Node-Ring Graph Visualization Clears Edge Congestion

Katayoon Etemad[*] Sheelagh Carpendale[†] Faramarz Samavati[‡]

University of Calgary

Figure 1: Node-Ring graph visualization, representing a dense graph with fourteen nodes and eighty four edges. Colors derived from "City view" by Hundertwasser [34].

Abstract

The most common graph visualization techniques still use node-link layouts; where the nodes represent the entities and the links represent the edges or relationships between the entities. In node-link layouts, the issues of edge density, edge crossings and general edge congestion remain one of the major challenges. In this paper, we introduce a new graph layout: Node-Ring layout. Our layout was inspired by concentric circles, which have appeared in art in numerous diverse situations. We have particularly noted Australian dot painting and Hundertwasser's paintings. The change in layout is that instead of the edges being represented as links (lines between nodes), we represent them as colored rings located inside the node. These concentric edge-rings are colored according to the node to which they connect. Nodes can be sized according to their weight, and for weighted edges a circular section whose angle is proportional to the weight can be drawn instead of a full ring. This alternative layout has no hassle with edge crossings or cluttering.

Keywords: graph drawing; alternate graph layout; information visualization; graph layout aesthetics

1 Introduction

Graphs are ubiquitous. They exist in a plethora of data. That is, any data that contains entities and the relationships between these entities can be represented as graphs. Entities are commonly drawn as nodes and the relationships between these entities are most commonly drawn as links, which are shown as lines or curves connecting the nodes and are often referred to as edges. These approaches

[*]e-mail: ketemad@ucalgary.ca
[†]e-mail:sheelagh@ucalgary.ca
[‡]e-mail:samavati@ucalgary.ca

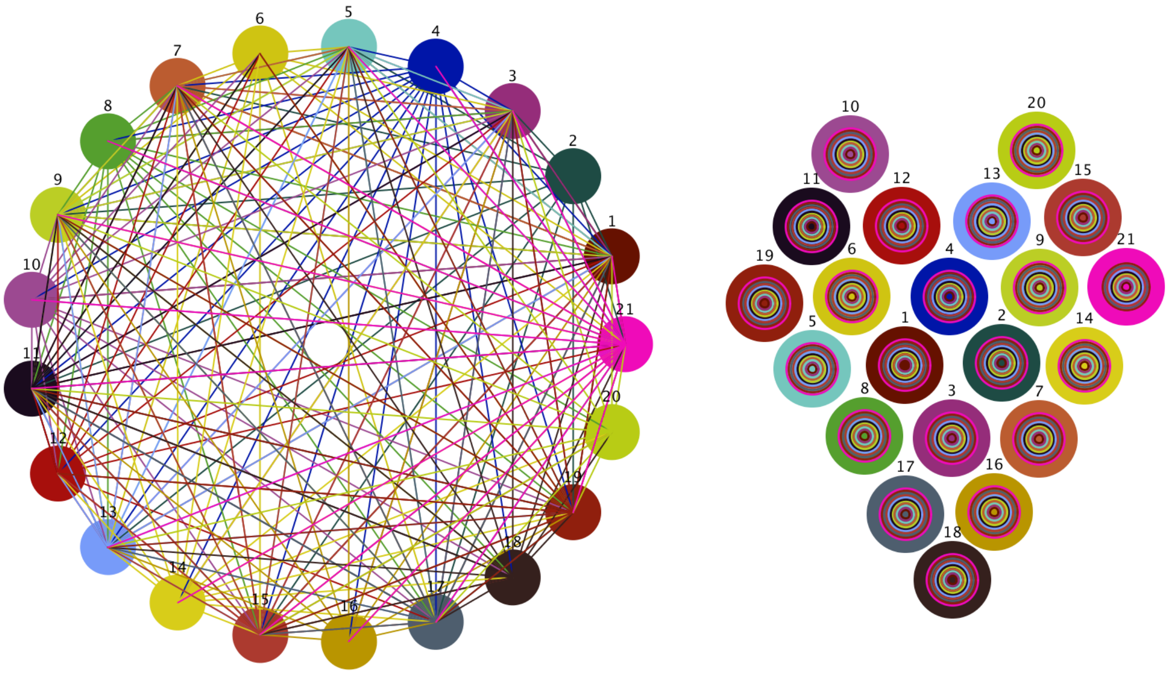

Figure 2: Node-link layout (left) and Node-Ring layout (right) both showing the same dense graph with twenty one nodes and two hundred and ten edges.

do specify the data, but the resulting layouts have perennial problems with edge congestion such as overlaps, crossings, and general clutter.

Some of the alternate edge representations such as adjacency and containment that work with more constrained data sets such as trees are less successful with graphs. Here we take a different approach. We turn to art for inspiration and from this inspiration offer a new graph layout approach that we call Node-Ring layouts.

