Visualizing Hierarchy Changes by Dynamic Indented Plots

Michael Burch, Tanja Blascheck, Christine Louka and Daniel Weiskopf
VISUS, University of Stuttgart, Stuttgart, Germany

Keywords: Dynamic Hierarchies, Indented Plots.

Abstract: Visualizing static hierarchical organizations has been a focus of information visualization for many years, but it still remains challenging to produce visual representations of evolving, i.e. dynamic hierarchies. In this paper we extend the concept of indented plots to also support the depiction of changing hierarchies. We exploit the concept of static diagrams in order to support the preservation of a viewer's mental map. Changes between subsequent hierarchies are precomputed and visually indicated by color coded straight or curved lines depending on the type of change. Interactive features can be used to aggregate or collapse the dynamic hierarchy data in the supported dimensions, i.e. the vertex as well as the time dimension on different levels of hierarchical and temporal granularity. The usefulness of our technique is illustrated by means of a bibliography dataset where we show the changes in the yearly prefix tree acquired by extracting words occuring most frequently in more than 2,000,000 paper titles from the digital library DBLP.

1 INTRODUCTION

There are many application examples where hierarchical data comes into play. Software developers typically organize their system into packages, directories, subdirectories, files, classes, functions/methods, and code blocks on the finest level of hierarchical granularity. Biologists structure all species living on earth into a hierarchical structure which is updated from time to time with newly classified organisms. As a third example occurring words in paper titles can be hierarchically organized into a prefix tree structure.

All these hierarchies are typically changing over time due to software development, the evolution of life, and progress in research articles. Since such a dynamic prefix tree structure contains frequent and also abrupt changes it will be used as illustrative application scenario in our work as a stress test.

In this paper we introduce a novel approach to visually depict the evolving behavior of hierarchical organizations. To allow good comparisons we use the concept of time-to-space mapping, i.e. a static display showing the sequence of hierarchies in a side-by-side representation according to the small multiples approach (Tufte, 1983). This stands in contrast to animation that only shows one hierarchy at a time and smoothly transforms one into the other (Card et al., 2006). It is also different from other approaches surveyed by Graham and Kennedy (2010) such as coloring (Munzner et al., 2003), matrix (van Ham, 2003), agglomeration (Burch and Diehl, 2006), 3D, or atomic representations. When using animation, a good layout algorithm has to be applied that takes the aesthetic appearance of all hierarchies into account and additionally targets a good dynamic stability of the animated sequence focusing on mental map preservation (Misue et al., 1995) and a reduction of cognitive load. Another drawback of animation is the fact that the viewers have to rely on their limited short term memory in order to make comparisons between subsequent hierarchies. Furthermore, it is very difficult to apply interactive features to an animated diagram. Similar perceptual and interaction drawbacks hold for other representation styles as discussed in the survey by Graham and Kennedy (2010).

In this work, instead, we make use of a sequence of indented plots (Burch et al., 2010) placed next to each other in the same orientation. Such plots are redundant-free, compact, and scalable indented curves depicting hierarchical structures by the concept of indentation similar to the concept of pretty printing applied by programmers. Differences between subsequent hierarchies are precomputed and visually indicated by color coded straight or curved links supporting viewers with mental map preservation by guiding them through the hierarchy changes via explicit links and not by smooth animation. This edge drawing approach has the benefit that analysts

Burch M., Blascheck T., Louka C. and Weiskopf D..
Visualizing Hierarchy Changes by Dynamic Indented Plots.
DOI: 10.5220/0004652400910098
In *Proceedings of the 5th International Conference on Information Visualization Theory and Applications* (IVAPP-2014), pages 91-98
ISBN: 978-989-758-005-5

can make comparisons visually, and not mentally, by exploiting the capabilities and strengths of their visual system and fast pattern recognition. As another benefit, interactive features are easy to apply because the display is static.

Our visualization tool is designed in a way following the Visual Information Seeking Mantra (Shneiderman, 1996), i.e. first we give an overview of all the changes, then we allow zoom and filter operations, and finally details on demand. We allow data aggregation in the vertex as well as the time dimensions and support the analyst by further interactive features such as finding trails of hierarchy elements.

