UNIVERSITY OF CALGARY

Graph Visualizations Inspired by Alternative Aesthetics

by

Katayoon Etemad

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF COMPUTER SCIENCE

CALGARY, ALBERTA

April, 2015

UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled “Graph Visualizations Inspired by Alternative Aesthetics” submitted by Katayoon Etemad in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY.

Dr. Sheelagh Carpendale
Department of Computer Science

Dr. Larry Katz
Faculty of Kinesiology

Dr. Richard Levy
Faculty of Environmental Design

Dr. Pierre Boulanger
Department of Computing Science
University of Alberta

Dr. Anthony Tang
Department of Computer Science

Dr. Jon G. Rokne
Department of Computer Science

Date

Abstract

Graphs are ubiquitous representations of data that are used in many applications. Our goal in this thesis is to explore the use of alternative aesthetics to visualize graphs. Graphs are defined as entities (nodes) and relationships (edges) between entities, and may have extra attributes such as weight.

We have designed three novel graph layouts and their applications in graph visualization. These layouts were inspired by decorative artworks and patterns, personally selected from different types of aesthetics. The first graph visualization is Node-Ring whose layout was inspired by Australian dot painting and Hundertwassers paintings. In this layout, concentric circles are used for an implicit representation of edges for visualizing dense graphs.

The second graph visualization is Daisy Vis inspired by ornamental patterns of daisy flowers. In this visualization graphs' attributes are mapped to floral elements. We use Daisy Vis for visualizing ecological networks of real ecosystem data-sets by supporting specific attributes of ecological networks (e.g. input/output edges, respiration).

Our third graph visualization is Eco-Spiro, specifically designed for ecological networks. The layout used for this visualization is a modification of Spirograph, which is another novel graph layout introduced in this thesis. In Spirograph layout all nodes are arranged on a large circle (boundary circle) which divides the space to the internal and external regions, a natural way to support external and internal edges of ecological networks. The circular form of Spirograph used in Eco-Spiro has an organic form for showing the closeness of ecosystem and for separating the environment into its internal and external spaces.

To evaluate our novel graph visualizations, we conducted three user studies. Participants' feedback support the overall design for all three visualizations. Furthermore, they provided us with useful comments about our design decisions to improve our visualizations.

Acknowledgements

First I want to thank Faramarz Samavati, my love, my friend, my mentor and my support, for always being there for me and supporting me no matter how crazy my ideas were. It was because of his continuous encouragements that I was able to go back to school after fifteen years and manage to finish it successfully. His support and advice always helped me in study and research.

I also want to thank my supervisor Sheelagh Carpendale for her support and guidance. She understood my needs to do research in both computer science and art, and she supported me even in the times when it seemed impossible. Her knowledge in both art and computer science was the crucial source of inspiration for my research. I was lucky to have her with her amazing collection of knowledge as my supervisor, in my interdisciplinary research. Her background and strength gave me confidence to move forward with my unusual interest in both art and mathematics. Being a mom and a scientist made her a special role model for me during my graduate school years.

Further, I want to thank Parsa and Kian for being patient and bearing with me during the times that I was stressed. Parsa and his interesting ways of support, and Kian with his soothing hugs. They made me feel that no matter what is going on in my life outside, they will always be with me in the comfort of our home.

I want to thank all my friends in Interactions Lab for being supportive and helpful during the discussions and brainstorming. I am honored to be considered as a lab member with all of them from 2007 until 2015.

This research would not have been possible without the generous support of several funding sources. Much of my dissertation research took place under the umbrella of the NSERC research network and Grand-NCE, and I am thankful for that support.

Table of Contents

List of Tables

List of Figures and Illustrations

List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
U of C	University of Calgary
Infovis	Information Visualization
HCI	Human Computer Interaction

Chapter 1

Introduction

In this thesis, we explore alternative aesthetics as a source of inspiration for creating new graph layouts. Through our exploration, we have become increasingly convinced that any intriguing pattern, mesmerizing ornament or exciting art piece may be used as the source of inspiration for new layouts. However creating a mapping between a graph and the selected pattern is hard and challenging. In this thesis, the viability of developing new graph visualizations through applying alternate aesthetics is demonstrated. This is done by describing the design process and presentation of three new layouts that each have been inspired by different aesthetics.

Aesthetics have long played an important role in graph drawing. Graph drawing aesthetics have been a topic of research for approximately the last thirty years [33, 31]. The common ideas in this research community are based on mathematics and measurable notions such as edge crossing, edge bending, and the number of incident edges. We agree that these graph drawing aesthetics have a type of beauty and are aware that they have also been shown to improve readability [107]. However, our intention is to expand the notions of aesthetics that are considered in graph drawing. We think that in our world there are a multitude of aesthetics arising from different cultures and different artistic practices. It is the wide variation of aesthetics we draw from when we refer to alternate aesthetics.

In this chapter we start with our motivation drawn from aesthetics in graph visualization in Section 1.1, followed by a short explanation about the scope of this thesis in Section 1.2. We then describe the goal of our research in Section 1.3. Next we specify the issues and challenges that are addressed in this thesis in Section 1.4, followed by the methods we use to address them in Section 1.5. We then list the specific contributions made in this work in

Section 1.6, and present an overview of the structure of the thesis in Section 1.7.

1.1 Drawing Motivation from Alternative Aesthetics for the Creation of New Graph Visualizations

Information visualization is a fast-growing research area in computer science. In recent years, the importance of InfoVis as a discipline has increased rapidly due to the spread of computer systems and the information explosion. Furthermore, since data presentations are becoming more a part of people's everyday lives, considering their aesthetic appeal is receiving more attention [94] [112].

Since the recent advancement and pervasive use of information technologies have resulted in several techniques for collecting data, today we are overwhelmed by massive amounts of data [6]. Collecting, processing and analyzing this data is fundamental in information technology; however, visualizing the data and making sense of it also has an essential role to play.

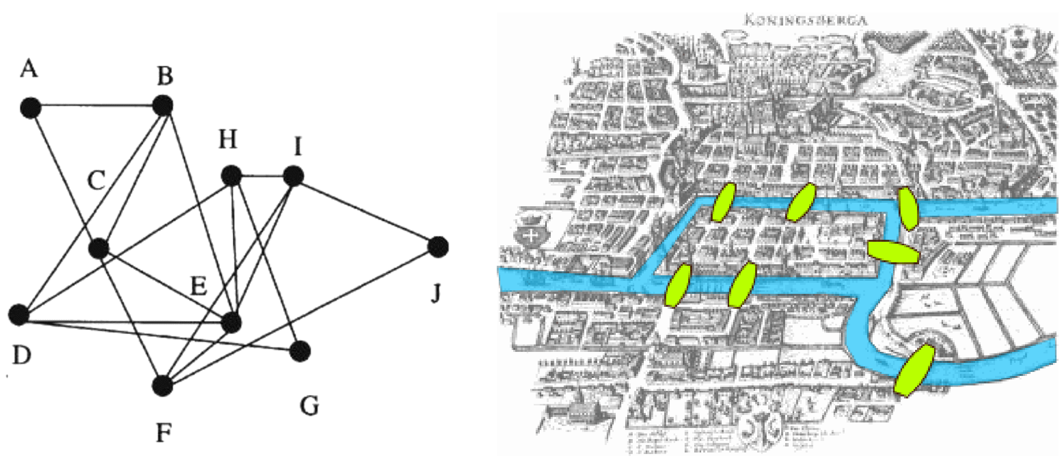


Figure 1.1: Left: Traditional node-link representation of a graph with 10 nodes and 17 edges. Right: The Konigsberg bridge problem [144].

One of the active areas of information visualization is graph visualization, which lies on the intersection of two major communities of graph drawing and information visualization.

Graphs are well-known mathematical models for representing objects and their relationships. A graph is defined by a set of nodes and their pairwise connections, represented by edges (see Figure 1.1, left). Graphs are commonly used for modeling networks (e.g. communication, social network and transportation), interconnected systems (e.g. ecological, energy, financial), and complex structures (e.g. organizations, molecular and data structure).

The relationship between the graph as a mathematical model and its visualization is interesting. Euler, for the first time in 1736, introduced graphs to solve the problem of Seven Bridges of Königsberg [70]. He used a graph as a visual abstraction of the Seven Bridges of Königsberg problem; abstracting islands and the bridges between them as nodes and edges respectively (see Figure 1.1, right). The locations of nodes and the shapes of edges were not important in this abstraction and perhaps the term graph was selected because this was a graphical abstraction. Despite this fact, graphs as mathematical models, were initially used in many areas and applications without immediate need of visual representation. Nowadays, the size of a data-set is usually large and computers are fast enough to store and represent large or complex graphs, but reading and extracting useful information often has to be done by humans. Thus, in recent years, the importance of graph visualization has increased rapidly due to our current information explosion.

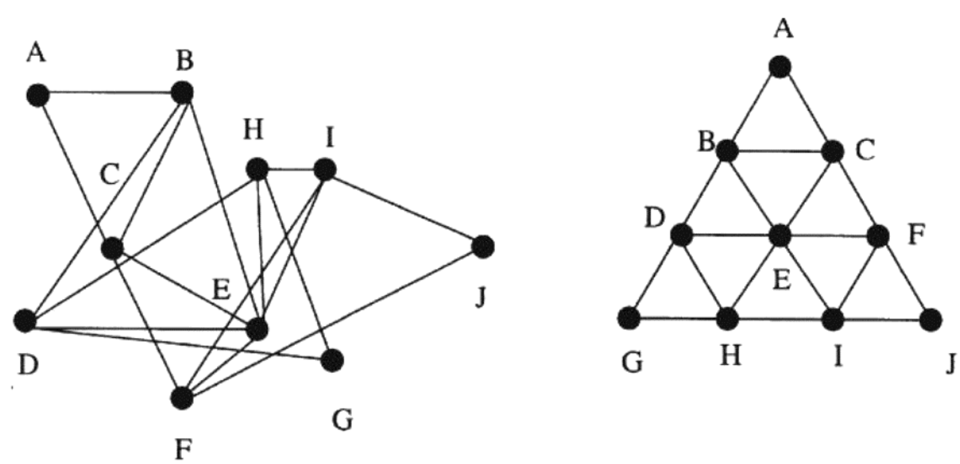


Figure 1.2: Node-link representation of a graph with 10 nodes and 17 edges. Left: random arrangement of nodes. Right: symmetric arrangement of nodes.

It is a challenging task to present large or complex graphs in the space of a screen, due to the possibility of node overlapping and edge crossing. This makes it tedious for a human to explore the information presented in large or complicated graphs [147]. Attractive and engaging visualization of graphs can help analysts in their tedious exploration tasks [25]. For more casual environments, aesthetically pleasing information visualizations may invoke curiosity, and excitement [105]. Also, in public spaces, this type of artistic information visualization can catch the attention and mesmerize the potential viewers. Nowadays, aesthetic appeal is a major concern in visualizations integrated in larger environment [116, 25].

Also the aesthetics of graph drawing is an important factor for the area of graph drawing. As we will discuss in Chapter 2, the goal of graph drawing is slightly different from graph visualization. Graph drawing usually covers algorithmic methods for creating suitable geometric arrangements of graphs where a position and a shape are assigned to each node, and edges are usually mapped to curves between their adjacent nodes. Whereas, in graph visualization interactive visual representations are explored while keeping a human in the loop. Therefore, since a human is in the loop, interactive techniques such as focus+context, zoom/pan, clustering and filtering can be used to generate a visual realization of the graph which maybe different from the outcome of graph drawings. Even with this difference, some of the concepts and methods used in graph drawing may be helpful in some graph visualizations. In [30], several important factors for graph drawing are discussed. One group of these factors is graph drawing aesthetics. Aesthetics in the context of graph drawing refers to the rules for increasing the readability of the graph drawing (e.g. reducing edge crossings, and total edge length). Most visualizations consider this interpretation of graph drawing aesthetics in graph visualizations; for example, symmetry is usually one of the important factors in readability [33]. Figure 1.2 shows the effect of symmetric arrangement of nodes to reduce the number of edge crossings [107, 108]. Cawthon and Vande Moere [25] report two different interpretations of aesthetic in data visualizations. The first interpretation indicates that aesthetic refers to the measurable factors used to improve the efficiency and effectiveness of tasks, which are the same factors considered in graph drawing. The second interpretation indicates that, aesthetic refers to the beauty of the visualization, as reflected by our personal judgement, like that of various forms of artwork. In this thesis, we mostly explore the application of the second interpretation of aesthetics in graph visualization.

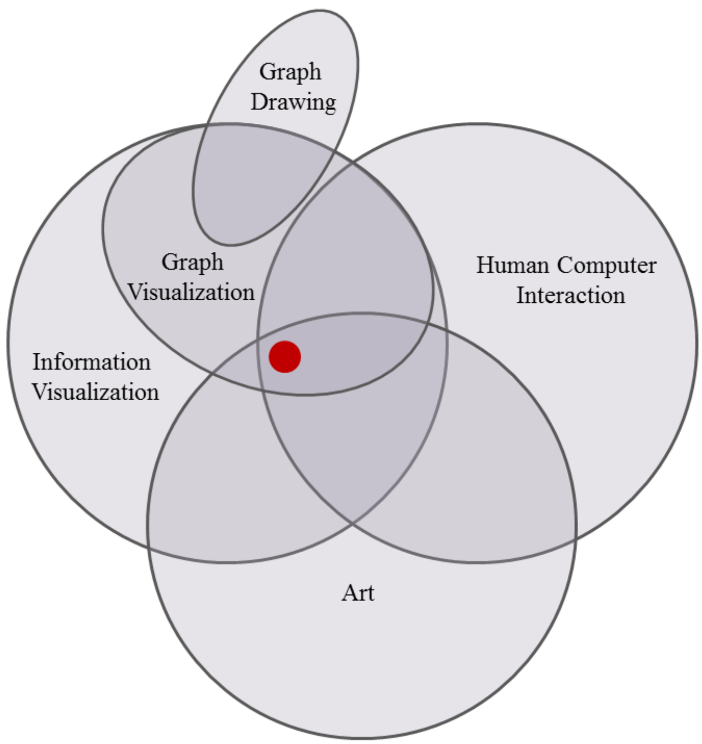


Figure 1.3: The research in this dissertation falls in the intersection of Art, Graph Visualization and HCI.

1.2 Scope

Graph visualization is part of information visualization and we can locate the scope of our research within the intersection of information visualization, art, and Human Computer Interaction (HCI). There is also an overlap between graph visualization and graph drawing (see Section 2.2 for more details). As demonstrated in Figure 1.3, our scope does not fall within the graph drawing research area; the scope of this thesis is on visualization techniques, which are more in InfoVis and HCI area.

1.3 Goal

Since attractive representations of graphs have been said to engage people and encourage analysts to perform common tasks in graph visualization [147, 25], in this thesis, we explore the application of alternate aesthetics to create new visualizations for graphs. We aim at expanding the types and variety of layout options for graphs. In particular we focus on graphs with complex structures choosing a variety of ecological networks as our data. We use artistic and traditional aesthetic patterns as sources of inspiration for designing new graph layouts.

1.4 Problems and Challenges

The main challenge in this thesis is to design layouts for graphs that effectively use ideas from different types of aesthetics. To address this challenge, we consider a variety of well-accepted aesthetic patterns as sources of inspiration. There exist a plethora of possibilities of interesting patterns in art. This, results in several questions and challenges:

Questions are:

1. Which patterns should be considered? Given such a huge choice in the world, are all productive? Or are some more effective and perhaps easier to map?
2. How can the selected patterns be mapped to new graph layouts?

Several major challenges are:

1. characterization of existing aesthetic patterns according to factors needed for creating a graph layout,

2. adhering to a given aesthetic pattern as one includes additional data complexities,

3. characterizing the design process by which a type of aesthetic pattern can be used to generate a new graph layout.

The scope and variety of alternate aesthetics is so wide, that exploring all of them is not possible. We explore these questions by choosing four diverse examples and use these four explorations to learn about the design process.

Answering these questions is very challenging due the following three objectives which are sometimes in conflict with each other:

- The layout should clearly and accurately represent the graph data.
- The layout should be pleasing in terms of the selected aesthetics (i.e. there should be a fair similarity between the layout and the selected pattern; and there should be an appropriate use of arrangements, color palettes, etc. in a manner that to some extent matches with the chosen aesthetic).
- The new layout that has just been created should be possible to use in practical scenarios.

1.5 Methodology

There are two streams in this thesis: information visualization (InfoVis) and human computer interaction (HCI). The InfoVis stream includes how to map abstract data and visual encoding. The HCI stream includes how people receive and understand our novel graph visualization and how these visualizations help people effectively use them. For this investigation, we choose four diverse examples to explore as sources of inspiration:

1. Nested circular patterns from a combination of modern painting and aboriginal painting,
2. Floral embellishment, including combining many varieties,
3. Celtic Knots, including traditional aspects of both mathematical models and traditional art, and
4. Spirograph patterns, to include the beauty of mathematical shapes.

Our proposed methods for solving the described problems and challenges can be categorized to four important parts: an initial design approach, the development of an algorithmic resolution, the discovery of what practicality means to domain experts, and a more general assessment.

1.5.1 Design Approach

Our general approach to design alternative layouts for graphs is to first search for traditional aesthetic inspiration. Any artistic pattern, from fascinating ornaments or exciting art pieces can be used as the source of inspiration. These patterns should be loosely map-able to graphs by containing elements similar to nodes and edges. The description of our design process is in Chapter 3.

1.5.2 Algorithmic Resolution

While the design process makes use of creating a hand drawn layout, it is part of our goal to develop the necessary methods to algorithmically create these layouts. We usually start with a simple initial rough layout, then verify whether we can find a high-level algorithmic and geometric description of this layout that adhere the traditional aesthetic. To address the challenge of the conflicting objectives (refer to Section1.4), we employ an iterative design process to refine the initial layout. During this process, we use various approaches such as hand-drawn sketches, computer graphics tools and coding in visual sketchbook software (e.g. Processing [109]) to verify the layout's concept.

Using this methodology, we have designed three graph layouts, Node-Ring, Daisy and Spirograph, which have been implemented as simple prototypes combined with appropriate interactions.

1.5.3 Understanding the Graph Problem from Domain Experts

We have selected ecological networks as a practical use case for this thesis. An ecological network is a directed, weighted graph in which nodes are species and edges represent the energy or material flow in the system. Ecological networks, even for a small sized system, are usually very complex. Therefore, a proper representation of these networks is required for the study of whole ecosystem. We have worked with a group of scientists who are actively working with these networks.

1.5.4 Assessment and Evaluation

We conducted a study to evaluate our three novel graph visualizations. We provide prototypes of our three visualization systems for participants to interact with and perform some common graph visualization tasks. Furthermore, we gathered feedback from participants about our design decisions, and collected their overall impressions about each visualization. A complete report of these evaluations is provided in Chapter 7, and a list of participant quotes about their opinions gathered in Appendix A.

1.6 Contributions

This thesis contains several important contributions. The main contribution of this dissertation is a methodological approach for turning art (i.e. aesthetical patterns) to new graph layouts for creating novel graph visualizations. The other contributions of this thesis, in point form, are:

- Layouts: The design of three new graph layouts: Node-Ring [41], Daisy, and Spirograph layout. The creation of Eco-Spiro Visualization [42], based on Spirograph layout, a visualization tool for ecological networks that provides interactions tuned to ecosystems, calculates and displays indirect effects of ecosystem dynamics such as cycles and throughput [69];

- Implementation: The implementation prototypes of each of these layouts with basic interactions, with the intention that these new layouts could be incorporated into graph visualizations;

- Mapping: The analysis of ecological networks as a practical case, where we explore how the mathematics of the ecological networks can be both exploited and revealed in the creation of the new layouts;

- Process: We delineate the design process we have introduced, which can be used as strategy for further exploration.

1.7 Structure of the Dissertation

This dissertation is organized as follows. A review of relevant related work and a brief overview of background material is presented in Chapter 2. In Chapter 3, we explain an overview of our methodological approach and the design processes which we have used to reach our novel graph layouts. This process includes several iterations for each design and in one case we had to completely change the pattern. In Chapter 3, we only present the general concept of the new layouts and details of these layouts are discussed in the following chapters. Chapter 4 presents Node-Ring graph visualization, a novel approach layout inspired by Hundertwasser's paintings and Australian aboriginal dot paintings. In Chapter 5, we introduce Daisy Visualization created by employing floral elements of Daisy patterns.

Eco-Spiro Vis is presented in Chapter 6. Eco-Spiro is a variation of a Spirograph layout which is specifically designed for ecological network visualization. In Chapter 7, we report the results of evaluation for these three new graph layouts and provide the relevant discussion. Finally, Chapter 8 concludes the thesis and offers some potential directions for future research. Appendix A contains our participants' feedback in their exact quotes, and all documents related to our evaluation study can be found in Appendix B. Appendix C, contains a short description about how to use each of these three visualizations.

Chapter 2

Background and Related Works

The goal of this thesis is to use alternative aesthetic in designing layouts for graph visualization. Therefore, in this chapter, we first provide a short background about graphs in Section 2.1. Then, we provide a review of graph drawing in Section 2.2, followed by a review of graph visualizations that are more related to our goals in Section 2.3. Since we use ecological networks as our case study, we gather an overview of these networks in Section 2.4. Also, since the design of Node-Ring and Daisy layouts may be considered similar to glyphs, we provide a short review of glyphs and visualizations that use glyphs in their designs 2.5. Furthermore, we provide a collection of art inspirations for our novel graph visualizations in Section 2.6.

2.1 Background on Graphs

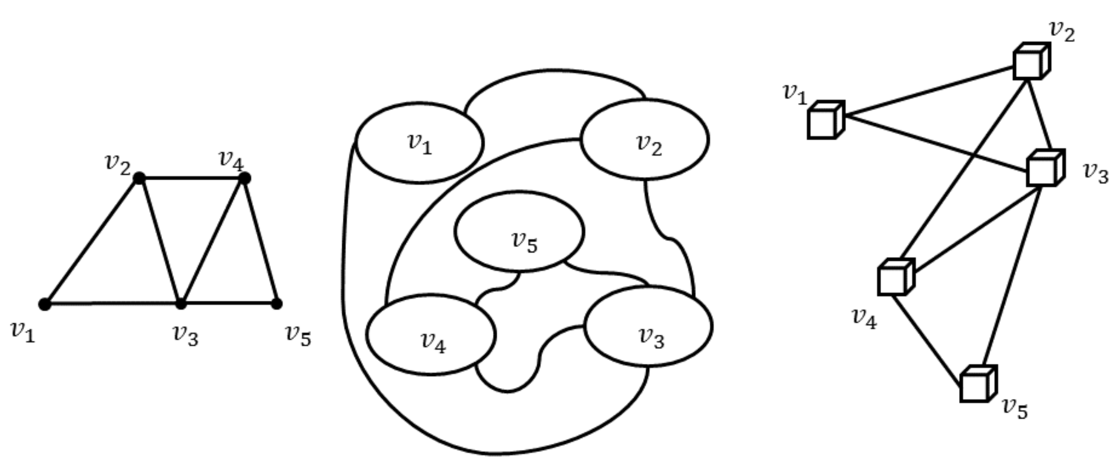


Figure 2.1: Three different drawings for a simple graph.

Graphs are mathematical models for representing entities and their relationships. Entities are commonly represented by nodes, and their relationships are represented by edges. Also graphs have simple and intuitive realization where nodes are shown by small shapes (usually circles) and edges by a line or curve joining two adjacent nodes. This graphical realization is called graph drawing and it is not unique. In fact several drawings are possible for a given graph. Figure 2.1 shows three different drawings of a simple graph with five nodes and seven edges.

Mathematically, a graph is represented by $G = (N, E)$ consisting of a set of nodes (or vertices) N , and a set of edges (or links) E. If e is an edge of G connecting node u to node v, then e is also denoted by (u, v). For the graph in Figure 2.1, N is $\{v_1, v_2, v_3, v_4, v_5\}$ and E is $\{(v_1, v_2), (v_1, v_3), (v_2, v_3), (v_2, v_4), (v_3, v_4), (v_3, v_5), (v_4, v_5)\}$. A graph may have loop (an edge connecting a node to itself) or multiple edges between two nodes. Figure 2.2 shows an example of a graph with four nodes, where node v_2 has a loop and there are two edges between v_3 and v_4.

