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The Design Space of Temporal Graph Visualisation

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Abstract

This paper presents our work in mapping the design space of techniques for temporal graph visualisation. We identify two independent dimensions upon which the techniques can be classified: graph structural encoding and temporal encoding. Based on these dimensions, we create a matrix into which we organise existing techniques. We identify gaps in this design space which may prove interesting opportunities for the development of novel techniques. We also consider additional dimensions upon which further useful classification could be made. In organising the disparate existing approaches from a wide range of domains, our classification will assist those new to the research area, and designers and evaluators developing systems for temporal graph data by raising awareness of the range of possible approaches available, and highlighting possible directions for further research.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—Graphical user interfaces (GUI)

1. Introduction

Temporal graph visualisation deals with the challenges involved in visually representing change in a graph over time, and is of interest across a wide range of disciplines. Given the growing interest in this area, we seek to categorise the disparate existing approaches to visualising temporal graph data to provide an overview of current techniques, and highlight possible directions for the development of new techniques. Our categorisation is presented at a high, abstract level, and seeks only to capture the visual appearance of the various approaches. It therefore does not consider, for example, the structure of the input data, or the algorithms used to produce the visualisations. It will be of benefit to researchers and tool designers by bringing order to the range of possible approaches across a wide range of domains. Further, on mapping the techniques from the literature to our proposed design space, we discovered a number of less-explored possibilities for visual representations. These possibilities are likely to be of interest to those researching new and novel techniques for temporal graph visualisation.

In section 2 we discuss related work. In section 3 we outline the design space, and describe the possibilities for encodings along the graph structural and temporal dimensions. Based on our mapping of the literature to the design space, we discuss possible directions for future research in section 4.1, and our plans for future work in section 5.

2. Related Work

A number of surveys and taxonomies of visual techniques exist in the literature. In addition to surveys and categorisations of graph visualisation techniques e.g. [SHS11, vLKS*11], of particular interest to our work are Javed and Elmqvist's [JE12] design space of composite visualisations and Gleicher et al.'s [GAW*11] taxonomy of techniques for visual comparison. Also relevant are the temporal visualisation surveys e.g. [AMST11, Wil12]. Some discussion exists in the literature with regard to classifying visual approaches for temporal graph data, however, to our knowledge, no survey specifically focussing on visual techniques for temporal graph data has yet been carried out. Hadlak et al. [HSS11] categorise visual approaches for large dynamic graphs based on the reduction techniques used: whether the temporal or structural element of the graph is reduced, and whether the reduction is via abstraction or selection, or is unreduced. Federico et al. [FAM*11] divide the possible representations with respect to the mapping of the temporal dimension: mapping to time (animation), space (juxtaposition), a visual variable (superimposition), or an additional spatial dimension (2.5D). Rufiange and McGuffin's [RM13] taxonomy is also based on the temporal dimension, dividing the techniques into small multiples, animation, embedded glyphs, linearised graph plus time axis, and 3D. Von Landesberger et al. [vLKS*11] classify graphs according to whether they are static or time dependent (involving attribute change, structural change, or both) and graph structure (trees, generic graphs, and compound graphs). In all of these discussions, a key distinction between the temporal and graph structural dimensions is apparent; we use this as the fundamental division to create a design space showing the possible combinations of graph structural and temporal encodings.

3. Design Space

We identify two independent dimensions upon which visual techniques for temporal graph data can be classified: graph structural encoding and temporal encoding. Based on these dimensions, we create a matrix into which we organise the existing techniques (Figure 1). We first consider the possibilities along each of these dimensions, then discuss where the existing techniques fit within this space.

3.1. Graph Structural Dimension

There is a vast amount of literature on static graph visualisation. The key challenge focusses on laying out the graph to represent relations between elements in a readable manner - affording the viewer an accurate, usable, and readily understandable, representation of the graph's structure - while being computable in an acceptable timeframe. As more than one layout can correspond to the same graph structure, a set of aesthetic criteria [BRSG07], along with numerous layout algorithms have been developed. The difficulties for graph layout are compounded at scale, and recent work has focussed on the problem of visualising large graphs (see [vLKS*11]). An additional challenge is that of multivariate graphs: while much of the focus for both static and dynamic graph drawing has been on representing the graph's topological structure, an additional problem is finding suitable ways to represent multiple node and edge attributes. Having used up the spatial dimensions for graph layout, possibilities for attribute representation are restricted; moreover, we often wish to represent attribute values in the graph context, thus the tiny amount of space available to represent each node and edge's attribute values is a major issue.

