

# Radial Edge Splatting for Visualizing Dynamic Directed Graphs

Michael Burch<sup>1</sup>, Fabian Beck<sup>2</sup> and Daniel Weiskopf<sup>1</sup>

<sup>1</sup>*VISUS, University of Stuttgart*, <sup>2</sup>*University of Trier*

Keywords: Graph visualization, node-link diagrams, radial layout, splatting

Abstract: We describe and discuss a novel radial version of a scalable dynamic graph visualization. The radial layout encodes dynamic directed graphs on narrow rings of a circle. The temporal evolution of the graph is mapped to rings that grow outward from the center of the circle. Graph vertices are placed equidistantly at the borderlines of each ring. Graph edges are displayed as curved lines starting from a source on the inner borderline of the ring and pointing to a target on the outer borderline. To better perceive link directions and structures of large datasets, visual clutter is reduced by exploiting an edge splatting approach that generates density fields of the displayed edges. The radial layout emphasizes newer graphs, displayed in the larger, outer parts of the circle. As a benefit, edge lengths are reduced in comparison to the non-radial visualization. Moreover, the radial layout guarantees the symmetry of the visualization under shifting of vertices. We illustrate the usefulness of the diagrams by applying them to call graph data of the open source software project Cobertura.

## 1 INTRODUCTION

Dynamic graph data occurs in various areas of application. For example, social networks express relationships among people. Those networks may evolve over time, i.e., new people come into the network or relationships change. In another example, distances between elements of dynamic systems can be modeled as dense graph structures and also these may change over time. In the area of software development, call graphs changing from release to release show which software constructs call each other.

Those graph datasets are often too large for a manual exploration of the raw data. When we have a clear and specific question, we may apply algorithmic approaches. But in many applications, neither we know such a question beforehand nor the problem can be reduced to a single question—some kind of visual representation of this dynamic data is required that helps us efficiently explore the dataset.

Creating such a visualization of dynamic directed and weighted graphs is challenging due to the many visual dimensions to be represented in a scalable way: First of all, many nodes could be part of the graph. Moreover, the graph could be dense; in other words, many edges connect the nodes of the graph. Finally, the graph may evolve in a significant number of changes over a long period of time.

Animation can be used to visualize the dynamic changes in a node-link diagram (Diehl and Görg, 2002; Frishman and Tal, 2008). However, animation

largely fails to provide an overview of the time dimension of the dataset; the cognitive issues of animated visualization are discussed by Tversky et al. (2002). A better overview is provided if the time dimension is mapped onto a (spatial) time line and the dynamic graph is visualized in a single static image. Such an approach that particularly focuses on the scalable representation of dynamic graphs was presented by Burch et al. (2011b). It displays snapshots of the dynamic graph side-by-side in narrow vertical stripes. Techniques like arranging the nodes onto parallel axes and applying edge splatting (representing edges in a density field) are used to increase the scalability of the single graph diagrams.

In our work, we introduce a radial version of parallel edge splatting (Burch et al., 2011b) to represent dynamic directed and weighted graphs. The radial layout shows the following beneficial characteristics:

- It avoids long links pointing from the top to vertices at the bottom and guarantees the symmetry of the visualization if vertices are shifted.
- It puts emphasis on newer graphs displayed at outer parts of the representation.

After discussing related work, we present the visualization technique in detail. The implemented visualization tool supports several interactive features such as filtering functions, aggregations in both time and vertex dimensions, and details-on-demand. We demonstrate the usefulness and the aesthetics of the radial diagrams by applying it to call graph data from

the open source software project Cobertura. Finally, we discuss the benefits and drawbacks of the radial visualization in comparison to its non-radial counterpart.

## 2 RELATED WORK

Graphs are usually visualized as nodes connected by graphical links. If not carefully laid out, visual clutter, often caused by many link crossings, makes the diagram hard to read. While Rosenholtz et al. (2005) provide a measure for such visual clutter, Purchase et al. (1996, 2001, 2002) evaluate aesthetic criteria for node-link diagrams. The minimization of link crossings is ranked very high, but also the maximization of symmetries and the maximization of angles at crossing points is of interest for good layout strategies. Beck et al. (2009) discuss a set of aesthetic criteria extended for designing dynamic graph visualizations.

Animated node-link diagrams represent dynamic graphs (Diehl and Görg, 2002; Frishman and Tal, 2008): A node-link diagram is shown to the viewer and is then smoothly animated and transformed into the next diagram. The layout algorithms try to keep the layout of the graph as stable as possible while concurrently presenting a readable layout in each single diagram. By doing this, cognitive efforts are reduced and the mental map of the viewer is preserved (Misue et al., 1995).

In general, layout algorithms for node-link diagrams can be very complex and time-consuming. Even elaborate approaches fail to produce nice layouts for large graphs due to many link crossings. The situation is even worse if a graph is not static but changes in an animation. While changes in one step can be observed by the user, animation cannot provide an overview of the time dimension. These problems led to the development of dynamic graph visualization that shows the graph—including its temporal changes—in a single static image.

A simple idea is to represent snapshots of the dynamically changing graph side-by-side on a time axis. Doing this leads to a better overview with respect to time but introduces also new problems like the much smaller screen space assigned to each diagram and the difficulty in tracking particular nodes across the sequence of diagrams. Greilich et al. (2009) proposed a tool called TimeArcTrees, where the vertices are placed on 1D vertical lines so that it is easy to track the nodes. Edges are drawn as curved arcs. Although an advanced layout is used for these arcs, the visualization quickly becomes cluttered for dense

graphs. A more scalable approach applies an edge splatting technique to compute density fields for the graph edges (Burch et al., 2011b). The visualization approach presented in this paper is a radial version of the technique by Burch et al. (2011b).