There is indication that attractive and engaging graph representations can help analysts in persist their exploration tasks [39]. Also, the effects of more mathematical aesthetics in graph visualization have been studied by Purchase et al. [30]. These studies show that maximizing symmetry as well as minimizing edge crossings, edge bending and node overlaps have strong effects on understanding the graph structure. In a series of studies conducted by Purchase et al. [31], participants were asked to draw graphs in a more understandable way. The results indicated that the participants tried to follow the same criteria in their drawings: reducing edge crossings, reducing edge bending and increasing symmetry. This seems to indicate that a layout where edges are implicit instead of explicitly drawn as links might be beneficial.

While the problem we tackle is a well-known one, that of edge congestion in graphs, our approach is an art inspired approach. We sample the world of alternate aesthetics to find inspiration for a new approach to graph layouts. It was frequently reoccurring aesthetic of concentric circles that formed the basis of our idea. Concentric circles have existed in art since rock carvings and have occurred repeatedly, as in Kandinskys Concentric Circles. Using the idea of concentric circles we introduce a visualization for graphs that uses an implicit representation of edges. The information about the edges is included without explicitly drawing them as links (See Figure 1). In our visualization, each node is represented by a circle with a specific color. Edges that connect two nodes are implicitly represented by colored rings nested inside the nodes. The direction of the edge can be captured by the color and the position of the rings. The ring is placed in the node from which the edge originates. The originating node has its own color and always retains the very center of its circle and its outer rim to display its own color. The color of the edge-ring shows the color of the destination node (See Figure 6). For visualizing weighted graphs we use weight-proportional edge-ring sectors.

The remainder of this paper is structured as follows. To explain our inspiration we start, in Section 2, with a short review of traditional and non-traditional artistic works discussing how they led to our Node-Ring link-less layouts for graphs. The challenges of graph visualization that we have tried to address in link-less graph visualization are discussed in the Section 3. Section 4.1 provides an explanation of Node-Ring layouts and contains overview of the visual encoding of our Node-Ring graph visualization. The interaction techniques that are currently included are discussed in the Section 5. We discuss the strengths and weaknesses of this visualization in Section 6 and finally, conclude the paper in Section 7.

2 Artistic Inspiration

Our design of Node-Ring graph visualization (see Figure 2) was inspired by concentric circle patterns. These patterns can be seen in several artistic pieces. They are a common feature in Hundertwasser's work [34]. Figure 3 shows the Hundertwasser painting "Columbus Landed in India" [3] (Creative Commons license [2]). Note the use of multiple multi-colored concentric circular shapes. These types of concentric circles are featured in many of his painting such as "The Silent Flowers" and "Blobs Grow in Beloved Gardens" [34]. He uses strong colors and repeating motifs, such as *lollipop* type flowers. He features colorful concentric shapes, often in loose circles, in many of his paintings.

One style of Australian aboriginal paintings is known as dot paintings [35]. While entirely different from Hundertwasser's work, one can also see concentric circle patterns [28]. Figure 4 shows "Stomping Grounds" an example of such a painting done by Michael Bruce Cummings, styled as kinjart [4] (Creative Commons license [1]). Dot Painting or Aboriginal Dot Art originated in the desert and uses natural substances from the ground for pigments

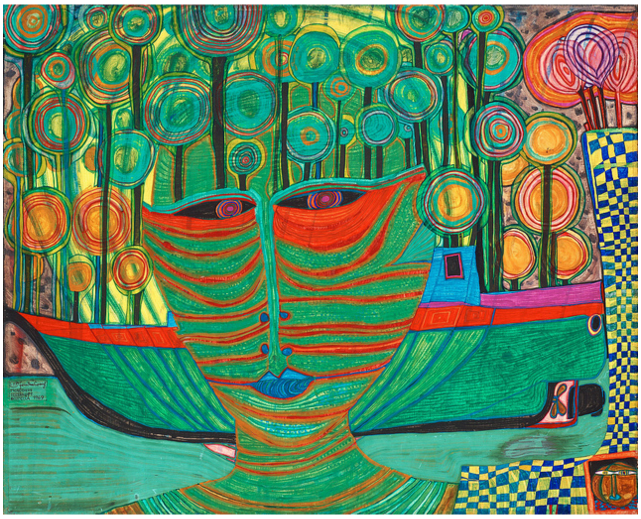

Figure 3: “Columbus Landed in India” by Hundertwasser 1969 [3] (Creative Commons license [2]).

resulting harmonious earth colors [35].

Colorful concentric circle patterns have also been used in information visualization. As part of a project related to visualizing physical activity to generate abstract ambient art, Chloe Fan used concentric circle patterns in a visualization she called Bucket (see Figure 5) [9]. As an example work related to both concentric colored circles and to reusing artistic color palettes, in their Luscious project Viégas and Watternberg [36], create artistic colorful designs by extracting colors from cover pages of luxury magazines.

3 Related Work

In this section we briefly review the related literature in two areas: art inspired visualizations and graph visualizations.

3.1 Art Inspired Visualization

Taking an aesthetic perspective in visualization is not a novel approach. Recently, increasing number of data visualization researchers have been considering aesthetics in their designs. Examples are Informative Art [20] and InfoCanvas [26]. Pousman et al. [29] provides a review of the visualizations that have considered aesthetic patterns in their designs. Viégas and Wattenberg present a survey of projects in artistic information visualization [37]. They explore how an aesthetic approach improves scientific analytical reasoning in information visualization. Etemad et al. present a visualization layout inspired by Spirograph patterns for representing ecological networks [15]. In this layout, nodes are arranged along the circumference of a large circle as arcs, and edges are mapped to thorn-like shapes that represent the direction and the weight of the edge.