We illustrate the usefulness of our technique by a case study exploring bibliography data from the digital library DBLP (Ley, 2009): we first extract all stored paper titles, count the occurring words in each year, generate a prefix tree of the most frequent words in the Newick format for each year, compute the changes of subsequent prefix trees, and finally visualize these results by our visualization tool.

2 RELATED WORK

Visualizing static hierarchical data has been a focus of research for many years where visual and algorithmic scalability (McGuffin and Robert, 2010) as well as readability and aesthetics have been taken into account as competing criteria to trade-off. Several visual metaphors exist to depict hierarchical organizations: Node-link diagrams clearly show the hierarchical structure by mapping objects of a hierarchy typically to circular shapes and by indicating parent-child relationships as straight or orthogonal links connecting the hierarchy elements (Eades, 1992; Reingold and Tilford, 1981). A top-down layout has been evaluated as the best performing one for the task of locating the least common ancestor of a list of marked leaf nodes, as found out by an eye tracking study conducted by Burch et al. (2011a).

Treemaps apply the concept of nesting enclosure to illustrate a hierarchy in a space-filling manner (Johnson and Shneiderman, 1991; Shneiderman, 1992). Many variations exist such as squarified (Bruls et al., 2000), cushion (van Wijk and van de Wetering, 1999), or Voronoi Treemaps (Balzer et al., 2005; Nocaj and Brandes, 2012) to enhance the layout and to make the hierarchy representations more readable and understandable. Though treemaps use the given display space efficiently, it is difficult to visually explore the hierarchical structure in a better way than in node-link diagrams and to use them for dynamic hierarchy visualizations (Tu and Shen, 2007).

The metaphor of layered icicles (Kruskal and Landwehr, 1983) applies the concept of stacking to build a visual depiction of a hierarchical organization which allows a small multiples visualization and edge drawing approach but on the negative side inner vertices are represented as bars being as long as the sum of the bars of all the child nodes' bars. A small multiples icicle representation would hence produce more crossings and overlaps.

All these approaches have one problem in common. There is no single representative element for each vertex — inner vertex as well as leaf vertex — on a one-dimensional line. Indented Pixel Tree Plots (Burch et al., 2010) instead use indentation omnipresent in graphical file browsers or pretty printing of source code. These plots allow the mapping of all vertices to a unique representative one-dimensional position and can hence be laid out in a side-by-side manner allowing good comparisons between subsequent hierarchies. As another benefit, these plots allow the attachment of additional information to each vertex in an aligned way (Burch et al., 2012) and scale to very huge and deep hierarchies still sufficiently representing the hierarchical structure. This mapping allows us to enrich the diagram by color coded links showing the differences and changes over time with a reduced overlap of links with the sequence of hierarchy visualizations — denoted as edge drawing approach in the survey by Graham and Kennedy (2010).

Generally, in graph visualization there also exist two major concepts to represent the dynamic behavior of a graph. Either animation can be used that shows each timestep in a single frame and then smoothly animates this toward the subsequent one by keeping a high degree of dynamic stability (Diehl and Görg, 2002; Frishman and Tal, 2007). This requires quite complex layout algorithms that follow aesthetic graph drawing criteria (Purchase, 1997) for each static graph in the sequence. Orthogonally to that, aesthetic criteria for the dynamics (Beck et al., 2009) have to be followed in order to preserve a viewer's mental map. This concept is referred to as time-to-time mapping whereas a time-to-space mapping stands for a representation of the inherent time dimension to space (Burch and Diehl, 2008; Burch et al., 2011b).

For dynamic hierarchy visualization we could follow a similar concept: We use a time-to-space mapping by exploiting the visual metaphor of indentation by vertically aligning the hierarchies on parallel axes. To achieve a compact and connected layout we do not leave gaps for the alignment but use connected indented plots and show the changes over time in the dynamic hierarchies by colored straight and curved lines similar to the concept used in CodeFlows (Telea

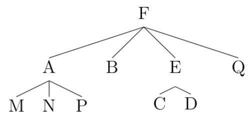


Figure 1: Hierarchy of depth 2 consisting of 10 vertices: 1 designated root vertex F, 2 inner vertices A and E, and 7 leaf vertices M,N,P,B,C,D, and Q.