An alternative solution for representing a dynamic graph in a single image is the radial TimeRadarTrees visualization technique (Burch and Diehl, 2008), where no edge crossings occur at all. Snapshots are still shown side-by-side, but matrix-like representations and color coding are used to depict graph edges. In the layered TimeRadarTrees approach (Burch et al., 2011a), this idea is enhanced to obtain a scalable version of the visualization.

Recently, matrices have been used to depict a dynamic graph in a static image where edges are represented as colored cells of a matrix (Brandes and Nick, 2011; Gove et al., 2011; Stein et al., 2010; Yi et al., 2010). For instance, Stein et al. (2010) split each cell of the matrix into subcells and use these to depict the changing edge weights on a folded time line. Brandes and Nick (2011) follow a similar approach relying on a different, yet more elaborate representation of dynamic information in the cells of the matrix. The main advantage of adjacency matrices is that they can easily handle dense graphs. When using the cells of the matrix to represent the dynamic information, each cell, however, requires a significant amount of screen space, which leads to a decreased scalability with respect to the number of nodes.

There are further approaches to represent dynamic relational data that are, among other graph visualization techniques, surveyed by von Landesberger et al. (2011). A survey of radial visualizations is provided by Draper et al. (2009). The evaluation paper by Diehl et al. (2010) analyzes strengths and weaknesses of radial representations. It was found out that non-radial representations outperformed radial ones with respect to memorizing positions of colored boxes. We adopt the discussion of radial vs. non-radial visualizations in Section 5, focusing on the particular cases of edge splatting of graph data.

## 3 VISUALIZATION TECHNIQUE

We introduce a novel visualization technique for displaying dynamic directed and weighted graphs in a single static diagram. We exploit the node-link visual metaphor and map the graph vertices equidistantly to circular rings and edges as curved lines inside the narrow annuli (circle rings) pointing from an inner to an outer annulus. For better visual perception of the many edges in cluttered regions, we use an

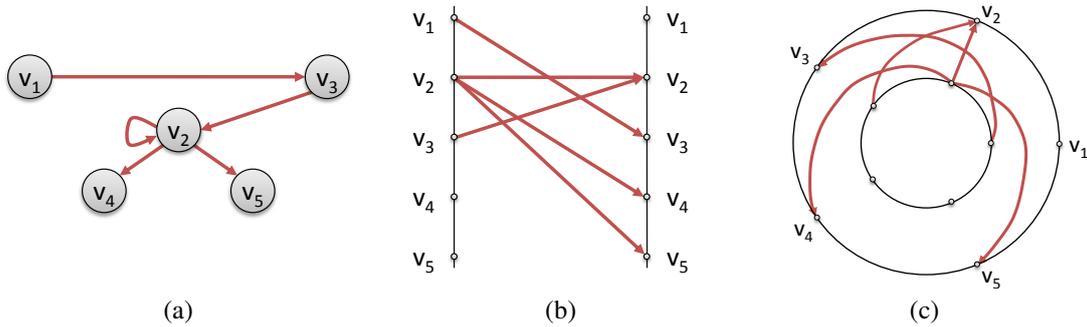


Figure 1: Visual encoding of graph data as node-link layouts: (a) Traditional 2D layout. (b) Mapping the vertices equidistantly to vertical parallel axes in the same order and drawing the direct links inside the resulting narrow stripe as proposed by Burch et al. (2011b). (c) Drawing the vertices equidistantly along the borderlines of an annulus in the same order and representing the edges as curved links pointing from the inside to the outside.

edge splatting technique to derive density fields and to allow users to explore edge directions and structures.

### 3.1 Data Model

In the context of this work, we model a directed and weighted graph in the graph-theoretic sense as

$$G = (V, E)$$

where  $V$  denotes the set of vertices and  $E \subseteq V \times V$  the set of directed edges. Each edge  $e \in E$  is attached with a weight  $w_e$ .

A dynamic graph of length  $n$  is a sequence of  $n$  single graphs and can be modeled as

$$\mathcal{G} := (G_1, \dots, G_n)$$

where  $G_i = (V_i, E_i)$ ,  $1 \leq i \leq n$ .

### 3.2 Single Graph Representation

Typically, node-link graph diagrams are laid out in the 2D plane, following several aesthetic criteria for graph drawing such as minimization of link crossings, maximization of angles at intersections, or maximization of symmetries if those exist in a graph. Since our focus is on dynamic graph visualization by static diagrams, we need a more compact representation that supports exploring and comparing a number of graphs in a side-by-side view to easily uncover trends and countertrends. We employ a visual mapping of the graph vertices equidistantly to 1D vertical parallel lines as demonstrated in the work of Burch et al. (2011b), a concept that is similar to parallel-coordinate plots (Inselberg and Dimsdale, 1990). In the following, we demonstrate how a single directed graph is represented as a traditional 2D drawing, as a Cartesian 1D drawing as in the work of Burch et al.

(2011b), and as a novel radial 1D drawing; see Figures 1 (a), (b), and (c).