Lin and Vuillemot [23] used Spirograph patterns for visualizing tweets collected during CHI 2013. In their work, many Spirograph patterns were created by tweaking control parameters in a drawing tool. Then the distribution of tweets over time was mapped to the petals of selected Spirograph patterns. Heinrich and Weiskopf [17] used parallel coordinates techniques to create artistic images, based on footprints. Their visualization is based on modeling data points similar to kernel density estimation (KDE).

3.2 Graph Visualization

The three particularly relevant aspects of graph layout for our research are graphs with edge congestion, directed graphs and weighted graphs.

Figure 4: This dot painting, “Stomping Grounds” by Michael Bruce Cummings, styled as kinjart [4] (Creative Commons license [1]) also shows use of concentric circles.

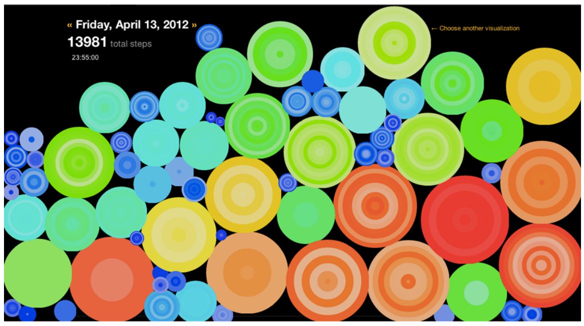

Figure 5: Bucket: visualizing the steps taken in five minutes [9].

3.2.1 Edge Congestion

Large graph visualizations suffer from the cluttering problem due to a large number of edge crossings and overlapping nodes. Techniques such as filtering, clustering and focus+context have been introduced to reduce these cluttering problems [19]. For example, Holten [21] uses hierarchical edge bundling for visualizing compound graphs. In this visualization, edge bundling techniques help to reduce the edge crossings between clusters. The NodeTrix [18] graph visualization offers a type of interactive filtering by allowing nodes to be clustered as a matrix representations within the node-link layout. Clustering and focus+context methods are used for exploring and interacting with large graphs [5, 7]. Also, a series of papers have explored using interaction to address edge congestion [32, 38].

3.2.2 Directed graphs

Traditionally, in directed graphs, the direction of an edge is illustrated by either arrowheads [12] or tapering curves [22]. These choices in visualization can cause more clutter (due to extra marks needed to specify the direction), especially when the number of edges is high. To address this cluttering some visualization techniques show the direction by changing the thickness of the directed edge in the space between the destination and origin [33]. In our visualization, including the direction reduces number of node rings as we only include the ring in the node associated with the origin of the edge direction.

3.2.3 Weighted graphs

In a node-link visualization of weighted graphs, the weight is mapped to either the length of the edge [10], or the thickness or color of the edge [13]. In matrix visualization of weighted graphs, the weight of each edge can be mapped to the color or the size of the corresponding cell [16]. Among all these visualization methods, people prefer node-link layouts that use thickness to indicate the edge weight [6]. Visualizations of weighted graphs have tended to be focused on the weights of edges, however, in our Node-Ring graph visualization; the weights of nodes can also be visualized.

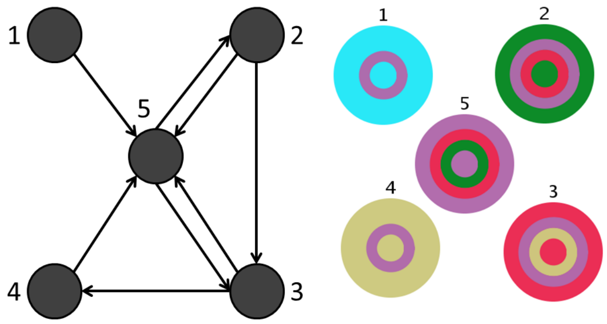

Figure 6: Node-link (left) and Node-Ring graph (right) visualization of a graph with five nodes.

4 Node-Ring Graph Layouts

Graphs are popular abstract models for representing objects and their relationships. They have been widely used to model data structures such as social networks, road systems, computer networks and organizational charts. A common approach for representing a graph is to use a node-link layout. In this layout, a position and shape are assigned to each node, and edges are usually mapped to links that are represented as lines or curves that connect appropriate nodes (see Figure 6 left). In graphs, typically the position of nodes can be arranged in various ways (e.g. layer, radial, and force-directed) [8]. Edges have been drawn using a variety of styles such as straight lines, poly-lines, curves [8]. Node-link layouts for graphs with a large number of edges usually suffer from edge congestion. To provide the common terminology, we will denote a graph as $G = (V, E)$ with a set of nodes, V, and a set of edges, E. G is called a complete graph if all of its nodes are connected to each other. In the case of simple graphs (undirected and without multiple edges), completeness of the graph implies that:

