DOI: 10.1111/cgf.14831
Eurographics Conference on Visualization (EuroVis) 2023
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(Guest Editors)

COMPUTER GRAPHICS *forum*
*Volume 42 (2023), Number 3*

# Unfolding Edges: Adding Context to Edges in Multivariate Graph Visualization

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**Abstract**

*Existing work on visualizing multivariate graphs is primarily concerned with representing the attributes of nodes. Even though edges are the constitutive elements of networks, there have been only few attempts to visualize attributes of edges. In this work, we focus on the critical importance of edge attributes for interpreting network visualizations and building trust in the underlying data. We propose 'unfolding of edges' as an interactive approach to integrate multivariate edge attributes dynamically into existing node-link diagrams. Unfolding edges is an in-situ approach that gradually transforms basic links into detailed representations of the associated edge attributes. This approach extends focus+context, semantic zoom, and animated transitions for network visualizations to accommodate edge details on-demand without cluttering the overall graph layout. We explore the design space for the unfolding of edges, which covers aspects of making space for the unfolding, of actually representing the edge context, and of navigating between edges. To demonstrate the utility of our approach, we present two case studies in the context of historical network analysis and computational social science. For these, web-based prototypes were implemented based on which we conducted interviews with domain experts. The experts' feedback suggests that the proposed unfolding of edges is a useful tool for exploring rich edge information of multivariate graphs.*

**CCS Concepts**

• ***Human-centered computing*** → ***Visualization techniques; Graph drawings; Interaction design;***

## 1. Introduction

When employing data visualization for humanist research, it is instrumental for scholars to bridge the semantic distance between visualizations and the underlying materials [LMA*20]. For network visualizations, multivariate edge attributes are central factors for credibility and trust in a visualization. For example, in the digital humanities, researchers work with networks as highly abstracted and reduced versions of a relational reality. To understand such networks, researchers need an opportunity to re-introduce context into network visualizations and anchor them in the underlying data [MBL*22]: *"There is, of course, a big difference whether you are a family member, a correspondence partner, or whether you met at a congress during a coffee break. These are all relationships, but of course they have different weights in their interpretation. This is, for example, something we would like to see in a visualization."*

Despite the critical importance of understanding the multivariate contexts of graph edges, it remains challenging to integrate them into network visualizations. Existing work on the visual display of multivariate graph attributes focuses primarily on representing node attributes [KPW14b], while our focus is on edge attributes. A common strategy is to encode edge attributes directly on the links of node-link diagrams (NLD) [NSML19]. While NLD are widely applied in many fields and have proven advantages for several graph analytic tasks [GFC04, ASA*23], an on-edge encoding is suited only for basic edge attributes, and applying it globally to all edges can quickly lead to over-plotting and clutter. As an alternative, one may outsource edge information into separate views, but this may harm the fluidity of the visual data exploration [EMJ*11]. Nobre et al. found that there is surprisingly little work that would address the challenge of representing multivariate edge attributes via interaction techniques [NSML19].

To narrow this gap in the literature, we propose *unfolding of edges* as an interactive approach for the in-situ exploration of multivariate edge attributes [BDT21]. The core idea of unfolding edges is to transform basic links dynamically into detailed representations of their associated edge attributes. In a first step, the overall graph layout is adapted via transformations such as zoom and rotation to make space. Then, edges are unfolded from a basic link to a more elaborate representation depending on the underlying data attributes, for which we discuss different options. Finally, we incorporate interactive ways to facilitate an edge-centered exploration of network data. To avoid visual clutter across the entire network representation our unfolding of edges is applied on-demand and only locally to a selected edge.

We explore the design space for unfolding edges and discuss its conceptual variants. By implementing two case-studies, a Nobel

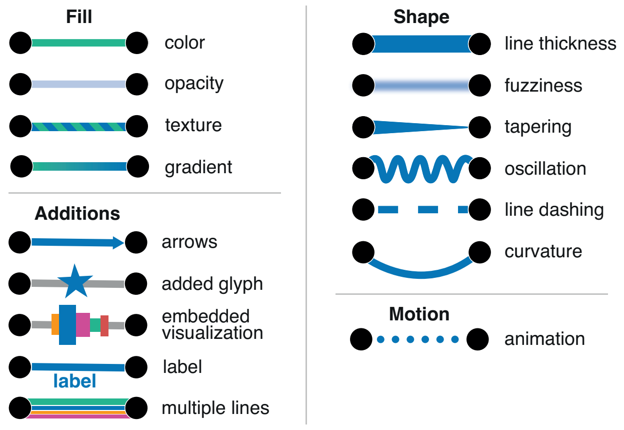


**Figure 1:** *Exemplary variants of on-edge encoding. Fill: color [BNML19], opacity [GHL15], texture [HIvWF11], gradient [VdEVW14]. Shape: line thickness [Wat06], fuzziness [GHL15], tapering [HIvWF11], oscillation [NJBJ09], line dashing [GHL15], curvature [RDLC12]. Additions: arrows [VdEVW14], added glyphs or embedded visualizations [SSSE16], label [WMP*05], multiple lines [KAW*14]. Motion: animation [RAB*18].* 

prize network and a political conflict network, we illustrate the potential of our approach. Finally, we report qualitative insights from a user study with domain experts from the fields of historical network analysis and computational social science. Their feedback suggests that unfolding of edges is a suitable approach to promote transparency and interpretability of NLD.

## 2. Related Work

In general, our research relates to fundamental interaction concepts, including focus+context to display details on-demand within an overview visualization [CKB09] and semantic zoom to enhance or reduce detail depending on the visualization scaling [PF93]. We are especially inspired by the notion of 'fluid interaction' suggesting that in-situ representation changes stimulate open-ended and engaging flow experiences by making use of direct manipulation and animated transitions between views [EMJ*11]. Such transitioned representations for the exploration of complex multivariate data have been characterized as flexible, elastic, and 'folded' spaces whose elements can be dynamically manipulated inside a given layout [BBD20, BBBD20, TAA*21]. Following this line of research, we developed the concept of unfolding edges. More specifically, our approach is informed by prior work on interactive graph visualization, in particular, on encoding and interaction techniques to display detailed information within visualization layouts, with a focus on edges in NLD.