In Figure 1 (a), one graph with five vertices and five edges is displayed by applying a graph layout algorithm that generates a planar drawing in this case. In Figure 1 (b), the graph vertices are mapped equidistantly to a vertical axis. The vertex set is copied and mapped in the same order to a second parallel vertical axis. The directed graph edges are displayed inside the resulting narrow stripe, starting at the vertical node position on the left axis and heading to the vertical position of its target vertex on the axis at the right hand side. Please note that arrow heads indicate the direction of the links in the figures. The arrow heads are for illustration purposes only and will be left out in the actual graph visualizations.

In Figure 1 (c), the novel radial technique is illustrated. To transform the Cartesian diagram into a radial one, we connect the endpoints of the narrow stripe and obtain an annulus representation with the links in between pointing from the inner border to the outer border of the annulus. To prevent links from leaving the annulus region, we transform the straight links of the Cartesian diagram into curved links, approximated by piecewise linear polygonal curves. Such a curve is specified by the sequence of  $n + 1$  points

$$\mathcal{P} := (P_0, P_1, P_2, \dots, P_n)$$

where

$$P_i := \left( r_1 + \frac{i \cdot (r_2 - r_1)}{n} \right) \cdot \begin{pmatrix} \cos(\vartheta + \frac{i\varphi}{n}) \\ \sin(\vartheta + \frac{i\varphi}{n}) \end{pmatrix}$$

and  $0 \leq i \leq n$ .

The parameter  $r_1$  is the radius of the inner border of the annulus and  $r_2$  the radius of the outer border of the annulus. The angle  $\vartheta$  is the angular position of the start vertex, whereas  $\varphi$  is the angle that is needed to point to the target vertex, i.e., the shifting angle.

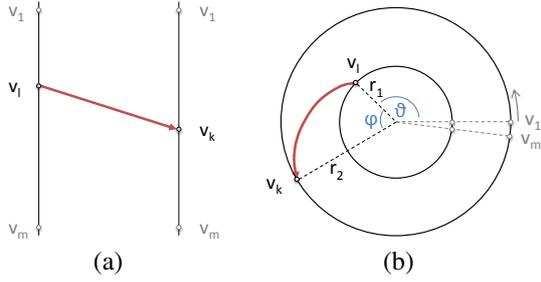


Figure 2: Mapping of a single directed graph edge: (a) Left to right mapping between two vertical parallel axes as a straight link. (b) Mapping to an annulus from the inside to the outside as a curved link.

The mapping of a single edge to a straight and a curved line is illustrated in Figures 2 (a) and (b), respectively. In Figure 2 (a), a directed edge leads from node  $v_l$  to another node  $v_k$  among  $m$  nodes  $v_1, \dots, v_m$ . The start vertex is displayed on the left axis and the target vertex is displayed at the corresponding position on the right axis. The directed edge is indicated by a red colored straight line between the two corresponding nodes. In the radial representation in Figure 2 (b), the same edge is shown. Now, the vertices are mapped to the borderlines of the annulus and the edge is displayed as a curved link running from the inside to the outside.

Figures 3 (a) and (b) demonstrate how long links in the Cartesian diagram are shortened by using a radial representation. In Figure 3 (a), a straight link points from node  $v_l$  to node  $v_k$ . This link crosses a large part of the display in a diagonal fashion and has a high probability to lead to link crossings. In the radial representation like illustrated in Figure 3 (b), there are two possibilities to render the curved link. Our edge layout algorithm minimizes link lengths by always picking the shorter of the two options. Hence, the dashed link in Figure 3 (b) will be avoided.

### 3.3 Dynamic Graph Representation

For representing a dynamic directed graph, we follow the same principle as for the Cartesian diagram of Burch et al. (2011b). In their work, all graphs are mapped to subsequent narrow stripes from left to right. In our work, we map each graph to an annulus and the whole graph sequence to many annuli starting in the circle center with the oldest graph and ending with the newest graph at the outside. By doing this, we put emphasis on newer graphs by mapping them to a larger display space, which is an intuitive concept for time-series data visualization.

Figures 4 (a), (b), and (c) demonstrate how a sequence of two directed graphs is visualized as an

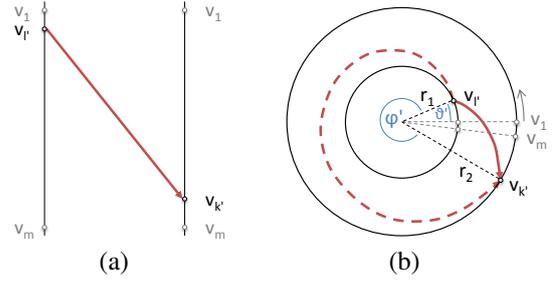


Figure 3: Reduction of link length by switching the orientation: (a) A directed straight link crossing a large part of the display. (b) A mapping to an annulus representation allows two possible directions of the curved link—clockwise and counter clockwise. Our edge layout algorithm minimizes link length by picking the shorter of the two potential links. Hence, it avoids the dashed link as illustrated.

animated node-link diagram (a), as a 1D node-link representation to parallel vertical axes (b), and as a sequence of annuli with curved links pointing from the inside to the outside (c). Please note that we do not distinguish between removed vertices and vertices that are not adjacent to any other vertex.

### 3.4 Edge Splatting

A negative consequence of node-link diagrams is the occurrence of visual clutter caused by many link crossings. By mapping the graph to 1D vertical axes and the edges as straight or curved links in between, we gain a lot of space to display the dynamics of the graph on the positive side, but we also increase the problem of visual clutter on the negative side.