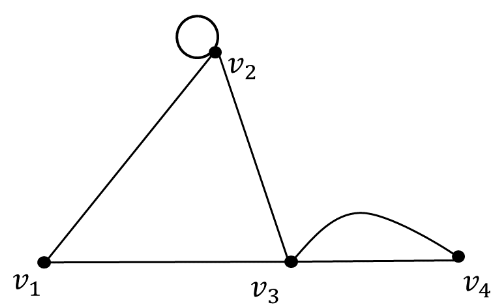


Figure 2.2: A graph may have loops or multiple edges between two nodes.

A graph is called *simple* if it does not contain any multiple edges or loops [21]. If there is an edge e between u and v, they are called adjacent vertices or neighbors. The number of neighbors of a node is called the degree of that node and denoted by deg function. For example, in Figure 2.1, $\deg(v_3) = 4$.

Another way to represent a graph is by its adjacency matrix. Let $N = \{v_1, v_2, \ldots, v_n\}$ be nodes of G. The adjacency matrix of G is defined [21], as $A(G) = [a_{ij}]_{n\times n}$ where:

$$
\begin{aligned}
a_{ij} &= 1, \text{ if } v_i \text{ is adjacent to } v_j, \\
a_{ij} &= 0, \text{ otherwise.}
\end{aligned}
$$

For example the adjacency matrix for the graph in Figure 2.1 is:

$$
A(G) = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 \end{pmatrix}. \tag{2.1}
$$

This matrix is symmetric. Also the sum of each row is the degree of the corresponding vertex. Adjacency matrix is commonly used in designing data structures for graphs. Also it has been widely used in graph visualizations [58, 59, 60] and graph measurements [21, 129].

A graph is *connected* if there is a path between any arbitrary pair of nodes in the graph. As shown in Figure 2.3, the graph on the left is not connected while the one on the right is connected. A closed path in a graph is called *cycle*, as shown in Figure 2.3 Left, there is a cycle v_1, v_2, v_3. A *tree* is a connected graph with no cycle [21]. Figure 2.3 Right, shows an example of tree. With this definition, graphs are superset of trees. For trees, it is not hard to show that:

$$
|E| = |N| - 1
$$

where $|E|$ denotes the number of edges and $|N|$ the number of nodes in the graph.

A simple graph $G = (N, E)$ is *complete* if each pair of vertices in graph are adjacent. A complete graph with n nodes is denoted by K_n. Figure 2.4 shows an example of a complete graph with five nodes.

A complete graph K_n has the maximum number of edges:

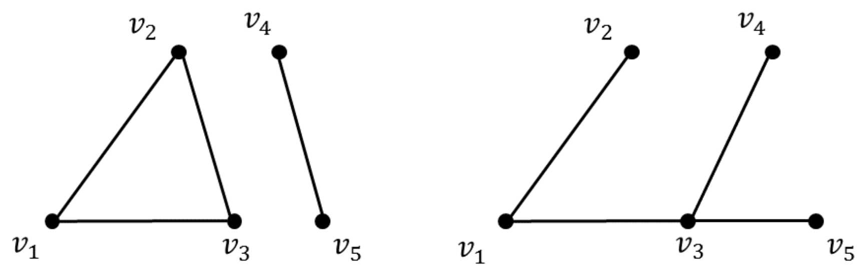


Figure 2.3: Left: disconnected, Right: connected graph.

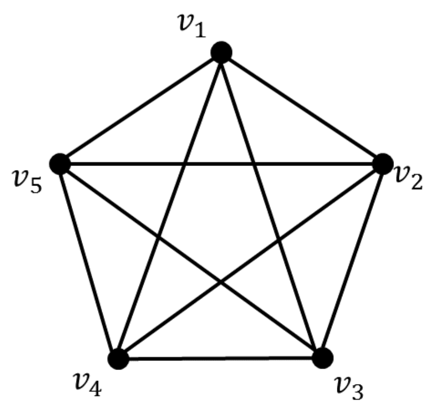


Figure 2.4: A complete graph with five nodes, k_5.

$$|E| = \binom{n}{2} = \frac{n(n-1)}{2}.$$

Complete graphs and trees are two extreme cases for number of edges in a connected graph. In essence, trees have an $O(n)$ edges while complete graphs have $O(n^2)$ edges.

Graph G is considered *dense* if it has almost as many edges as a complete graph with the same number of nodes n. Visualizing dense graphs [90] is more challenging than trees, due to the possibility of edge crossings. The density of the graph G is defined by:

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

The definition of graphs can be modified such that edges can have direction. Figure 2.5 shows an example of a *directed* graph where all edges have directions.

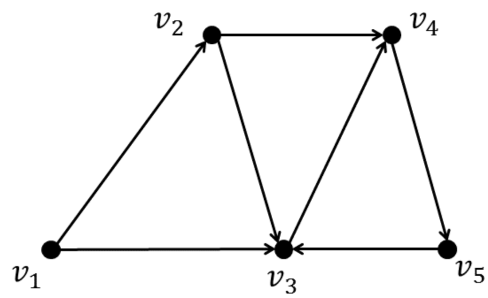


Figure 2.5: A simple directed graph with five nodes and seven edges.

Directed graphs are commonly used for modeling networks and road systems. Notice that the adjacency matrix for directed graphs is not necessarily symmetric anymore.

A weighted graph is defined as a graph where a weight (a real number) is assigned to each edge. For example in road system graph, the length of each road can be considered as the weight of the edge that is representing that road. A simple weighted graph is shown in Figure 2.6.

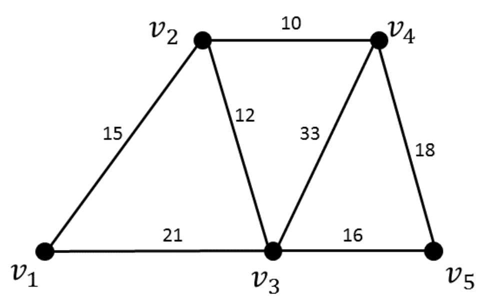


Figure 2.6: A simple weighted graph with five nodes and seven weighted edges.

In this thesis, we introduced three new graph visualizations, with each, we have worked towards extending our methods to be usable for representing weighted and directed graphs.

With this background, readers should be able to grasp the concepts related to graphs in this thesis. For further readings related to graphs and their data structures, please refer to these references [21, 66, 23].

2.2 Graph Drawing

The history of a graph as a geometric abstraction for entities and their relationships goes back to Euler's era when he introduced graphs to solve the problem of Seven Bridges of Königsberg [70, 145]. The geometric realization of graphs is not unique and can be done in many ways. The process and methods for converting a graph to its geometric form is called *graph drawing* [30]. Although, originally the graph drawing methods were designed for manual drawing of graphs, algorithmic description is the current trend of this paradigm.

The common approach for graph drawing is to use node-link layout where a position and a shape are assigned to each node, and edges are usually mapped to curves between their adjacent nodes (see Figure 2.1). Notice that in the node-link layout it is possible to position nodes with different arrangement patterns (e.g. regular grids, layers, radial) and use various styles for edges (e.g. lines, poly-lines, curves) [30]. The exact methods for arranging nodes and edges and their styles depend on many factors. In [30], several factors are discussed:

- Drawing Conventions: the basic rules used for specific types of the graph and specific domain application (e.g. orthogonal and grid drawings for electrical circuits, or top-down drawing for hierarchal date-sets, horizontal layered drawings for Sankey layouts [114]). See Fig 2.7 for example graphs based on these conventions.

- Aesthetics: the rules for increasing the readability of a graph drawing have been termed graph drawing aesthetics (reducing edge crossings, area of the drawing, total edge length, edge length variation, total edge bending, edge bending variation, and aspect ratio of drawing; increasing the smallest angle between two adjacent edges on one node; and imposing symmetry). Fig 2.8 demonstrates impact of symmetry.

- Subgraph Constraints: rules for constraining some subgraphs of the drawing

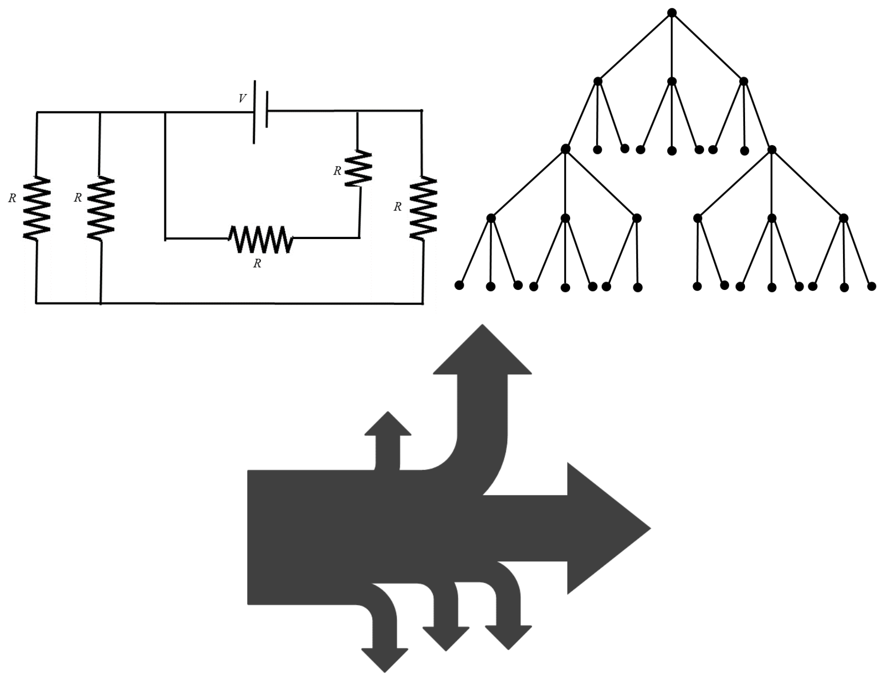


Figure 2.7: Three drawing conventions: grid drawing for electrical circuits, top-down drawing for trees, and layered drawing for Sankey layouts.

(e.g. making a vertex as the center of the drawing, or position a subset of vertices as a cluster, or external vertices toward the boundary of drawing). See Fig 2.9 demonstrates subgraph constraint.

- Efficiency: the drawing algorithm should be efficient to enable us for an interactive (i.e. very fast) graph drawing application.

It is unlikely to find a drawing to satisfy all these factors. Therefore, depending on the application and the usability of the graph some of these factors must be prioritized. For example, orthogonal drawing tries to arrange the nodes on a grid and connect the corresponding edges with perpendicular line segments [124, 30]. Layered drawing, another graph drawing method used mostly for hierarchical graphs, tries to arrange nodes in layers, based on their distances from the root [19, 30]. Force-Directed techniques refer to a group of graph drawing methods based on physical models ([5, 119, 11, 134, 63, 64]). In this general

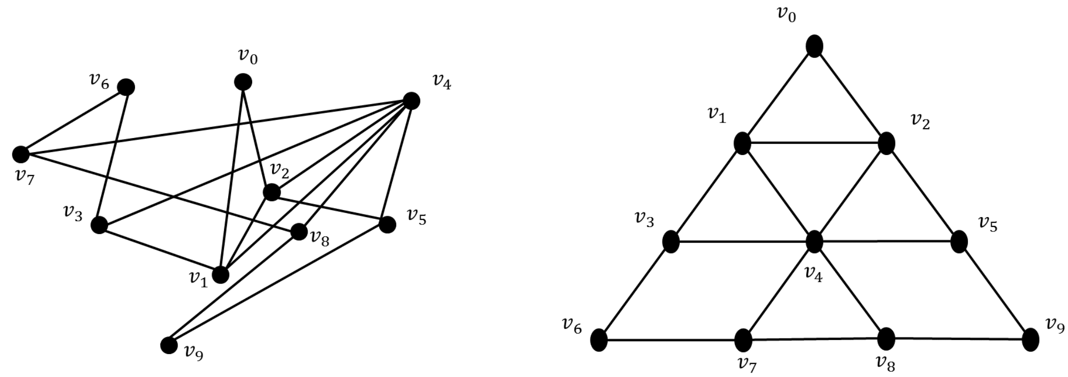


Figure 2.8: Symmetric arrangement of nodes can improve the readability of graph.

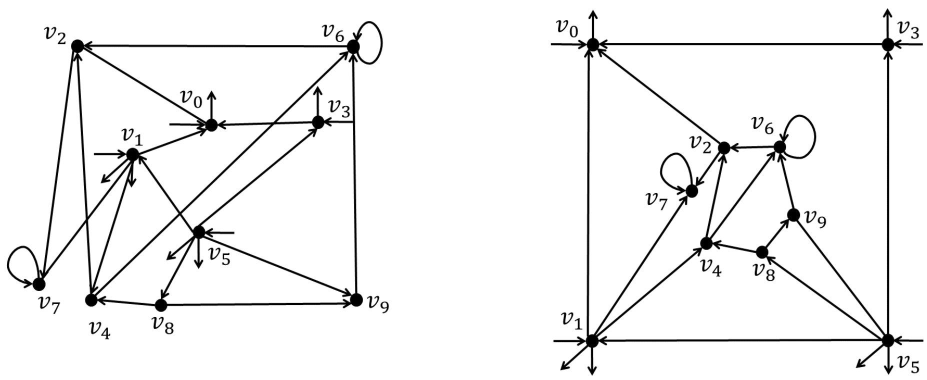


Figure 2.9: Some of the nodes have external edges (i.e connection with a phantom vertex). In the right, as a subgraph constraint, these nodes are drawn on the boundary.

approach each node is replaced by electrically charged particles that repel each other and edges are replaced by springs that connect the particles. The steady state of this physically based model usually provides a favorite distribution of nodes and edges. Also, there has been a large body of work for drawing planar graphs. Battista and Frati in [18] survey more than 100 papers for drawing force-directed graph. There is also an older graph drawing survey paper with more than 300 references [31].

The main objective of this thesis is to create novel graph visualizations. While some of the graph drawing factors can provide useful insights for graph visualization, graph visualization is different from graph drawing. In the next section, we explain this difference and provide graph visualization related works.

2.3 Graph Visualization

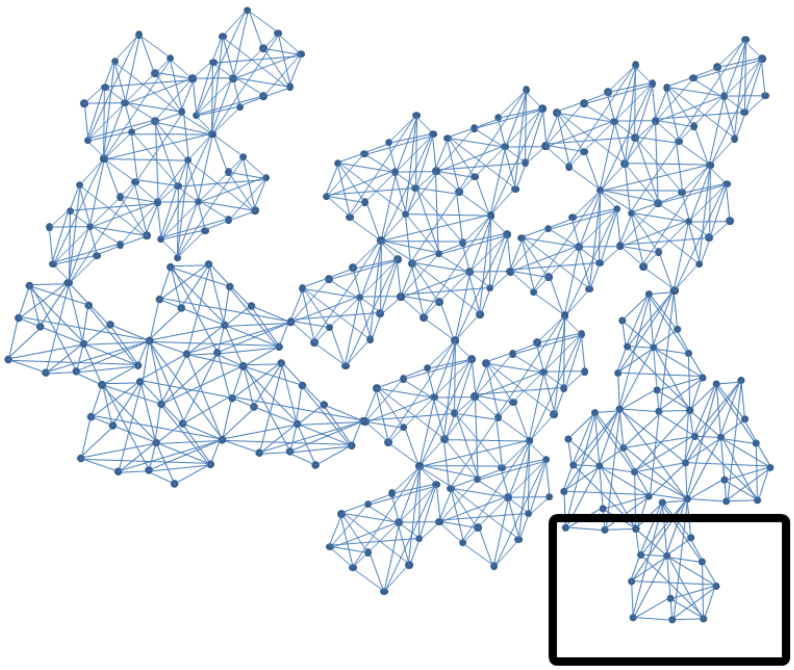


Figure 2.10: Interactive techniques such as focus+context can help human perception.

The difference between graph drawing and visualization is slightly fuzzy. Graph drawing methods are commonly based on node-link layout. These algorithmic methods are designed to efficiently manage the geometric aspects of graphs by arranging their nodes and drawing edges with respect to a set of factors described in Section 2.2. Graph visualization, similar to other areas of information visualization, refers to a visual representation that augments human perception [94]. Therefore, in addition to geometric realization of graphs, other encoding attributes such as colors, shades, symbols, icons, line styles and labels are used for the final representation. Furthermore, since a human is in the loop, interactive techniques such as focus+context, zoom/pan, clustering and filtering [94] can be used to generate a more abstract realization of the graph and its elements (see Figure 2.10). As evidenced in the related work (Sub-Section 2.3.1), there exist many graph visualization methods that rely on the adjacency matrix as a layout which is not common for graph drawing. The main subject of this thesis is graph visualization; therefore, we provide more detailed review of research work in graph visualization.

2.3.1 Graph Visualization Related Work

Survey papers relating to graph visualization provide a rich related work about general graph visualization methods. Herman et al. [61], surveyed 130 papers about visualization techniques of hierarchies and graphs published before the year 2000. In this survey they reviewed interaction techniques that are mostly related to focus+context interaction and lenses. They also reviewed clustering techniques and categorized them into three groups: ghosting, hiding and grouping. In a more recent work, von Landesberger et al. [138], surveyed 157 papers relating to graph visualization published before the year 2010. They grouped the visual representation of graph applications into static and dynamic graphs. Additionally, they reviewed applications contributing to interactions in graph visualization. Here, we try to be brief and review only the more relevant work or those papers which point out some of the facts related to the goal and methods of this dissertation.

Graph visualizations, particularly for large graphs, suffer from the cluttering problem due to a large number of edge crossings and overlapping nodes in the limited space of the screen. Techniques such as filtering, clustering and focus+context have been introduced to reduce these cluttering problems [61].

Clustering, filtering and focus+context

As demonstrated in Figure 2.11, clustering is a method for grouping some of the nodes or edges in graphs. This clustering creates a graph G_s with a new simpler structure from the original graph G, by grouping nodes and edges of G to meta-nodes and meta-edges in G_s (see Figure 2.11).

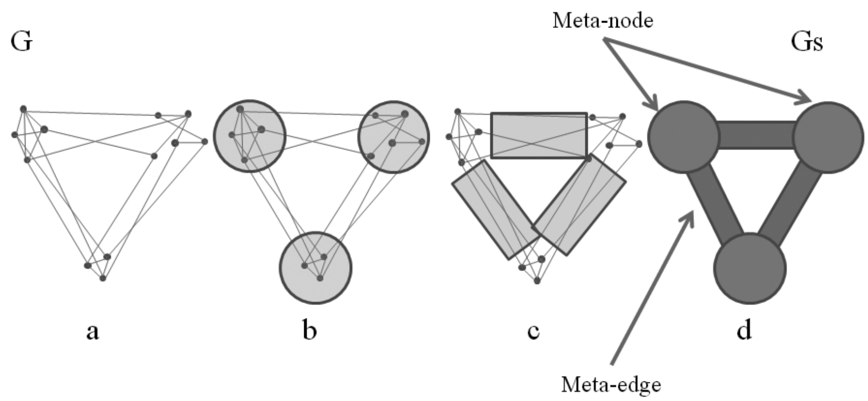


Figure 2.11: Cluster creation; a: a general graph. b: clustering nodes. c: clustering edges. d: meta-nodes and meta-edges.

Focus+context techniques are used in graph visualization to provide a seamless transition between global and local views of the representation. The main idea in focus+context technique is to emphasize the focus area using a mapping technique, concurrently within the context area. One of the well-known examples is the use of fisheye lens in graph visualizations [113, 52], to provide more detail of a particular section of the graph. Filtering, as another clutter reducing technique has been used in several graph representations [45, 13]. The idea is to present only the nodes and edges with a specific attribute.

Batageli et al. [17] use the combination of clustering and orthogonal node-link methods. First, a clustering technique is used for creating the graph G_s (see Section 2.2) and then each cluster is presented by different node-link drawing, such as radial node-link or regular grid. The overall structure of G_s is presented by force-directed orthogonal drawing [30], and depending on the type of data, and the density of each cluster, a layout and its specific variation are interactively chosen. Abello et al. [5] introduced a visualization technique that uses fisheye views and clustering to explore and interact with large graphs. In their visualization they present more details of the graph in the focused area using the compound fisheye lens, and fewer details in the unimportant areas. Instead of simply shrinking the unfocused areas, they show farther areas with coarser representation.

Clustering techniques may create tree structures from general graphs. Trees are special

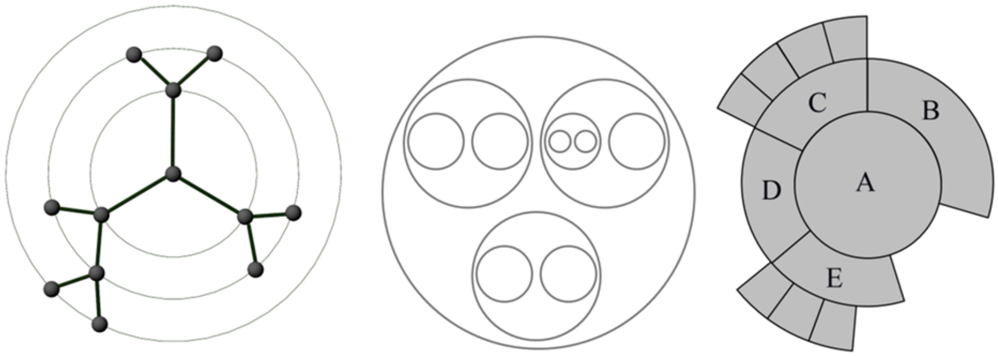


Figure 2.12: different tree layouts: from left radial node-link, nested and adjacent tree layouts.

cases of graphs (i.e. acyclic connected graphs), and there are more possible layouts and visualizations for them. This is perhaps due to their important applications for hierarchical structures and also their simplicity (i.e. low number of edge numbers and their planarity). Even the node-link tree layouts can be drawn with more variation (e.g. layered layouts or radial layouts). In addition to node-link and matrix layouts, they can be presented by nested and adjacency layouts by which edges are not explicitly drawn. In nested layout, each node is positioned inside its parent's node. In adjacency layout - which is different from adjacency matrix layout- nodes are attached to their children. These layouts are schematically shown in Figure 2.12. The availability of assorted tree layouts creates a good potential for designing new layouts by combining two or more of them. Such hybrid approach has been used in PaisleyTree [39] (see Figure 2.13). In this hybrid layout the goal is to represent a large tree in the proximity of the node of interest. The ancestral relationship between the node of interest and its parent nodes are represented by adjacency layout, and the relationship between the node of interest and its descendant subtree is represented by nesting and node-link layout.

The idea of using tree layouts for clustering graphs has been used in several papers. Holten [63] uses hierarchical edge bundling, for visualizing compound graphs. What is referred to as a compound graph is one in which nodes are clustered and, each cluster is a tree (see

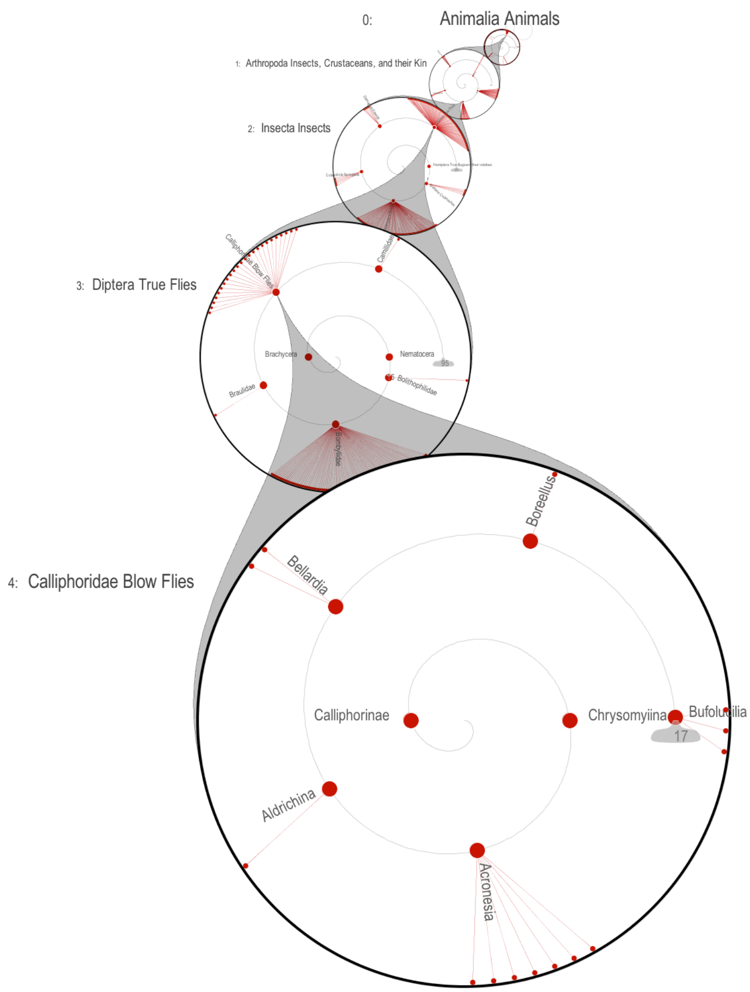


Figure 2.13: PasileyTree, hybrid visualization for large trees.