### 2.1. Visualizing Edge Attributes

In NLD, edge attributes are commonly visualized via on-edge encoding (see Fig. 1), for which the visual properties of links (e.g., stroke width, dash pattern) or additional graphical components (e.g., glyphs, labels, animation) represent the edge attributes [NSML19]. A single numeric or categorical edge attribute (e.g., weight or class) can be encoded by varying stroke width or color [Wat06, BNML19]. Arrows, gradients [HIvWF11], and animated particles [RAB*18] can encode edge direction. Textual edge information can be visualized via curved and tapered labels that connect adjacent nodes [WMP*05]. Fuzziness of edges can indicate data uncertainty [GHL15]. Other on-edge encoding possibilities include the compression of edges into oscillating waves in order to represent edge length [NJBJ09], parallel or curved sub-edges to visualize multiple edges simultaneously [KAW*14, RDLC12], and miniature visualizations directly embedded on edges for representing multivariate edge attributes [SSSE16].

An on-edge encoding of a single data attribute usually integrates well with NLD and leaves the representation of the graph topology intact. However, as on-edge encoding is typically applied to all edges, it usually does not scale well to large networks and tends to lead to cluttered and overcrowded displays, depending on the size of the graph, the number of edge attributes, and the richness of their encoding. Hence, despite the diversity of options for encoding edge attributes in NLD, in practice their individual use is often limited to basic variations of line width and color, and their combined use for multivariate attributes remains challenging [KPW14a, NSML19].

### 2.2. Interactive On-Demand Techniques

Instead of encoding all information globally in full detail, visualization techniques can make use of interactivity to allow the viewer to vary the level of detail for specific parts of interest on demand [TS20]. Usually, this involves reducing the complexity of a graph visualization, typically in a focus+context manner. For example, one can resort to filtering by edge attributes [NSML19] together with cross-filterable coordinated views [Wea10], or to rolling up multiple edges into one aggregated element [Wat06]. Several interaction techniques aim to separate edges to make them more distinguishable in dense areas or to bundle edges to reduce the overall complexity of the visualization. Such techniques include edge plucking [WC07], edge bundling [Hol06], interactive link curvature [RDLC12], edge expansion [FHH*20], edge lenses [WCG03, TAvHS06], interactive modifications of force-layouts [SHW*20], or multi-touch gestures [SNDC10].

While the purpose of these techniques is to reduce visual complexity to simplify the interpretation of graph visualizations, our goal is to utilize the available space to dynamically add more detail and contextual information. To this end, we enhance classic NLD with edge-based interactions that enable the on-demand integration of contextual details within a local scope.

### 2.3. Embedding Additional Information

In general, different visual representations with varying levels of detail can be combined by nesting, juxtaposing, integrating, superimposing, or overloading detail representations into a parent visualization [JE12]. In terms of graph visualizations, hybrid techniques [DGDMT21], such as NodeTrix [HFM07] or Responsive Matrix Cells [HBS*21], embed alternative visualization types into an underlying global NLD or matrix representation. Similarly, interactive lenses can alter a representation locally on demand [TGK*17]. Lenses specifically designed for graphs can clean up edge clutter and create local in-situ neighborhood overviews to support the navigation in graphs [TAS09, BBT23]. A rather radical approach is SurgeryCuts, where a visualization is cut open to embed additional information without over-plotting [ABK*19].

Several approaches exist to integrate additional details to the nodes in NLD [vLKS*11, NSML19]. Again, semantic zoom [RUK*10] and interactive lenses [JDK10] are well suited for this purpose. Interactive expand and collapse operations on aggregated meta-nodes can be used to either reveal or hide their internal nodes for exploring larger graphs in a hierarchical manner [AvHK06, AMA08, TAS09, VBW15]. While all these examples are concerned with adding information to nodes, our work focuses on adding context to the graph edges.

In contrast to enhancement techniques for nodes, there is still a scarcity of comparable techniques to reveal multivariate edge attributes [NSML19]. However, there is one promising example that is quite similar to our idea of unfolding edges: WordBridge dynamically expands edges in NLD into word clouds to add textual context information [KKEE11]. This example indicates that there is potential in dynamically adding context to edges, however, the broader design space of such approaches still remains largely unexplored.

## 3. Opening the Design Space for Unfolding Graph Edges

Our work addresses multivariate graphs consisting of nodes and edges with multivariate data attributes. The focus lies on edge attributes, which define some form of *context* for each graph edge. The meaning of the context can vary depending on the application. It may be related to the classic notions of attributed edges (e.g., weight, direction, class label) or aggregated edges (e.g., edges consisting of multiple sub-edges), as well as to temporal information (e.g., different time series for individual edges), spatial aspects (e.g., edges as geo-referenced paths), semantic annotations (e.g., text documents associated with edges), or any combination thereof.

As a baseline for the visualization of such multivariate graphs, we use a standard NLD as shown in Figure 5 (left). The base visualization primarily focuses on representing the topology of the graph. Node positions are usually generated by force-directed layout algorithms [FR91, Hu05], but can also be based on node attributes, for example, in the form of semantic substrates [SA06] or geospatial placements [SYPB21]. For the edges, simple on-edge encodings [NSML19] may represent a selected edge attribute or foreshadow the amount or type of hidden contextual information. Standard interaction techniques are available allowing users to zoom and pan as well as to highlight and select nodes and edges. To provide access to the contextual information of edges, we further give users the option to interactively unfold edges.

With *unfolding of edges*, we propose a general interaction concept for the in-situ display of edge context in NLD. The edge unfolding relies on the use of animated transitions to gradually transform an edge to represent more details about its semantic context or data provenance, and to navigate between global and local network views without mode changes. The term *unfolding* refers to the metaphorical operation of "folding", a fluid motion between folded and unfolded display states that are connected by carefully designed and smoothly animated transitions [BBD20].

For the edge unfolding, we define four essential design goals, which are based on our collaborations and discussions [BBD20, TAA*21, MBL*22] with scholars from different domains and our prior literature research:

**DG1 — Expose edge contexts on demand:** To help users explore and analyze multivariate graphs, understand the provenance of the data, and ultimately build trust in the obtained insights, it is paramount to provide access to the contexts of the connections between entities [MBL*22]. In contrast to techniques that reduce the complexity of NLD, the aim is to support the interactive enhancement of relevant contextual information for individual edges.

**DG2 — Display contextual information in situ:** Building and maintaining a mental map of the data is crucial when analyzing graphs [AKM18]. Therefore, we aim for an in-situ embedding of contextual edge information directly where the user needs it without permanently disrupting the overall mental map. Through an in-situ display, we want to promote flow and reduce semantic and spatial separation between the data and their representation.