To alleviate the problem, we apply the concept of edge splatting as it is also used in the work of Burch et al. (2011b). By computing density fields for the edges, the link directions and structures become visible again.

### 3.5 Benefits of Radial Edge Routing

The technique has the benefit that formerly long links become shorter by only allowing a maximal link length  $l \in [r_1 \cdot \pi, r_2 \cdot \pi]$  where  $r_1$  and  $r_2$  are the radii of the inner and outer borders of the respective annulus. In our case we use a curved link representation style that exactly generates links of length  $\pi \cdot \frac{r_1+r_2}{2}$ . Figure 5 (a) and (b) illustrate the minimization of link length for an example dataset. In Figure 5 (a), there is an X-pattern leading to visual clutter caused by crossings with the parallel horizontal lines, which is resolved in Figure 5 (b) by just connecting the upper and lower endpoints of the Cartesian representation. The radial version transforms the finite and bounded

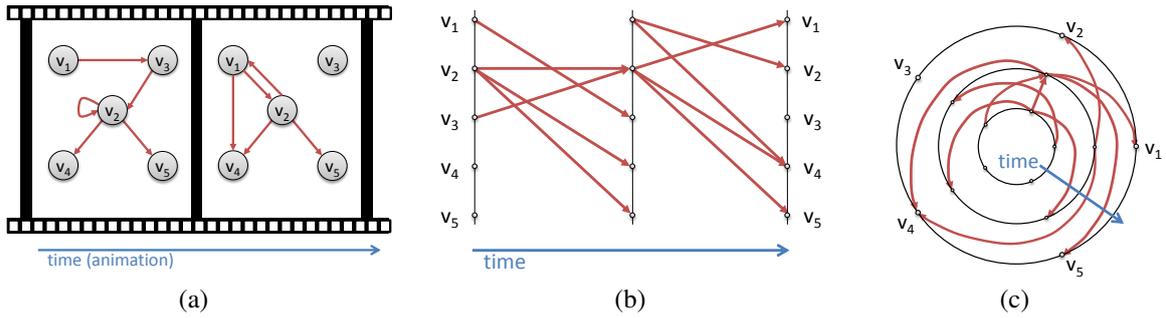


Figure 4: A sequence of two directed graphs can be represented in different styles: (a) Animated node-link diagrams. (b) Sequence of node-link diagrams mapped to 1D parallel vertical axes. (c) Sequence of annuli starting in the circle center and ending with the newest graph at the outside.

vertical axes of the Cartesian diagram to cyclic annuli (i.e., without bounding the angle position of vertices).

Another consequence of routing the edges in a radial fashion is that the visualization becomes invariant under shifting of vertices. In Figure 5 (c) and (d) we shifted the vertex positions of Figure 5 (a) and (b) by 10 positions. In the Cartesian version, this results in a visualization that looks significantly different from the original non-shifted version because the vertices that created the dominating X-pattern are no longer split by the borders of the stripe. In contrast, the shifted radial visualization only changes marginally—it is only rotated by a small angle.

### 3.6 Interactive Features

Since we follow the Visual Information Seeking Mantra introduced by Shneiderman (1996), we first generate an overview representation of the graph sequence that serves as a starting point for an exploration process. Apart from the static overview, the visualization supports the following interactive features such as aggregation in the vertex and time dimension and several filtering functions. Also graph-specific tasks such as shortest path detection can be solved algorithmically and their evolution over time can be displayed visually.

- **Selection of time intervals:** Representing many timesteps results in very narrow radial annuli and consequently, each graph of a displayed sequence is difficult to interpret. For this reason, the user is supported by selecting a specific time interval and only the graphs which belong to this interval are represented.
- **Graph aggregation:** In many cases, a stability pattern occurs in the graph sequence, i.e., there are only a few changes between subsequent graphs. It makes sense to aggregate all those graphs to

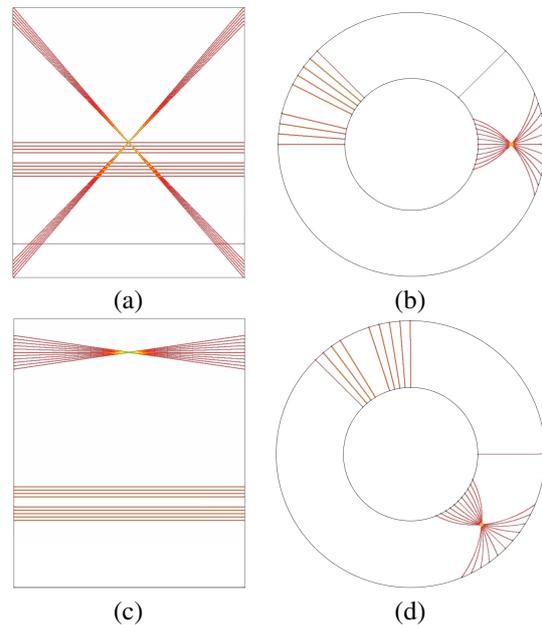


Figure 5: Beneficial characteristics of radial edge routing: (a) Cartesian representation with links crossing the whole display. (b) The radial version with shorter links. (c) A shifted Cartesian visualization, which results in major visual changes. (d) The equivalent shifted radial visualization, which only results in minor visual changes.

have more display space for graphs that frequently change.