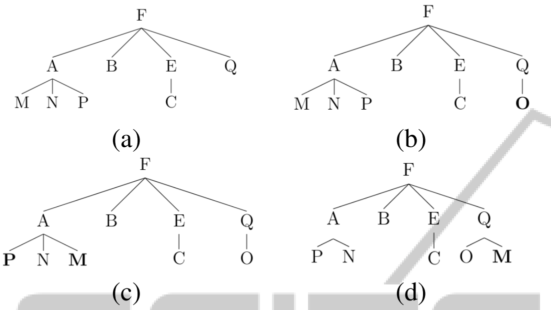


Figure 2: Node changes: (a) Deletion of node D from original hierarchy (Figure 1). (b) Addition of node O. (c) Exchange of positions of sibling nodes M and P. (d) Modified position of node M.

and Auber, 2008). This approach is most related to our technique but it is restricted to showing source code (indented metaphor) and not hierarchies in general. Moreover, the code representation is mirrored at the vertical axes and the depth is not indicated by pure indentation but differently long bars for each line of code. Also collapsing and expanding features in the time and vertex dimension are not supported. This mapping allows juxtaposition of subsequent hierarchies as also applied by (Holten and van Wijk, 2008) and (Munzner et al., 2003). However, in those papers only the changes among leaf vertices are displayable. In contrast, our approach is extended to show changes among any kind of vertex — inner as well as leaf vertices.

3 DATA MODEL

We model a hierarchy as an acyclic directed graph

$$H = (V,E)$$

where V denotes the set of vertices and $E \subset V \times V$ the set of directed edges, i.e. parent-child relationships. One vertex is the designated root vertex and the complete hierarchy is always directed from this root vertex to the leaf vertices.

A dynamic hierarchy $\mathbb{H}$ of length $n \in \mathbb{N}$ is modeled as a sequence of subsequent hierarchies

$$\mathbb{H} := H_1, \ldots, H_n$$

where $H_i = (V_i, E_i)$, V_i is the i-th vertex set, and $E_i \subset V_i \times V_i$ is the i-th edge set, i.e. the parent-child relations of the i-th hierarchy in the sequence.

3.1 Newick Format

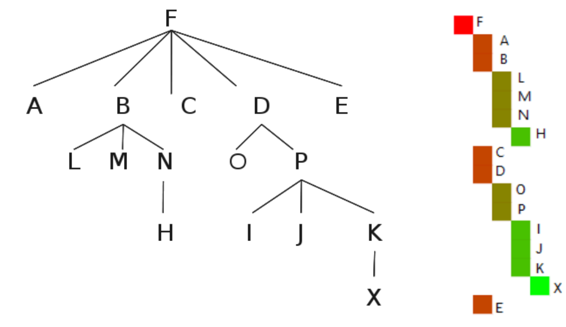
Our visualization tool uses the Newick data format for storing hierarchy data and for representing hierarchies in computer-interpretable form. The correspondence between a hierarchy and the nesting of parentheses is exploited in this concept. A sequence of hierarchies is given by a set of files containing one hierarchy each. Our Java-based visualization tool first extracts all hierarchies from the given files and stores them in the corresponding internal data structures. The Newick format can easily be extended to allow additional information attached to the vertices and also to the edges such as distance functions as commonly existing in the field of bioinformatics for modeling phylogenetic trees. The tool is able to handle additional data attachments by just introducing the corresponding parsing interfaces.

3.2 Hierarchy Comparison

For the hierarchy comparison two successive H_i and H_{i+1} of $\mathbb{H}$ are first transformed by depth-first traversal into two vertex lists L_i and L_{i+1}. Since all hierarchy elements are given a unique identifier a simple algorithm can be used to compute changed nodes between two compared hierarchies. Both representative lists are processed and three new lists are generated for added, removed, exchanged, and modified hierarchy elements (see Figure 1 and Figures 2 (a) - (d)). The contextual information is important for this visualization, which means that we additionally store where in the list vertices have been added or deleted. Furthermore, for a changed position we need to store the position of the vertex in list L_i and also the new position in list L_{i+1}. If there are several vertices with the same textual description we additionally take the depth and contextual information into account for a good comparison.

4 VISUALIZATION TECHNIQUE

The approach of mapping static hierarchical data to one-dimensional indented curves is extended to visually encode time-varying hierarchies in a static diagram giving a good overview of both dimensions in the data: vertices and time. Parent-child relationships are visually expressed by the idea of indentation. In



(a) (b)

Figure 3: A hierarchical dataset presented in two visual metaphors: (a) Node-link diagram in top-down traditional layout. (b) Indented plot using color coding for visually encoding depth information.