Figure 2.15, left). Therefore, it is natural to use tree layouts for each cluster of the graph while using a traditional node-link for representing the global view of the graph. In this visualization, edge bundling techniques help to reduce the edge crossings between clusters. Notice that in contrast with methods that try to rearrange the nodes of the graph, edge bundling techniques reduce edge crossings by grouping edges in one abstract unit. The edge bundling can be considered as a filtering technique. For example Ersoy et al. [38] introduced Skeleton-based edge bundling, that presents beautiful images of large graphs which look organic (see Figure 2.14). Gou et al. [48] also designed a visualization system named TreeNetVis for representing TreeNet graphs, which are special type of compound graph.

This system uses the combination of edge bundling and radial space filling layout [30]. The radial space filling techniques is used for presenting the tree structure (local views). The circular layout is used for presenting the overall structure of the graph (global view). And finally, edge bundling is used to reduce edge crossing problems (see Figure 2.15 right)[48].

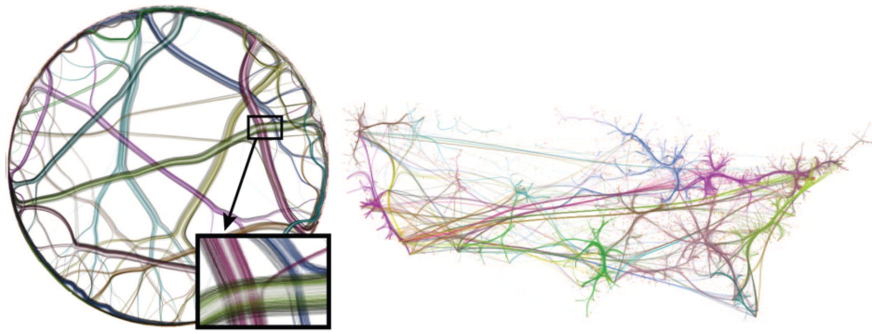


Figure 2.14: Skeleton-Based Edge Bundling for Graph Visualization [38].

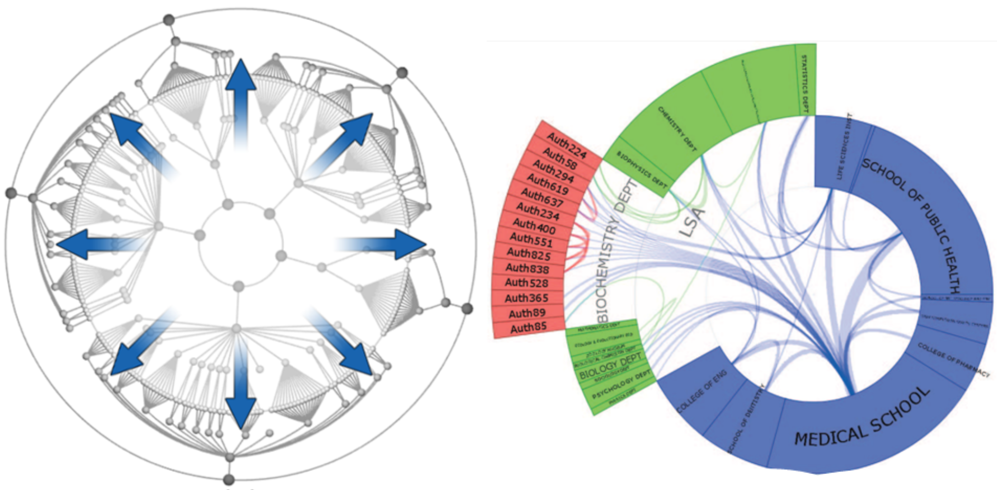


Figure 2.15: Left: Hierarchical edge bundling in combination with radial tree layout [63]. Right: TreeNetVis combination of radial space filing, edge bundling and circular layout [48].

Adjacency Matrix Representation

Many graph visualization methods rely on adjacency matrix representation. The clustering, grouping and filtering possibilities work better in the matrix layout, while the node-link layout usually provides a better geometric representation [58]. In order to take the advantage of both layouts, Henry and Fekete introduced MatrixExplorer that uses a combination of node-link and matrix representation to visualize social scientists collaboration relations [58]. Later they introduced NodeTrix [60] which is a hybridization of node-link and adjacency matrix representations for visualizing large social networks. In this visualization the global structure of a social network is presented by node-link and the local dense parts are represented by matrices. Data entities are presented as labels of the matrix's rows and columns. Furthermore, using a slightly different strategy, Henry et al. [59] introduced Matlink, a graph visualization for social networks. One of the main characteristics of large social networks is that they usually include many nodes with few links, and some few nodes with many links. This latter group of nodes usually holds the most important ones. While the node-link layout provides a specific relationship between the nodes, the matrix layout provides the global view of the relations in order to recognize clusters and the highly connective parts of the graph. Matlink concurrently uses node-link and adjacency matrix for the entire graph. In this method, all nodes are positioned on the top and left edges of the matrix and also connected by curved edges In order to reduce edge crossing, the longer edges are drawn over the shorter ones.

Recently Bach et al. [14], introduced OntoTrix, a visualization system for presenting ontology graphs (see Figure 2.16). Ontology graphs are usually non-planner, and contain many nodes and edges. Hence, a node-link representation of these kinds of graphs will result many edge crossings and node overlapping. Matrix representation on the other hand will make it difficult to follow the paths of the graphs. Therefore, a combination of these two graph layouts is used for visualizing ontology graphs. This visualization uses filtering by rendering the unimportant parts with a low-contrast color which makes the more important parts stand out, and provides a focus+context lenses in order to magnify the focus part of the view.

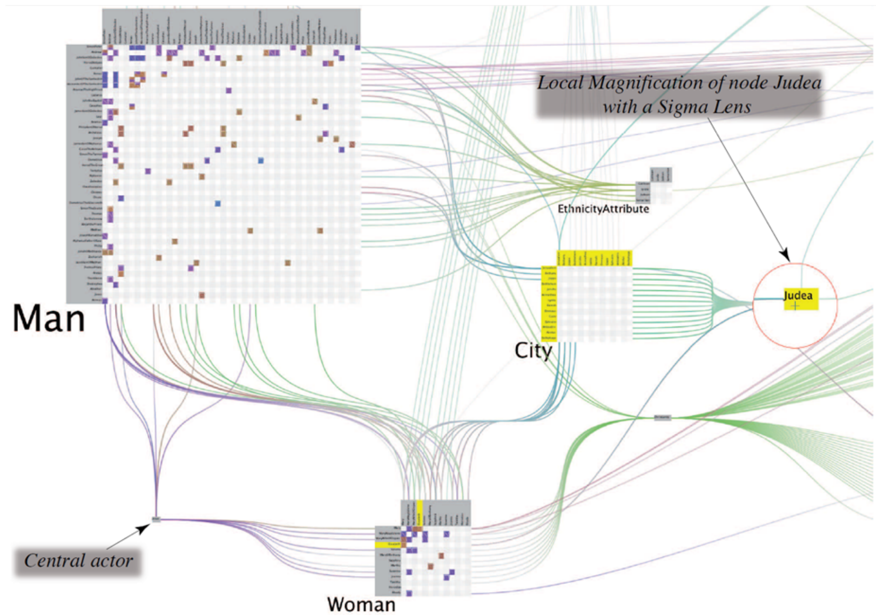


Figure 2.16: A screen shot of OntoTrix interface: ontology of men and women who live in cities in Judea, and people who are connected to them [14].

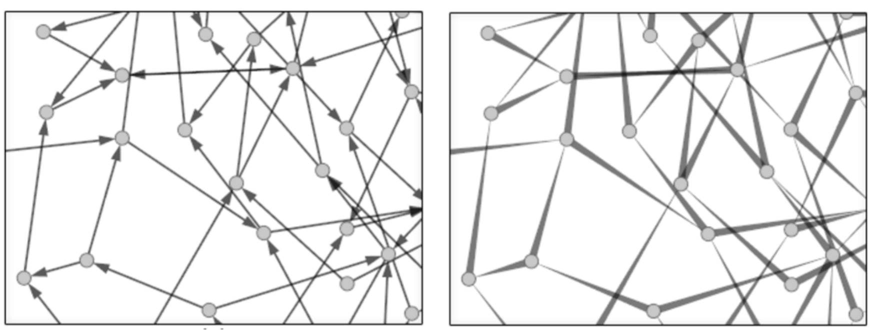


Figure 2.17: Direction of the edge can be presented by arrowhead links or tapering curves [65].

Directed Graphs and Weighted Graphs

The challenge of graph visualization is not just due to its size, visualizing attributes of graphs can be challenging too. For example, adding direction and weight to graph edges adds to the complexity. In simple node-link drawings, the direction of an edge is presented by arrowhead line [35] or tapering curves [65] (see Figure 2.17). When many edges are connecting nodes adding details like arrowhead can cause more clutter in the visualization. In recent directed graph visualizations, the direction is represented by altering the thickness of edge in proximity to origin and destination nodes [65]. Partial Linked Drawing [24] present a visualization technique for directed graphs by partially representing edges. In this visualization, the authors have tried to move one step away from explicit representation of edges to implicit representation and replace directed edges with only a short arrow connected to the original node pointing towards the destination node. In one of the variations of our Daisy Visualization (see Chapter 5), we use a similar approach for implicit representation of edges. In our Node-Ring Visualization (Chapter 4), we dropped the traditional form of edge and use colors and shades to represent directional edges. In this visualization we present directed edges implicitly inside their original node.

As defined in [9], weighted graphs are graphs with real numbers as the weight of each edge. A simple way to include weights in graph visualization is to use weights as the label for edges. This method adds to the edge cluttering issue. Also, having a more visual sense of the weight can be helpful in the context of graph visualization. Therefore, representing weighted edges in node-link graph visualization usually is done by either mapping the weight to the length [28] or the thickness [37] of the edge. While in matrix visualizations, usually attributes of edge like weight are mapped by the color of the corresponding cells [132]. Studies show that users prefer node-link visualizations in which weighted edges are mapped by thickness of links [9]. Our Eco-Spiro Vis (see Chapter 6) uses thickness for representing weighted edges, while Node-Ring maps the weight of the edge to the angular size of the corresponding arc. In general, directed weighted graphs are not as well studied as other types of graphs.

Dense Graphs

As discussed in Section2.1, complete graphs have the maximum number of edges among simple graphs. This massive amount of edges makes the edge cluttering issue more challenging for graph visualization. *Dense graphs* are graphs, similar to complete graphs, whose number of edges is close to the maximal [90]. Some cases of *Small world*[1] [133, 67] graphs, which are knows as being locally dense, and *Scale free* [101] graphs are examples of this cat-

[1]Small world graphs usually contain cliques (i.e. complete subgraphs)

egory [32, 90]. Social networks are also known as locally dense graphs, which are not useful to be represented by Node-Link [46]. Our Node-Ring (Chapter 4) graph visualization can provide an alternative way to represent dense graphs. Since we use implicit representation of edges, the problem of edge cluttering won't happen.

2.4 Ecological Networks

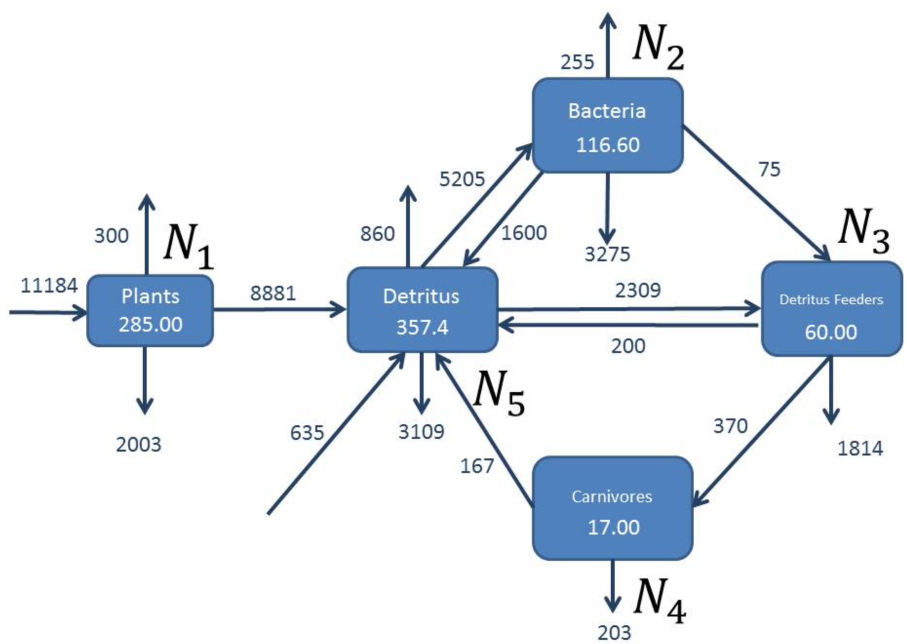


Figure 2.18: Ecological network with five nodes. Nodes have weights, indicating the biomass of the species they represent. Edges have weights, representing the amount of energy or matter in the transactions. Some edges represent transactions between species within the network, while others represent transactions external to the ecosystem.

Visualization of ecological networks is the practical use case for this thesis. We approached by ecologists from the University of Maryland for this task. These networks are a specific example of weighted directed graphs [130]. Ecological networks have complicated structure which makes their visualization more challenging. In these networks nodes represent species in the ecosystem, and node's weight represents the species biomass. Edges that represent the energy/matter flow between species, are categorized into four groups, known as Inputs, Outputs, Respirations and Exchanges, and they are all weighted and directed. Exchange edges represent the relations between nodes in the ecosystem, while other types represent the relations between ecosystem and outside environment. Figure 2.18 shows a simple five-node example of this type of network. In this diagram the weight of nodes and edges are simply added as numerical labels. The weight of each edge shows the amount of material that flows from one node to another. Directions are shown via arrows. Note that even a small example of these networks, with only five nodes, is complex.

Understanding ecosystems both from the perspective of necessary exchanges within the ecosystems and from their relationships and possible impact upon other external entities is challenging. To improve our understanding, these systems are often studied at many different scales including the relatively small scale of just a few nodes. This is important because larger ecosystems are often composed of smaller ones and because even small ecosystems are complex. This complexity arises from internal and external exchanges, energy flows, cycles and dynamics.

Relatively less attention has been paid to details of the visualization of weighted directed graphs, particularly in context of ecosystem dynamics. Commonly, this type of graphs is laid out using node-link with thickness as the weight and arrowhead as the direction of the edge. The primary purpose of these networks is to support ecologists in their analysis and exploration of ecosystems, and to use visualization to gain a better understanding of exchanges of nutrients and energy that form the dynamics and flow of the ecosystem [129]. These networks often contain one or more cycles (see Section 2.1). Figure 2.19 shows a more complex ecological network with 28 nodes. In this figure all relationships between species are represented by traditional node-link layout, which is a combination of orthogonal node-link and simple node-link layouts.

We have used ecological networks as a practical use case for all three visualizations which we introduce. Our Node-Ring Visualization is capable of representing a special case of

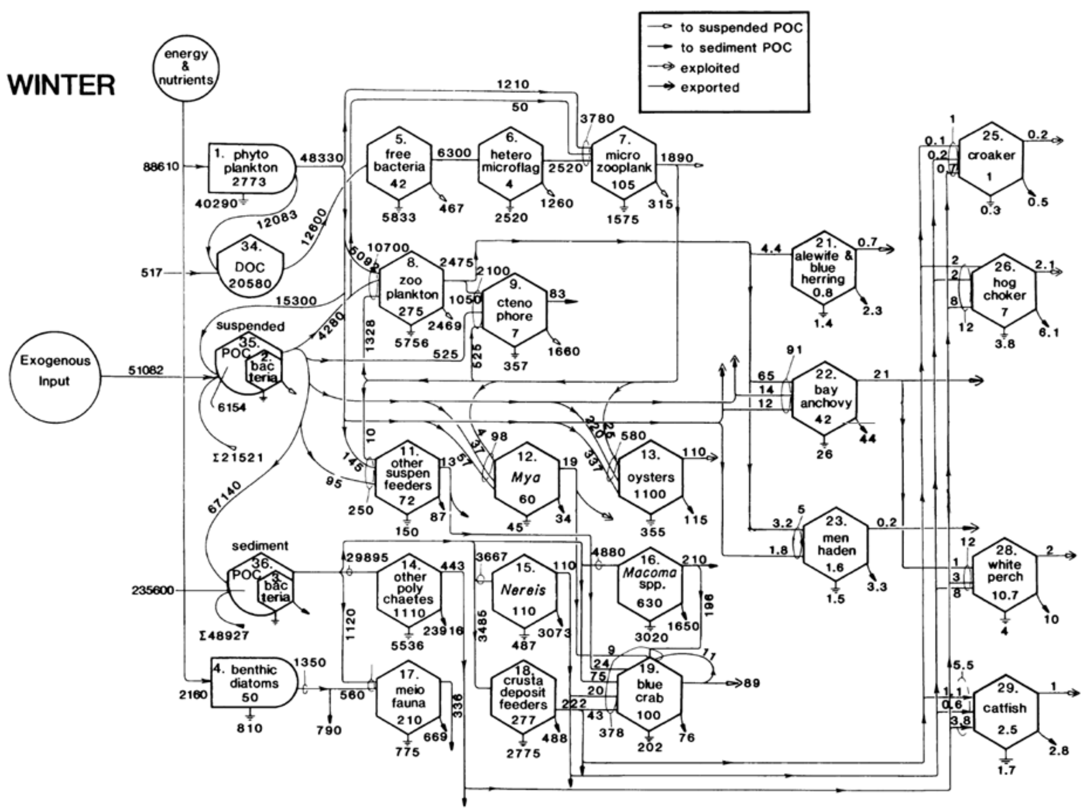


Figure 2.19: Simple node-link diagram is not sufficient for presenting this data [15].

ecological network called Food Web [97]. Our Daisy Visualization (Chapter 5) is capable of representing the whole ecological networks, and Eco-Spiro Visualization (Chapter 6) can represent ecological networks with a better solution for separating the internal and external relations in ecosystem.

While it may be tempting to think that traditional graph visualizations would be adequate for ecosystem networks most of the details that are of particular interest to ecologists get suppressed, and the complexity of even small networks becomes visually overwhelming.

Currently variations on flow diagrams as used in computer hardware and software diagrams are in use. With these flow-based node-link diagrams, for simple networks the visual representation is helpful in establishing an overview of the network. Furthermore, it may be possible to capture some of the topological connections (who eats whom) and simple measurements of the flow. However, as the system grows even moderately larger, this type of node-link layout quickly becomes cluttered, making it difficult to answer even simple and direct questions (e.g. discovering all adjacent nodes) (see Figure 2.19) [15]. In addition, exploring indirect and more global effects commonly used by ecologists, such as qualifying cyclic fractions of the network or the total amount of the flow from a node to another, is still challenging [129].

There exist other data visualizations that might be considered similar to ecological networks. Citation Patterns [93] is a visualization project that gives an overview of the citation network. However, as the direction and weight of edges were not important for this application, they were not included in this visualization. Krzywinski et.at. [80] introduced Circos, a visualization tool to assist the procedure of comparison of genomes. In this work, a circular layout is motivated and used for visualizing data with a high data-to-link ratio. However, the nature of our data is different. In ecological network this rate is usually small, but other external edges and indirect effects should be supported. Holten [63] used a similar orientation of nodes in his hierarchical edge bundling visualization, and in MizBee [91] Meyer and Munzner, designed a multi-scale browser for biologists to explore species' genome, chromosome, and block levels. In both visualizations, the direction and weight of the edges were not considered. Allesina et al. [8] used a node-link layout to visualize food webs (see Figure 2.20), which are a special kind of ecological network where only connectivity (who eats whom) is presented, but the flow of energy (i.e. the weights of the edges) is not visualized.

Sankey diagrams are a type of layout used for weighted layered networks (see Figure 2.21). This type of networks is commonly used for representing energy systems. Riehmann et al. in [110] present an interactive visualization system for Sankey diagrams. The layered structure of these networks has been used to design a layer-by-layer layout. Recently, Almasoom et al. [7] introduce a visualization tool that provides an interactive system for exploring time-varying, multi-attribute and spatial properties of a particular energy system. The tool integrates several visualization filtering techniques to facilitate exploration of a particular

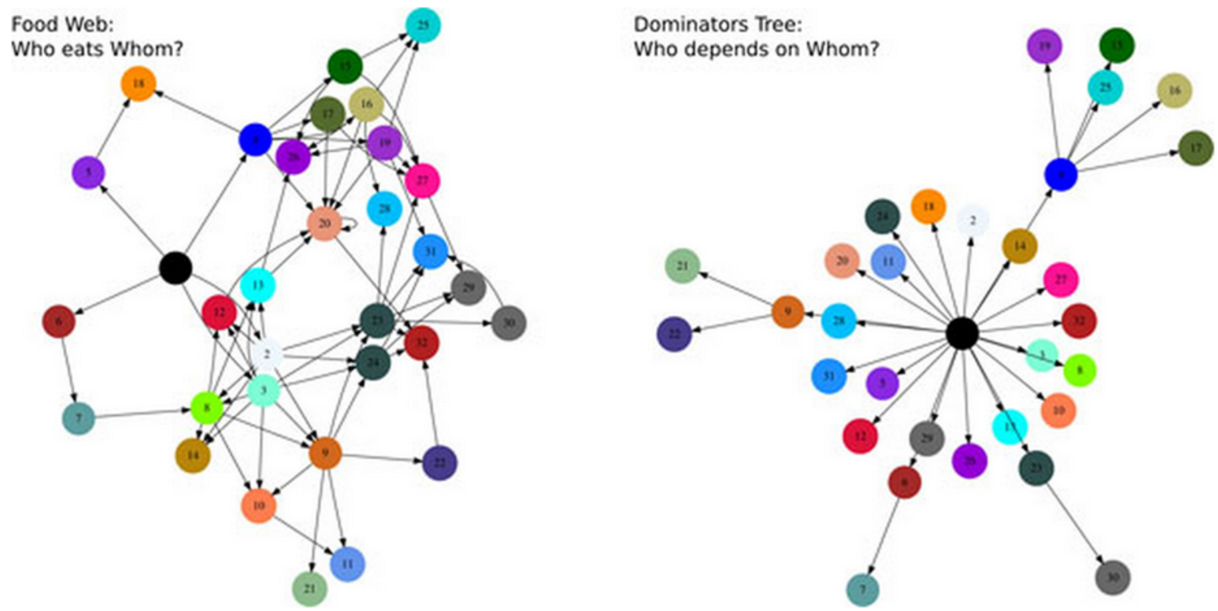


Figure 2.20: An image of a current ecological network [8]. This image shows a food web, which is a special kind of ecological networks. Food web shows the *who eats whom* part of the network.

energy system (see Figure 2.21). Given that ecological networks are generally cyclic, it is not clear how to customize Sankey in order to support cycles.