The underlying structure of the graph data largely determines the visual approach which can be taken: von Landesberger et al. [vLKS*11] divide their discussion into trees (those with hierarchical structure), general graphs (which may be directed, undirected or mixed) and compound graphs (those with both hierarchical structure and other relations between nodes). The two main ways to represent general graphs are node link diagrams or matrix representations. Schulz and Schumann [SS06] distinguish three possible ways in which network visualisation techniques can be categorised: directed vs undirected; explicit vs. implicit edge representation; free, styled, or fixed node layout. Similarly, for tree representations, Schulz [Sch11] identifies three 'design axes': dimensionality (2D, 3D, or hybrid); edge representation (explicit, implicit, or hybrid); and node alignment (radial, axis-parallel, or free). We use a simple classification in our matrix of visual techniques, dividing the possible graph structural encodings into five general categories: space filling (enclosure, adjacency, overlap), node-link, matrix, compound graph representations, and 'other' (e.g. no structural encoding, topological statistics only). For the sake of simplicity, we do not consider directionality, dimensionality or node alignment in our categorisation.

3.2. Temporal Dimension

Considerable work has been carried out in visualising general time-oriented data. Aigner et al. [AMST11] distinguish the possibilities for visual representation by whether time is mapped to space (static) or time (dynamic), and the dimensionality of the presentation space (2D or 3D). However, the possibilities for temporal graph visualisation are restricted by the need to show both graph structure and time: Moody et al. [MMB05] note that a key problem is that the two spatial dimensions - the most visually salient channels - are usually taken up in laying out the graph, raising the question of how to represent the third, temporal, dimension. In classifying the approaches, in addition to extracting those commonly discussed in the temporal graph literature, we draw on Javed and Elmqvist's [JE12] design patterns for composite visualisation (juxtaposition, superimposition, overloading, nesting, integration), and Gleicher et al.'s [GAW*11] categories of comparative designs (juxtaposition, superposition, explicit encoding). We identify the following temporal encoding categories: (1) sequential views (2) juxtaposition (3) additional spatial dimension (4) superimposition (5) merged views (6) nested views (7) time as a node in the graph. These categories can be grouped based on whether multiple temporal snapshots are presented (1-4), or time is 'embedded' within the graph structure (5-7).

The first four approaches show a series of what Archambault et al. [APP11] refer to as 'timeslices': snapshots encoding the structure of the graph at a given time. These approaches require particular consideration to be given to the readability and computation of the layout of the graph structure at each timeslice: much work to date has focussed on the computational difficulties of adapting and developing layout algorithms for dynamic graphs e.g. [EGI99, FT08], given the trade-off between the accepted set of aesthetic heuristics for (static) graph drawing and maintaining the user's 'mental model' over a series of timeslices, and also in assessing the resulting representations in terms of user comprehension e.g. [APP11]. These 'timeslice approaches' can be divided based on whether the timeslices are mapped to time (dynamic presentation) or space (static presentation). *Sequential views* are dynamic: timeslices are presented one

			Graph structural encoding				
			Space filling	**Node-link**	**Matrix**	**Compound**	**Other**
Temporal encoding	**Multiple timeslices**	**Sequential view**	TS08 (5)	BdM06 (47)	FQ08 (1)	RPD09 (4)	
		Juxtaposition	TJ92 (1)	RM13 (20)	PS12 (3)	BD08 (4)	*Graph statistics* GGK*11 (4) *Alluvial diagrams* RB10 (3)
		Additional spatial dimension		ADM*04 (12)	BPF14 (1)		GHW09 (1)
		Superimposition		FAM*11 (5)	MGK11 (1)		
	Embedded	**Merged**		GdBG11 (5)	BPF14 (1)		
		Nested	HDKS05 (2)	SLN05 (2)	YEL10 (3)		
		Time as a node		TDKB07 (2)	Hoe11 (1)		

Figure 1: *Design space of temporal graph visualisation. Examples from the literature are shown in the appropriate cells. More densely shaded cells indicate more papers used these encodings; the number of publications is also included in brackets. Our full mapping of techniques in the literature to the design space is included in the supplementary material.*

after the other, in sequence, each replacing the last. Navigation through the timeseries may be automated (play/pause functionality) or interactive (e.g. through use of a timeslider). Transitioning techniques, such as animation and interpolation of node positions, may be employed to assist the user in following changes between timeslices. The other three approaches are static: *juxtaposition* most often resembles Tufte's 'small multiples' [Tuf83], with timeslices laid out adjacent to one another in sequence; however, we adopt Gleicher et al.'s [GAW*11] wider definition, including in this category examples where timeslices are positioned separately, but in the same display space e.g. Tree-ring Layouts [FHQ11] use concentric circles to indicate the temporal aspect of the network. We also include in this category general time series views of graph-based statistics (where statistical values represent the graph or its attributes at multiple points in time), and *alluvial diagrams* [RB10], which plot node-related statistics (topological or attribute based) as lines over time, with relatedness in the graph represented by positioning the nodes' timelines closer together. Where an *additional spatial dimension* is used, timeslices are either presented as separate layers on an additional plane ('2.5D' [FAM*11]), or the nodes of the timeslices are 'stacked' resulting in three dimensional objects. *Superimposition* [JE12] (or 'superposition' [GAW*11]), involves overlaying objects in the same display space; in the temporal graph case, timeslices are stacked on top of one another and 'flattened', with a visual variable (such as colour, transparency etc.) distinguishing elements belonging to different timeslices [FAM*11]. This results in the same nodes and edges appearing more than once in the same view.