- **Vertex Aggregation:** Neighbored vertices can be aggregated to also increase scalability in the vertex dimension. If a hierarchical organization of the vertices exists, this can be used to collapse or expand vertex groups.
- **Edge weight filtering:** Edges can be filtered by selecting a weight interval. Only those edges with a weight contained inside the defined interval are represented on screen. All the others are either grayed out or not drawn on screen at all. Another

filtering can be applied to the values of the edge density field generated by our edge splatting approach.

- **Added and removed edges:** We allow two additional operations for the edges. Added and removed relations between two subsequent graphs in the sequence can be computed and only those edges are displayed by the tool. This feature helps to analyse the differences between subsequent graphs even if the graphs are very dense.
- **Textual search:** The tool allows to search for substrings in the set of descriptive informations for the vertices, i.e., for substrings in labels.
- **Path tracking:** By specifying a start and a target vertex, the shortest path between these vertices is computed and highlighted on screen in all of the displayed graphs. This feature can be used to obtain an overview about the evolution of a graph-specific property.
- **Color coding:** The tool supports different color schemes that can be applied to the visualization. By doing this, a viewer can analyze the data on different levels of weight granularity.
- **Details-on-demand:** We also support details-on-demand to analyze the corresponding meta information of the dataset, e.g., the timestamp, the release number, or the labeling information of the vertices.

The tool supports many more interactive features that cannot be mentioned all in this paper and many more will be implemented in future.

## 4 CASE STUDY: CALL GRAPH VISUALIZATION

In this case study, we want to illustrate how the tool can be applied in practice. We decided to visualize the method calls of a software project that change from release to release. Such a graph does not only explain the design of a single version, but also how this design evolves over the versions. Visualizing such a dynamic graph, however, is challenging since already small software projects may consist of hundreds or thousands of methods. We chose the open source project Cobertura<sup>1</sup> as a comprehensive example to be analyzed.

<sup>1</sup><http://cobertura.sourceforge.net/>

### 4.1 Cobertura

Cobertura is a software engineering tool for retrieving the test coverage of Java programs. It instruments the Java bytecode of the program, runs the test cases, and finally generates a report on test coverage. Cobertura itself is written in Java and released as open source. In the latest analyzed version (version 1.9.4), it consists of 99 classes and 18 packages. Since version 1.0 was released in 2005, 13 stable update releases have followed quite regularly up to version 1.9.4.

We downloaded these 14 stable versions of Cobertura, analyzed the bytecode using the tool DependencyFinder<sup>2</sup>, and extracted the method call graph of the project. This dynamic graph is described by a sequence of 14 graphs (versions of Cobertura). In total, the static graphs consist of 4,812 individual nodes (methods) and 27,208 edges (method calls). Figure 6 (a) shows the call graph by radial edge splatting. To highlight the changes in the graph, we also computed the method calls that were added or removed between two consecutive versions. Figure 6 (b) depicts the added method calls while Figure 6 (c) illustrates which ones were removed.

### 4.2 Observations

A first observation in Figure 6 (a) is that the project in terms of the number of method calls is growing, however, more stepwise than continuously. The two steps that come along with the most significant modifications are version 1.8 and version 1.9.3. They refer to the `javancss` package, which is first introduced in version 1.8 and heavily extended in version 1.9.3. These abrupt modifications suggest that this package was not developed stepwise as a part of the Cobertura project, but imported from somewhere else. A web search confirmed this assumption: `javaNCSS`<sup>3</sup> is a command line tool for computing software metrics. Different versions of `javaNCSS` seem to relate to the observed changes.

An interesting information that the visualization indicates is the similar visual pattern that repeatedly appears in `javaNCSS` in versions 1.9.3 and 1.9.4 of Cobertura. This pattern is repeated four times in both versions, whereas two of the repetitions are smaller than the other two. A detailed analysis revealed that each of the repeated patterns is related to a Java parser. There are four parsers integrated into `javaNCSS` because two versions of Java are supported and for both versions also a debug parser exists. In version 1.8 up to version 1.9.2 of Cobertura, there is only one parser

