perspective considers VA from the application domain, i.e. what MLNs are used for. In this perspective, we think creating and using visual representations of the formal model itself to convey the idea of MLN to domain experts might be fruitful. Such visual representation might articulate a multiplicity of levels that clarify the different possible networks and facilitate the appropriation of the model by researchers. The use of "levels" supports how social scientists (and many other disciplines) think about relationships and data modeling (e.g., [3]). Figure 2 shows one example of such a representation, where each level represents one entity type and relationships within. It can have many layers organized by "aspects" and include edges between these layers. For example, a level consisting of "users" can have n x m layers where n is the number of social network platforms (twitter, FB, etc.), and m is the number of mechanisms for posting (e.g. phone, computer, etc.). In this case, it is possible to represent a tweet sent from a phone and received on a computer.

The purpose of this perspective is not necessarily to be presented as a whole to the final user but can be used to question the research hypothesis and data: "do you have a two-mode graph in your data?" "Do you have multiple relationships between same type nodes?" – "So here are different ways to visualize and analyze them", that can be articulated, or viewed from this or this angle (the "scenarios").

4.3.1.3 Systems perspective

The systems perspective consider how MLNs for VA are implemented, how they are stored, and how they are queried. We recognize that MLN reminds of OLAP structures. For example, Kivelä et al. [4] p. 209 discuss their terminology, saying that they use aspect and not dimension to "avoid terminology clash". In OLAP structures, MLN might be realised by reserving one of the axes specifically for "entity type".

While the framework of MLN is not a cube, the cubic and well aligned appearance is a convenient way of representing things to make them understandable and less abstract so that they can be easily applied. However, in the model of Kivelä et al., layers are less strictly organised. By considering a unification of MLN based on OLAP cubes, we think we might introduce slightly more organisation so that the operations on the data are facilitated and visually explicit. Realising that the cubic form of OLAP cubes suggest that there are only three dimensions available, we stress that MLNs might have many more aspects than that. However, in the examples that we have observed, 3 aspect-networks are common.

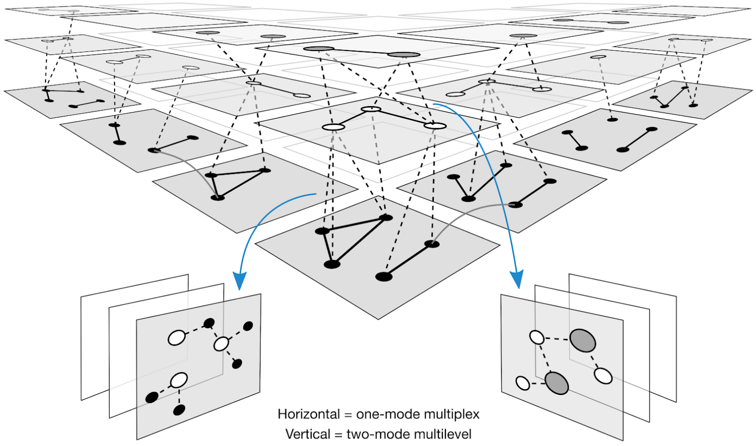

Figure 3 Figure 2: Application perspective. In collaborating with domain experts, using visual representations of the formal model might be beneficial. This figure provides just one example of a visual representation of the formal model itself, which might be used in collaborating with domain experts to establish a common grounding of what we might consider MLNs. In this representation, the multilayer network system is made of three 1-mode and two 2-mode networks organized on three interconnected levels. At each level, this representation explicitly shows the possibility of developing the graph depending on two (or more) aspects, which is also the case for the 2-mode network connecting the levels (vertical layers outside the aligned layers).

The inconvenience of the concept of the OLAP cube is that not all levels will have the same number of dimensions, and these dimensions will not necessarily be aligned. This recalls that this is only an intellectual framework and not a grid where all the layers will be filled and analyzed at the same time.

As a side note, space-time cubes [1] might be a useful starting point for considering a unification of OLAP and MLN.

4.3.2 Discussion

We presented three different perspectives on MLN and VA. While these have differences, they have important and relevant similarities. For example, the faceting perspective can also be used for collaborating between VA experts and domain experts. The facet list can serve as a checklist for inquiring whether a domain problem requires a certain characteristic. This might be more approachable than working directly with the visual representation of the MLN model discussed in the application perspective and might be a more direct way of discussing with domain experts what kinds of complex multilayer networks are required for the problem at hand.