2.5 Glyphs

In our Node-ring Visualization, we map nodes and their adjacent edges to a new colorful shape. Specifically, in Daisy Visualization, we map nodes and their adjacent edges to a daisy flower and its petals. This concept is considered similar to the use of *glyphs* in data and information visualization. Glyphs are commonly small graphical objects that are used for representing individual data entities with multiple attributes [22] (See Figure 2.22). Different

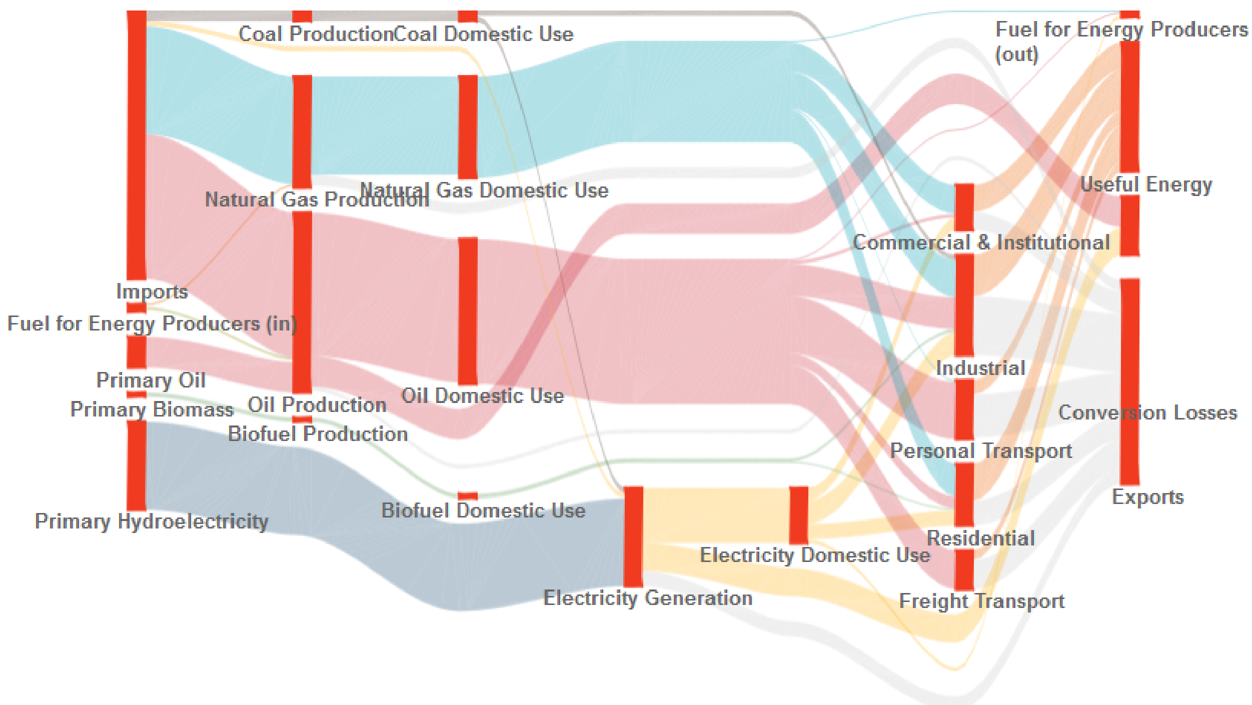


Figure 2.21: Sankey diagram visualizing the energy system (image courtesy of H. Alemasoom and F. Samavati, University of Calgary).

visual characteristics, such as shape, size, and texture of the glyph, can be used for mapping multiple attributes of the data [22]. Glyphs are usually designed to provide diverse features that can be mapped to different attributes of data. Since the shape and spatial relationships of glyphs are more apparent, these attributes have received more attention in designing glyphs [27]. Glyphs can be simple (e.g. circle used in [120, 103]) or complex (e.g. flow probe used in [29, 127]). Ward in [139] provides a more comprehensive list of possible glyphs and their characteristics.

One of the important aspects of glyphs is their placement. In spatial data visualization (e.g. geo-visualization), glyphs are commonly positioned in relation to the position of their associated entities (see [99, 148] as example references). For non-spatial information visualization, the placement of glyphs is free and can be used for depicting other aspects of the data-sets. For example, in [140], it is suggested to use the placement of the glyphs to show connections between entities. Lee et.al. [83] analyzes the use of glyphs' position for

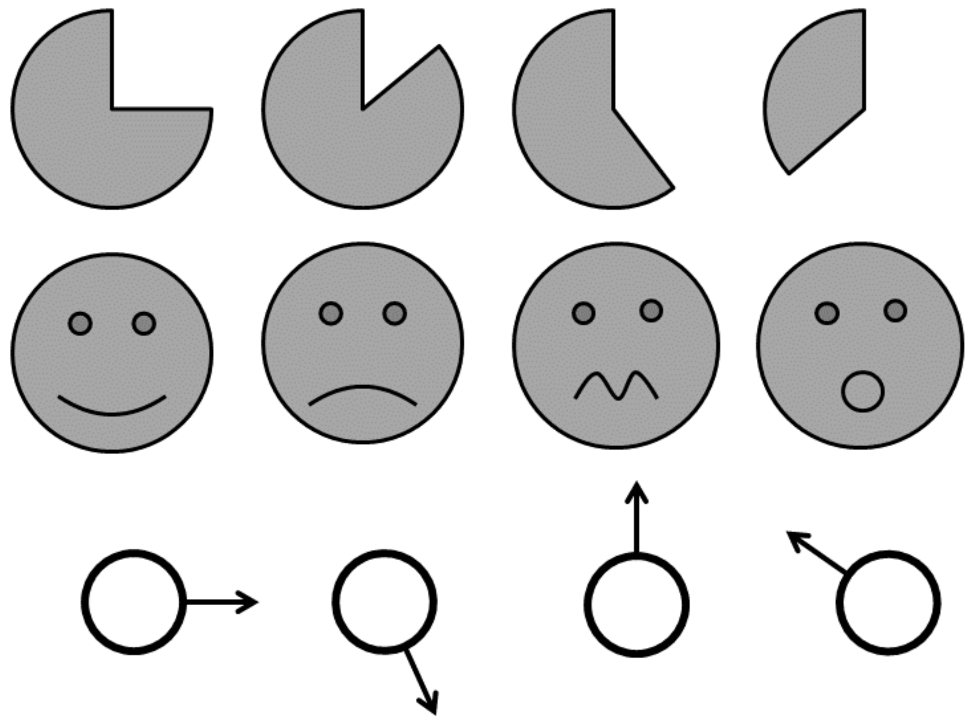


Figure 2.22: Small graphical objects for representing individual entities with multiple attributes.

representing similarity to other glyphs.

Ropinski et. al. in [111] propose guidelines to incorporate glyph based techniques in visualization. Some of these guidelines are: to ensure mapping emphasizes important variables, and to include a range of values and semantics of data. They also suggest a balanced placement of glyphs, and that the glyphs be clearly detectable while supporting quantitative analysis.

In Node-ring (See Chapter 4), similar to glyphs, we map each node of the graph to a circle whose size is proportional to the weight of that node. However, the important aspect of Node-Ring is the mapping of edges to concentric rings inside their source node's circle. In essence as a unique characteristic of Node-Ring, the connectivity of the graph is captured by the node's representation rather than the use of spatial position or explicit links. Furthermore, in Daisy (See Chapter 5), we map nodes of graphs to daisy cores, and edges of graphs to daisy petals.

2.6 Art Inspired Visualization

In this thesis, we explore the application of alternative aesthetics in graph visualization. The effects of considering aesthetically pleasing patterns in data visualization have been studied in [25]. In this work, Cawthon and Vande Moere appropriately report two different interpretations of aesthetic in data visualizations. By the first interpretation, aesthetic refers to the measurable factors used for improving the efficiency and effectiveness of tasks. For example, the aesthetic factors used in graph drawing (e.g. minimizing edge crossing or edge bending discussed in Section 2.2) belong to this type of aesthetic. By the second interpretation, aesthetic refers to the beauty of the visualization and reflects our personal judgement by which we observe paintings or other artworks. Interestingly, their study shows that even application of the second interpretation of aesthetic reduce task abandonment and erroneous response. Consequently, attractive visualization can help people to perceive information and engage analysts to perform their tasks [147, 25].

Recently, increasing number of data visualization researchers have been considering attractiveness in their designs. Examples are Informative Art [62] and InfoCanvas [92]. Pousman et al. [105] provides a review of the visualizations that have considered the use of selected aesthetic patterns in their designs. In InfoCanvas [92], people are provided with a tool to create their own screen design. They can start with a landscape image and add interactive features that present some sort of information. For example, they can present daily stock market performance with the weather shown in the landscape. The clear skies can indicate good performance, or a storm can be related to the down situation of the market. While these projects may not yet be fully successful in presenting data in a pleasing way, this type of research does consider the aesthetical pleasing approach when presenting data, and does offer ideas about how this might be done. Viégas and Wattenberg present a survey of projects in artistic information visualization [136]. They explore how an aesthetically pleasing focused approach improves scientific analytical reasoning in information visualization.

Lin and Vuillemot [85] use 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 [57] 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) [36].

As mentioned in Section 2.1, trees are special cases of graphs, and graphs can be represented with combination of tree visualization and graph visualization techniques too. Earlier, we introduced ShamsehTree [40] as a novel visualization for large trees.[2] In this artistic representation of trees, we employed Persian floral patterns, to design a tree visualization that can present a large tree (around 75000 nodes). The self-similarity and symmetrical structure of Persian floral patterns provide a well suited capacity for tree visualization system. PaisleyTree [39] introduces a novel approach for hybrid visualization of trees with arbitrary depth and breadth. In this size-invariant tree visualization, three different tree layouts have been combined to represent large trees. Node-link, Adjacency and Nested tree layout are all employed in PaisleyTree.

2.6.1 Symmetry in Information Visualization

Symmetry is one of the measurable aesthetic factors and its effects in information visualization have been acknowledged in several ways. In his book [141], Colin Ware argues that symmetry (including similarity) has long been recognized as playing a basic role in human perception. According to [142] Gestalt's principles[79], symmetry and similarity can provide powerful methods of recognizing elements within an image. Furthermore, symmetrically arranged pairs of elements can create a strong holistic impression, while similarity is an important feature for grouping individual elements with the same properties [141]. Humans

[2] The works related to tree visualization, ShamsehTree [40] and PaisleyTree [39] had been done earlier as part of my Masters thesis.

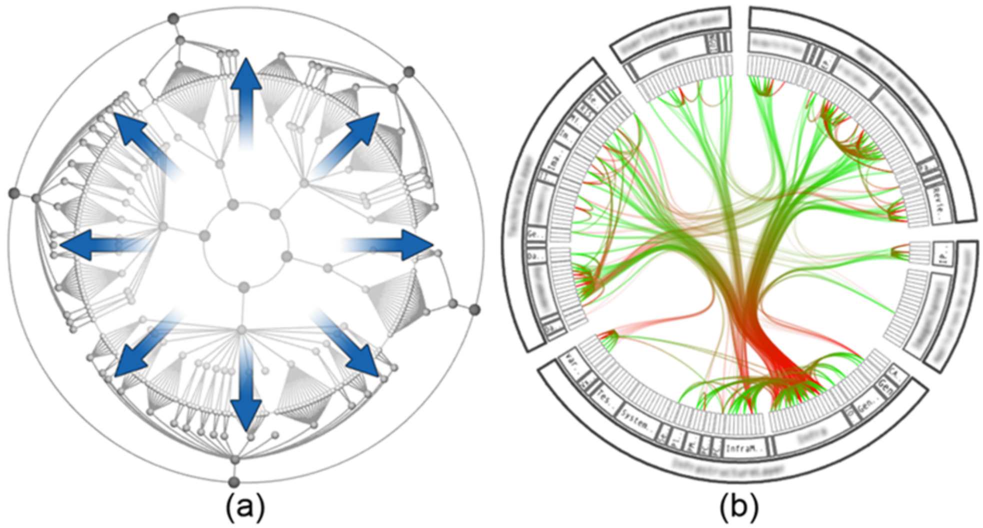


Figure 2.23: Hierarchical edge bundling in combination with radial tree layout [63].

have a mechanism which naturally detects symmetry in objects [104], thus using symmetry in visualization enables recognition and understanding the geometry of object's structure [128]. The fact that symmetry can be recalled at ease by human visual system is shown and supported by an observation in [12]. Attneave [12] observed that when subjects were given a random pattern of dots and a symmetric pattern of dots, the symmetric patterns were more precisely remembered and reproduced than the random patterns. The effects of aesthetics in graph visualization have been studied in [107] by Purchase et.al. They show that maximizing symmetry as well as minimizing node overlapping, edge crossing and edge bending have strong effects on understanding the graph structure. In the series of studies conducted by Purchase et.al, in [108], participants were asked to draw graphs in a more understandable way. The results show that participants try to follow some criteria in their drawing: reducing edge crossings, edge bending and increasing symmetry. Therefore, symmetry is one of the aesthetic principals that may improve the design of graph layout [33] (see Figure 2.6). A graph with a symmetric structure requires us to concentrate only on its *motif* while other parts can be symmetrically mirrored from the original structure [89]. Thus a display of graph symmetry becomes crucially important for producing good graph layouts [33].

2.7 Summary

In this chapter we provided a background for graph and its mathematical definition. Then we reviewed some background for graph drawing and graph visualization techniques. In the graph visualization section we explained the difference between graph drawing and graph visualization, while providing a review of graph visualization related works. Since the design of our Node-Ring Visualization can be considered similar to glyphs, we added a review of Glyph based visualizations in this chapter. Furthermore, since ecological networks are the practical use case for this thesis, we provided a background for this kind of network. Finally, since the goal of this thesis is to introduce alternative aesthetic graph visualizations, we reviewed some artistic inspired visualization.

Chapter 3

Design Process

3.1 Introduction

As discussed in the first chapter, several novel graph visualizations are introduced in this thesis, each based on different types of aesthetics. These visualizations are the results of a challenging process involving several design iterations for each visualization. In this chapter we provide an overview of our design process for these graph visualizations.

First we schematically explain the steps of this process, using diagrams. Then we illustrate the process of designing our four graph layouts. These layouts are inspired from artistic and aesthetic patterns. *Node-Ring Visualization* is inspired by Hundertwasser's colored circles paintings and Australian aboriginal dot paintings. *Daisy Visualization* inspired by daisy flower ornamental patterns and *Knots* is inspired by Celtic Knot art. *Eco-Spiro Visualization* is inspired by Spirograph patterns and is specifically designed for visualizing ecological networks. In this chapter we provide only the design process and the basic layout for these visualizations. The thorough discussion of Node-Ring, Daisy and Eco-Spiro Visualizations are presented in the following chapters.

3.2 Process Overview

The main objective of this thesis is to draw upon various aesthetically pleasing design patterns from artworks to design of new graph layouts. These new layouts should adhere at least some of the unique factors from each different aesthetics. Our main approach is to map the graph's features to well-accepted aesthetic patterns. Any intriguing pattern, mesmerizing ornament or exciting art pieces can be used as the source of inspiration for designing the

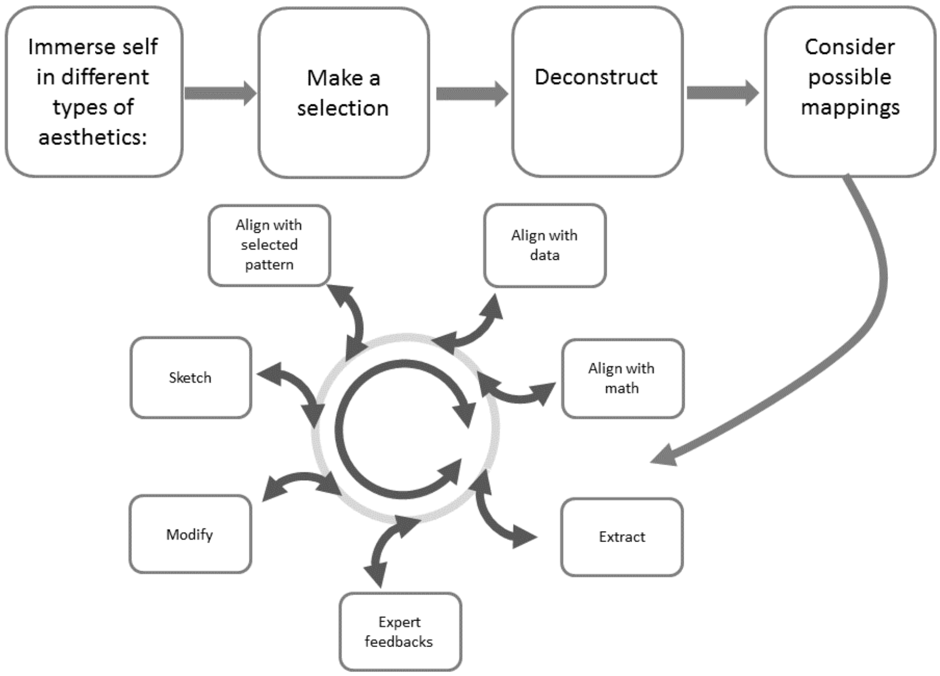


Figure 3.1: Schematically representing design process.

new layout. The main steps of design process can be described as follows:

Step 1 Immerse self in different types of aesthetic patterns. This is part of establishing a personal context. Explore widely, and look for patterns from formal, traditional, fabric, jewelry or math. Include variations from art and design. Examples of what we have chosen include Persian floral patterns, star patterns, Celtic knots, Escher and Voronoi diagrams.

Step 2 Make a selection from above.

Step 3 De-construct the selected pattern by looking for structural repetitions and motives. Build an understanding of what makes the selected pattern work.

Step 4 Consider possible mapping to a graph. In this step working on a concrete data is helpful. Data characteristic can sometimes show the way in developing a mapping.

Step 5 Conduct an iterative process between, sketching, modifying, extracting the layout, aligning with math/algorithm, aligning with data, aligning with selected pattern, and getting feedback from expert(s). As illustrated in Figure 3.1 there is no *Start* and *End* to this iteration step, and each action can be connected to any other action depending on the design process. For example after sketching a mapping, we may start with getting feedback from expert and then move to aligning with data, and aligning with math, or we can first align with selected patterns and then move to aligning with math and get expert feedback.

However, the particular choice of patterns depends on the *personal context* which is explained in the next subsection.

3.2.1 Personal Context

[1] The personal context of the work presented in this thesis has been greatly influenced by my fascination with floral ornaments and symmetric patterns (e.g. star patterns and Escher's patterns). This fascination became an obsession when I realized that these intriguing patterns usually have simple and elegant mathematical and algorithmic definitions. My mathematical background has been a great factor in my long journey with 2D patterns. One of my first experiences of working with these patterns goes back to designing Persian floral patterns for decorating books during 1993-1995. In doing that task, I used METAFONT a descriptive language for creating a family of fonts [78]. METAFONT was designed by Donald Knuth a renowned computer scientist who revolutionized computer typesetting and font designing by his famous TEX, in the 1980s. Unlike interactive systems such as Adobe Illustrator, in METAFONT, curves and strokes are defined based on mathematical objects which are controlled through some algebraic equations. These algebraic equations are set based on some control parameters (e.g. stroke thickness, dot size, cap size). In fact a family of fonts can be generated through unique definitions of each character. For designing each

[1] Personal context is based on authors background, hence we use I as the subject, only for this section.

pattern, I spent many hours figuring out the key points of the pattern, understanding its constructive curves, the relationships between points and the exhibited symmetries. So, in summary I used a mathematical approach for designing a number of calligraphic items for books. Certainly, using Adobe illustrator was an easier way to do this, but the requirements of the project and also my own mathematical and algorithmic desire directed me to use METAFONT.

In 2007, I did a research project at the University of Calgary for animating Persian floral patterns. My vision was to bring these wonderful patterns to the life by animating them. Vila had executed the same idea for making a short animation for SNAKES, a famous design from M.C. Escher [137]. In this project I explored techniques for dynamic recreation and animation of floral patterns, using different scenarios: visualizing pattern symmetries, illustrating their design process, and simulating plant growth. Furthermore, in order to create the illusion of never-ending animations, I created an infinitely cycling effect for self-similar patterns. With the help of my collaborators this work was published in the ACM Symposium of Computational Aesthetics in Graphics, Visualization, and Imaging [43].

This research project encouraged me to start a Masters in Computer Science at the University of Calgary with the hope of exploring the use of these beautiful patterns in novel applications. These patterns, like a painting, create a personal feeling for each viewer, so why not make use of this grace in creating novel applications for information visualization. This goal was the focus of my MSc thesis, which was a new look at visualizing large hierarchical data. In that research I introduced two novel layouts for visualization of large trees. In ShamsehTree [40], I designed a nested layout based on emphasizing the node of interest and tree-cut in the proximity of it. This was inspired by Shamseh patterns, from the family of circular islamic floral patterns [123, 88]. In PasileyTree [39] I designed a layout inspired by Paisley [10] (or Boteh), a droplet pattern from the ancient Persian floral patterns.

Being pleased with the joy of working with these patterns during my MSc program, in my

PhD I considered the problem of making use of different aesthetics in generating new graph visualizations. Graph visualization is a more challenging problem than tree visualization, as trees are a simple case of graphs with lower number of edges (see Section 2.1). As before, I have been aiming to design beautiful layouts which may trigger personal aesthetics.

In the past few years, I have surrounded myself with many decorative artworks, floral patterns, ornamental decorations and colorful paintings to come up with new designs for visualizing these kinds of graphs. My personal choice of patterns have been: floral, star, circular, Escher's, Voronoi [34], and Celtic knots.

I usually use the following arrangements for repeating the motives of the patterns: simple symmetry (i.e. affine transformations), dilatational symmetry (self-similarity), phyllotaxis and spirals. Finally, in addition to the simple 2D space, I desire to map the patterns into circular and radial spaces. This can be done by a simple polar mapping or with more advanced methods such as Poincare metric [50]. In general, circular forms are not only my favorite choice for the space, but also they are commonly used in most of the motifs/element in my previous works and the proposed layouts in this thesis (see Figure 3.2).

After selecting the desired pattern, we need to map these aspects (patterns and arrangements) to a graph layout. However, this is a hard task and sometime impossible. A long and iterative process has been used for designing the graph layouts introduced in this thesis.

3.2.2 Process

Creating a mapping between selected patterns and graph layout is hard task as we should respect two objectives that are commonly in conflict:

- The layout should clearly and accurately represent the graph (data).
- The layout should be pleasing and adhere to the principles of the chosen aesthetic, by increasing the similarity of the layout and selected pattern, and appropriate use of arrangements, color palettes, etc.

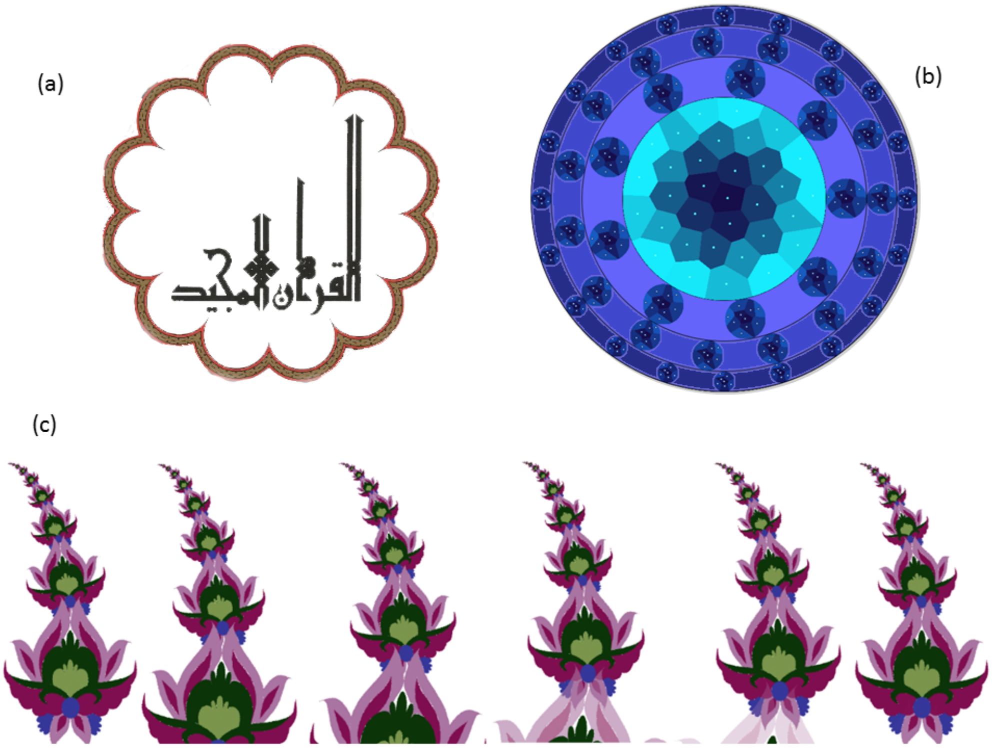


Figure 3.2: Samples of my previous works. (a) Calligraphy and floral pattern design for "Quran Khodava" [4]. (b) Hierarchical data visualization, inspired by voronoi [16, 122] diagrams and Poincare disc [50] structure. (c) Animated Persian floral patterns [43].