<sup>2</sup><http://depfind.sourceforge.net/>

<sup>3</sup><http://javancss.codehaus.org>

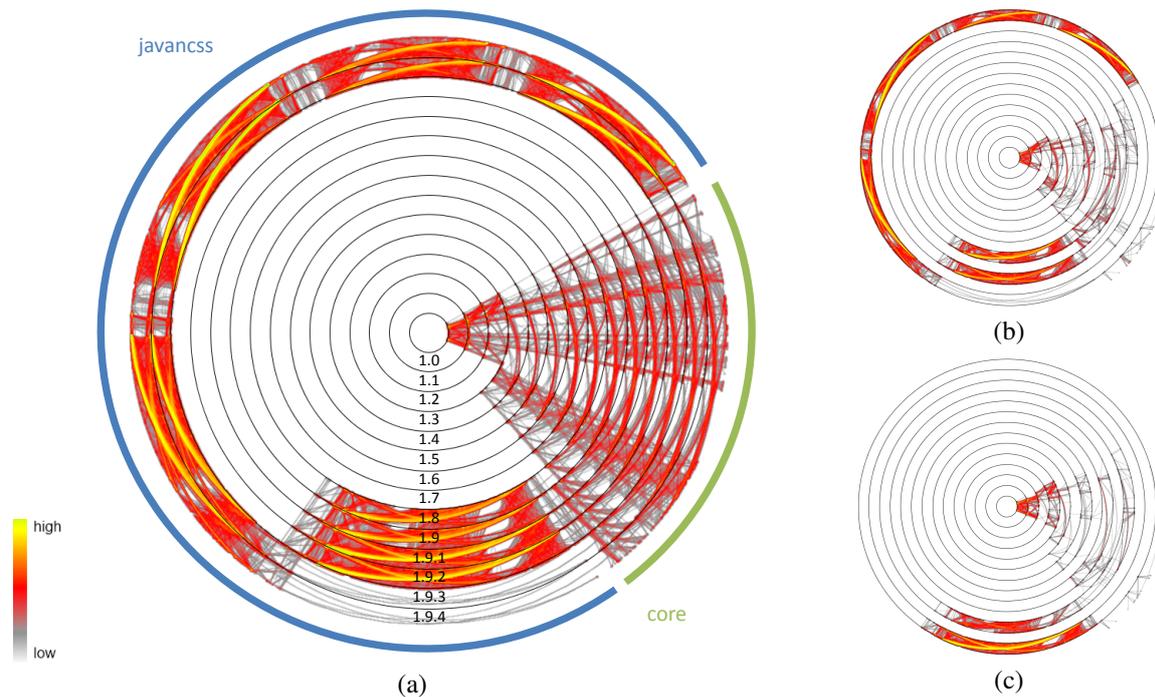


Figure 6: Visualizing the call graph of methods in Cobertura over different releases. (a) All method calls. (b) Added method calls. (c) Removed method calls.

version, which creates a similar visual pattern. Although this single pattern does not seem to change significantly, Figures 6 (b) and (c) reveal that there were some significant changes in version 1.9.1.

The rest of the system beside the `javancss` package is what we labeled as the `core` of Cobertura in Figure 6 (a). In contrast to `javaNCSS`, the development takes place much more steadily in this part. While in the first three versions the graph structure is quite volatile, it forms a stable corpus from version 1.4 onwards. However, still significant changes are made in the subsequent versions as the number of added edges tell in Figure 6 (b). This development continues up to version 1.9—the following versions seem to be indeed only minor releases as already indicated by the version number.

## 5 DISCUSSION

Many visualization approaches are based on a radial layout (Draper et al., 2009). But often, it would have been possible to implement the same approach in a non-radial fashion. Besides the often aesthetically pleasing appearance of the radial visualizations, it is not clear whether this design decision in favor of a radial is also justified by increased readability.

For instance, pie charts are radial versions of bar charts. While pie charts seem to be very popular in practice, information visualization researchers often complain about their frequent usage. The effectiveness of both types of diagrams was empirically evaluated in comparative experiments (Cleveland and McGill, 1986; Schonlau and Peters, 2008; Spence and Lewandowsky, 1991). These experiments, however, do not come to a consistent conclusion. Other types of radial visualization approaches were also compared to their non-radial counterparts (Andrews and Kaskanicka, 2007; Burch et al., 2008; Kobsa, 2004; Stasko et al., 2000). But it would be questionable to generalize the results retrieved for those specialized visualizations and directly apply these to the visualization presented in the current work.

Diehl et al. (2010) compared radial and non-radial layouts choosing a more generic visualization and task. They analyzed how users are able to memorize positions in radial and Cartesian (non-radial) coordinate systems. The general trend was that users made more mistakes and needed more time remembering the positions in the radial visualizations. But looking at the details of the study, there were also advantages of radial visualizations: Participants could memorize circle sectors much better than circle rings, and also than rows or columns in the Cartesian coordinate system. In the following, we discuss the new radial vi-

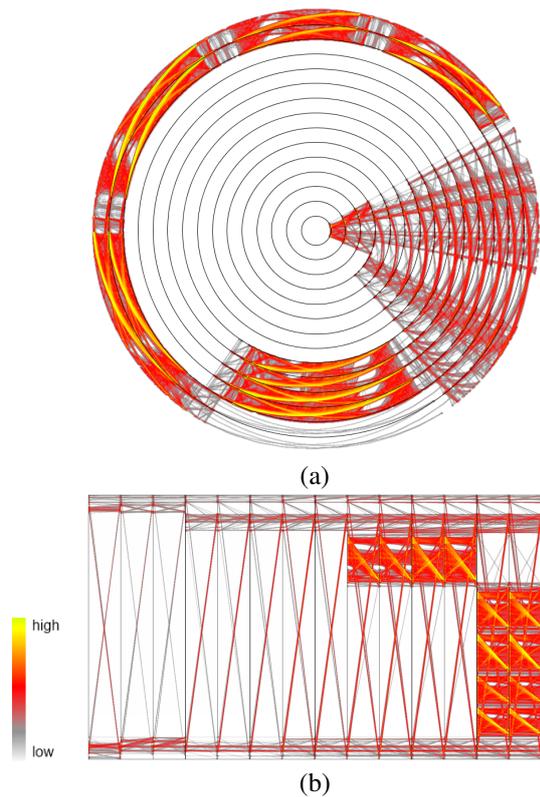


Figure 7: Comparing the radial visualization to its Cartesian counterpart based on the Cobertura call graph: (a) The radial diagram. (b) The Cartesian diagram.

sualization in the light of these empirical results and theoretical considerations.

Figure 7 compares our radial visualization (a) to its Cartesian counterpart (b) following the approach of Burch et al. (2011b). Both parts show the Cobertura dataset presented in the case study. They serve as an example for discussing the benefits and drawbacks of the radial version.