**DG3 — Support continuous exploration:** Exploratory data analysis is a fluid process that involves studying the unknown, but also backtracking to previous views in order to continue on alternative exploration paths [EMJ*11]. We aim to devise techniques for continuous data navigation, allowing users to move seamlessly between a global overview and local contextualized detail views using the graph topology as pathways.

**DG4 — Transition between views smoothly:** There is positive evidence that users favor animated transitions for smooth view changes over abrupt display switches [FPS*21]. We aim to design useful animated transitions that support users in comprehending the embedding of contextual information into a global network view and in navigating between different parts of the data.

Based on these design goals, we develop the core principles of our approach. In the following, we consider three key conceptual and design questions: **1)** How to visualize the edge context? **2)** How to embed the edge context in situ and facilitate navigation? **3)** How to provide transitions that enhance orientation?

### 3.1. Design Alternatives for Visualizing Edge Contexts

As the design of in-situ representations of edge contexts (DG2) depends on various factors, including network characteristics, multivariate attributes, and domain conventions, there is no single solution that would satisfy all situations. Therefore, we discuss different alternatives from a larger design space. Conceptually, two basic options exists for representing edge context in situ. One can either (A) alter the original edge representation or (B) create a dedicated new representation (see Figure 2). On-edge encoding (see Figure 1) is an example of case (A), where the appearance of an edge is varied to visualize its attributes. On-edge encoding is usually limited to one or very few attributes only. For more attributes or sub-edges, an edge can also be fanned-out from the original straight line to a fan of curves, similar to [RDLC12, FHH*20]. Each curve can encode a different attribute, time stamp, or sub-edge, and the curves can be ordered meaningfully, for example, according to time. Alternatively, one could alter the shape of an edge to indicate an underlying geo-spatial path, a textual label, or a sub-network (see Figure 2A).

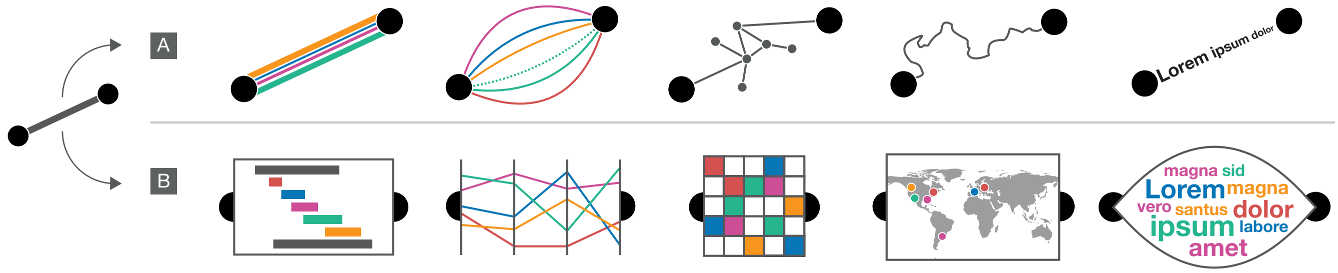


**Figure 2:** *Simplified examples of edge context representations, with alterations of the original edge representation making use of on-edge encoding strategies (see Figure 1) (top) and dedicated new edge context representations (bottom).*

Still more encoding options exist for case (B), where the original edge is replaced with a dedicated new representation (see Figure 2B). In this case, unfolding an edge morphs its straight link into a visualization inset, which may take various forms, e.g., a box or a bubble as inspired by SurgeryCuts [ABK*19]. Once created, an inset can show a dedicated visual representation depending on the edge context to be communicated:

- Temporal context, such as dating of a connection, can be visualized in the form of time-series, temporal histograms, or timelines and provide temporal context for a link between two nodes. For example, the dates of correspondences between two people could be mapped on a timeline.
- Geospatial context of a link between two nodes can be visualized, for example, on a map. Locations could be marked on a map or heatmaps could be used to provide geospatial context, such as locations where two actors of a network had contact.
- Structural context for an edge could complement the global graph visualization. Structural contexts can for example be embedded as a matrix view [HFM07] or NLD. They may show additional selection-related nodes and edges that are not visible in the global network, or display quantitative aspects of sub-edges.
- Semantic context can, for example, provide the terms used by two actors in their correspondences. In cases where edges are derived from textual corpora, it may be useful for validation to show the sentence from which a relation between two entities was extracted from, e.g., in form of word clouds [KKEE11].
- Multivariate context, including overlaps and blends of temporal, geospatial, structural, and semantic context, can be visualized through individually crafted embedded visualizations, using multiple encoding strategies, for example, parallel coordinates offering an overview of multivariate attributes.

### 3.2. Interactive In-situ Access to Edge Contexts

Once the visual encoding of the edge context is decided, the next question is how to embed it into the base visualization. A global display of all edge contexts would not be useful due to the risk of severe information overload. Therefore, we follow the information seeking mantra [Shn96] and design an interactive approach (DG1) that starts with an overview and adds details on demand: **1)** Start with an overview in the NLD. **2)** Select an edge of interest. **3)** Unfold edge context in situ. **4a)** Fold edge context and return to overview, or **4b)** Navigate to another edge context. This procedure involves several interaction steps, which require appropriate interaction design and corresponding visual feedback.

**Selecting edges (2)** To help users select edges worth unfolding, hovering an edge foreshadows its context in a tooltip, such as the names of its incident nodes or the amount of contained contextual information. By clicking or tapping on an edge it is marked as the edge of interest. In larger networks, dynamic filtering or search queries could further simplify the selection. Dedicated graph interaction techniques [MJ09] in combination with semantic zooming [PF93] and the possibility to drag nodes can facilitate selection in dense parts of a network. Once selected, the edge of interest will be emphasized and its contextual information be unfolded.

**Unfolding the edge context (3)** Depending on the length of the edge of interest and the structure of the overall network, there may not be enough space to directly add contextual information. Therefore, our concept of in-situ edge unfolding involves modifications of the general graph layout to put the edge of interest into focus and create space for its unfolding. Different strategies (see Figure 3) were derived via an iterative design process coupled with a literature review, where strategies were tested and discussed among the authors. The strategies can be used individually or in combination and can roughly be divided into global and local layout modification strategies. Global strategies affect the layout as a whole and therefore can have a substantial impact on the cognitive load:

*Rotation:* For particular context representations, a consistent edge orientation (e.g., left to right) may be preferable or even required. On the other hand, standard graph layouts usually have much variance in the orientation of their edges. Therefore, the unfolding of edges may involve a global rotation of the entire graph layout to create a required edge orientation. For example, a horizontal alignment would be beneficial for representing time or textual information.