Agreeing on an understanding of the MLN framework and how it might be used, the VA community might stand to create more fruitful visualization techniques for MLN, improve our understanding and appropriation of MLN concepts for different application domains, and allow us to build systems that, not implement MLN concepts, but allow interoperability between different tools and systems in this area. While existing visualization tools and techniques (e.g., [5], [2], [6]) have almost literately provided visualization designs that show MLN, a more structured approach based on a framework can bring more clarity to the table.

4.3.3 Conclusion

We have outlined challenges in unifying the framework of multi-layer network and visual analytics. In discussing these challenges, we offered three perspectives (faceting, application, and systems perspectives). The faceting perspective discusses gradually introducing more and more complexity of MLN based on visualization techniques. The application perspective discusses how we might collaborate on MLN projects with domain experts. The systems perspective discusses how we might start to think about implementing these concepts in concrete systems and tools based on OLAP cubes, and how these might be interoperable. Having these three conceptual perspectives allow us to reason about the concept of multilayer network and visualization from different perspectives. While we think these are useful starting points, other perspectives might also be fruitful.

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4.4 Analytics, Communities Comparison and attributes

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The task taxonomy presented as part of McGee *et al.*'s state of the art report on multilayer network visualization [1], highlights the multilayer specific tasks related to interaction between layers which are themselves important entities in addition to the nodes and edges. Part of understanding the relationship between layers is understanding the relationships between the nodes of the layers. This concept has been explored in the context of bipartite graphs by Latapy *et al.*, with the notion of node redundancy [2]. Kivelä *et al.* [3] also refer to a range of metrics for relating layers.

A natural question that arises from the treatment of multilayer networks is how much layers interact. We propose a general measure of between-layers interaction that lends itself to comparing different real-life multilayer networks. We base it on Shannon entropy and call it multilayer entropy or ML. It is based on a null model of random-uniform distributions of inter-layer links from one node in one level to all other nodes in the other level, corresponding to maximum entropy. Low levels of ML correspond to high preferentiality in linking from that node to only some (or even only one) nodes in the other layer considered. Multilayer entropy across the layers of a multiplex network is always 0.

Let us be more precise. We are looking for:

- One or more *quantitative* measures.
- That would apply to *multilayer* networks.
- With an *intuitive interpretation.* A $[0, 1]$ normalized measure would be preferred.
- And are *general*: they apply to both multiplex networks and networks of networks.

Our final goal is to apply this hypothetical measure to several different multilayer datasets. This gives us a comparative dimension, leading to statements like "this measure is close to 0 when the layers represent hierarchies", or "this measure is exactly 1 when the layers are randomly connected", and so on.

The perspective of our our working group discussion is along the lines of "Real world multilayer networks are (not) X", where X is some property. This would be the multilayer equivalent of Barabási's claim that scale free networks abound in real life, or, conversely, Braido and Clauset's that they are rare. A full paper elaborating on this type of claim requires diverse data from different disciplines for validation, which was the case of the seminar.

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4.5 Visual Encodings

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There are several ways to visualize Multilayered Networks [1]. In an interactive analysis, however, not only the final visualization plays an important role, but also the ability to quickly create and link new layers depending on the filtering or relevance of the underlying data. It is also important to keep an overview of the specific properties and important parameters of the individual layers. Another important question is how analysts explore multilayered networks. Either via a bottom-up approach based on individual interest (e.g. a specific node in one layer) or a top-down approach (e.g. similarity between layers, identifying clusters across layers) could be facilitated. A top-down approach would help users to get a high-level (holistic) view of the layered networks. But it is unclear how to achieve such an informative high-level view. There does not seem to be any real approach to providing an overview for multilayered networks. Hiveplots or parallel cooridnates, for instance, cannot show all the data for large inputs and for smaller ones they still do not give a high-level view of the structure. The working group discussed the following questions:

- How is the data aggregated?
- Is there a possibility to use t-SNE for multilayered data?
- Are there limits of specific visual encodings?
- How to design visualizations to give users an overview of layers and their interconnections?

Goal of this working group is to define a design space of possibilities to draw multi-layer approaches. How could we facilitate the reduction of information to show the important measurements of layers and their connections? A possible way would be to visualize layers as a supergraph/layergraph in order to show possibile path's to interactively aggregate and visualize data and connections. This is done to assist users in getting an overview of their data and provide a way to interactively create individual network views based on selections of nodes and edges in the supergraph. The supergraph could show meta-information about the underlying graphs and interconnections, such as the type of graph (unconnected, tree, directed/undirected graph, completely connected graph, etc.). The details of the visualization and what kind of interactions are used exactly have to be discussed in detail.

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