### 5.1 Traceability of Edges

The technique of our new visualization has the benefit that some formerly very long links become shorter because now there are two ways to come from a source to a target: clockwise and counter-clockwise. The edge routing algorithm chooses the shorter one as discussed in Section 3.5. This could have a significant impact on the visualizations: The example of Figure 7 (b) shows a quite dominating x-pattern consistent over all versions of Cobertura, which, however, is only a visual artifact. In contrast, the radial version in Figure 7 (a) shows no such exaggerated artifact.

Moreover, in the radial visualization formerly straight links become curved. Our first subjective im-

pression was that these curved lines are harder to follow. This could be related to the observation that the positions of rings are hard to memorize (Diehl et al., 2010) because, especially when learning the position relative to another position, following circular lines would be required. This research question is also related to whether curved links in node-link diagrams are beneficial in general—some empirical evidence suggests that they are not (Holten et al., 2011). But to finally judge whether the curved links are a drawback of the radial visualization, the impact of this effect needs to be empirically evaluated for our radial visualization.

### 5.2 Space Efficiency

The radial visualization provides an inherent focus-and-context mechanism. The outer rings of a radial layout cover more space than the inner rings. This automatically focuses the outer graphs in the sequence of graphs, which are the newer ones when the time line starts at the circle center. Depending on the application, this can be a valuable benefit: In many applications we are interested most in the recent development—the longer history just provides a context. Analyzing the evolution of software projects as demonstrated in the case study is an example for that. In applications where the focus should not be fixed, inverting, rotating, or reordering the time line may switch the focus appropriately. Nevertheless, deactivating the inherent focus is not possible.

Comparing the single stripes (annuli) in the radial visualization to the stripes of the Cartesian version, the stripes are longer, but even narrower in the radial version. Although it is not clear what the ideal aspect ratio of these stripes should be, it seems that the radial stripes might be too narrow. Hence, interactively focusing and enlarging a stripe is more important in the radial visualization.

Computer screens usually have a rectangular format. This format better fits a Cartesian coordinate system. In a radial visualization some space in the corners of the screen cannot be directly used by the visualization. Nevertheless, often the spare screen space can be used for displaying additional information like a legend or some interactive controls.

### 5.3 Visual Patterns

Different visual patterns that could help to interpret the visualization are discussed by (Burch et al., 2011b). These patterns show also up in the radial version of the visualization. But here, they are somewhat harder to detect since they occur not only in scaled

and transposed versions, but could also be rotated. An advantage of the radial version, however, could be that the direction of the edges is better expressed through the growing size of the annuli—incoming edges can only hardly be mistaken for outgoing edges.

Reordering the vertices may change the look of the visual patterns significantly, both in the radial as well as in the Cartesian visualization. When, however, only shifting a set of vertices, the radial visualization guarantees stable patterns among the shifted vertices. In contrast, those patterns are obscured in the Cartesian visualization when moving the set of vertices across the upper or lower border of the diagram. The advantage of the radial diagram is that those borders do not exist as each strip forms a ring (Section 3.5).

## 6 CONCLUSION AND FUTURE WORK

We have introduced and discussed a novel radial visualization technique for displaying dynamic directed and weighted graphs in a static diagram. The visualization is a radial version of the parallel edge splatting approach (Burch et al., 2011b). It employs a 1D mapping of the graph vertices to circle circumferences. The resulting annuli are used to draw the graph edges from the inside to the outside in a curved style. To support a viewer with the difficult task of tracing links in large and dense graph structures, the visualization is based on the concept of edge splatting, which color codes the edge density. We illustrate the usefulness of the technique by applying it to a dataset of evolving call graphs extracted from an open source software project.

By using a radial representation, we achieve shorter links than in the Cartesian counterpart; in addition, the visualization is invariant under shifting the positions of all vertices, which is not the case in the Cartesian counterpart. Furthermore, we put emphasis on newer graphs in the evolution that are mapped to the outer annuli covering more screen space. A major drawback of the radial technique could be the curved links that seem to be harder to follow.

Whether the advantages outweigh the drawbacks of choosing a radial layout is not clear, but it probably depends on the particular application. Performing a thorough empirical study with different tasks and datasets to evaluate this is part of possible future work. Another unanswered question and a quite challenging task is to generate an optimal vertex ordering with the goal to further reduce link crossings. Since this belongs to the class of NP-hard problems

and is related to the optimal linear arrangement problem (Garey and Johnson, 1979), we would have to apply some heuristic approach to find a good solution.