*Centering:* The view on the entire network is globally moved in a way that puts the edge of interest into the center.

*Zoom:* By changing the zoom level, one can guarantee for any edge, irrespective of its original length, that sufficient space is available for its unfolding. The zoom level for an edge depends on its length in the NLD layout. Shorter edges need to be zoomed in more to provide the same space between their two incident nodes compared to longer edges. Note that the zooming, as a variant of semantic zooming [PF93, TS20], operates only on the

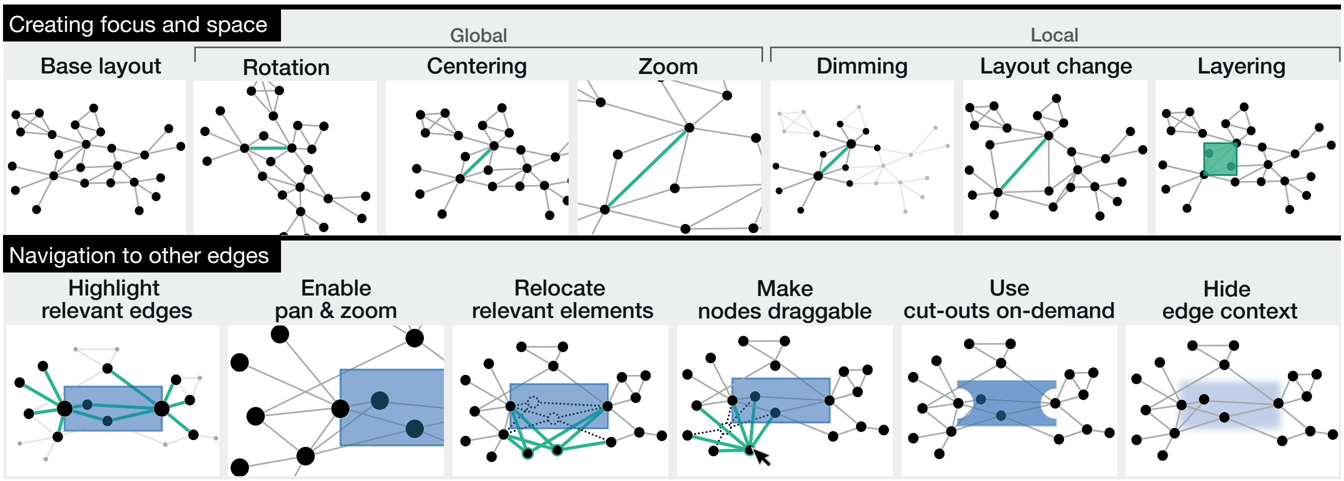


**Figure 3:** *Strategies to create focus and space for unfolding of edge context (top) and to facilitate navigation to other edges (bottom).*

positions of nodes in the layout, but not on the geometry of the graphical marks. That is, during zooming, the distances between nodes, and hence, the lengths of edges change, but node size remains untouched. This way, zooming can generate sufficient space between nodes for a subsequent edge unfolding. The zooming may also affect the context representation itself. For example, the context representation may be responsive to zooming and only show as much detail as the current zoom level permits.

In contrast to global strategies, local strategies affect the layout only partially, e.g., by changing individual nodes or edges:

*Dimming:* Less relevant edges, nodes, and labels are dimmed, e.g., by reducing opacity, size, or saturation. The salience of the edge of interest and its incident nodes is increased through the use of visual variables, such as color or size, and the addition of labels. Relevant neighboring edges and nodes might also be highlighted.

*Layout changes:* Rotation and centering can also be applied locally in the vicinity of the edge of interest. This may involve focus+context distortion [CKB09], space-making tools [ABK*19], or specific edge lenses [BBT23], where irrelevant nodes and edges are moved aside based on given space demands.

*Layering:* New elements emerge from an edge that are layered above the original layout, without the necessity of creating new non-overlapping space or extensive layout changes. This superimposition can include planar insets that can be used as a canvas for further details, but also additions such as annotations.

**Navigating to other edges (4b)** Ideally, users can seamlessly navigate from edge to edge along paths in the graph (DG3). However, navigation along the paths of connected edges may be impeded if the unfolded edge context obscures its immediate vicinity. Therefore, our design space also includes strategies for ensuring access to the neighboring edges of an unfolded edge (see Figure 3):

*Highlight relevant edges:* Relevant edges (e.g., directly connected neighboring edges) can be highlighted through visual variables, while making less relevant elements less salient.

*Enable pan & zoom:* The viewport should remain changeable even after details are unfolded. This allows for zooming and movement around a focused network view.

*Relocate relevant elements:* Relevant elements that are obscured by an unfolded edge context are relocated inside the graph layout to allow easy access.

*Make nodes draggable:* Nodes can be dragged to allow repositioning of individual elements based on a user's need to make sense of a graph or to avoid occlusions.

*Use cut-outs on-demand:* Interaction can be used to create cut-outs in the detail-insets around the two nodes of the edge of interest in order to make it possible to access all their connected edges.

*Hide edge context:* The unfolded edge context could be hidden temporarily, blended down, blurred, or moved to the background to reveal otherwise occluded edges.

The outlined designs for selecting edges (2), unfolding the edge context (3), and navigating to other edges (4b) form the basis for concrete implementations of edge unfolding. While we derived these designs systematically, we do not claim completeness as we only begin to understand the underlying design space.

### 3.3. Smooth Display Transitions

Animated transitions have advantages and disadvantages. While they may have negative effects on working memory loads, studies often report animations to be considered more enjoyable [FPS*21]. Although there is still limited conclusive evidence on whether animated transitions facilitate or hinder comprehension [FPS*21], researchers also observed positive effects of transitions between views to convey meaning, explain operations on the data, or provide coherence between views [KCH19, HR07, BBBD20]. For our unfolding of edges, we consider transitions as a possibility to create engaging, cohesive graph visualizations with fluid interaction [EMJ*11].