Therefore, as illustrated in the Figure 3.1 we use an iterative approach. We start by searching for patterns which have specific features in their structure, which may map to the elements of the graph. For instance, patterns with repetitive elements, or symmetrical structure are good candidates for this purpose. More specifically, in order for a designer to be able to show a given feature of data, she or he needs to find an aspect of the pattern to which that feature can be mapped.

Since graphs are defined in term of nodes and edges, or the relationship between nodes, one strategy is to find a way for mapping nodes and edges to some components of the selected pattern. To do this, we need to look for patterns with repetitive elements which can be used for this mapping. These elements should be capable of being presented with variety of different sizes, colors and/or shapes. These variations are needed for mapping different attributes of the graph. For example, weights of nodes can be mapped to the size of the elements in the pattern. We may also encounter graphs with different types of nodes, in which case, the diversity of elements found in the selected pattern can be used to address this need.

Since the role of edges in graph applications is also fundamentally essential, we can consider the above strategy for edges. Equivalently, nodes of the dual graph [21], can be mapped to the repetitive elements similar to the strategy for mapping edges.

The goal of the iterative step is to increase the degree to which the new layout adheres to the selected aesthetic principles of the chosen pattern. In this step, we may try to include more details and features of the graph with more intricate patterns. We also, may tweak the design by rearranging the nodes' representatives, by reducing clutter, by changing color palette, and by enhancing the symmetry of design.

Even after these refinements, we might come to the point that we need to change the pattern and the mapping (see Figure 3.1). In the following sections, this design process for four of our layouts is described briefly.

3.3 Node-Ring Layout

Node-Ring is our first layout for graph visualization. Since traditionally, nodes of graphs have been represented by small circles, we searched artworks to see if there is a pattern with many small circles (dots). Hundertwasser's paintings and Australian aboriginal dot paintings were selected for this design (See Figure 3.3).

Figure 3.4, schematically shows the mapping steps for Node-Ring layout. For the mapping, we decided to represent each node with a colored circle, and initially, each edge with colored line. The arrangement of nodes (Figure 3.4, (a)) and the selection of colors for both nodes and edges were initially random (Figure 3.4, (b)). In the next iteration, we explored other arrangements of nodes such as circular, spiral and symmetrical (see Figure 3.4, (c)). In another iteration we colored edges based on the color of their origin or destination node

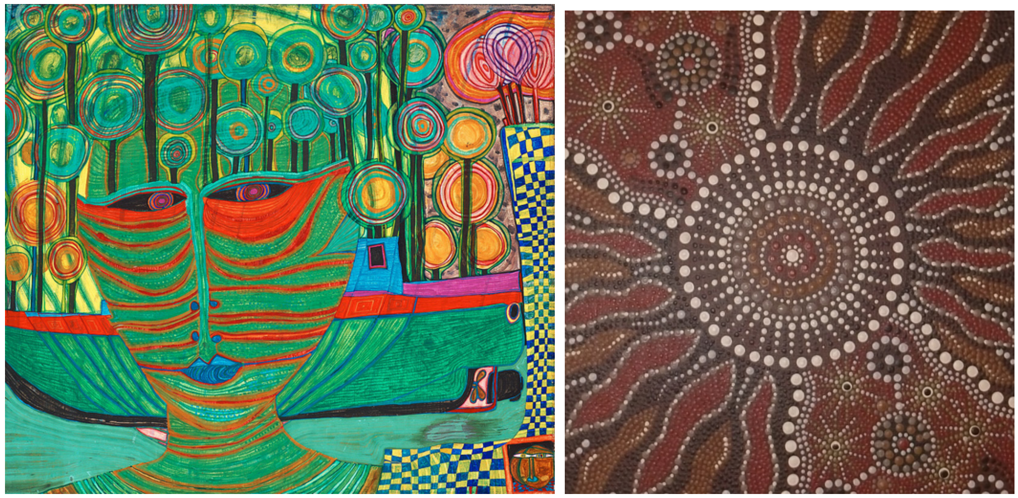


Figure 3.3: “Left:Columbus Landed in India” by Hundertwasser 1969 [3] (Creative Commons license [2]). Right:This dot painting, “Stomping Grounds” by Michael Bruce Cummings, styled as kinjart [77] (Creative Commons license [1]) also shows use of concentric circles.

(Figure 3.4, (c) and (d)). As it is clear in the figure, even a small graph, in this layout is crowded with many colored edges and their arrowheads. To reduce this clutter, we use a novel color-coding for edges: if we use the color of destination node on edges, we can drop the arrowheads since directions of edges can be realized by their colors (Figure 3.4, (e)). For example a red edge between the blue and the red node implies that the edge direction is from blue to red. Even with this color-coding, edges occupy a large space and restrict on the nodes' arrangement. In the next iteration, and inspired by Hundertwasser's paintings, we took the color coding idea further and mapped the entire edge to a colored ring inside of the source node (Figure 3.4, (f)). In essence, all adjacent edges of each node are nested in that node. To clarify, a red ring inside the blue node represents the directed edge from red node towards the blue node.

Figure 3.5 demonstrates the transition of edges from lines to rings. This final design forms the basic structure for our Node-Ring Visualization which is discussed in details in Chapter 4.

In summary, the basic idea used in this layout is to map a node and all its adjacent edges to concentric colored circles. The remaining iterations (see Figure 3.1) for Node-Ring are

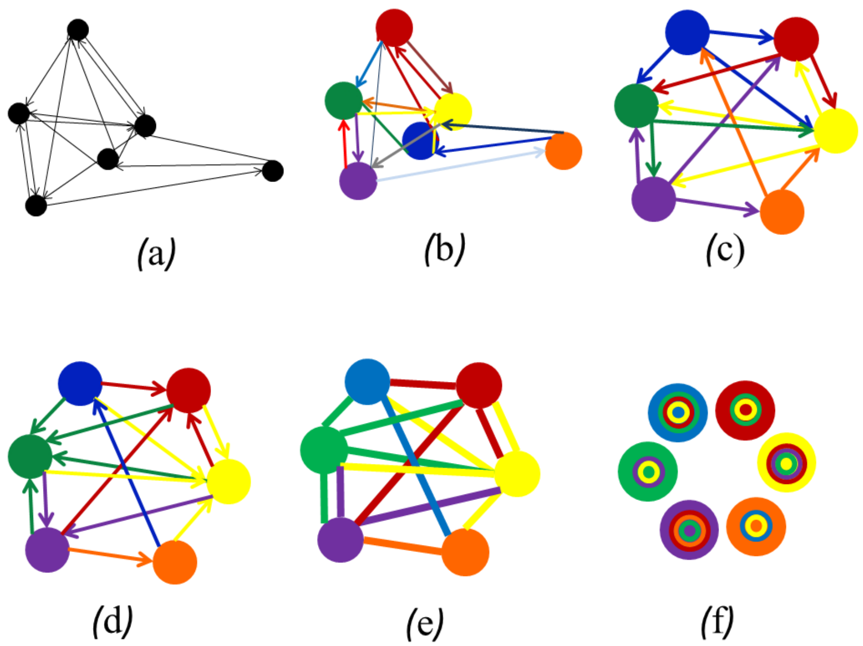


Figure 3.4: Schematically representing the design process of Node-Ring layout.

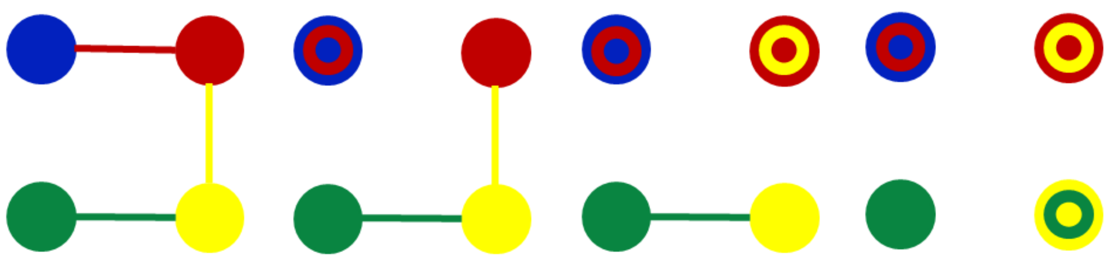


Figure 3.5: Step by step replacing edges with colored rings. Red edge that shows the directed edge from blue node towards the red node, is replaced with a red ring inside the blue node.

described in Chapter 4, which is devoted to the Node-Ring Visualization. In that chapter, we also improve Node-Ring layout by including other features of the data (i.e. weights of edges and nodes). The visualization based on Node-Ring layout has been published as a peer-reviewed paper "Node-Ring Graph Visualization Clears Edge Congestion" [41] which is the main source used for Chapter 4. Finally, as described in Chapter 7, we have conducted a study to evaluate Node-Ring graph visualization.

3.4 Daisy Layout

Figure 3.6: An example of ornamental patterns including daisy flowers [131].

Our second layout for the visualization of directed graphs is inspired by ornamental patterns of daisy flowers (see Figure3.6). The general concept of mapping nodes is similar to Node-Ring. In this mapping, nodes are also represented by circles but the edges are represented differently. In Node-Ring layout, edges are converted from lines between vertices to colored rings inside of the source node. However in Daisy layout, we represent edges by a linear element attached to the source node, pointing to the destination node (directional constraints). These linear elements, could be simple lines as demonstrated in the Figure 3.7, (b), (c) or more decorative elements such as daisy petals shown in the Figure 3.7-d.

In our attempts, we first colored all daisy cores by a unique color and all edges (daisy petals) by another color. However as seen in the Figures 3.7-d and 3.9-a the overall representation is still different from the daisy ornamental pattern. In traditional patterns, the arrangements of daisy petals around the core is usually symmetric. In our design, the symmetry can be satisfied if all edges (petals) are distributed symmetrically around a node (see

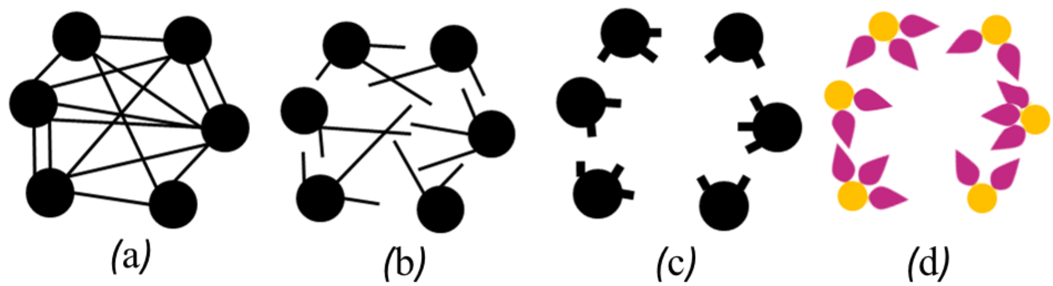


Figure 3.7: From left to right representing steps to replace line edges by daisy petals.

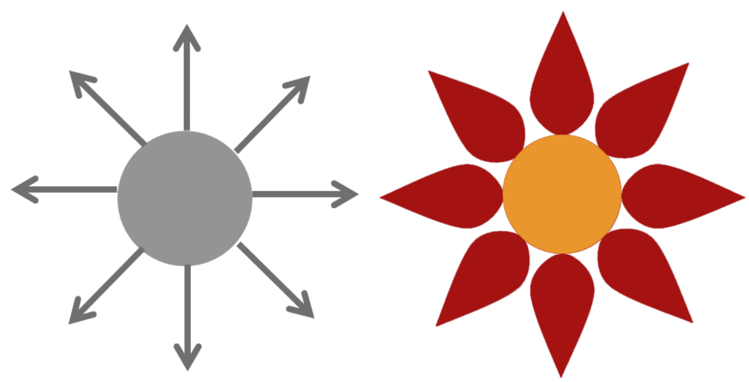


Figure 3.8: Left: One node of the graph with eight directed edges. Right: Same node, replacing arrowhead links with daisy petals.

Figure 3.8). However, edges in our design point to the destination node (see Figure 3.9-a).

In order to have a symmetric arrangement of petals around a daisy core, we need to have another strategy to encode the destination of edge, so in the next iteration in our design process similar to Node-Ring, we assigned different colors to nodes. Now we need to determine how to color petals in a way that enables us to remove the directional constraint on edges. Since daisy petals are positioned on the perimeter of their source node, we choose the destination node's color for coloring the edge as is shown in the Figure 3.9-b. In another words, the position of the petal shows the source node and the color of the petal shows the destination node.

Figure 3.9, shows two arrangements of Daisy Visualization of a directed graph. This figure compares the overall view of this visualization with symmetric arrangement of petals on left, and arrangement with directional restriction on petals on right. In the symmetric ar-

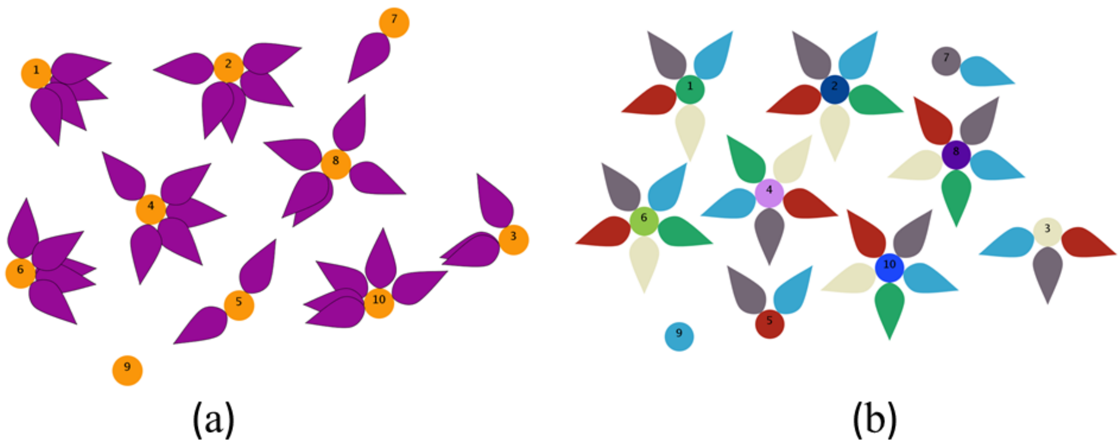


Figure 3.9: Directed graph with 10 nodes 35 edges. Left: non-symmetric arrangement, petals are oriented toward their destination nodes (directional constraint). Right: symmetric arrangement, petals are uniformly distributed around the node's circle. When there is a blue petal on the red node it means there is a directed edge from red node towards blue node. And since there is no red petal it means there are no edges towards red node.

rangement, colors represent the direction of edges. While in the non-symmetric arrangement, each petal represents a directed edge towards the destination node. As shown in Figure 3.9, although there is no edge crossing in this layout, in some cases where, adjacent petals of one node may overlap. This issue makes it harder to see petal's destination node. Therefore, the choice between symmetric and non-symmetric arrangement (directional constraint) depends on the application, and requires evaluation.

In Chapter 5, Daisy layout is used for creating another novel graph visualization. for doing this, we use visual encoding for other features such as node and edge weight and also other features that are specific to ecological networks.

3.5 Celtic Knot Layout

Our third design for visualizing graphs (particularly, weighted graphs) was inspired by Celtic knot patterns (see Figure 3.10). In mapping this layout, nodes are represented by circles and edges are represented by interlacing curves.

To have a symmetric structure and reduce cluttering, we position vertices uniformly on a

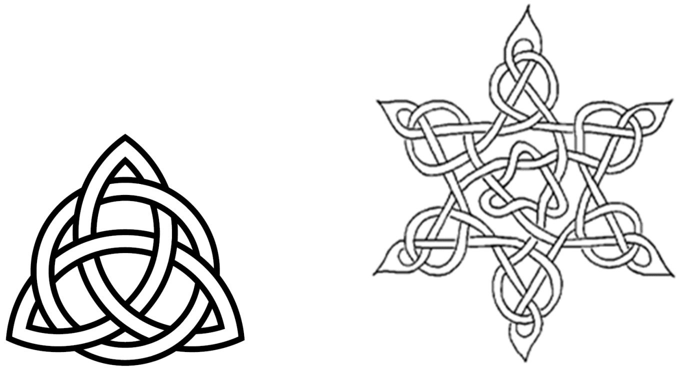


Figure 3.10: Two examples of Celtic knot patterns with interlacing curves.

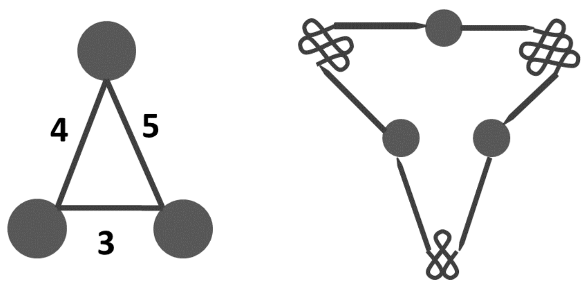


Figure 3.11: Left: A small graph with three nodes and three weighted edges as indicated by the numbers placed beside the edges. Right: The sketch of the same graph in the Celtic-Knot layout. The number of knots shows the weight of each edge.

circle. Since the space inside the circle may not be enough for the interlacing curved edges, we draw them outside of the circle (see Figure 3.11-b). The number of repeating knots (loops) on each edge can be used to visualize the weight of each edge (i.e. proportional to the weight), which is demonstrated for a simple graph in the Figure 3.11.

Figure 3.12: Four different options for representing directed edges.

For directed graph, we can use arrows, double line, tapered, or a color coded curves (similar to Node-Ring and Daisy layout) to represent edges. Figure 3.12 demonstrates these ideas for a simple interlacing edge, and a simple graph is shown in the Figure 3.13 to demonstrate possible representation of direction.

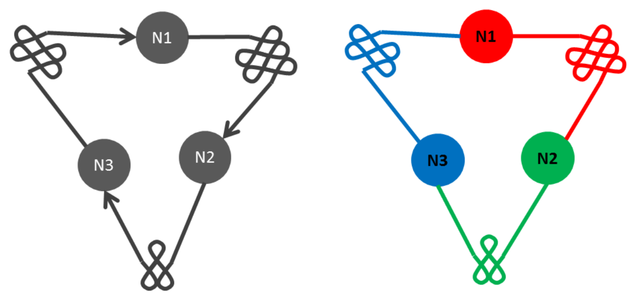
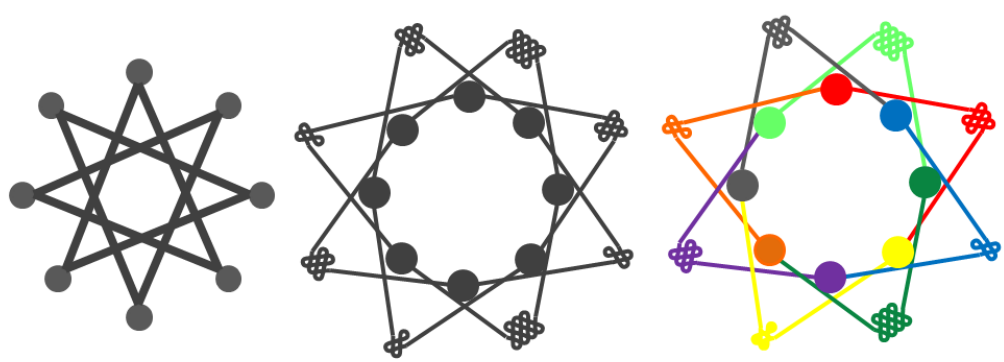


Figure 3.13: Left: A small graph with three nodes and three weighted directed edges, the direction of edges are represented with arrowhead links. Right: Same graph, nodes are colored and the direction of edges are represented with colors.

In Figure 3.14, Celtic-Knot layout for a graph with eight nodes is shown, and a color-coding method is used to represent the direction of edges.



(a) (b) (c)

Figure 3.14: Stages of design process for celtic knot graph visualization, representing a weighted directed graph with eight nodes and eight edges.

After sketching this layout for larger and denser graphs, it became apparent that it has some shortcomings. Figure 3.15 shows a sketch of Celtic-Knot layout for a more complex graph. For denser graphs the intersections of interlacing edges in addition to original edge crossings, makes the layout more cluttered and more complex for accurate representation of the data. Due to these drawbacks, we decided that this way of using the knots doesn't

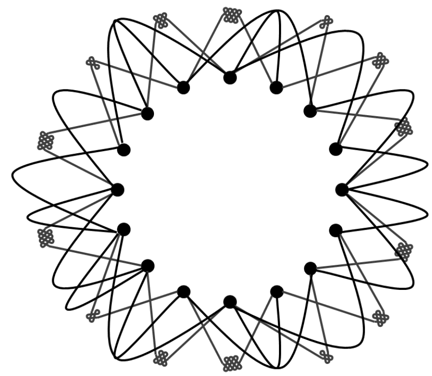


Figure 3.15: Celtic-Knot layout for a graph with sixteen nodes and thirty three edges.

provide enough benefits to develop a layout for graph visualization, yet the idea of using simple, nice curves for representing edges may prove to be helpful in different applications. In our next iteration, we decided to change for creating a more practical layout: Spirograph Layout.

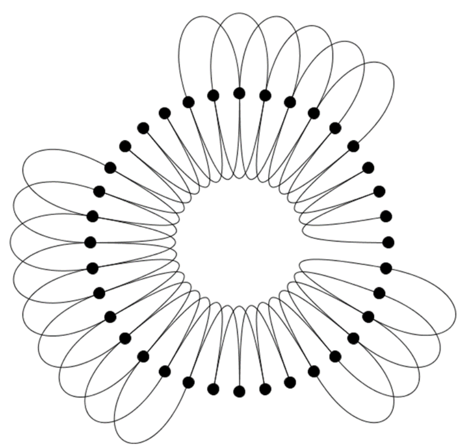


Figure 3.16: Mapping edges to circular arcs.

3.6 Spirograph Layout

As discussed in the previous section, the idea of this layout was initially seeded from Celtic Knot layout, where nodes are represented by circles and arranged on the boundary of a large circle called *the boundary circle*. But rather than mapping edges to interlacing curves, they are mapped to simpler curves with no knots. As explained in the personal context in Section 3.2.1, circles and arcs are our desired shapes, therefore, we consider arcs for connecting nodes (see Figure 3.16). Arcs can be internal or external to the boundary circle. Circular arcs, which have been used extensively in traditional patterns and our own designs (see Section 3.2.1), are really simple and elegant curves and are available in any graphical library. Furthermore, some amazing circular arrangements can be created using the famous toy: Spirograph (see Figure 3.17 for some examples of Spirograph patterns). In fact, the presence of many circular arcs in Figure 3.16 looks like Spirograph patterns.

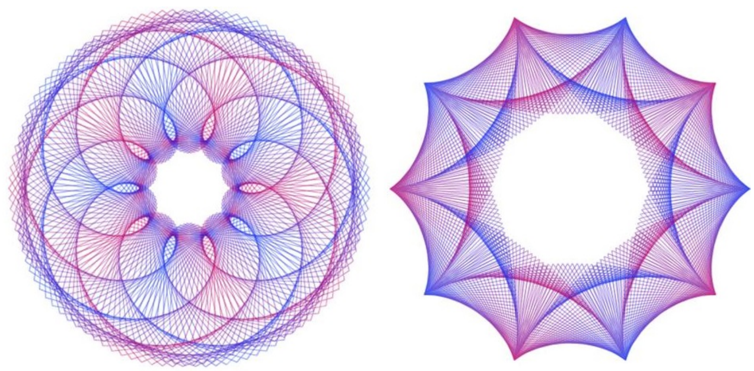


Figure 3.17: Samples of Spirograph patterns.