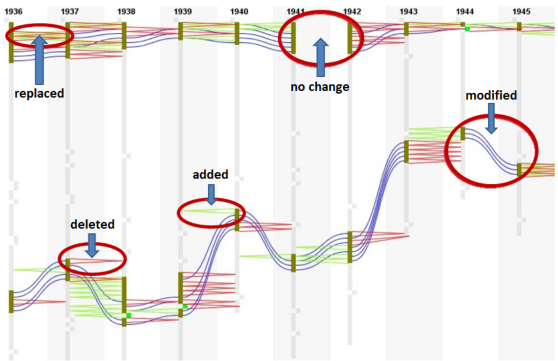


Figure 4: Dynamic hierarchy visualization of an evolving prefix tree structure generated from frequently occurring words in more than 2,000,000 paper titles extracted from DBLP. Only vertices matching a specific text pattern are taken into account.

this section we first introduce the general idea of indented plots, show how this approach can be extended to the dynamic case, explain how changes and differences are visualized, and finally propose several interactive features to manipulate and navigate through the data.

4.1 Static and Dynamic Indented Plots

Since our visualization technique allows changes in all nodes — inner nodes as well as leaf nodes — we apply the concept of indented outlines that have a representative hierarchy element at a single 1D line. Following this visual metaphor we are able to display a sequence of hierarchies in a scalable side-by-side representation and plot occurring links in between.

Figure 3 illustrates how a traditional node-link diagram looks like when an indented visual metaphor is used. The color coding in Figure 3 (b) is applied to better indicate the depth metric in the indented plot. Here, a red to green color gradient is used, i.e. the root node is represented in red color whereas the nodes located deepest in the hierarchy are colored in green. This design is helpful when only the indented plot sequence is inspected and gives a better impression about depth in the hierarchy. If edges are drawn this feature can be switched off to not lead to irritations when several color codings are used on top of each other. Instead, a black-to-white color or transparency gradient can be used instead.

For the time-varying hierarchy data we use a time-to-space mapping by encoding each hierarchy on one indented plot in a side-by-side view to parallel vertical lines similar to the concept used in parallel coordinates plots (Inselberg and Dimsdale, 1990); see Figure 4 for an illustration of such a side-by-side view.

4.2 Change Phenomena in Hierarchies

There are several change phenomena that may occur when comparing two different hierarchies. In our design we decided to use red for removed objects, green for added objects, and blue for persisting but moved objects.

- **Deletion of a node:** If a node disappears from a hierarchy H_i to a subsequent hierarchy H_{i+1} we indicate this by two red straight lines starting at the position in hierarchy H_i where the node is still present and pointing to the position in hierarchy H_{i+1} where this specific node was originally located, see change from Figure 1 to Figure 2 (a) and Figure 4.
- **Addition of a node:** If a node is added in a hierarchy H_{i+1} that was not present in hierarchy H_i we draw two green straight lines that originate at the position of this added node in hierarchy H_i and point to the position where it is located now in hierarchy H_{i+1}, see change from Figure 2 (a) to Figure 2 (b) and Figure 4.
- **Exchange of node positions:** The exchange of two positions can be modeled by two modified node positions and hence, two twisted blue colored curved lines are drawn between hierarchy H_i and hierarchy H_{i+1} indicating the exchange, see change from Figure 2 (b) to Figure 2 (c) and Figure 4.
- **Modified node position:** If a node changes its position in a displayed hierarchy H_i to a subsequent hierarchy H_{i+1} this is indicated by curved blue colored lines connecting both representative objects of the same node, see change from Figure 2 (c) to Figure 2 (d) and Figure 4.

All other more complex hierarchy changes can be achieved by combining these simple rules.

Figure 4 shows how the change phenomena illustrated in Figures 2 (a) - (d) can be represented by a side-by-side view of indented plots with color coded straight or curved links. The color coded links — red, green, and blue ones — can serve as an overview to get a first impression if and in what time step more vertices are added, deleted, exchanged, or modified. Our tool also allows the user to obtain some statistics about these change phenomena indicated as color coded bar charts, see Figure 5 where the graphical user interface (GUI) of our visualization tool is illustrated.

