Unifying the framework of Multi-Layer Network and Visual Analytics

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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.

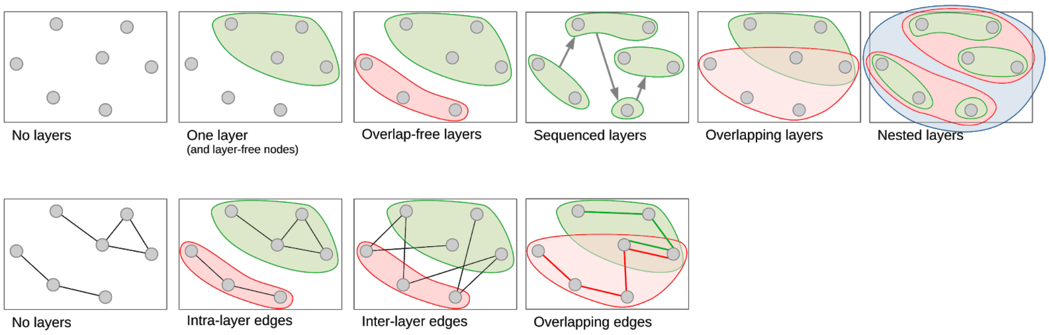

Figure 2 Faceting perspective. In this, we consider the types of visualizations we can create by gradually introducing more and more complexity of MLN.

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.

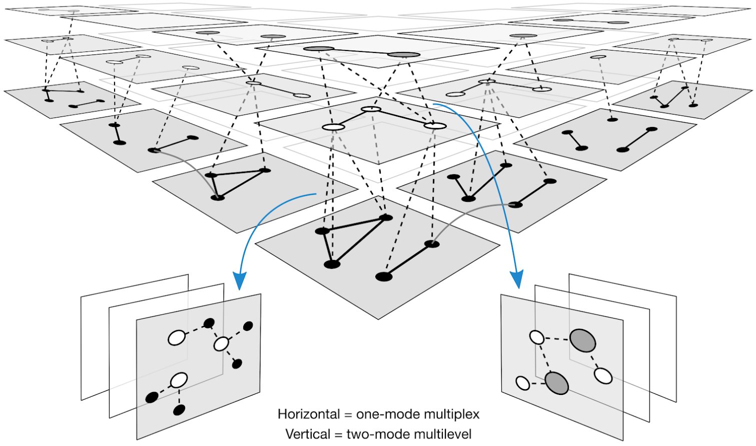

Figure 3 Figure 2: Application perspective. In collaborating with domain experts, using visual representations of the formal model might be beneficial. This figure provides just one example of a visual representation of the formal model itself, which might be used in collaborating with domain experts 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.