In order to smoothly unfold an edge and to bridge the involved, potentially drastic, view changes, we make use of strategically designed transitions (see Figure 4). The goal is to create coherent

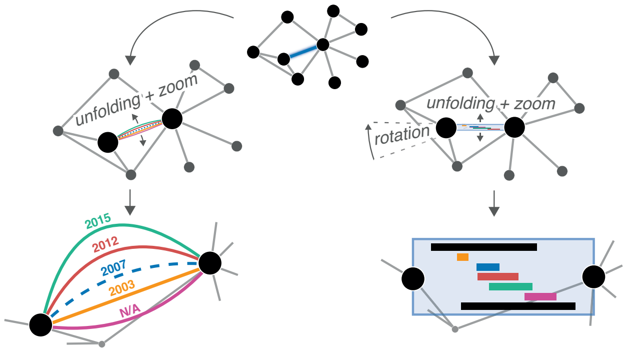


**Figure 4:** *Smooth edge unfolding may involve zoom and rotation depending on the particular edge context to be displayed.* 🅭🅯

and comprehensible transitions [TAA*21] that help users gain and maintain a sense of orientation in a potentially complex network. For example, by making rotation and zoom changes perceivable through animated transitions and by showing contextual information emerging directly from an edge of interest, we aim to help facilitate comprehension of layout changes and to provide engaging data analysis experiences (DG4). When it comes to functional transitions, it is important to take into account various aspects, including the timing and staging of changes, minimizing perceptual impact (e.g., using the shortest rotation angle to prevent disorientation), assessing the effects of animations on the performance, and maximizing comprehension of layout changes with the help of strategic transitions [TLLS20, vWN03].

## 4. Usage Scenarios

To validate our approach, we implemented two case studies in collaboration with domain experts in historical network analysis and computational social science. The design process was partially iterative, in that we closely collaborated with one of the two domain groups during the first phase of this research, and entered into conversation with the second group at a later stage for iterative refinements. For both case studies, we use a NLD with a visual design that is intentionally kept simple: Node size encodes node degree and textual labels contain the names of the entities, while the amount of information hidden in edges is foreshadowed by varying line width. Basic interactivity is available, including highlighting, tooltips, semantic zoom, and pan.

While the steps to prepare and execute the unfolding as well as to navigate from edge to edge are rather application-agnostic, the actual embedding of context visualizations has been designed in collaboration with our domain experts and in accordance with the requirements of their respective domain. The prototypes were implemented using web technologies and the visualization library D3.js [BOH11] and are available together with the source code at: `https://uclab.fh-potsdam.de/unfoldingedges`

### 4.1. Historical Network Analysis: Nobel Prize Network

**Domain background** In historical network analysis, graph edges typically correspond to relations between actors derived from historical material such as letters or other documents [RDGSS17, NMM*14]. For example, an edge is created between two people if they had mail correspondence. But an edge may also be created if the same two people worked together at the same institution or attended the same scientific congress. In other words, edges between nodes may not only be based on one source, but can be constructed from multiple sources, including various additional attributes, such as certainty, duration, direction, dating, and more. For the interpretation of historical networks, it is therefore crucial to be able to observe the provenance of the relations contained in the network, that is, to understand why edges are present in the network [DvK15].

To analyze the potential of unfolding of edges in this context, we worked with a dataset on a Nobel Prize network generated from multiple heterogeneous data sources. The network contains 318 persons who are all connected to the keyword Nobel Prize (e.g., Albert Einstein) and 687 relations between them. The edge attributes capture relevant contextual information, including the type of relationship (e.g., colleagues), source types (e.g., letters), URLs to sources, and temporal information (e.g., date of a letter). The network analysts need to understand an interplay of several multivariate attributes, entailing several sources, a strong temporal dimension, but also differences with regards to context of a relation.

**Solution design** The base visualization of the Nobel Prize network is shown in Figure 5 A1/B1. For its analysis, we implemented two exemplary variants of edge unfolding.

***Variant: Edge fan-out*** – To give an overview of the contained edge attributes, the unfolding of an edge triggers a transition that fans out multiple sub-edges from the original edge (see Figure 5 A1-A3). These sub-edges are ordered temporally and use multivariate on-edge encoding strategies (see Figure 1). Color is used to encode the original source of an edge (e.g., a specific archive), and solid and dashed lines encode direct (i.e., recorded) and indirect connections (e.g., two persons mentioned in the same letter), respectively. After unfolding, hover or click operations may be used to see further details in a tooltip or access an original source. While the edge context gets added, the global network structure is not touched. The unfolded sub-edges are simply overlaid on top of the network without any provisioning of additional space or triggering substantial view formations. Instead, only zooming on the selected edge and blending down of less relevant data elements is used to steer the observer's focus toward the selection.

An advantage of this variant is that the unfolded edge context (i.e., the fanned-out edges) merges easily into the global graph visualization as it relies on already known visuals (i.e., edges as lines). Thanks to the gaps between the fanned-out edges, there is only little occlusion introduced by the unfolding operation and critical information remains visible. At the same time the curved style of the sub-edges makes them clearly distinguishable from the global network. Moreover, this variant does not use rotation of the global network, which may have benefits on the orientation of viewers and on the preservation of their mental map. A drawback of this variant is its limited communicative power. The on-edge encoding and the fan order of the sub-edges offer only limited opportunities to encode multivariate data attributes. Overall, this first variant can provide a visual sense of quantity and order of multivariate aspects