4.3 Interactive Features

The tool supports several interactive features to explore the dynamic hierarchical data such as collapsing and expanding specific nodes, getting information on a specific element, and selecting a subregion for a hierarchy on a larger scale for a better exploration. Some of the tool's features and functionalities are explained in the following:

- **Region selection:** Parts of the indented plot can be selected and this region is then highlighted and displayed to the right hand side of the original hierarchy in a larger scale.
- **Hierarchy expanding/collapsing:** Clicking on a node allows the user to collapse or expand the corresponding subhierarchy. When a node is collapsed all its children are hidden, and whenever the node is expanded again the children reappear.
- **Text pattern search:** Typing in certain text fragments starts a search for the specified text as a substring in the textual descriptions of the vertices and highlights the corresponding nodes found, see also Figure 4. This features can be used to find word trails for example.
- **Zooming:** A zoom in/out horizontal slider bar can be used for a larger/smaller scale.
- **Details-on-demand:** By moving the mouse on any element on the display screen a more detailed information for a specific node like the node name, number of children of the node, the parent name, and the depth is displayed.
- **Color coding:** For a better visualization of the different hierarchy levels, each level of nodes is represented in a different color to distinguish it from other elements. The used color gradients can be changed at user's demand.
- **Change filter:** Only the changes of interest can be displayed, i.e. either added, deleted, modified, or exchanged elements. This means that only the colored links of interest are displayed to the viewer.
- **Delta percentage:** The percentage of change for added, deleted and modified/exchanged nodes between two consecutive hierarchies selected can be displayed.

5 CASE STUDY

The DBLP bibliography dataset contains more than 2,000,000 paper titles to date. From this data, all words occurring in the paper titles can be extracted and prefix hierarchies can be generated for each year starting in 1936 and ending up in 2012 resulting in 77 hierarchies.

Displaying the hierarchical organization of the prefix trees as indented plots in a side-by-side representation can give us interesting insights into newly introduced, deleted, or moved words or word groups in the lexicographically ordered and vertically mapped tree structure. For this case study we first compute the 100 most frequently occurring words in paper titles (stop words removed) for each year that occur at least 10 times in this year. From these prefix trees we compute the dynamic prefix tree differences. By our visualization approach we are now able to see both the hierarchical structure in each year as well as the added, deleted, modified, or exchanged vertices. This means that we are able to analyze how the publication behavior of researchers changes due to novel findings and breaking hot topics or obsolete and uninteresting research areas.

Figure 5 shows the dynamic prefix tree structure and the added, deleted, exchanged, and modified elements for a selected time interval (years 1942 until 1951). The first insight that we get is the fact that before the year 1948 there are not even 100 words that occur at least 10 times in all of the paper titles published. In 1944, there is a minimum of words occurring at least 10 times. From 1942 to 1943 many words are removed from the list of the top 100 and are not replaced by new words occuring at least 10 times in this year. We hypothesize that there was a hot topic in these early years which is not researched anymore that much in the following years. Having a look at our visualization (Figure 5) we see the many red straight lines starting at 1942 and ending at 1943 for example. Using a filter function for showing only the deleted elements we can now easily hover the mouse to the sin-