Figure 3.18 demonstrates how a simple graph in node-link layout is converted to Spirograph layout. As shown in Figure 3.18-a, first all nodes are arranged on the boundary circle. Note that the boundary circle is drawn to clearly show the circular arrangement of the nodes. Then we divide edges to two sets of internal and external edges. In Figure 3.18-b, external edges are drawn outside of the boundary circle. In the next step (Figure 3.18-c), all edges are drawn as circular arcs. One of the issues of the layout in Figure 3.18-c) is the boundary circle. Drawing this circle, may create the inaccurate connectivity interpretation for consecutive nodes. For example, nodes 1 and 2 in Figure 3.18-c are not really connected to each other. Therefore, in our next design iteration, we gave a thickness to the boundary circle (i.e. boundary ring) and replaced nodes by arcs on this ring (Figure 3.18-d).

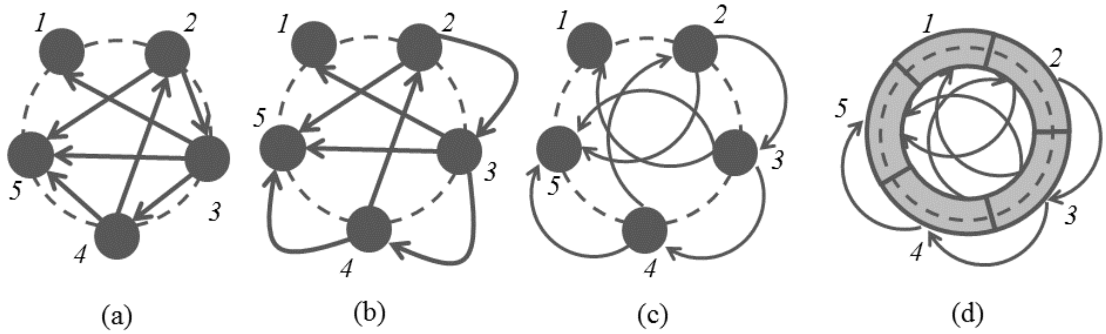


Figure 3.18: Some edges are moved outside of the boundary circle.

Spirograph provides a natural way to support external and internal edges. We have also managed to include other features such as node and edge weights. These aspects of Spirograph are discussed in Chapter 6 which is devoted to this layout and its visualization for ecological networks. The possibility of having internal and external edges is very useful for this type of graphs. This work is published as a peer reviewed paper "Spirograph Inspired Visualization of Ecological Networks" [42]. Also, we have conducted a study for evaluating this layout (refer to Chapter 7).

3.7 Summary

In this chapter we provided the design process and basic ideas behind the use of different types of aesthetics in generating our new graph layouts. Node-Ring layout is chosen for creating visualization for a special case of ecological networks. The prototype for Node-Ring and Daisy Visualizations are explained in chapters 4 and 5. Sketching the idea of Celtic Knot layout revealed potential challenges for this approach for creating new layouts. Therefore, we decided not to implement any visualization prototype for this layout. However, our efforts in designing Celtic Knot layout aided us in developing the Spirograph layout (chapter 6), which has been our ultimate tool for visualizing ecological networks.

Chapter 4

Node-Ring Visualization

4.1 Introduction

Figure 4.1: Node-Ring graph visualization: representing a dense graph with fourteen nodes and eighty four edges. Colors are derived from "The Silent Flower" by Hundertwasser [118].

In Section 3.3 we explained how we initially arrived at the design of Node-Ring layout by explaining the process of designing the underlying layout. In this chapter, we introduce Node-Ring Visualization for graphs which is a revised version of our published paper: "Node-Ring Graph Visualization Clears Edge Congestion" [41].

As described in Chapter 2, node-link is a common layout for graphs in which, nodes are represented by a shape (e.g. circle) and edges are shown as lines or curves connecting adjacent nodes. One of the important issues with node-link layout is the problem of edge

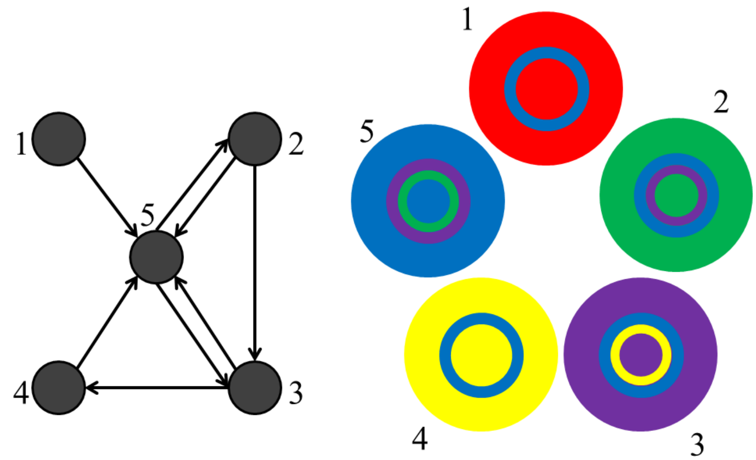


Figure 4.2: Node-link graph layout (left) and Node-Ring graph (right) visualization of the same graph with five nodes and eight edges.

congestion (i.e. overlaps, crossings, clutter). Another way to represent a graph is by its adjacency matrix, which is a useful layout for emphasizing on clusters and grouping nodes (see Section 2) [58]. Here we take a different approach. We turn to art for inspiration and from this inspiration offer a new graph layout.

As discussed in Chapter 1, there is an indication that attractive and engaging graph representations can help analysts in persist their exploration tasks [147]. Also, the effects of more mathematical aesthetics in graph drawing have been studied by Purchase et al. [107].

While the problem we tackle is a well-known one, that of edge congestion in graphs, our approach is an art inspired approach as described in Chapter 3. In our design process, we sample the world of alternate aesthetics to find inspiration for a new approach to graph layouts. Concentric circles have existed in art since rock carvings and have occurred repeatedly, as in Kandinsky's Concentric Circles [71]. As briefly described in Section 3.3, using the idea of concentric circles we introduce a visualization for graphs that uses an implicit representation of edges. The information about edges is included without explicitly drawing them as links (see Figure 4.1). 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 (see Figure 4.2).

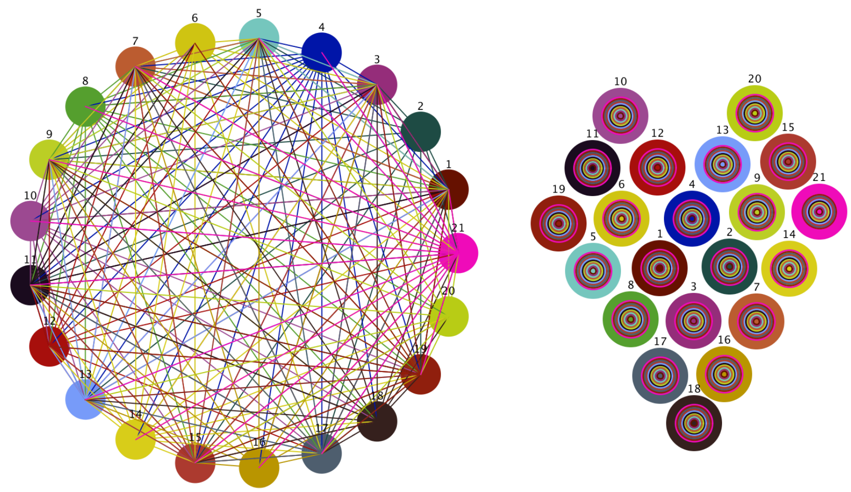


Figure 4.3: Node-link layout (left) and Node-Ring layout (right) both showing the same dense graph with twenty one nodes and two hundred and ten edges.

The practical case used for Node-Ring Visualization is a special kind of ecological network, called "Food Web" [97]. A detailed explanation of ecological networks is provided in Chapter 2. Food web shows the *who eats whom* part of the ecological network [8].

The remainder of this chapter is structured as follows. To explain our inspiration we start, in Section 4.2, with a short review of traditional and non-traditional artistic works related to Node-Ring or link-less layouts for graphs. Section 4.3 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 in our prototype are explained in Section 4.4. We discuss the strengths and weaknesses of this visualization in Section 4.5.

4.2 Artistic Inspiration

Our design of Node-Ring graph visualization (see Figure 4.3) was inspired by concentric circle patterns. These patterns can be seen in several artistic pieces. They are common features in Hundertwasser's work [118]. These types of concentric circles are featured in many of his paintings such as "City View" and "Blobs Grow in Beloved Gardens" [118]. 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 painting is known as dot paintings [121]. While entirely different from Hundertwasser's work, one can also see a frequent use of concentric circle patterns in these pieces [102].

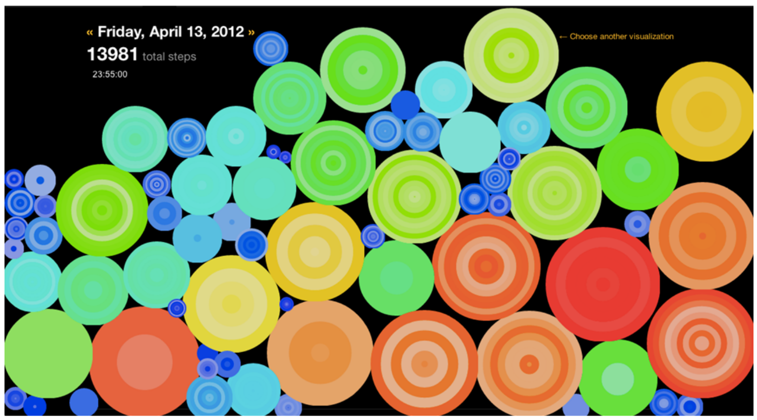


Figure 4.4: Bucket: visualizing the steps taken in five minutes [26].

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, Fan used concentric circle patterns in a visualization she called Bucket (see Figure 4.4) [26]. As an example work related to both concentric colored circles and to reusing artistic color palettes, in their project known as Luscious, Viégas and Watternberg [135], create artistic colorful designs by extracting colors from cover pages of luxury magazines.

4.3 Node-Ring Graph Visual Encoding

Node-Ring can be used for weighted, directed graphs. Section 2.3.1 covers a review of related works on visualization techniques for this type of graphs. We introduce a visualization for weighted, directed graphs that uses an implicit representation of edges. Therefore information about edges is included without explicitly drawing them as links (see Figure 4.3). In general if node v is connected to node w then there is a ring with the same color of the node w inside v (see Figure 4.2). Therefore, in this design, edges are shown by 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.

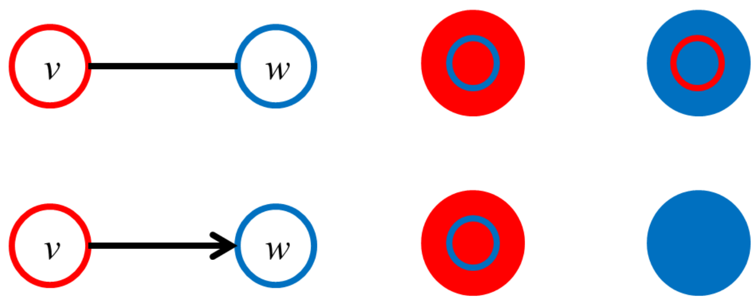


Figure 4.5: Directed and undirected edges can be shown in Node-Ring graph visualization. Top row shows undirected edge between two nodes with node-link and Node-Ring layout. Bottom row shows directed edge in between two nodes with both node-link and Node-Ring layout.

4.3.1 Node-Ring for Weighted Edges

In addition to undirected graphs, Node-Ring Visualization is capable of representing weighted directed graphs. However, including the weight and direction attributes is optional. The weights of the nodes are mapped to the size of the nodes' 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 4.6(left). With this design we tried to clarify the difference between weights of edges by mapping them to the angular size of the sectors. Alternatively, weights can be mapped to the ring's thickness (Figure 4.6, right). Each of these encodings can be used for visualizing weights. It seems that the weight differences are more visible in the sector representation. While the use of complete rings seems to be more similar to the selected artworks. We have compared these two choices in our study, (refer to Chapter 7). Figure 4.7 shows Node-Ring Visualization for a graph with fifteen weighted nodes and thirty six weighted and directed edges shown in both traditional node-link and in our new Node-Ring Visualization. This graph represents the *Food Web* for "Aggregated Baltic Ecosystem", which is a special class of ecological networks (see Section2.4). Weighted edges are represented with sectors of rings, and the weight of the ring is proportional to the angular size of the ring's sector.

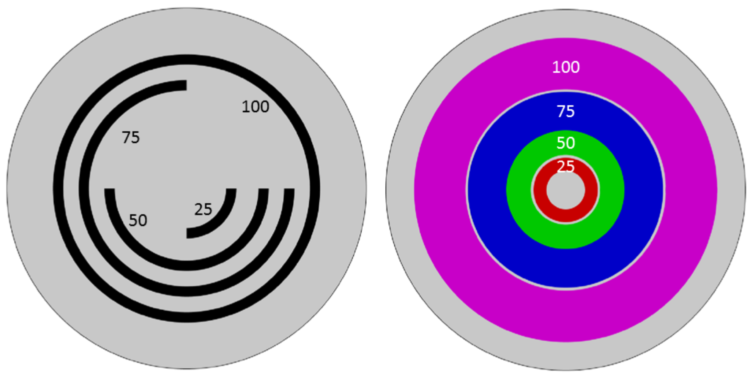


Figure 4.6: Left: weights of edges are mapped to the sectors of the rings. Right: weights are mapped to ring thickness.

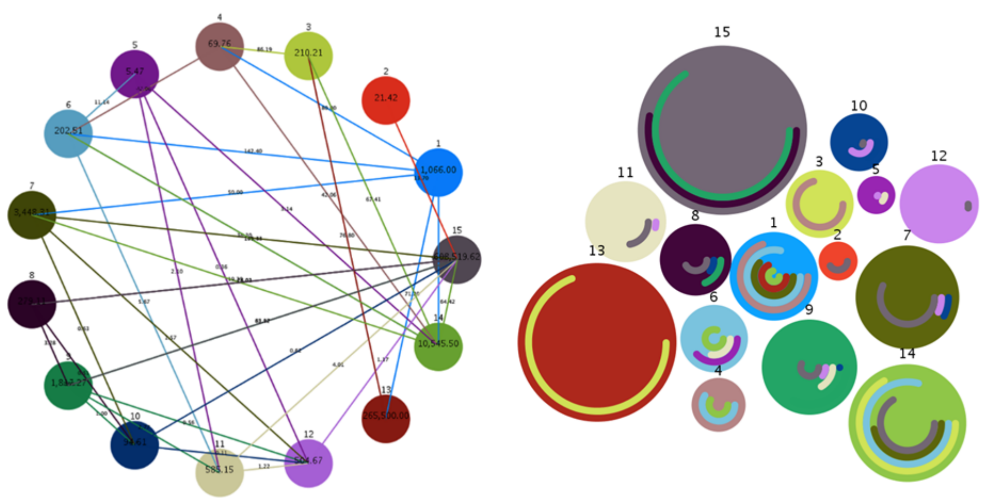


Figure 4.7: Node link (left) and Node-Ring (right) graph visualization, representing a food web for "Aggregated Baltic Ecosystem", which is a weighted directed graph with fifteen nodes and thirty six edges.

4.3.2 Mapping Weight to Concentric Rings

Here we describe how to map a given graph to concentric rings used in Node-Ring. The node v of the graph is mapped to a colored circle with the radios of r, and its adjacent edges to nested concentric rings inside that circle. To have a clean and simple design, we consider a constant thickness of t for all rings. Notice that changing thickness of the rings is also one of our possible strategies for weighted graphs (see Section 4.3.1). Also, for the sake of compactness, we assume successive rings are adjacent (no gap between rings). Furthermore, we use the central and outer rings as part of the original node and allocate only the remaining space for the neighbors' rings. Therefore, we need to draw $deg(v) + 2$ concentric rings for v, where $deg(v)$ denotes the degree of v. To find t, the constant thickness of the rings, we need to consider the node with largest degree as the guide. Therefore, we first find the maximum degree d^* in the graph. Then t can be defined as:

$$t = \frac{r}{d^* + 2}$$

Where r is the radios of the circle. In essence, t represents the minimum ring thickness across all nodes of the graph. Therefore, since nodes of a given graph can have different degrees, drawing them with the minimum thickness occupies different spaces in nodes. For example, in Figure 4.1, we draw the rings from inside toward outside of the node. This makes the outer ring corresponding to the remaining space to have a variable thickness, which is the effect of the variability of nodes' degrees. Alternatively, these rings can be drawn from the outside toward the inside which varies the thickness of the inner ring (see Figure 4.8).

For weighted graphs when nodes have weight, we simply resize each node with respect to its weight. If the range of weights is large, a linear or logarithmic function can be used to proportionally map this large range to a more sensible range to be used for radii of circles. For example, the original weight range of the graph in Figure 4.7) is $[21.42, 608519.62]$ which requires a logarithmic mapping for a range that is viewable on the screen as seen in the same

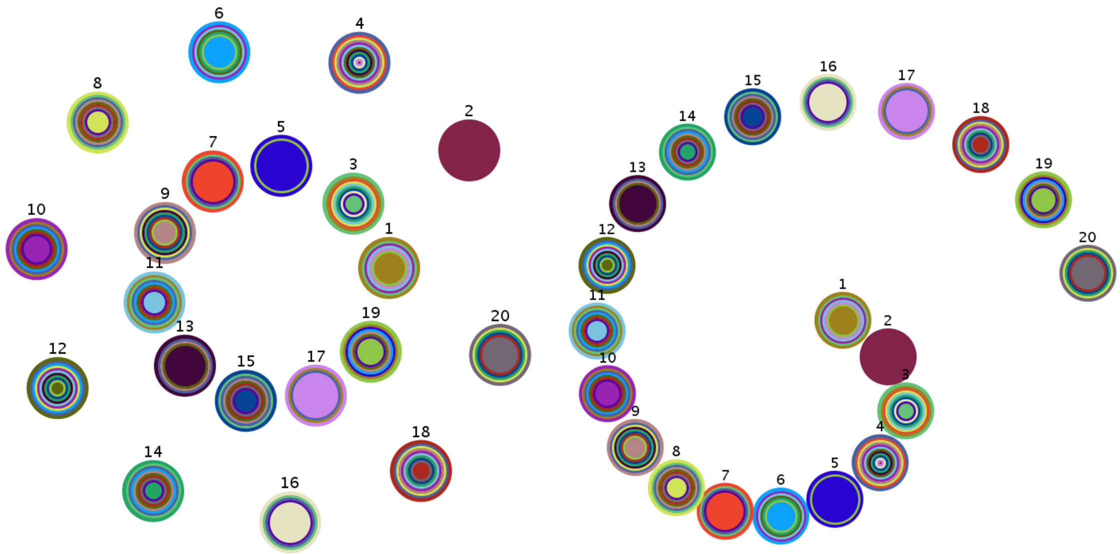


Figure 4.8: Rings can be positioned from the outside toward the inside of their circle.

figure.

The size variation of nodes impacts the way t (thickness of rings) is calculated. Now, t is not only a function of the degree but also a function of the size of nodes. To calculate t, let $r_1, r_2, \ldots r_n$ are radii of nodes of the weighted graph. Therefore, the thickness for each node can be found by:

$$t_i = \frac{r_i}{deg(v_i) + 2}.$$

For making these per node thicknesses uniform, we only need to find the minimum of t_i on all the nodes:

$$t = \min_{i=1,\ldots n} t_i.$$

Now rings of every node is drawn uniformly using t as the thickness. For weighted graphs, since t can be a small number, we draw rings from outside toward inside of the node.

4.3.3 Node Arrangement

One benefit of Node-Ring is the freedom of relocation nodes without any constraints commonly imposed by edge crossing and edge length factors. Consequently, different arrange-

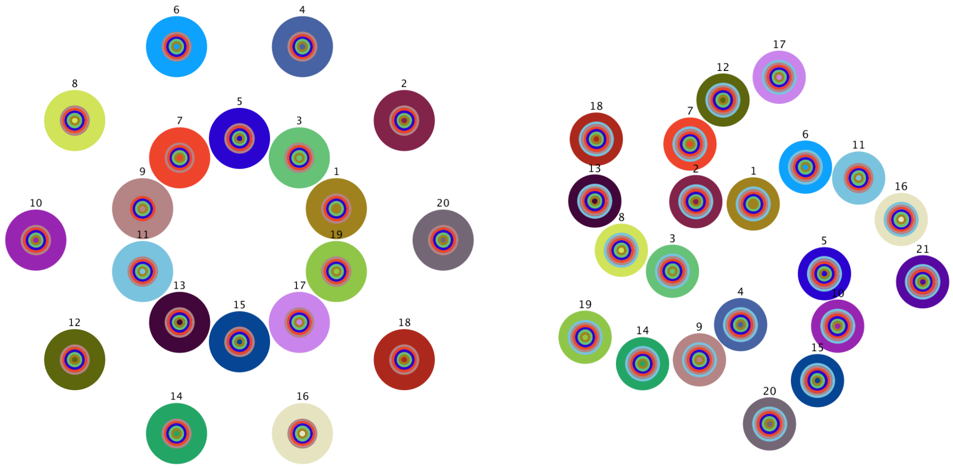


Figure 4.9: Different arrangements can be used to position the nodes.

ments can be used to position the nodes (e.g. Phyllotactic patterns [95], Voronoi [34], symmetric [40]). Figure 4.9 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.

The freedom of relocating nodes opens a door for many fun and exciting possibilities such as animating between arrangements, and arrangement reactive to playful interactions. Figure 4.10 demonstrate the animation between two different arrangements. This feature can be used in an initiative visualization.

4.3.4 Node Coloring

An important factor in our design is the issue of node coloring. Naive color assignments can complicate the task of understanding edges connections. Figure 4.11 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 variety of contrasting colors. We found that Hundertwasser's paintings are one example that has such features. Using color extracting techniques such as Colorvis [87], we created color palettes from the contrasting

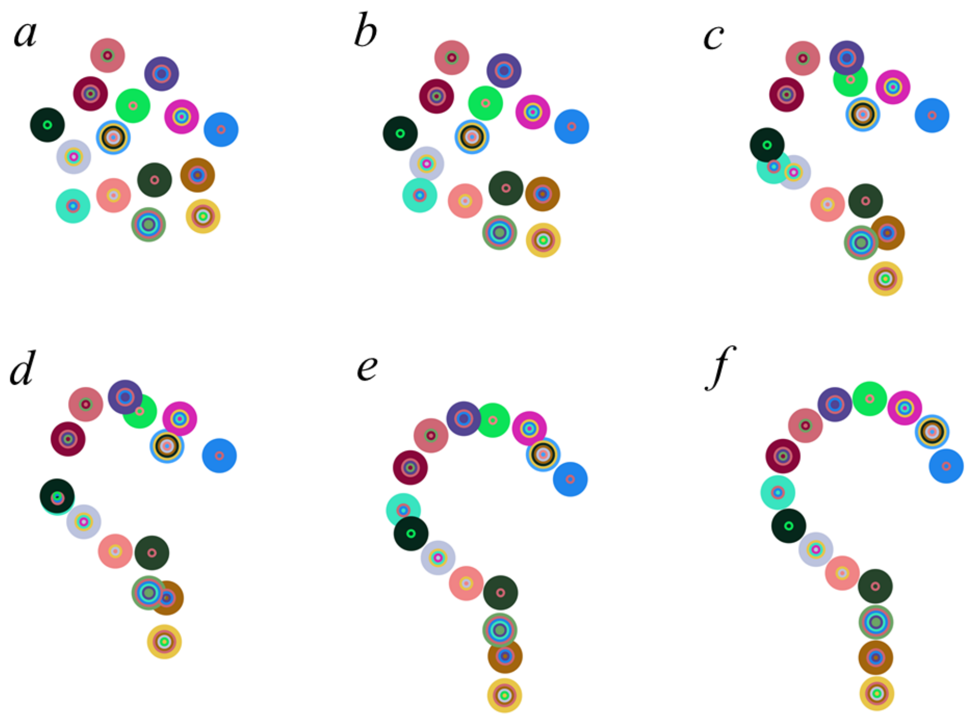


Figure 4.10: Six key-frames from animation between two arrangements.

colors of the selected paintings. Figure 4.11 right, shows the results after using the color palette extracted from "The Silent Flowers" by Hundertwasser [118].