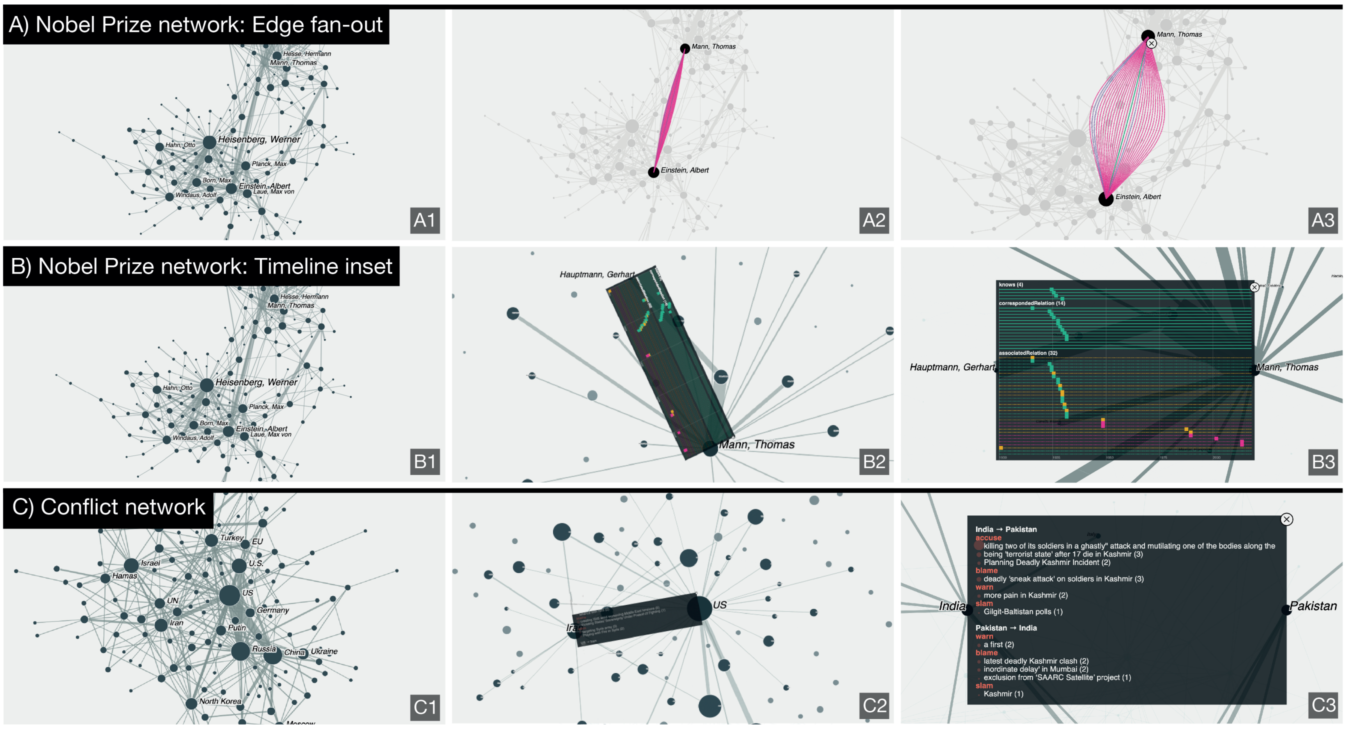


**Figure 5:** *Visualizations of a Nobel Prize (As & Bs) and a conflict network (Cs) using unfolding of edges: Selection of an edge in an initial graph (A1, B1, C1) triggers a transition (A2, B2, C2) that unfolds a context visualization of the edge (A3, B3, C3).* 

of an edge, but it lacks encoding possibilities for more complex data dimensions, such as the representation of temporal context.

***Variant: Timeline inset*** – The second variant illustrates the more advanced possibilities of our approach (see Figure 5 B1-B3). Here, the unfolding of an edge triggers a transition that accommodates substantially more information by first adjusting the global view on the graph layout and then embedding a timeline inset. This involves rotating and zooming the whole graph layout such that the edge of interest is aligned horizontally in the center of the view. Here, the zooming enlarges the edge exactly as much as to create sufficient space between the edge's incident nodes to embed a timeline inset. As additional visual guidance, less relevant graph elements are again dimmed by reducing their opacity and saturation.

The unfolded edge gradually transforms from a straight line into a timeline inset. The time axis extends along the x-axis and shows the data's overall temporal scope. Individual timeline rows show instances of connections between two persons (e.g., co-authorship) ordered by relation type and date. The exact connection dates, if available, are marked with a small rectangle. Line color and dash style show the same edge attributes as for the fan-out variant. Hovering a timeline row reveals a tool tip with further edge information and clicking opens the original data source for further validation.

A clear advantage of the timeline variant is that it can show the temporal edge context in greater detail. A drawback though is the collateral occlusion of other possibly relevant information, in particular of all the edges that emanate from the two nodes being incident to the unfolded edge. To mitigate this problem, we employ the *hide-edge-context* strategy (see Figure 3). A longer hovering on either incident node will blur the timeline inset and smoothly fade it to the background, effectively resolving any occlusion and granting access to all relevant edges. Hovering on the blurred background will bring the timeline back into the focus.

**Exploring the network** Network analysts start with the NLD as an overview. Then they drill down into details using the unfolding of edges to selectively add contextual information, for example, to trace the correspondence between two people over time or to appraise the quality of a relationship. A collaborating Nobel Prize researcher stated that the observation of such details, including sources, may be especially relevant for research questions that involve individual relations: *"For Nobel research, it is very interesting to see what kind of connections there are professional, personal, social, or through institutions. And to see, to what extent science is judged according to objective criteria or whether social components play a role between candidates and nominators."*

For our concrete Nobel Prize network, an observation could be made, for example, for Albert Einstein and the author Thomas Mann. In the global network, Einstein and Mann appear to be closely connected with many individual connections and a thicker edge. However, upon closer inspection after unfolding of the timeline, it becomes clear that most of the connections are indirect and exist only because Einstein and Mann are often mentioned together in the literature. Once such a finding could be confirmed through the added edge context, the data exploration can continue either by returning to the overview or by switching to a different edge. When returning to the overview, the unfolding is reversed, meaning that the edge context is folded back into a simple line and the original view on the NLD is restored. When switching to a different edge, the currently visible edge context is reversed, and simultaneously, the context of the newly selected edge is unfolded. In particular this edge-to-edge navigation revealing one edge context after another is interesting, as it enables analysts to explore and interpret a network topology along paths as prescribed by the underlying sources.

### 4.2. Computational Social Sciences: Conflict Network

**Domain background** For the second case study, we worked with experts from computational social science. They analyze multivariate graphs that capture claims and conflicts between actors as extracted from news corpora using natural language processing and machine learning [MR19]. The concrete network we are dealing with consists of 192 nodes and 325 edges and includes conflicts between political actors such as countries (e.g., United States), organizations (e.g., Human Rights Watch), companies (e.g., Google), or persons (e.g., Donald Trump). The actors and conflicts are a sample of a network extracted from headlines shared on Reddit (r/worldnews) between 2013 and 2017. Conflicts are defined by an edge with a source node, a target node, and edge attributes describing the conflict topic (e.g., "rising tensions in South China Sea"), a predicate word for the conflict (e.g., "accuses"), and the original source of the news headline (e.g., "nytimes.com"). Multiple conflicts between a dyad are aggregated into a single meta-edge and the number of conflicts is mapped to the edge weight.

In the conflict network, not only the existence or the amount of conflicts is of interest to the researchers, but especially the types and topics of conflicts. Since the network is based on news items and reporting of a topic may vary, for example, based on the political alignment, also the sources are relevant for interpretation.

**Solution design** As for the previous case study, we vary the line width of edges in the NLD to foreshadow the amount of information being revealed upon edge unfolding (see Figure 5 C). The general interactions and animations of the unfolding of edges also follow the same principles as described for the Nobel Prize network. Yet, as the edge context, we now show a hierarchically structured list of the conflicts subsumed by an edge. This puts the textual information into the focus. In our case, the conflicts are sorted by direction (e.g., "EU → UK") and by their predicate type. Predicates and topics are sorted by number of entities. Red circles next to the conflicts encode the number of sources for conflict via their area size, complemented by the respective number behind the conflict. A hover over a conflict reveals the sources in a tooltip.