$$e = \frac{n(n-1)}{2}$$

where $e = |E|$ and $n = |V|$. Graph G is considered dense if it has almost as many edges as a complete graph with the same n. Visualizing dense graphs [25] is challenging due to the edge crossings. The density of the graph G is defined by:

$$D = \frac{e}{n}$$

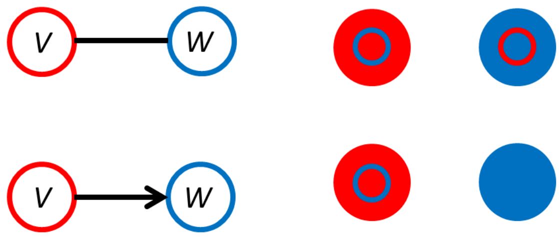

Figure 7: Directed and undirected edges can be shown in Node-Ring graph visualization.

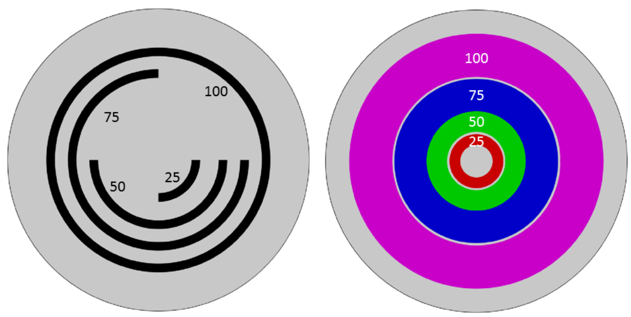

Figure 8: Left: weights of edges are mapped to the sectors of the rings. Right: weights are mapped to ring thickness.

We introduce a visualization for graphs that uses an implicit representation of edges. Therefore information about the edges is included without explicitly drawing them as links (See Figure 2). In our visualization, each node is represented by a circle with a specific color. For example, if a red node is connected to a blue node then there is a blue ring inside the red node's circle. If the graph is undirected, then there will be a red ring inside of the blue node too. Hence, the direction of the edge is also captured by the color and the position of the rings. The color of the ring shows the destination of the edge and the placement of the ring shows the origin of the edge (See Figure 6 (right)).

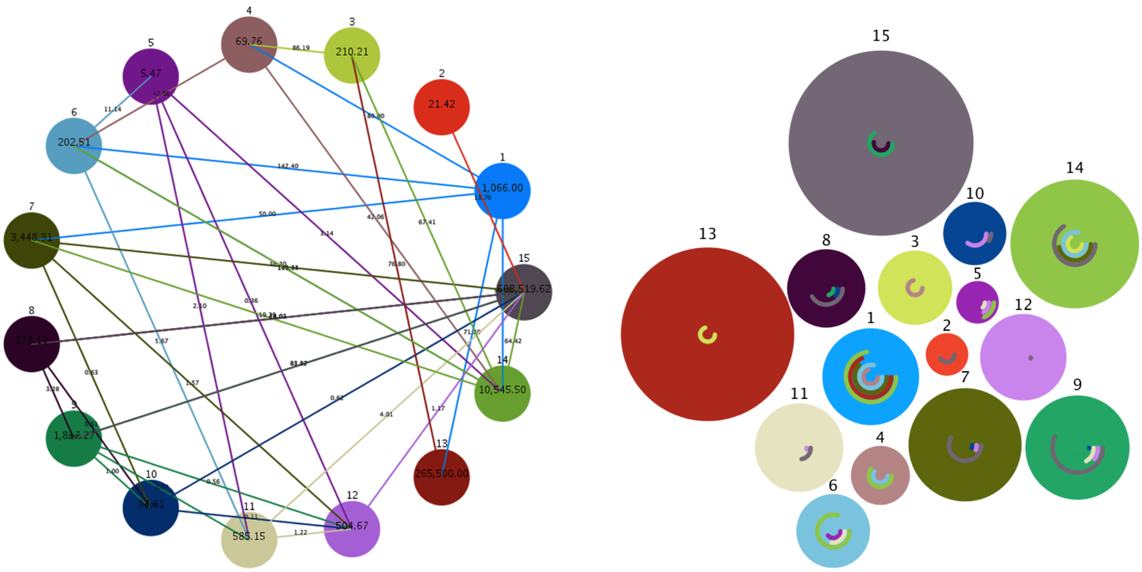

Figure 9: Node link (left) and Node-Ring (right) graph visualization, representing a weighted directed graph with fifteen nodes.

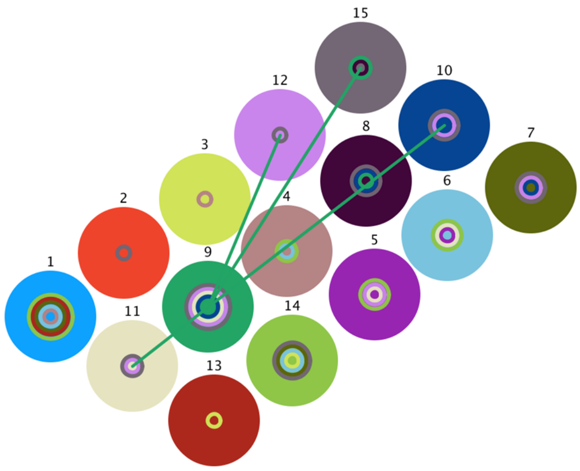

Figure 10: When one node is selected, all outgoing edges from that node become explicit.