4.4 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 (e.g. around the node of the interest).

4.4.1 Color Palette

As discussed in Section 4.3.4, the assignment of a specific color to each node is very important and it can be improved by exporting color palettes from well-known artists' paintings using tools like Colorvis [87]. In our prototype, people can load a painting from a saved library

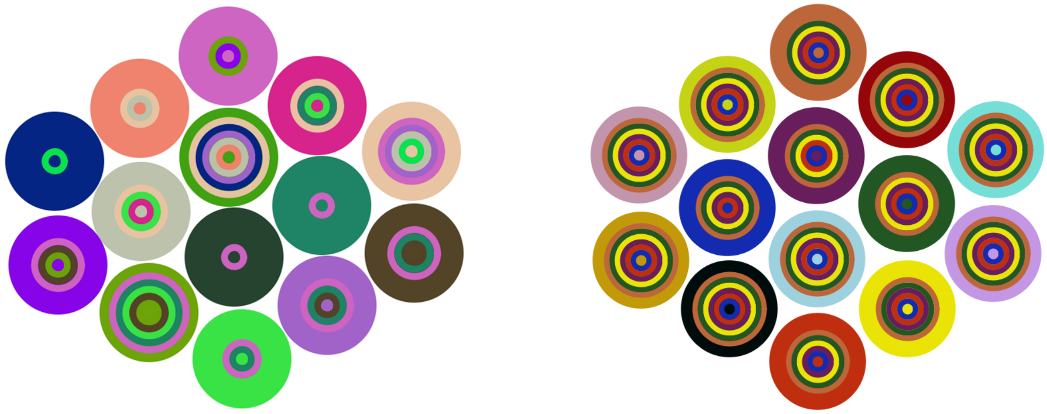


Figure 4.11: Node-Ring graph visualization. Left, random color selection. Right, color palette derived from “The Silent Flower” by Hundertwasser [118].

and select contrasting colors from their favorite painting using mouse clicks. The number of colors that are chosen has to be at least the same as the number of nodes in the graph. Then a color palette is created based on selected colors. Figure 4.13 shows two different Node-Ring Visualization of a graph with fourteen nodes. Left shows the graph with color palette that has been selected from “City View” and the Right image shows the same graph with color palette, selected from “The Silent Flower” [118].

4.4.2 Highlighting the Conventional Edges of 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 conventional edges of that node. In the directed graphs, we show only outgoing edges where the color of these edges is the same color as the color of the node they are originated from. Figure 4.12 illustrates this feature. Alternatively, all the incoming edges can be highlighted.

4.4.3 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 4.14, the neighbors of the node 1 and 9 have been moved. This feature gives the opportunity to create specific

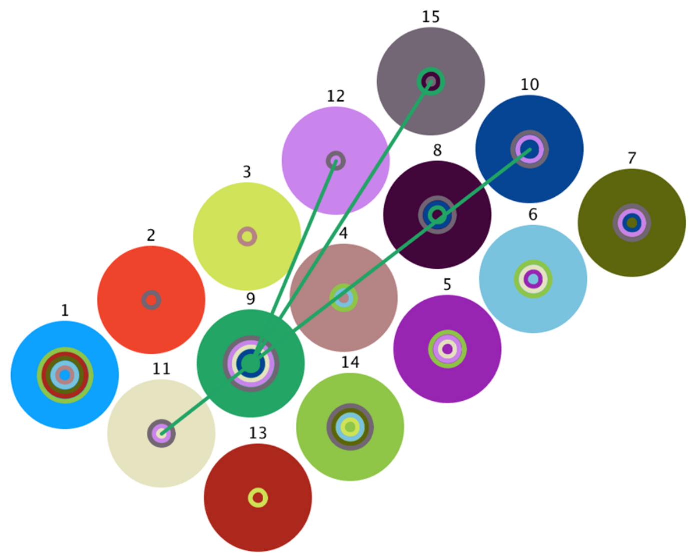


Figure 4.12: When one node is selected, all outgoing edges from that node become explicit.

arrangements of nodes in playful interaction (see Figure 4.15).

4.5 Discussion

In Node-Ring graph visualization, we eliminate the explicit representation of edges and instead map the edge relationship between the connected nodes to colored rings. Therefore, Node-Ring graph visualizations can be particularly useful for relatively small but dense graphs, when the graph has significantly more edges than nodes (see Section 2.1). Visualizing these types of graphs using conventional techniques is challenging because of the high number of edge crossings. The clean and colorful presentation of Node-Ring increases its potential for more fun and artistic driven solutions. On the other hand, the lack of a direct connection between nodes might make for a less obvious edge interpretation mostly when there is a large number of nodes where it is hard to assign distinguishable colors to the nodes.

One possible strategy for taking advantage of both Node-Ring and conventional graph visualizations is to create a combined or hybrid visualization. For example, as demonstrated in Figure 4.12, a partial use of node-link can help to increase the recognition of edges in tasks. Alternatively, for graphs with a large number of nodes it is possible to use combinations

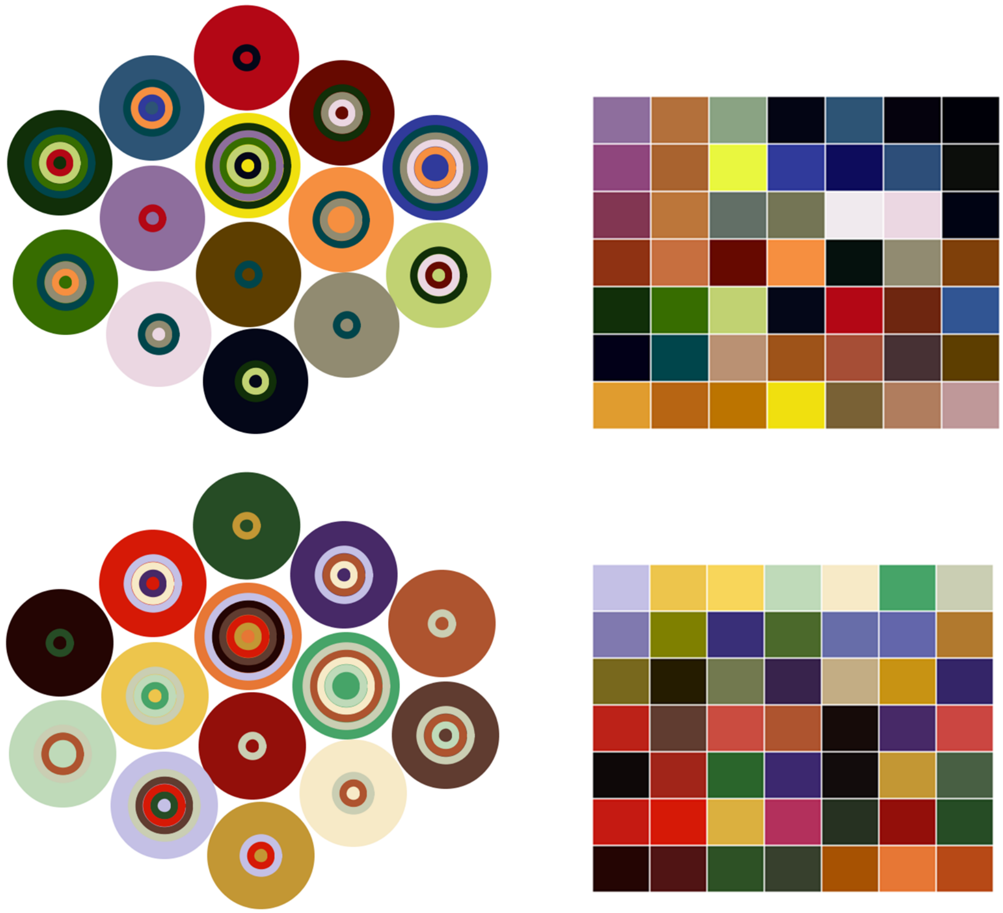


Figure 4.13: Node-Ring Visualization of a graph with fourteen nodes, color palette selected from Hundertwasser's paintings. Left, palette selected from "City View". Right, color palette selected from "The Silent Flower" [118].

of patterns and textures along with various hues, tints, shades, and tones. Furthermore, assorted shapes can be used for different subsets of nodes. For example, circles for the first subset, square for the second, hexagon for the third subset and so on.

As demonstrated in Figure 4.7, Node-Ring Visualization is capable of visualizing Food Web which is a special case of ecological networks (the use case of this thesis). In food web networks only nodes and relationships between them are presented and other features (respirations and inputs/outputs) are not considered. Including these features in Node-Ring seems to be hard. In essence, putting edges inside of the nodes' space makes it hard to include other features (e.g. respirations and inputs/outputs) into the same space. Rather

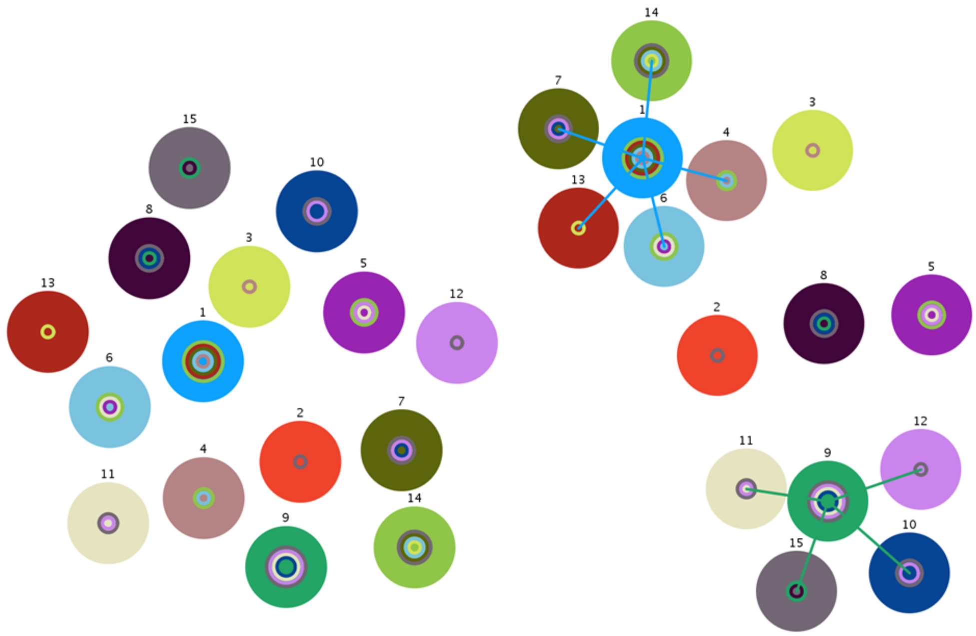


Figure 4.14: We can move and rearrange nodes based on the desired task.

than incremental improvement of Node-Ring layout, continuing our journey of alternate aesthetics exploration, we have created other novel visualizations more successful for these additional aspects of ecological networks. These visualizations are discussed in the next two chapters. The evaluation of Node-Ring Visualization, together with other visualizations of this thesis, is provided in Chapter 7.

4.6 Summary

In this Chapter, we introduced Node-Ring graph visualization, which is a new approach for representing dense, weighted, directed graphs. In this visualization, node-node relationships are presented by nested color-coded rings instead of using line or curve for connecting those nodes. The color of the ring shows the destination node and the placement of the ring shows the origin. We also explained the visual encoding of this visualization as well as a brief discussion of its interactive aspects.

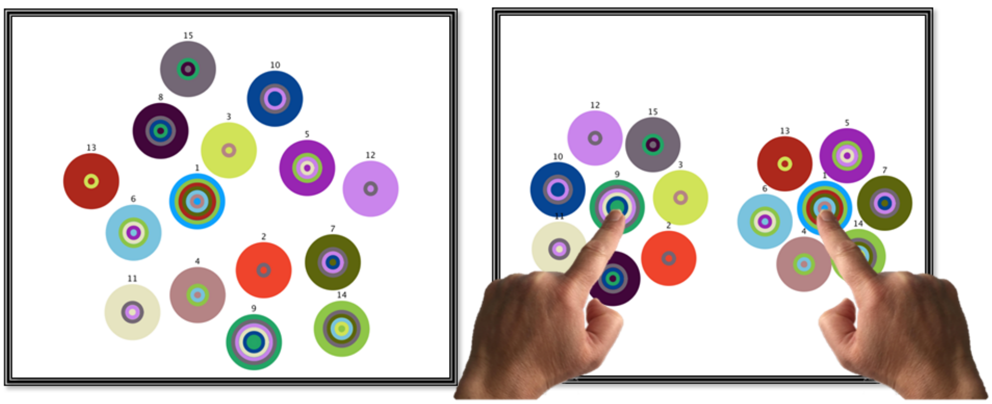


Figure 4.15: We can interact with nodes using mouse or touch.

Chapter 5

Daisy Visualization

5.1 Introduction

Our second graph visualization is based on floral patterns that include Daisy motives, inspired by ornamental patterns of daisy flowers (Section 3.4). In this layout, nodes are represented by circles and edges are presented by petal shapes attached to the nodes. In essence, in Daisy Visualization, edges are mapped to a shape adjacent to the node while in Node-Ring they are mapped to a shape inside of the node. This change of mapping provides us greater flexibility to include more decorative elements of floral patterns that can support more features in the graph (e.g. respirations and inputs/outputs in ecological networks). Therefore, in this Chapter, we explore this potential by creating another novel graph visualization. Floral patterns have been very popular and well received for a long period of our history. Thus, they can be a great source of inspiration for designing novel information visualization systems. A simple google search of images provides countless inspiring floral examples. But the challenge is to find an application that can go beyond their decorative purpose.

The remainder of this chapter is structured as follows. In Section 5.2, we explain our inspiration through a short review of works relate to generating ornamental patterns. Section 5.3 provides an explanation of Daisy layouts and contains an overview of the visual encoding used in our Daisy graph visualization. Interaction techniques that are currently included, are discussed in Section 5.3.3. Since the goal of designing Daisy Visualization is to represent ecological networks, in Section 5.4 we review the structure of these networks and explain how we represent them in Daisy Visualization with extra floral elements. We then discuss the strengths and weaknesses of this visualization in Section 5.5.

5.2 Artistic Inspiration

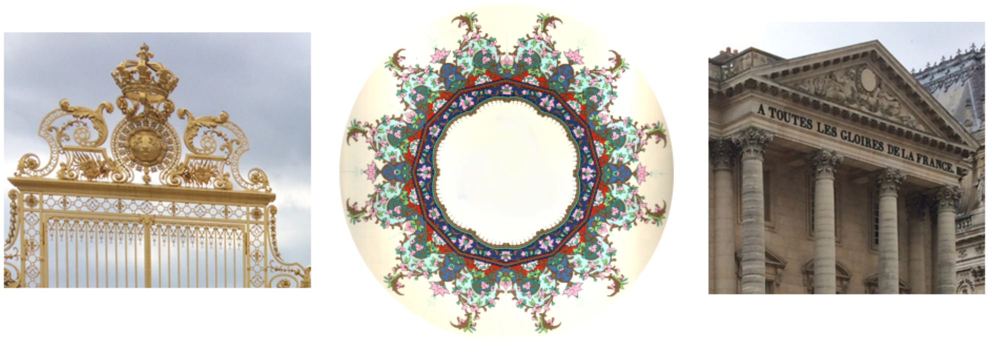


Figure 5.1: Ornamental patterns have been used for decorating books and buildings for several years. These are abstractions of floral patterns inspired by nature.

Floral ornaments are well accepted aesthetic patterns that have been used for decorating buildings, carpets, furniture, and illuminating books and textiles for more than two thousand years [98] (see Figure 5.1). These mesmerizing patterns are inspired by nature and they are abstractions of real plants and flowers. Their various forms and styles have been adopted by different cultures. Much effort in art and design has been spent on enhancing these patterns and optimizing them for use in a the traditional contexts (e.g. books, stones, walls). Figure 5.1 shows some examples of these patterns in traditional contexts.

Recreating these patterns for digital media has been investigated in computer graphics for many years. Procedural modeling techniques, particularly L-systems, are commonly used for creating the complex and repetitive structure of these patterns [117, 146, 106, 43]. In essence, an algorithm, or some high-level grammars are used for creating the structure and its ornamentations. However, manipulating a grammar or changing the source code of a program are not approachable means of interacting with these visual art forms. Interactive tools, including commercialized software packages (e.g Adobe illustrator) have been widely used for creating these patterns through a direct mechanism. Recently, sketch-based and brush-based interfaces are used for creation and manipulation of floral patterns, while in back-end, procedural or data-driven methods are used for including detailed ornaments [86].

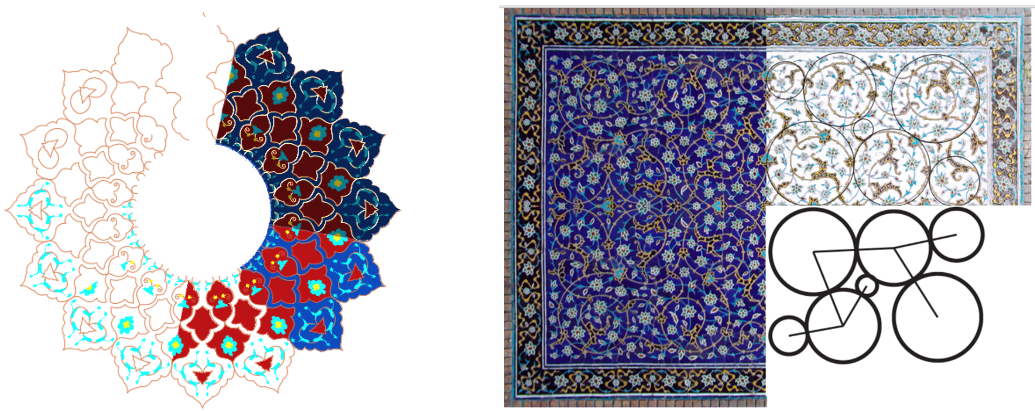


Figure 5.2: Left: Animating floral patterns [43]. Right: Floral patterns decomposed to underlying configuration of circles [54].

A number of techniques have been proposed for a particular class of patterns. Etemad et al. have considered the recreation of Persian floral pattern in [43] (see Figure 5.2, left). Hamekasi and Samavati in [54] analyze and generate Persian floral patterns, while taking advantage of circle packing concepts and tools, (see Figure 5.2, right). There are many other classes of patterns such as Islamic, Celtic and Escher patterns. Although, they are not considered floral, they also have been frequently used in decorative and ornamental artworks. Kaplan [76] and Jacobstal [68], both present the construction of Celtic artworks using computer modeling. Algorithmic techniques for generating Islamic star patterns are explored by Kaplan in [75] and [72]. Meanwhile, interactive modeling techniques to generate Muqarnas (3D star patterns used in Islamic architecture) is presented by Hamekasi et.al [53]. Generating Escher-like patterns have also been explored by Kaplan in [73] and [74].

Our interests in floral patterns is different from the above research papers which mostly focus on the challenges of generating the patterns in an algorithmic way. In our work, we need to find a specific meaning for these patterns beyond their apparent shapes and colors. There are several works in information visualization which share the same goal as ours. For example in Keystrokes, a visualization of typed messages, Neumann et al. use petal shapes to represent messages with semi-transparent artistic strokes [96]. Based on the pattern of the typed messages and how they are typed, a brush stroke is created. In regards to tree visualization, Etemad and Carpendale introduce a fresh visualization for large trees [40], that uses a nested layout, where trees are mapped to a pattern that mimics Shamseh, a pattern often used in decorative Persian ornament (see Figure 5.3). Etemad et al. in PaisleyTree [39] also introduce a novel approach for hybrid visualization of trees (i.e. Node-link, adjacency and nested layouts), in which, trees are mapped to Paisley floral patterns. While our goal is similar to these works, graphs have more complex structures. The interconnections of the nodes particularly in dense graphs makes the mapping between graph and floral pattern much harder.

As shown in Section 2.1, a tree with n nodes, at most can have $n-1$ edges, while graphs, particularly dense graphs, may have up to $n(n-1)/2$ edges.

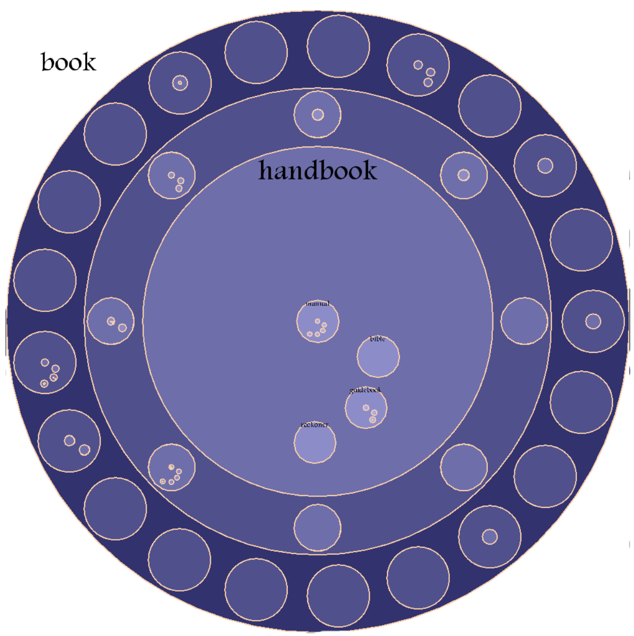


Figure 5.3: ShamsehTree [40], representing a tree with 85 nodes and six levels.

5.3 Daisy Graph Layout Encoding

In this section we explain the encoding of Daisy Visualization for graphs. The main goal is to map the graph and its attributes to a floral pattern. As explained in Section 1.4, this is a challenging task with conflicting properties, since the layout should clearly and accurately represent data, while usable in practical scenarios and pleasant to view. To solve this problem, first we should specify how nodes and edges of the graph will be represented as floral elements. As discussed in Section 3.4, our solution is the outcome of several iterations. The basic idea of our approach is to replace nodes of the graph by a colored circle (the flower's center) and the edges of each node by petals of that flower (see Figure 5.4).

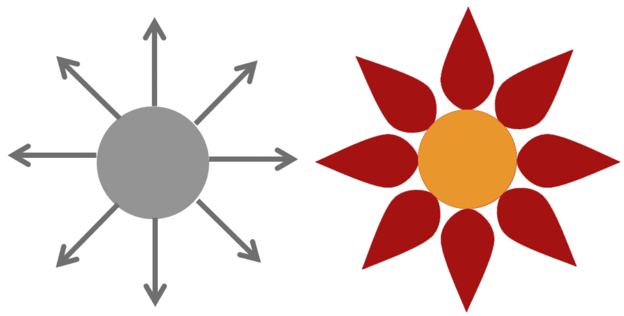


Figure 5.4: Mapping nodes to the flower core and edges to flower petals.

Figure 5.5-Left demonstrates the transition from traditional node-link to our representation. As seen in the second row of Figure 5.5-Left, an edge can be replaced by two partial edges. These two partial edges, are replaced by two petals, one for the source and one for the destination (Figure 5.5-Left). Therefore, the direction of each petal points to the destination node (direction constraints of the petal). In a large and crowded graph, this direction may be blocked with other nodes which makes finding the destination hard and ambiguous. To address this issue, as demonstrated in Figure 5.5-Left (the last row), we can assign colors to the circles and petals such that the color of the petal is the same as the color of the destination node (color constraints of petals).

For visualizing directed graphs, Daisy layout can be modified easily. As demonstrated in Figure 5.5-Right, only outgoing edges are mapped to petals. So, directed graphs can be presented with less clutter.