**Exploring the network** Again, with the help of unfolding of edges, the researchers could be provided with contextual information exactly when and where it was needed. We hypothesize that the added contextual information is beneficial for the interpretation of the claims and conflicts contained in the data. To give a concrete example, a domain expert in conflict analysis found: *"For example, in this case I see there is only one edge from Berlin to Moscow. And I see that there are seven instances of this same conflict with the same topic, but they all came from the same source."*

## 5. Expert Interviews

To better understand the impact of unfolding edges on the understanding of multivariate graphs, we collected qualitative feedback in expert interviews carried out in the context of the case studies.

### 5.1. Setup and Procedure

We used two prototypes, the Nobelprize network with timeline insets (see Figure 5B) and the conflict network (see Figure 5C). For both, a baseline version was created where edge unfolding was disabled and edge contexts appeared in separate side panels on demand. The purpose of the baseline versions was to compare our approach with conventional methods and to learn more about the role of animation, in-situ unfolding, and the involved layout changes.

Four domain experts participated in the interviews, two historical network researchers (P2, P3) and two computational social science researchers (P1, P4). Their experience with interactive graph visualizations varied: P1 and P4 were very experienced, P2 had basic experience, and P3 had limited experience. Using a think-aloud protocol [Car08], we wanted to find out how participants would interact with the edge unfolding and how our solution is perceived compared to traditional approaches. The interviews were conducted as one-to-one remote video meetings.

All four participants were shown all four prototypes, which means that the historical network experts were also shown the conflict network and vice versa. Both datasets and their base visualization were shortly introduced to the participants, but the functionalities of the prototypes were not explained beforehand. The participants were asked to explore and freely interact with the four prototypes while sharing their screen. The participants started with the networks from their own domain first, but the order of the prototype variants (with or without edge unfolding) was varied. We instructed the participants to describe what they see, do, think, and interpret. Each session was set to take about 45-60 minutes, and all sessions were recorded and subsequently transcribed. We extracted the following main insights on the basis of the transcriptions.

### 5.2. Observations

While we received much general feedback on basic usability and encoding aspects in NLD (e.g., force-directed layout), we will report mainly the feedback relevant for the edge unfolding. Overall, none of the participants had problems understanding the functionality and transitions of unfolding edges: *"I mean the animation of the rotation made it very obvious what was going on, I immediately got it."* (P1). It was clear to all participants that the unfolding provided additional contextual information for an edge and that line width in the network encodes the amount of hidden information: *"I'm attracted to the rich edges, which are indicated by their width in a natural way, that's very natural."* (P4). Additional feedback suggests that maybe even more foreshadowing beyond the basic variation of line width would be useful: *"I'm a bit blind about what to expect when clicking on these edges."* (P4).

**Appreciation of in-situ integration and visual design** The in-situ integration of the edge context was perceived as natural and visually pleasing: *"So it feels more natural. It's as if we were opening* *the edge"* (P4). *"This kind of, what I call popup, is exactly between the two participants, which is very good and kind of acts almost like an expanded link. [...] I love that everything always remains inserted in the network in a sense, but without being confusing, just pretty clever."* (P1). The smooth transitions and the design of the edge unfolding variants were perceived positively: *"This is beautiful. I mean, this is very aesthetically pleasing.", "I really like that it's both aesthetic and functional."* (P1). However, for some participants the appreciation of the visuals did not necessarily translate to usefulness: *"That's maybe more an add-on, than a must-have. [...] So it looks cool, but I don't really know what I'm going to do with it."* (P3). One participant expressed their disapproval: *"In my opinion, it's a visual gimmick that makes no sense to me as a user and gives no added value, but on the contrary irritates me."* (P2).

**Polarized opinions on view changes** The mentioned irritations were mostly related to the rotation of the network during the edge unfolding. These were not unexpected to us, since the rotations involve some considerable view changes. In particular, two participants stated that the rotation and, to a lesser degree, the zoom had a negative impact on their orientation: *"Okay, this is again this mode where the network changes, so it's rotated, but why it's rotated the way it is right now is not clear to me."* (P2), *"You end up in an unfamiliar environment."* (P4). In stark contrast, one participant found the combination of rotation and zoom helpful to focus and to orientate: *"It's very nice. I particularly like the orientation of the network."* (P1). Mixed comments were made regarding the rotation during the data exploration: *"If you focus on a pair I think it's super useful, but if you move from a pair to another pair, it gets confusing."* (P4), *If the question is, you have this network, choose a pair and you will really explore it in detail, I think this rotation is great."* (P4). Some discomfort with the rotation might be related to domain practice: *"It's very unusual for a network practitioner to have this movement, it's the most surprising thing. Maybe it's also professional bias of being used to fixed orientations."* (P4).

**Relevance for research** All participants stated that general access to contextual edge information is directly relevant for their research: *"So it really makes sense as a research tool, that you can see the individual connections or what's behind the connections. [...] It's even more central that you then can be forwarded to the original source."* (P2). Using the edge unfolding, the participants could immediately answer domain-relevant research questions: *"Okay, [...] now I see what I suspected, namely that it is an exchange of letters between Heisenberg and someone else, where Otto Hahn is mentioned."* (P2). Also the utility for data validation and hypothesis generation was recognized: *"First and foremost to validate and check mistakes on the parsing side, or get intuitions about [...] what did we store in the database. And that feels very comfortable to be able to navigate in the relational database in such a graphical way."* (P4), *"It might invite a little bit to play around and to develop new research questions."* (P3).

**Ideas for improvements** Playing with the folding and non-folding variants, two domain experts stated that they would enjoy a hybrid approach of in-situ edge unfolding combined with a classic separated detail panel. For instance, P2, who was skeptical toward edge unfolding, but also P4 would favor a hybrid version: *"So I would find it quite exciting if there was a version where the edges [...] unfold directly visually in the representation [...] and then hybrid, so that there would be another representation in parallel, [...] where the individual connections are listed."* (P2). Along similar lines P4 commented: *"What I'd like very much, I would say, is an intersection of both. [...] Because I like very much the fact that the information is directly visible on the edge."* (P4).

Unfolding single edges was deemed useful according to the collected feedback. When asked about the possibility of side-by-side comparisons of multiple unfolded edge contexts, the domain experts attested comparison possibilities to have much potential with high relevance for their work.