## REFERENCES

- Andrews, K. and Kasanicka, J. (2007). A Comparative Study of Four Hierarchy Browsers Using the Hierarchical Visualisation Testing Environment (HVTE). In *Proceedings of International Conference on Information Visualization (IV)*, pages 81–86. IEEE Computer Society Press.
- Beck, F., Burch, M., and Diehl, S. (2009). Towards an Aesthetic Dimensions Framework for Dynamic Graph Visualisations. In *Proceedings of International Conference on Information Visualization (IV)*, pages 592–597. IEEE Computer Society Press.
- Brandes, U. and Nick, B. (2011). Asymmetric Relations in Longitudinal Social Networks. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2283–2290.
- Burch, M., Bott, F., Beck, F., and Diehl, S. (2008). Cartesian vs. Radial — A Comparative Evaluation of Two Visualization Tools. In *Proceedings of International Symposium on Visual Computing (ISVC)*, pages 151–160.
- Burch, M. and Diehl, S. (2008). TimeRadarTrees: Visualizing Dynamic Compound Digraphs. *Computer Graphics Forum*, 27(3):823–830.
- Burch, M., Höferlin, M., and Weiskopf, D. (2011a). Layered TimeRadarTrees. In *Proceedings of International Conference on Information Visualization (IV)*, pages 18–25. IEEE Computer Society Press.
- 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.
- Cleveland, W. S. and McGill, R. (1986). An Experiment in Graphical Perception. *International Journal of Man-Machine Studies*, 25(5):491–501.
- Diehl, S., Beck, F., and Burch, M. (2010). Uncovering Strengths and Weaknesses of Radial Visualizations—an Empirical Approach. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):935–942.
- Diehl, S. and Görg, C. (2002). Graphs, They Are Changing. In *Proceedings of International Symposium on Graph Drawing*, pages 23–30. Springer.
- Draper, G., Livnat, Y., and Riesenfeld, R. (2009). A Survey of Radial Methods for Information Visualization. *IEEE Transactions on Visualization and Computer Graphics*, 15(5):759–776.
- Frishman, Y. and Tal, A. (2008). Online Dynamic Graph Drawing. *IEEE Transactions on Visualization and Computer Graphics*, 14(4):727–740.
- Garey, M. R. and Johnson, D. S. (1979). *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W. H. Freeman & Co., New York, NY, USA.

- Gove, R., Gramsky, N., Kirby, R., Sefer, E., Sapan, A., Dunne, C., Shneiderman, B., and Taieb-Maimon, M. (2011). NetVisia: Heat Map and Matrix Visualization of Dynamic Social Network Statistics and Content. In *Proceedings of IEEE Conference on Social Computing*. IEEE Press.
- Greilich, M., Burch, M., and Diehl, S. (2009). Visualizing the Evolution of Compound Digraphs with TimeArc-Trees. *Computer Graphics Forum*, 28(3):975–982.
- Holten, D., Isenberg, P., van Wijk, J. J., and Fekete, J.-D. (2011). An Extended Evaluation of the Readability of Tapered, Animated, and Textured Directed-Edge Representations in Node-Link Graphs. In *Proceedings of the Pacific Symposium on Visualization*, pages 195–202.
- Inselberg, A. and Dimsdale, B. (1990). Parallel Coordinates: A Tool for Visualizing Multi-Dimensional Geometry. In *Proceedings of IEEE Visualization*, pages 361–378.
- Kobsa, A. (2004). User Experiments with Tree Visualization Systems. In *IEEE Symposium on Information Visualization*, pages 9–16. IEEE Computer Society.
- Misue, K., Eades, P., Lai, W., and Sugiyama, K. (1995). Layout Adjustment and the Mental Map. *Journal of Visual Languages and Computing*, 6(2):183–210.
- Purchase, H. C., Carrington, D., and Allder, J.-A. (2002). Empirical Evaluation of Aesthetics-Based Graph Layout. *Empirical Software Engineering*, 7(3):233–255.
- Purchase, H. C., Cohen, R. F., and James, M. (1996). Validating Graph Drawing Aesthetics. In *Proceedings of International Symposium on Graph Drawing*, pages 435–446.
- Purchase, H. C., McGill, M., Colpoys, L., and Carrington, D. (2001). Graph Drawing Aesthetics and the Comprehension of UML Class Diagrams: An Empirical Study. In *Proceedings of the Asia-Pacific Symposium on Information Visualisation*, pages 129–137.
- Rosenholtz, R., Li, Y., Mansfield, J., and Jin, Z. (2005). Feature Congestion: A Measure of Display Clutter. In *Proceedings of SIGCHI Conference on Human Factors in Computing Systems*, pages 761–770.
- Schonlau, M. and Peters, E. (2008). Graph Comprehension: An Experiment in Displaying Data as Bar Charts, Pie Charts and Tables With and Without the Gratuitous 3rd Dimension. *Social Science Research Network Working Paper Series*.
- Shneiderman, B. (1996). The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations. In *Proceedings of IEEE Symposium on Visual Languages*, pages 336–343. IEEE Computer Society Press.
- Spence, I. and Lewandowsky, S. (1991). Displaying Proportions and Percentages. *Cognitive Psychology*, 5(1):61–77.
- Stasko, J., Catrambone, R., Guzdial, M., and McDonald, K. (2000). An Evaluation of Space-Filling Information Visualizations for Depicting Hierarchical Structures. *International Journal of Human-Computer Studies*, 53(5):663–694.
- Stein, K., Wegener, R., and Schlieder, C. (2010). Pixel-Oriented Visualization of Change in Social Networks. In *Proceedings of the International Conference on Advances in Social Networks Analysis and Mining*, pages 233–240. IEEE Computer Society.
- Tversky, B., Morrison, J. B., and Bétrancourt, M. (2002). Animation: can it facilitate? *International Journal on Human-Computer Studies*, 57(4):247–262.
- von Landesberger, T., Kuijper, A., Schreck, T., Kohlhammer, J., van Wijk, J. J., Fekete, J.-D., and Fellner, D. W. (2011). Visual Analysis of Large Graphs: State-of-the-Art and Future Research Challenges. *Computer Graphics Forum*, 30(6):1719–1749.
- Yi, J. S., Elmqvist, N., and Lee, S. (2010). TimeMatrix: Analyzing Temporal Social Networks Using Interactive Matrix-Based Visualizations. *International Journal of Human-Computer Interaction*, 26(11):1031–1051.