4.1 Node-Ring Graph Visual Encoding

As shown in Figure 6, nodes are presented as colored circles. If node V is connected to W then there is a ring with the same color of W inside V (see Figure 7). Therefore, in this design, edges are shown by the colored rings inside of each node. The color of the ring shows the destination of the edge. For undirected graphs a ring for V is also drawn inside W but for directed graphs only one of the two rings is drawn.

Node-ring graph visualization is capable of representing weighted directed graphs. However, including the weight and direction attribute is optional. The weights of the nodes are mapped to the size of the circles. For representing the weights of edges, we use partial sectors of the rings. The full circular ring shows the maximum weight. Other smaller weights are proportionally mapped to smaller sectors as demonstrated in Figure 8 left. Alternatively, weights can be mapped to the ring thickness, however, with dense graphs the differences in ring thickness can be hard to read. In one of our design experiments we mapped the weight of the edges to the thickness of edge's corresponding ring. However, when there are several rings in one node, it becomes difficult to distinguish the thickness variations of these small rings. Figure 8 right, shows an example that uses thickness of the rings instead of partial rings (Figure 8 left) for mapping the weight of the edges. Figure 9 shows Node-Ring visualization for a fifteen node weighted directed graph with both node weights and edge weights shown as edge-ring sectors.

Different arrangements can be used to position the nodes (e.g. Phyllotactic patterns [27], Voronoi [11], Symmetric [14]). Figure 11 shows two of these possible arrangements. It is also possible to interactively move the nodes and change their positions according to current needs or desires.

An important factor in our design was the issue of node coloring. Naive color assignments can complicate the task of understanding the edges. Figure 12 left, shows a random choice of colors for nodes. The color assignment becomes even more challenging if the aesthetic impression of the colors is also a goal. As part of our exploration of this issue, we studied various artistic paintings to find styles which use contrasting colors. We found that Hundertwasser's paintings are one example that has such features. Using color extracting techniques such as Colorvis [24], we created color palettes from the contrasting colors of the selected paintings. Figure 12 right, shows the results after using the color palette created from "The Silent Flowers" by Hundertwasser [34].

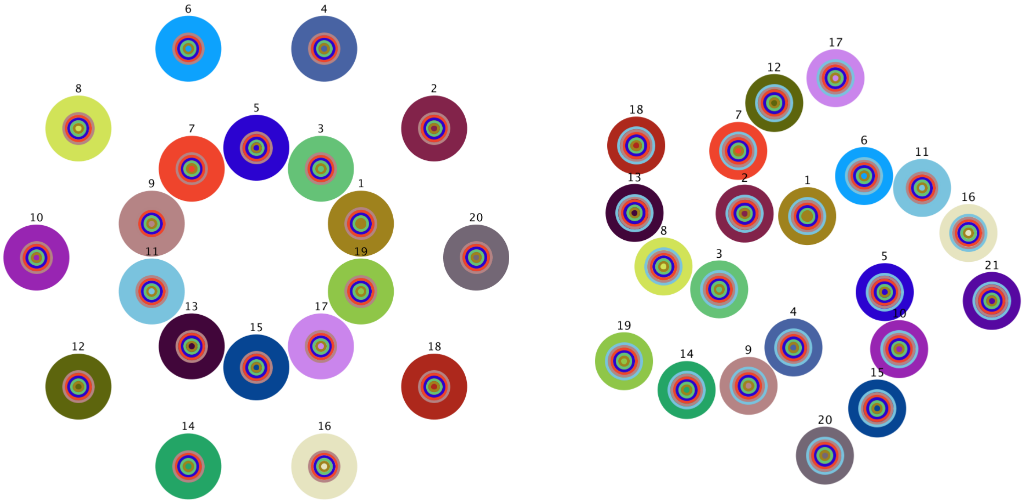

Figure 11: Different arrangements can be used to position the nodes.