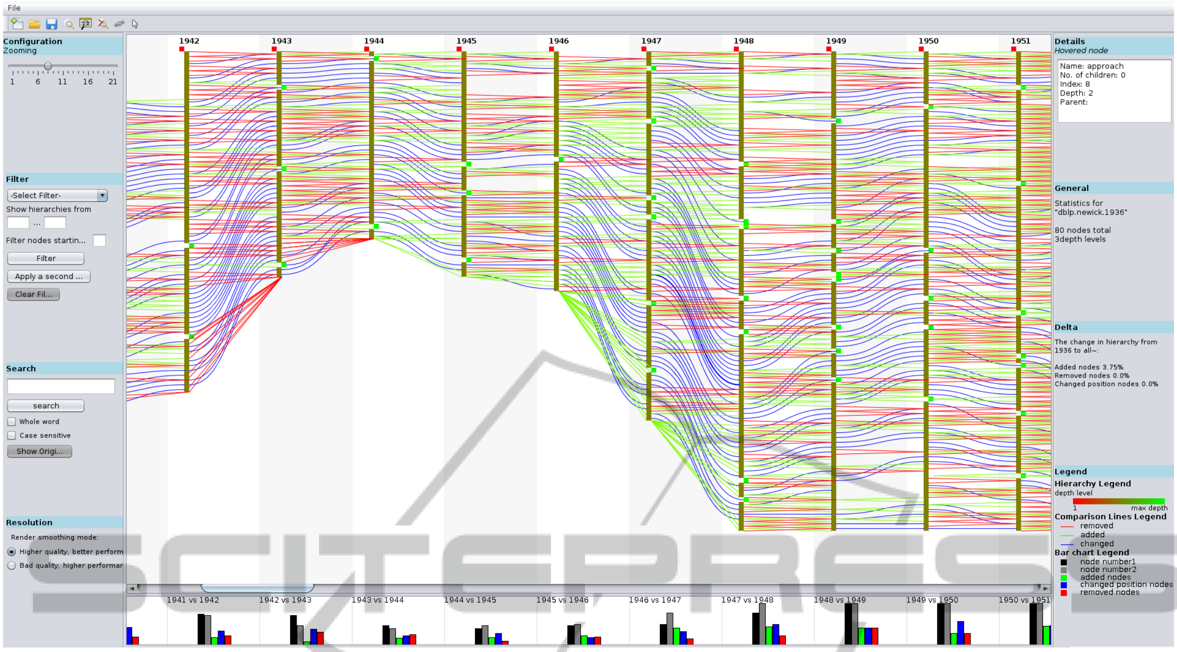


Figure 5: The graphical user interface of our visualization tool for analyzing dynamic hierarchies. It is divided into four main parts. The panel on the left hand side is responsible for parameter settings and filter values. The center panel shows the time-varying hierarchies whereas the panel on the right hand side is used for data output such as details on demand and legends. The bottom panel shows some statistical information about the vertices from different categories such as added, deleted, or changed vertices.

gle lines and obtain textual details about the deleted words:

For example, we see that the words 'types', 'tarski', 'paradox', 'analysis', and 'application' do not belong to the prefix tree of the top 100 words in 1943. On the other side, words like 'theorem', 'theory', 'system', 'set', or 'sequence' are still present in 1943 which can either be found out by inspecting the blue colored curved lines or looking for empty gaps which means nothing has changed there from one year to the other.

We can also use the visualization for finding longer word trails in the dynamic prefix trees. For this we first filter for modified or exchanged elements and get only blue colored curved lines (added and deleted ones are grayed out). By hovering the mouse to blue colored lines or corresponding nodes we find words that occur for a longer time. The words 'calculus' and 'calculi' can be found which are present for several subsequent years: 'calculus' starts to occur at least 10 times in 1936 and is present until 1955, disappears in 1956 and 1957, and reappears in 1958 and 1959 again. From 1960 on, it will never occur in the top 100 words. The plural form 'calculi' first occurs in 1939 and 1940 in the top 100, then from 1942 to 1945, and again from 1947 until 1951. In later years (1956 until 1958) the word 'calculation' as well as 'calcul' occurs at least 10 times in the top 100. After 1960, all of these words never occur again in the top 100 which shows that research in this field may have changed.

6 DISCUSSION

Our novel visualization approach is based on the visual metaphor of indentation used for representing hierarchies in order to allow a redundant-free and compact representation with a low data-ink ratio. Furthermore, we use the concept of time-to-space mapping that has some benefits when inspecting time-varying phenomena in the hierarchical data such as trends, countertrends, periodicities, temporal shifts, and also anomalies. Benefits and drawbacks of the proposed visualization technique can be summarized in the following way.

For visualizing a static hierarchy several aspects concerning benefits and drawbacks can be discussed:

- **Parent-child relationships:** By using the concept of indentation for representing a hierarchy we do not need explicit links for illustrating parent-child relationships as for example in node-link diagrams. These are only shown implicitly by indenting subhierarchies. This results in a redundant-free diagram and additional crossings and overlaps with the lines indicating changes between subsequent hierarchies are avoided. On the negative side the hierarchical structure is not that clearly visible as in traditional node-link diagrams.

- **Representative elements:** Indentation allows representative elements for each hierarchy vertex — inner as well as leaf vertices — mapped to a single line. This mapping can be used for attaching additional attributes or in our case showing explicit lines for changes between subsequent hierarchies.