## 6. Discussion

Overall, our results indicate that while some implementation details result in polarized opinions, the unfolding of edges can create visually pleasing and useful representations thanks to a more direct and transitioned embedding of contextual information. While some users may prefer simpler or more familiar representations of data, the feedback also suggests that a transitioned context embedding may have positive effects on user engagement. This aligns with previous user study results on engaging effects of animated transitions [FPS*21]. Furthermore, the general possibility of accessing the edge context showed usefulness for the validation and interpretation of relations in networks.

### 6.1. Limitations

We see usefulness of our approach especially when the observation and validation of individual edges is of high interest for the interpretation of the data. So far, our approach is limited to unfolding a single edge. Comparing edge contexts is hence difficult and demands back and forth movements between edges. The unfolding of several edges at the same time to facilitate direct side-to-side comparisons is left for future work.

Furthermore, our approach is based on NLD and inherits their (dis)advantages. Our main motivation for using NLD is based on their high familiarity and intuitiveness to many people, and the wide use of NLD in many fields [GFC04, Mun14]. NLD are considered more effective than tabular layouts or adjacency matrices for small networks, memorability, topology, and path-based tasks [GFC04, OJK19, NWHL20]. But still general disadvantages of NLD, such as occlusions, crossing edges, or cluttered areas in dense networks [Mun14] may hinder interaction with and interpretation of the visualization. We could only partially address these general concerns with our different design options and strategies. Depending on the given graph, goals, and target audiences, other graph visualizations such as adjacency matrices might be favored. They may be similarly extended with interactive detail enhancement capabilities of edges, as for example in Responsive Matrix Cells [HBS*21].

### 6.2. Scalability

Unfolding edges was built on the premise that on-edge encoding techniques tend to result in difficulties when displaying multivariate edge attributes due to the increased visual complexity affecting the entire visual representation. With unfolding edges, we do not aim to address general scalability and "hair ball" issues of NLD. The scale and density of the network and the amount of edge attributes and context therefore naturally influence the success of our approach. For example, very dense networks with many overlaying edges and other elements can make the selection of edges difficult and a high amount of short edges may lead to unsatisfactory results. Here, setting a minimum edge length may help, but will influence the topology of the network in undesired ways. For dealing with such and similar issues, additional tools and techniques may be necessary, including attribute filters, search functionality, dedicated selection assistance, or edge lenses.

Depending on the extent of edge context, further abstractions, or interaction possibilities (e.g., scrolling, on-demand animation) might be needed to be able to generate compact in-situ edge visualizations. In the current conception an edge is either folded or unfolded, the various possible visual forms between these two display states are part of the animation, but are not interactively controllable. However, it could be useful to gradually disclose the most important information first and expand the edge further depending on the information need and interest. With regard to unfolding strategies, additionally, a large number of global layout changes, especially node re-locations where new positions have to be calculated based on necessary space, can have a negative impact on performance, especially for larger networks.

### 6.3. Design Considerations

The expert feedback provides preliminary insights from a small number of network researchers. Both our case studies are based on computationally generated graphs and in both cases, researchers rely on the ability to validate their approach to make appropriate interpretations. These insights attested a general demand for techniques to provide edge context. Although the use of rotational layout changes need to be considered critically, since they may have negative effects on orientation, we observed that in general, the dynamic, transitioned embedding of details directly in the graph led to positive feedback among most of our domain experts.

While engaging, the animated transitions and layout changes may still be distracting or interfere with the mental map, depending on whether the chosen design strategies affect the NLD globally or only locally. Based on our first observations, especially with regards to feedback on the global rotation, a combination of multiple and high impact layout changes of the NLD may lead to disorientation. Therefore, the relevance of factors such as the orientation and needed space for a context representation should be carefully considered in the design process. Many design decisions, especially of the visualized context, remain use-case dependent and should be considered based on the needs to visualize specific aspects of data. For instance, using detail insets as the canvas for the contextual representation provides more flexible options for a visualization of edge context, but also obscures more of the overall network and hinder navigation to other edges. Additionally, the chosen visual representation of the edge context will naturally impact the readability and effectiveness. More unfamiliar and complex visual representations may require the integration of a legend or explanation to ensure that viewers understand them properly.

### 6.4. Future Research Directions

With our approach, details are revealed upon selecting an edge of interest. To support the selection step, it makes sense to further investigate ways to help users anticipate the richness or interestingness of edges in the first place. Different levels of foreshadowing of edge context beyond our basic use of edge strength and tooltips should be explored in the future. Dynamic filtering and highlighting across the whole graph, and also local contextual highlighting depending on the unfolded edge may offer promising opportunities for guidance toward information worth exploring in detail.

Some user-study participants mentioned that comparison tasks might be a promising direction for future work. To support on-the-fly comparison of edges and their associated contexts, it is necessary to extend the unfolding of edges with dedicated layouts (e.g., side-by-side, superposition) and corresponding transitions as well as interaction techniques. For such comparison tasks of multiple edges, also hybrid approaches as emphasized in the collected feedback should be investigated more. The combination of visual in-situ edge unfolding for short-term dynamic access with traditional separated spaces for more long-term preservation of contextual details seems particularly promising.

Our design space still offers room for further exploration. This includes looking beyond NLD. In general, more in-depth evaluation involving more diverse participants should be conducted next. The effects and selection of individual design choices should be evaluated more systematically in order to provide more generalizable guidelines and to further revise, extend, and validate our design space. Additionally, a variety of transition techniques, especially techniques with less rotation and only few animated elements, should be observed to better understand the effects of individual design choices. Also the question of why, for instance, the rotation was partly perceived as a useful and partly as a disorienting feature raises more general research questions with regard to effects of layout changes on the orientation inside a network.

## 7. Conclusion

With unfolding edges we started to explore a design space to dynamically add multivariate edge context to graph visualizations. The approach was developed iteratively in a design and research process and was informed by literature research and exchanges with domain experts. The concept aims to highlight the central importance of edge contexts for the interpretation of multivariate networks represented as NLD. Our approach dynamically enhances contextual detail at the edge, integrated into the space of typical NLD. With this research we hope to inspire visually coherent and well transitioned representations of the usually hidden edge context and by that facilitate the critical interpretation of network data through interactive visualization.

## Acknowledgments

We thank our collaboration partners for providing the data, for their valuable feedback during the design process, and for their participation in our interviews. This work is related to the DFG projects 514630063 and 414792379. Open access funding enabled and organized by Projekt DEAL.

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