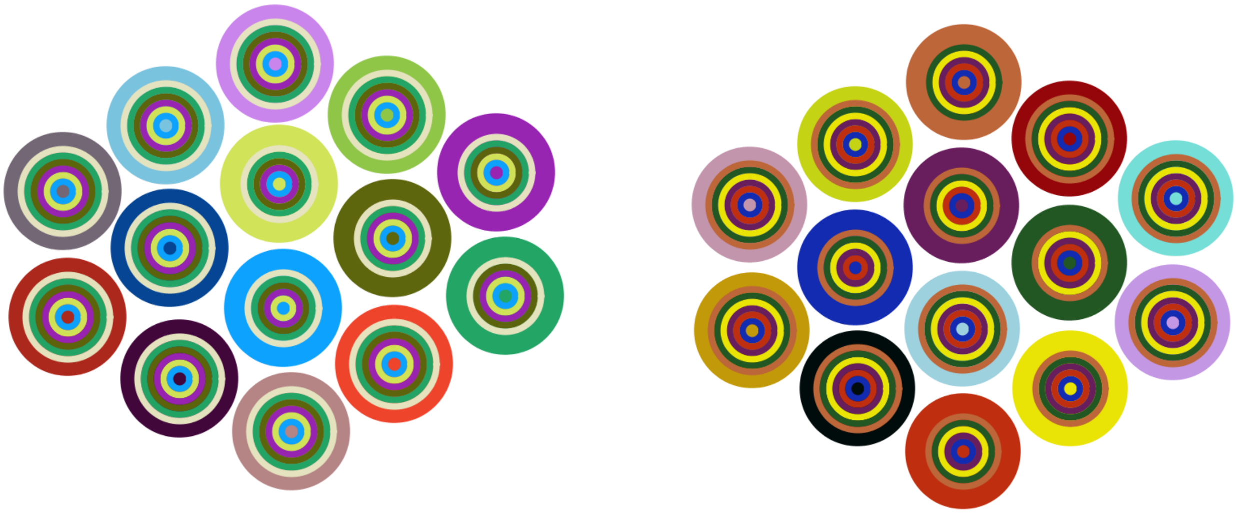

Figure 12: Node-Ring graph visualization. Left, free color selection. Right, color palette derived from "City view" by Hundertwasser [34].

5 Interaction

Here we describe our current basic interaction techniques. These techniques offer the opportunity to a) select the color of the visualization based on a favorite painting, b) highlight the traditional node-link relationships between a selected node and its connected nodes and c) rearrange the nodes based on the current tasks.

5.1 Color palette

An important factor in Node-Ring graph visualization is the assignment of a specific color to each node. The procedure of color assignment can be improved by exporting color palettes from well-known artists' paintings using tools like Colorvis [24]. In our prototype, people can load a painting from a saved library and select contrasting colors from their favorite painting. The number of colors that are chosen has to be the same as the number of nodes in the graph. The color palette that has been used to create the Node-Ring graph visualization with twenty one nodes in the Figure 2 is extracted from "City view" by Hundertwasser [34].

5.2 Highlighting the outgoing edges from a selected node

Since at some times it may be important to explicitly represent edges, this can be done by selecting a node to explicitly draw all outgoing edges of that node. The color of each edge is the same color as the color of the node they originate from. Figure 10 illustrates this feature.

5.3 Rearranging nodes

The position of nodes can be interactively rearranged. Since there are no displayed edges, the movement of nodes can be done relatively easily. For example, in Figure 13, the neighbors of the node 1 and 9 have been moved. This feature gives the opportunity to create specific arrangements of nodes.

6 Discussion

In this work, our goal was to create a visualization that, presents a weighted directed graph with limited number of nodes but large number of edges. While the Node-Ring visualization has potential

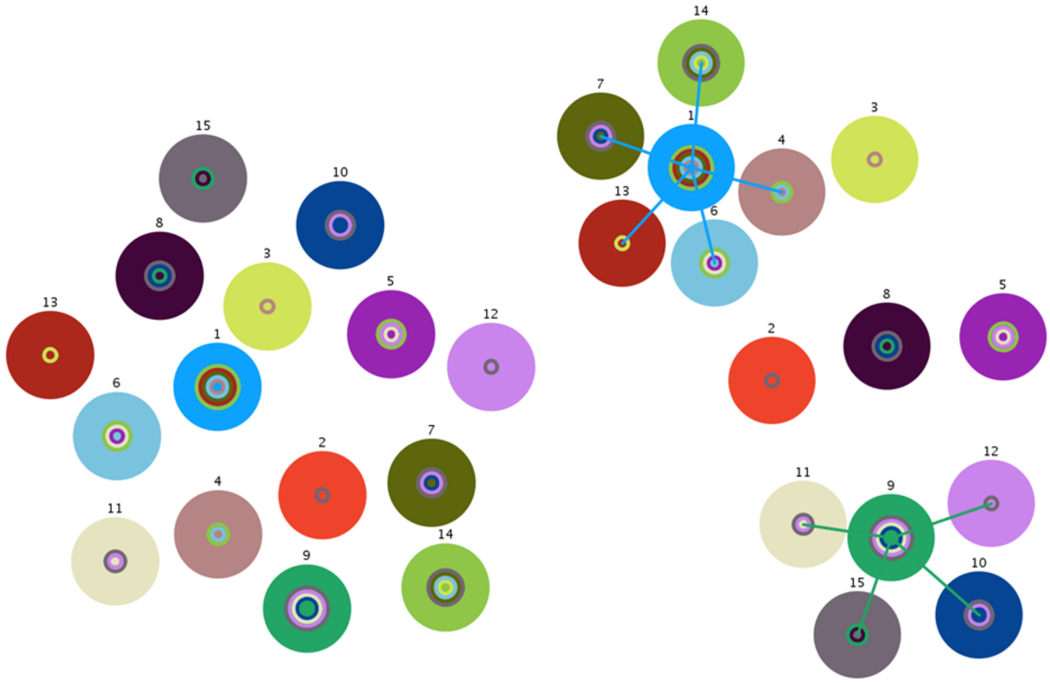

Figure 13: Nodes can be moved and rearranged them based on the desired task.