For dynamic hierarchy visualization several benefits and drawbacks can be found when comparing time-to-time mappings (animation) with time-to-space mappings (static display):

- **Mental map preservation:** We use a static representation for the evolving hierarchies. This has several benefits over an animated diagram. When abrupt changes occur in the sequence an animated representation may lead to losing the mental map, which may make the data unreadable. To solve this problem in our static representation we use a side-to-side hierarchy visualization and use explicit links to guide the eye as also described by (Graham and Kennedy, 2010). This static representation reduces cognitive load, allows for interactive features, and reduces the runtime complexity that would be needed in the animated approach to produce layouts benefitting from high dynamic stabilities.
- **Time-dependent phenomena:** Time-varying behaviors can be explored visually in a static representation. In an animated sequence this seems to be problematic since the viewers have to do the comparisons by relying on their short term memory. Consequently, trends, countertrends, periodicities, temporal shifts, or anomalies can be detected much easier in a static representation of dynamic data.
- **Application of interactions:** An animated diagram makes it difficult to apply interactive features. The animation has to be stopped first and then a graphical element can be interactively selected and manipulated. This is easier to apply in a static diagram where the viewer has much more time to apply mouse interaction.
- **Algorithmic complexity:** In an animated diagram for hierarchical data good layout strategies have to be used in order to achieve dynamic stability, a concept that is also used in graph animation. This is required to preserve the viewer's mental map of the animated diagram. In a static plot of dynamic data such complex algorithms are not needed. Here, the vertex ordering is not changing and hierarchies can be added on-the-fly without computing a totally new layout.
- **Visual scalability:** Animated diagrams only show one hierarchy at a time and hence, benefit from visual scalability. The whole display can be used to represent this hierarchy. In a side-by-side visualization, i.e. a time-to-space mapping, display space is needed for many timesteps which allows each single diagram to be displayed only on a small region on screen.

7 CONCLUSIONS AND FUTURE WORK

In this paper we introduced a visualization technique for visualizing dynamic hierarchies in a static diagram by making use of the indented outline metaphor. Large hierarchies are represented by using the concept of several indented plots in a side-by-side representation. The changes and differences between subsequent hierarchies are indicated by color coded straight or curved lines. Interactive features can be applied to further navigate in the data, to explore and analyze it, and to aggregate it in the vertex and time dimension. A case study for bibliography data from the digital library DBLP was presented illustrating the usefulness of the novel dynamic hierarchy visualization.

In the future we plan to make the visualization technique more scalable in the time dimension. Moreover, the vertex ordering for reducing cluttering of the display by blue colored lines may be a good strategy to be investigated. The continuation of the lines across evolution is hard to follow in a cluttered display and hence, occlusion problems may be reduced by computing a good hierarchy layout for each timestep. Also, a user study should be conducted investigating the performance of participants when working with the novel technique. Exploring other application examples for dynamic hierarchies are also of interest for future work.

ACKNOWLEDGEMENTS

In part, this work was supported by Deutsche Forschungsgemeinschaft (DFG) within SFB 716 / D.5.

REFERENCES

Balzer, M., Deussen, O., and Lewerentz, C. (2005). Voronoi treemaps for the visualization of software metrics. In *Proceedings of Software Visualization*, pages 165–172.

Beck, F., Burch, M., and Diehl, S. (2009). Towards an aesthetic dimensions framework for dynamic graph visualisations. In *Proceedings of Information Visualisation*, pages 592–597.

Bruls, M., Huizing, K., and van Wijk, J. J. (2000). Squarified treemaps. In *Proceedings of Joint Eurographics/IEEE TVCG Symposium on Visualization*, pages 33–42.

Burch, M. and Diehl, S. (2006). Trees in a Treemap: Visualizing multiple hierarchies. In *Visualization and Data Analysis, SPIE Press, 6060*, pages 224–235.

Burch, M. and Diehl, S. (2008). TimeRadarTrees: Visualizing dynamic compound digraphs. *Computer Graphics Forum*, 27(3):823–830.

Burch, M., Heinrich, J., Konevtsova, N., Höferlin, M., and Weiskopf, D. (2011a). Evaluation of traditional, orthogonal, and radial tree diagrams by an eye tracking study. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2440–2448.