Approaches 5-7 embed the temporal dimension within a single graph structure. *Merged views* show a single (cumulated) graph structure, and use an additional encoding (e.g. colour) to indicate ageing of nodes and edges. *Nested views* [JE12] in the temporal graph case show the temporal aspect of the data by embedding small timeseries charts or glyphs in the nodes and/or edges. A bipartite graph including *time as a node* can be created; any node linked to a time node indicates that it appeared in the graph at that time. A variation of this is 1.5D [SWW11], where a focus node contains an embedded timeline glyph and other nodes connect to the appropriate section of the timeline.

Integration [JE12], which involves the use of visual links between views, and *explicit encoding* [GAW*11], where the relationship between two objects is computed and visually encoded, are not categories in our design space, which is concerned solely with temporal and graph structural encodings. However, these techniques may be used in conjunction with the timeslice approaches of the design space to show the differences or matches between timeslices. This is often of interest in temporal graph visualisation, which is closely related to graph comparison. Visual links are often used in conjunction with 2.5D views to map node positions between timeslices e.g. [EHKW04, FAM*11], but could potentially be used with any of the static timeslice approaches (2-4). There are a number of examples of 'explicit encoding' in the graph comparison literature, for example, difference maps [Arc09] and ratio contrast treemaps [TS07]. Used in conjunction with a timeslice approach e.g. [EHKW04], they can show the evolving relationships between timeslices over multiple different timepoints. Finally, in *overloading* [JE12] the space of one visualisation is utilised for another; some examples of this can be seen when views are combined, as discussed in the next section.

3.3. Combining Views

The importance of offering multiple views on the data in order to maximise insight, balance the strengths and weaknesses of individual views, and avoid misinterpretation, is a well-established design principle in visualisation. In temporal graph visualisation, it is increasingly common for systems to combine a number of visual approaches. Use of time series displays of network statistics as an accompaniment to sequential views is particularly common, often being integrated with the temporal navigation. Several systems allow the user to select and switch between the most appropriate representations for the data and task at hand [BPF14, EHKW04, FAM*11, ITK10]. Federico et al. [FAM*12] note the importance of supporting the user's mental map when switching between views; their 'vertigo zoom' interaction technique does this through use of smooth transitions between the structural and temporal aspects of the data. Different temporal encodings can also be shown in the same screenspace e.g. Bach et al. [BPF13] combine animation and small multiples. Further, systems which allow the user to select views and show them in the same screen space include Hadlak et al.'s [HSS11] 'in situ' technique, which allows multiple views of both the temporal and structural aspects of the data to be shown in a single, tightly integrated view, and DiffAni [RM13], which incorporates small multiple, animation and difference map 'tiles' which can be selected to represent different parts of the timeline.

4. Mapping Existing Techniques to the Design Space

We surveyed the literature relating to temporal graph visualisation, including system and technique papers, comparative evaluations of techniques, and those discussing the use of tools to perform analysis, and mapped it to our design space based on the techniques being discussed. We include examples from our mapping in Figure 1; the complete mapping can be found in the supplementary material.

4.1. Discussion

The most common graph structural representation we encountered in the temporal graph visualisation literature was node-link. This is in-keeping with findings from the static graph literature, where the majority of systems are node-link based [HFM07]. Matrixes are particularly useful for visualising dense networks due to the absence of edge crossings, and they have been shown to outperform node-link diagrams on a number of user tasks in the static context [GFC05]. We therefore suggest that further research could be applied in this area. There is also room for further exploration of temporal visualisations utilising space filling techniques.

While we found a number of examples of juxtaposition, sequential views were by far the most widely discussed temporal encoding. This is interesting, as juxtaposed views have performed well in studies comparing them with sequential approaches [APP11, FQ10]. The other approaches to temporal encoding featured less prominently in the literature.

There are a number of gaps and sparsely populated cells in the design space; while there may be good reason for this (e.g. incorporating time as a node in a space-filling representation would not be possible given that a hierarchical graph structure is required), our mapping shows some possible interesting directions for further exploration.

5. Conclusions

We have presented a design space of temporal graph visualisation techniques based on the temporal and graph structural encodings employed. Our mapping of existing techniques from the literature to this design space has so far highlighted a number of less-explored possibilities for visual representations. In our future work we plan to investigate further useful dimensions upon which the visual techniques can be classified, and produce a more detailed categorisation. For example, the techniques could be categorised based on their support for topological and/or attribute change, while sequential approaches could be further subdivided based on the navigation and/or transitioning techniques employed. When creating the design space, we did not carry out a full review of the general time visualisation literature, and it may be the case that there are additional possibilities for temporal encodings which have not yet been applied to temporal graphs. We also plan to map the techniques to the temporal graph tasks [KKC14] which they support, in order to be of additional benefit in the design and evaluation processes: for example, we anticipate that temporal trends in the attributes of individual nodes or edges may be more easily identified using nested views, while tasks involving changes in graph structure, or attribute distributions over the graph, may be better supported by e.g. the timeslice approaches.

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