for presenting dense graphs with limited number of nodes, there are some limitations when the number of nodes increases. For example, the number of readily distinguishable colors that can be used in one layout is limited. When presenting graphs with a larger number of nodes it may be possible to use combinations of patterns and textures along with various hues, tints, shades, and tones. However, even then Node-Ring layouts will probably be best used with relatively small dense graphs. Figure 9 shows a comparison between traditional node-link and Node-Ring layouts for presenting a weighted graph with fifteen nodes. Removing edges from the presentation affect the appearance of the visualization. Mapping the nodes weights to the circle radius and edge weights to the ring arcs segments whose angles are proportional to the edge weights offers a new aesthetic in layouts.

7 Conclusions

We have introduced Node-Ring graph visualization, which is a new approach for representing dense weighted directed graphs. In this visualization we eliminate the explicit representation of edges and instead map the edge relationship between the connected nodes to colored rings. The color of the ring shows the destination of the edge and the placement of the ring shows the origin of the edge. Our Node-Ring approach can also be combined with conventional graph visualization techniques to create hybrid visualizations. Node-Ring graph visualizations can be particularly useful for relatively small but dense graphs when the graph has significantly more edges than nodes. Strongly connected graphs or dense graphs (e.g. complete graphs) are examples of these types of graphs. Visualizing these types of graphs using conventional techniques is challenging because of the high number of edge crossings.

Full or partial use of our Node-Ring method can reduce the edge crossing issue. Although the lack of a direct connection between nodes might make for a less obvious edge interpretation, the cleaner and more colorful layout increases its potential for a more fun and artistic driven solution. To make the node connections more apparent, it is best to assign contrasting colors to the nodes. For our visualization we use color palettes derived from Hundertwasser's paintings [34]. Interestingly, concentric circles are an important feature in his colorful paintings (see Figure 3). In summary, our Node-Ring graph visualization features colorful concentric circles using an aesthetic inspired by the paintings of Hundertwasser.

Acknowledgements

This research was supported in part by NSERC, SMART Technologies, AITF, NSERC Surfnet, and GRAND NCE.

References

[1] Creative commons attribution-no derivative works 3.0 license, http://creativecommons.org/licenses/by-nd/3.0/ http://creativecommons.org/licenses/by-nd/3.0/legalcode.

[2] Creative commons license: Cc by-nc-sa 2.0, https://creativecommons.org/licenses/by-nc-sa/2.0/ https://creativecommons.org/licenses/by-nc-sa/2.0/legalcode.

[3] Friedensreich Hundertwasser. Columbus Landed in India, In Gandalf's Gallery; accessed august 2014, 1969 :https://www.flickr.com/photos/gandalfsgallery/10165932273/.

[4] Kinjart. Stomping Grounds, In Deviant Art; accessed august 2014, 2011 :http://kinjart.deviantart.com/art/stomping-grounds-208538959/.

[5] J. Abello, S. G. Kobourov, and R. Yusufov. Visualizing large graphs with compound-fisheye views and treemaps. In *Graph Drawing*, pages 431–441. Springer, 2005.

[6] B. Alper, B. Bach, N. Henry Riche, T. Isenberg, and J.-D. Fekete. Weighted graph comparison techniques for brain connectivity analy-

sis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 483–492. ACM, 2013.

[7] V. Batagelj, F.-J. Brandenburg, W. Didimo, G. Liotta, P. Palladino, and M. Patrignani. Visual analysis of large graphs using (x, y)-clustering and hybrid visualizations. *Visualization and Computer Graphics, IEEE Transactions on*, 17(11):1587–1598, 2011.

[8] G. D. Battista, P. Eades, R. Tamassia, and I. G. Tollis. *Graph drawing: algorithms for the visualization of graphs*. Prentice Hall PTR, 1998.

[9] F. Chloe. Spark: Visualizing physical activity using abstract ambient art, 2014.

[10] C. Collberg, S. Kobourov, J. Nagra, J. Pitts, and K. Wampler. A system for graph-based visualization of the evolution of software. In *Proceedings of the 2003 ACM symposium on Software visualization*, pages 77–ff. ACM, 2003.

[11] H. Edelsbrunner and R. Seidel. Voronoi diagrams and arrangements. *Discrete & Computational Geometry*, 1(1):25–44, 1986.

[12] M. Eiglsperger, M. Siebenhaller, and M. Kaufmann. An efficient implementation of sugiyamas algorithm for layered graph drawing. In *Graph Drawing*, pages 155–166. Springer, 2005.

[13] S. Epskamp, A. O. Cramer, L. J. Waldorp, V. D. Schmittmann, and D. Borsboom. qgraph: Network visualizations of relationships in psychometric data. *Journal of Statistical Software*, 48(4):1–18, 5 2012.

[14] K. Etemad, S. Carpendale, et al. Shamsehtrees: Providing hierarchical context for nodes of interest. In *Proceedings of Bridges 2009: Mathematics, Music, Art, Architecture, Culture*, pages 293–300. Tarquin Books, 2009.