Burch, M., Raschke, M., Greis, M., and Weiskopf, D. (2012). Enriching indented pixel tree plots with node-oriented quantitative, categorical, relational, and time-series data. In *Proceedings of Diagrams*, pages 102–116.

Burch, M., Raschke, M., and Weiskopf, D. (2010). Indented Pixel Tree Plots. In *Proceedings of the International Symposium on Visual Computing*, pages 338–349.

Burch, M., Vehlow, C., Beck, F., Diehl, S., and Weiskopf, D. (2011b). Parallel edge splatting for scalable dynamic graph visualization. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2344–2353.

Card, S. K., Suh, B., Pendleton, B. A., Heer, B., and Bodnar, J. W. (2006). Time tree: Exploring time changing hierarchies. In *IEEE VAST*, pages 3–10.

Diehl, S. and Görg, C. (2002). Graphs, they are changing. In *Proceedings of Graph Drawing*, pages 23–30.

Eades, P. (1992). Drawing free trees. *Bulletin of the Institute for Combinatorics and its Applications*, 5(2):10–36.

Frishman, Y. and Tal, A. (2007). Online dynamic graph drawing. In *Proceedings of EuroVis*, pages 75–82.

Graham, M. and Kennedy, J. B. (2010). A survey of multiple tree visualisation. *Information Visualization*, 9(4):235–252.

Holten, D. and van Wijk, J. J. (2008). Visual comparison of hierarchically organized data. *Computer Graphics Forum*, 27(3):759–766.

Inselberg, A. and Dimsdale, B. (1990). Parallel coordinates: A tool for visualizing multi-dimensional geometry. In *IEEE Visualization*, pages 361–378.

Johnson, B. and Shneiderman, B. (1991). Tree-Maps: A space-filling approach to the visualization of hierarchical information structures. In *Proceedings of IEEE Visualization Conference*, pages 284–291.

Kruskal, J. and Landwehr, J. (1983). Icicle plots: Better displays for hierarchical clustering. *The American Statistician*, 37(2):162–168.

Ley, M. (2009). DBLP: Some lessons learned. *Proceedings of Very Large Data Bases*, 2(2):1493–1500.

McGuffin, M. J. and Robert, J.-M. (2010). Quantifying the space-efficiency of 2D graphical representations of trees. *Information Visualization*, 9(2):115–140.

Misue, K., Eades, P., Lai, W., and Sugiyama, K. (1995). Layout adjustment and the mental map. *Journal of Visual Languages and Computation*, 6(2):183–210.

Munzner, T., Guimbretiere, F., Tasiran, S., Zhou, Y., and Zhang, L. (2003). TreeJuxtaposer: Scalable tree comparison using focus+context with guaranteed visibility. *ACM Transactions on Graphics*, 22:453–462.

Nocaj, A. and Brandes, U. (2012). Computing Voronoi treemaps: Faster, simpler, and resolution-independent. *Computer Graphics Forum*, 31(3):855–864.

Purchase, H. C. (1997). Which aesthetic has the greatest effect on human understanding? In *Proceedings of Graph Drawing*, pages 248–261.

Reingold, E. M. and Tilford, J. S. (1981). Tidier drawings of trees. *IEEE Transactions on Software Engineering*, 7(2):223–228.

Shneiderman, B. (1992). Tree visualization with tree-maps: 2-d space-filling approach. *ACM Transactions on Graphics*, 11(1):92–99.

Shneiderman, B. (1996). The eyes have it: A task by data type taxonomy for information visualizations. In *IEEE Symposium on Visual Languages*, pages 336–343.

Telea, A. and Auber, D. (2008). Code Flows: Visualizing structural evolution of source code. *Computer Graphics Forum*, 27(3):831–838.

Tu, Y. and Shen, H.-W. (2007). Visualizing changes of hierarchical data using treemaps. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1286–1293.

Tufte, E. R. (1983). *The visual display of quantitative information*. Cheshire, CO: Graphics Press, p. 197.

van Ham, F. (2003). Using multilevel call matrices in large software projects. In *INFOVIS*, pages 227–232.

van Wijk, J. J. and van de Wetering, H. (1999). Cushion treemaps: Visualization of hierarchical information. In *Proceedings of Information Visualization*, pages 73–78.