[15] K. Etemad, S. Carpendale, and F. Samavati. Spirograph inspired visualization of ecological networks. In *Proceedings of the Workshop on Computational Aesthetics*, pages 81–91. ACM, 2014.

[16] F. Ham, H.-J. Schulz, and J. Dimicco. Honeycomb: Visual analysis of large scale social networks. In T. Gross, J. Gulliksen, P. Kotz, L. Oestreicher, P. Palanque, R. Prates, and M. Winckler, editors, *Human-Computer Interaction INTERACT 2009*, volume 5727 of *Lecture Notes in Computer Science*, pages 429–442. Springer Berlin Heidelberg, 2009.

[17] J. Heinrich and D. Weiskopf. State of the art of parallel coordinates. In *Eurographics 2013-State of the Art Reports*, pages 95–116. The Eurographics Association, 2012.

[18] N. Henry, J. Fekete, and M. J. McGuffin. Nodetrix: a hybrid visualization of social networks. *Visualization and Computer Graphics, IEEE Transactions on*, 13(6):1302–1309, 2007.

[19] I. Herman, G. Melançon, and M. S. Marshall. Graph visualization and navigation in information visualization: A survey. *Visualization and Computer Graphics, IEEE Transactions on*, 6(1):24–43, 2000.

[20] L. E. Holmquist and T. Skog. Informative art: information visualization in everyday environments. In *Proceedings of the 1st international conference on Computer graphics and interactive techniques in Australasia and South East Asia*, pages 229–235. ACM, 2003.

[21] D. Holten. Hierarchical edge bundles: Visualization of adjacency relations in hierarchical data. *Visualization and Computer Graphics, IEEE Transactions on*, 12(5):741–748, 2006.

[22] D. Holten and J. J. van Wijk. A user study on visualizing directed edges in graphs. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2299–2308. ACM, 2009.

[23] Y. Lin and R. Vuillemot. Spirograph designs for ambient display of tweets. *Proceedings of the IEEE VIS Arts Program (VISAP)*, 2013.

[24] S. Lynch, J. Haber, and S. Carpendale. Colourvis: Exploring colour in digital images. *Computers & Graphics*, 36(6):696–707, 2012.

[25] G. Melancon. Just how dense are dense graphs in the real world?: a methodological note. In *Proceedings of the 2006 AVI workshop on BEyond time and errors: novel evaluation methods for information visualization*, pages 1–7. ACM, 2006.

[26] T. Miller and J. Stasko. Infocanvas: A highly personalized, elegant awareness display. In *Supporting Elegant Peripheral Awareness, workshop at CHI03*. Citeseer, 2003.

[27] P. Neumann, S. Carpendale, and A. Agarawala. Phyllotrees: Phyllotactic patterns for tree layout. In *Proceedings of the Eighth Joint Eurographics/IEEE VGTC conference on Visualization*, pages 59–66. Eurographics Association, 2006.

[28] H. Perkins. *One sun one moon: aboriginal art in Australia*. Art Gallery of New South Wales, 2007.

[29] Z. Pousman, J. T. Stasko, and M. Mateas. Casual information visualization: Depictions of data in everyday life. *Visualization and Computer Graphics, IEEE Transactions on*, 13(6):1145–1152, 2007.

[30] H. Purchase. Which aesthetic has the greatest effect on human understanding? In *Graph Drawing*, pages 248–261. Springer, 1997.

[31] H. C. Purchase, C. Pilcher, and B. Plimmer. Graph drawing aestheticscreated by users, not algorithms. *Visualization and Computer Graphics, IEEE Transactions on*, 18(1):81–92, 2012.

[32] N. H. Riche, T. Dwyer, B. Lee, and S. Carpendale. Exploring the design space of interactive link curvature in network diagrams. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, pages 506–513. ACM, 2012.

[33] M. Rosvall and C. T. Bergstrom. Maps of random walks on complex networks reveal community structure. *Proceedings of the National Academy of Sciences*, 105(4):1118–1123, 2008.

[34] D. H. Spennemann. Hundertwasser: art, architecture and heritage in bad soden, germany. *The Journal of Architecture*, 5(2):117–136, 2000.

[35] A. Store. Aboriginal dot paintings. http://www.aboriginalartstore.com.au/aboriginal-art-culture/aboriginal-art/aboriginal-dot-paintings/, May 2014.

[36] F. Viégas and M. Wattenberg. 9 luscious. *Net Works: Case Studies in Web Art and Design*, page 104, 2012.

[37] F. B. Viégas and M. Wattenberg. Artistic data visualization: Beyond visual analytics. pages 182–191, 2007.

[38] N. Wong, S. Carpendale, and S. Greenberg. Edgelens: An interactive method for managing edge congestion in graphs. In *Information Visualization, 2003. INFOVIS 2003. IEEE Symposium on*, pages 51–58. IEEE, 2003.

[39] K. Zhang. From abstract painting to information visualization. *Computer Graphics and Applications, IEEE*, 27(3):12–16, 2007.