The direction and color constraints of petals together help to read graphs better. However, those constraints can be loosened for different scenarios. For example, if the similarity with the floral patterns is more important than the ease of reading edge connectivity, we

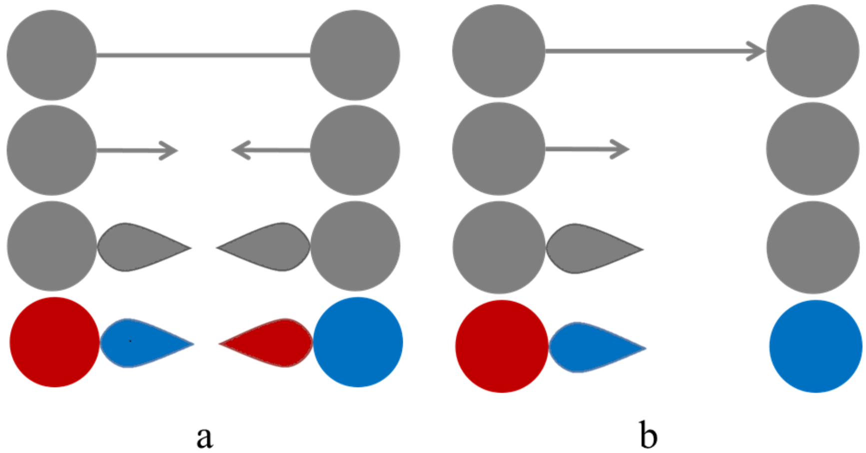


Figure 5.5: Mapping edges to daisy petals. Left: undirected edges Right: directed edges. From top to bottom, first, nodes are connected with traditional edge. Next, edges are replaced by arrowheads, then by petals. Finally edges are replaced by colored petals, the color of petals match with the color of opposite node.

can remove the directional constraints to distribute petals symmetrically around the node. This *symmetric layout*, is similar to Node-Ring, in that only the color of petals implies the destination node. Figure 5.6 demonstrates visualizations of a graph with and without (symmetric layout) directional constraints. Petals of one single flower in symmetric layout may have different colors which is not very common in some Daisy artworks (see Figure 5.6).

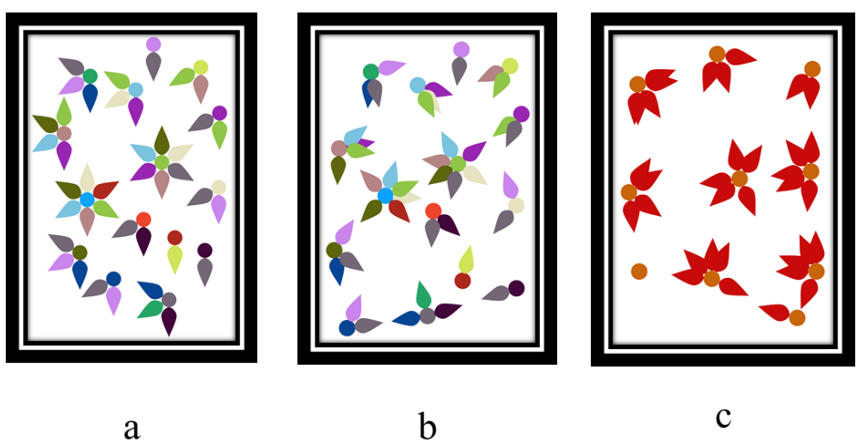


Figure 5.6: a: daisy petals are arranged symmetrically. b: daisy petals are arranged around their original node with directional constraints, the direction and color of petals represent the destination node. c: daisy petals are arranged with only directional constraint.

5.3.1 Weight

As we have seen in ecological networks (Section 2.4), weights can be assigned to both edges and nodes of graphs. In our Daisy Visualization, we have considered several methods for depicting weights. Figure 5.7 shows three methods of mapping the weight for three nodes. In the first method, the weight of the nodes can be mapped directly to the size of the node's circle (see Figure 5.7-a). In the second method weight of the node can be mapped to the size of the node's circle using logarithmic mapping. In the third method, the weight can be mapped to the number of small flower seeds inside of the flower's node (Figure 5.7-c).

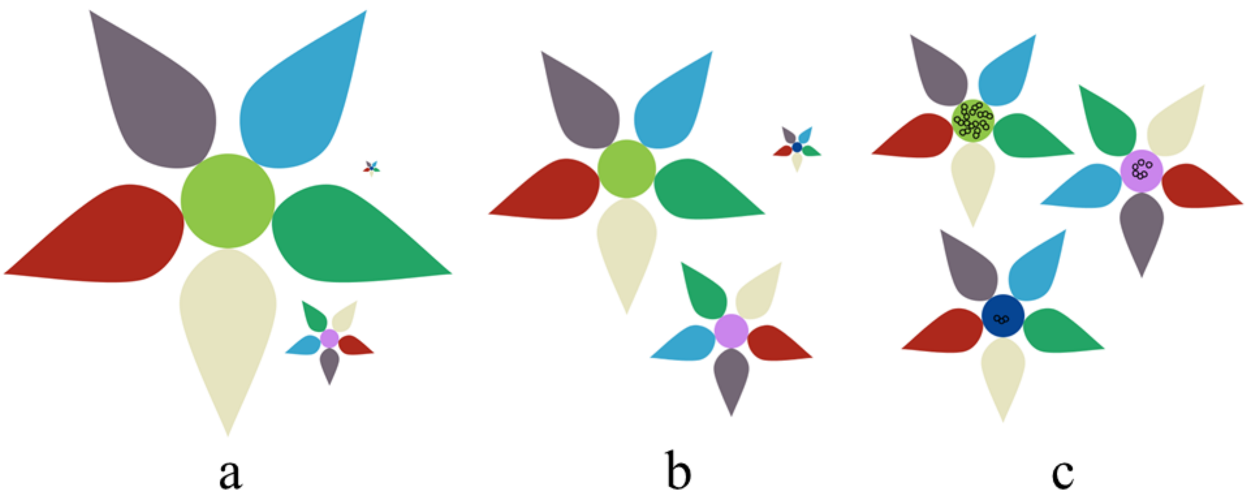


Figure 5.7: Weight of the node can be mapped to the size of the flower by direct mapping (a), or by logarithmic mapping (b). Also it can be mapped to the number of flower seeds inside the circle (c). The weight of the nodes are: 3, 6, and 20.

Slight variation in the size of the daisy cores exists in nature and artworks but extreme variation of this size might be unusual. Therefore, the mapping of the weight to the size should be determined carefully to prevent extreme variation on the flowers. In addition to the use of linear transformations, we can use logarithmic function for reducing the size variation. Figure 5.7-a and b demonstrate the use of linear and logarithmic mapping on node weights, respectively. Notice that if we apply any non-linear mapping (including logarithmic function), the size variation might get confusing. In general, depicting numeric values by geometric attributes (e.g. size and height) is commonly useful, only for showing the relative differences between these values. Furthermore, in interactive visualizations, this issue can be addressed by supporting simple interactions for displaying the exact weight as a label or legend near to the nodes.

Flower seeds are also visible features in nature and many artworks. These seeds can be depicted by smaller circles inside the node. The idea here is to proportionally map the amount of the weight to the number of seeds drawn in the nodes. Again an aspect to consider is creating a suitable range for the number of seeds. Importantly, the size of the seeds should be determined such that the space used by all the seeds never exceed the size of the node's circle. Any arrangement (e.g uniform, spiral, phyllotactic [81]) can be used for distributing seeds in the node's space [40].

For assigning weight to the edges, we have also explored several methods. One possible method is to map the weight of the edge to the size of the petal. The variability of the petals' size in a single flower is very low in nature and artworks. Therefore, it is better if the mapped range of petal weights do not radically change the size of the petals (see Figure 5.8-b). This makes the weights less visible for edges (see Figure 5.8-c) so we have examined other methods too.

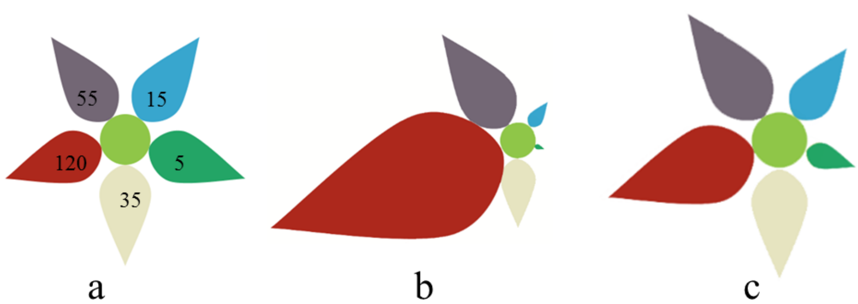


Figure 5.8: Edge weights can be mapped to the size of daisy petals by direct mapping (b) or logarithmic mapping (c).

In addition to the size of petals, other alternative would be to keep the size of daisy petal constant but map the weights into a feature inside petals. The space inside of each petal provides a good opportunity for placing various visual clues for the weight. An easy answer is to put a label showing the weight (see Figure 5.8 (a)). However, to make the visualization closer to floral patterns, we have explored four different designs for this possibility. In these designs, we have tried to map the weight into *venation feature* [100], an abstraction of venation patterns in the petal, shown in Figure 5.9. The venation feature in these four methods is represented by:

(a) a stroke whose thickness is proportional to the weight,

(b) a filled (black) droplet (sub petal) whose size is proportional to the weight,

(c) a filled (white) droplet whose size is inverse proportional to the weight (i.e. the remaining space of the petal depicts the weight),

(d) a set of lines or curves passing through a single point (e.g. the base of the petal) where the number of lines is proportional to the weight.

Figure 5.9: Edge weight can be mapped to venation features inside petals.

All these variations can be found in floral artworks (for example, see Figure 5.10).

5.3.2 Node Arrangement

Since edges are only partially presented in Daisy layout, we can employ most of the arrangements discussed for Node-Ring in Sub-Section 4.3.3. In the case of the arrangement with directional constraint, moving nodes can change the petals orientations. In extreme

Figure 5.10: Various venation patterns are used in artworks [49].

cases, petals of one flower may intersect other petals (see Figure 5.11, left) while there is still enough space around the node. A simple interactive tool can help to modify the arrangement to mitigate this issue (see Figure 5.11, right).

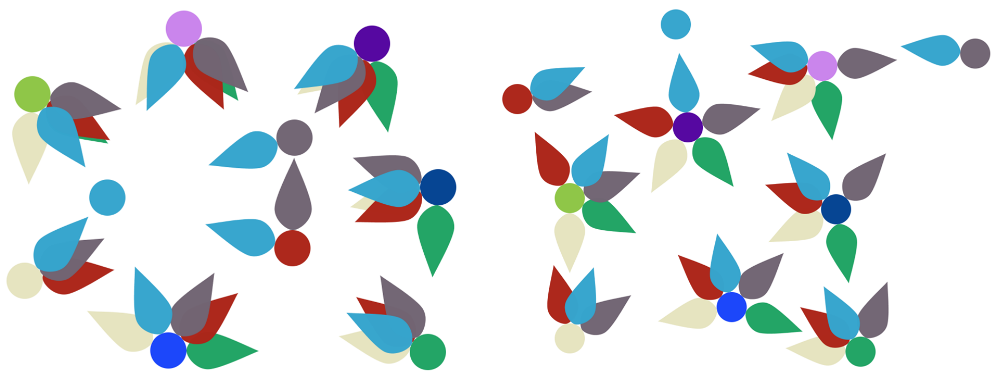


Figure 5.11: Left: With directional constraints on edges, sometimes they may overlap. Right: Nodes can interactively be moved to be arranged with less overlaps.

Alternatively, symmetric layout (no directional constraint) can be used exactly as Node-Ring

To prevent overlapping between petals of different nodes, a larger circle containing the entire flower (core and all the petals) of daisy can be used as the bounding area (see Figure 5.12). This is comparable with the node's circle in Node-Ring, Figure 5.12, schematically compares the bounding circles of Daisy with the node ring circle.

Daisy Visualization has potential for including more features into the arrangements to mimic floral patterns. We discuss this in the context of ecological network visualization for which Node-Ring was difficult to use.

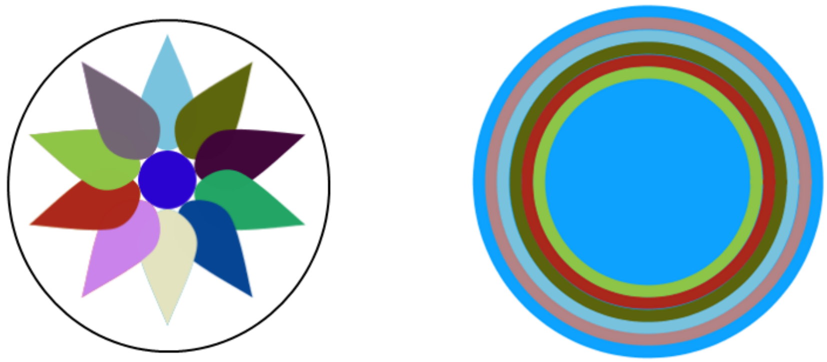


Figure 5.12: In Daisy Visualization, the circle that contains node and its edges, is larger than Node-Ring Visualization.

5.3.3 Interaction

Daisy Visualization supports some basic interaction techniques. These techniques include

- changing position of nodes, orientation of petals (see Figure 5.11-Left and Right)
- highlighting the traditional node-link relationships between a selected node and its adjacent nodes (see Figure 5.14),
- toggling between symmetric and directional constraints,
- displaying exact weights of nodes and edges (see Figure 5.13).

In addition to these simple interactions, we have implemented other interactions to support visualization tasks related to ecological networks.

For coloring the nodes, in addition to interactive color assignment techniques , we can load color palettes from famous painting as described in Node-Ring (Section 4.3.4). Figure 5.15 shows a comparison between two different color palettes used for the same graph.

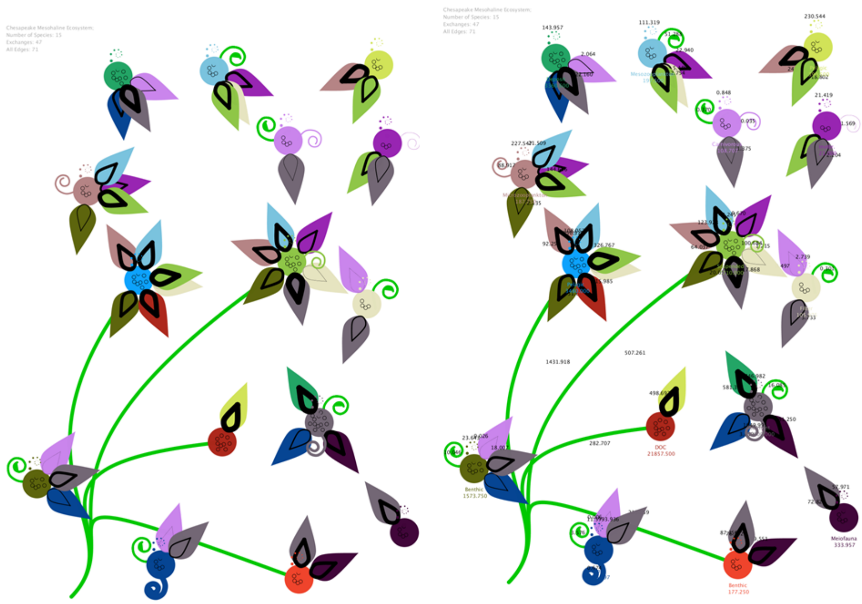


Figure 5.13: Interactively showing more details of the network.

5.4 Ecological Network Visualization

As mentioned in Section 4.5, it is possible to use Node-Ring for visualizing Food Web (weighted directed graph). Food Web is only a simple and special case of ecological networks where features such as respirations and inputs/outputs are not present. Including these features in Node-Ring is hard mostly because the node's space is not large enough for nesting several types of edges. In contrast, in Daisy, edges are *adjacent* to the node providing more space for mapping various types of edges. Also, in daisy artworks, there are many interesting elements around the flowers that can be used as inspiration for attributes in ecological network. Our general approach is to map features of ecological networks to these elements.

5.4.1 Mapping

As demonstrated in Figure 5.16, there are four types of edges in ecological networks (input, output, exchange and respiration). Exchange edges represent the amount of energy/matter

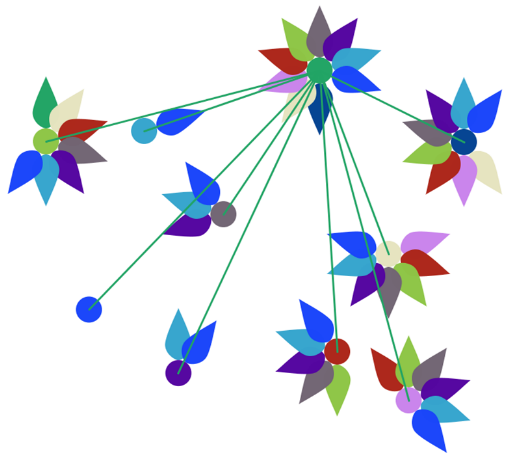


Figure 5.14: In Daisy Visualization, outgoing edges can be highlighted.

that transfer between species in ecosystem. Inputs/Outputs are the amount of energy/matter that enters and leaves ecosystem. In practical cases, it is possible to have multiple attribute outputs. In the example networks provided by our ecologist colleague, in addition to output energy, there exists respiration or breathing as the second type of output edges.

Exchange edges are treated as usual edges in the Daisy layout, consequently nodes and exchange edges are mapped to the core and petals respectively. However, we need a new solution for other attributes. Since input and output edges show transactions of nodes to the *outside* of the system, a simple solution could be to use a phantom node for representing the outside. This special node can be treated similar to other nodes or handled in a different way. In our visualization, rather than using another flower for the phantom node, we introduce an alternative solution. As seen in our previous examples (e.g. Figure5.6), our patterns are missing any stem or branching structure, which are important elements that are exist in both abstract and real floral patterns. To address this issue, we map the outside (phantom) node to the root of the flower. Therefore, input edges show the transaction from the root to each node. With this metaphor, we can map each input edge to a branch from the root to that node (see Figure 5.17).

The same strategy can be used for output edges. However, using another branch for

Figure 5.15: Color assignments can be based on color palettes from favorite paintings. The color palette for the Left image is based on "Silent Flowers" and for the Right image is based on "City View" by Hundertwasser [118].

connecting the node back to the same root is creating loops which is not usually acceptable for floral patterns (see Figure 5.17). Also, using a secondary phantom node may create flowers with two stems (one for the input and one for the output) which is also not common form in floral patterns. Therefore, a different method is required for this type of edges. Interestingly, flowers have several parts (e.g. pistil, filament and sepal) that can be used for representing other features (see Figure 5.18 for real flowers and Figure 5.10 for artwork exhibiting similar elements).

Inspired by these elements, in our visualization, output edges are represented by spiral leaflet shape attached to the node. The color used for these elements is the same as the branching structures (see Figure 5.19). With this consistency of color, we attempt to show that the input and output edges are connected to a unique outside node (phantom). Respiration edges are represented by a small stamen attached to the node. They are colored with the same color as their nodes but it is better to render them with a dashed or dotted

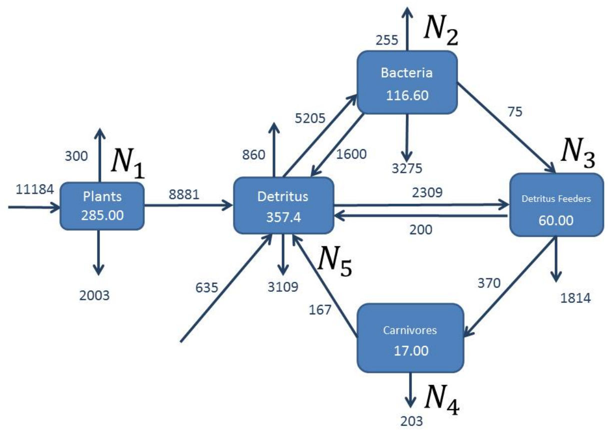


Figure 5.16: Ecological network with five nodes. This figure has been used in Chapter 2,for explaining the features of ecological networks.

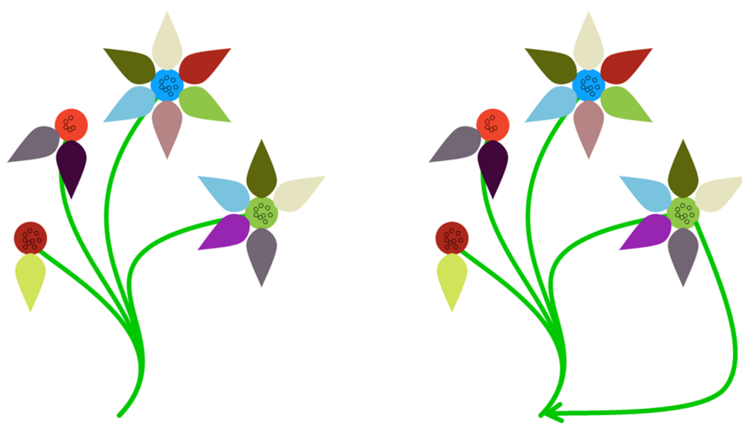


Figure 5.17: Left: Daisy Visualization with input edges. Right: Same visualization with one output edge presented by stems, similar to the input edges. Using the same phantom node for inputs and outputs causes confusion.

lines as a hint to respiration to the air (see Figure 5.19).

One of the uncommon attributes of ecological networks is the possibility of having loops for some of the nodes (see Section 2.1). For example, as it is shown in Figure 5.20, there is a loop exchange edge for the node “blue crab” in network. Our solution for this type of edges is to use another floral feature. We have sketched numerous shapes and features, and chose to use a circular type of leaflet attached to the node (see Figure 5.21-Left).

With this mapping we can represent the entire ecological networks, with their complex

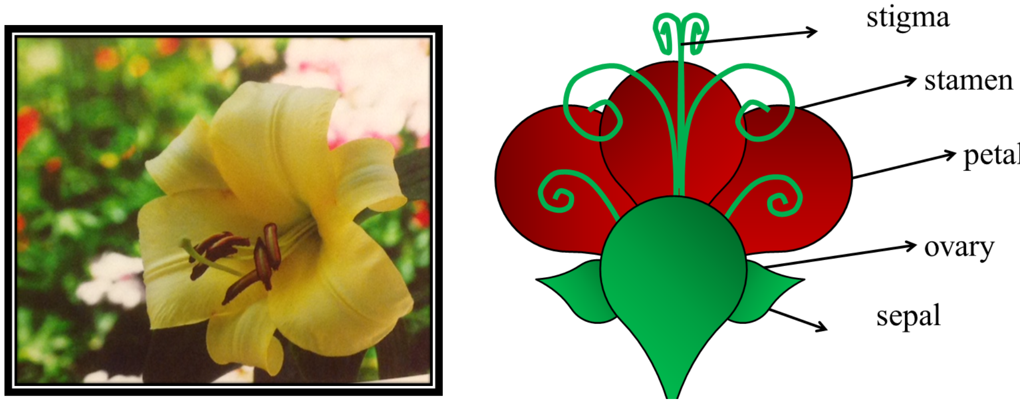


Figure 5.18: Flowers have several elements that can be used for mapping data attributes.

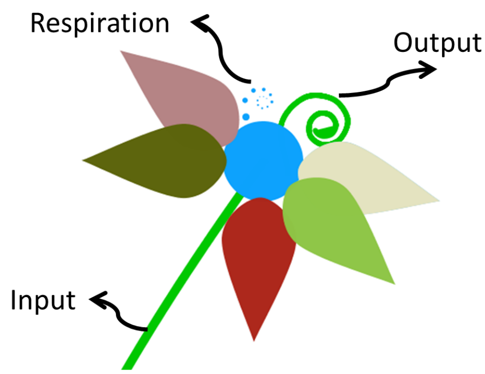


Figure 5.19: External edges (e.g. input, output and respiration) can be mapped to other flower elements.

structures, as variations of floral patterns. Although, our current representation is based on several iterations of designing floral elements and their mappings, this is only one feasible solution from many possibilities. The richness of floral patterns and their assorted elements, enables us to map multiple attributes of nodes of the graph.

5.4.2 Interactions and Element Arrangements Specific to Ecological Networks

In Sections5.3, we described some basic interactions and arrangements that can be used for Daisy Visualization. Some other interactions/arrangements specific to ecological network visualization may be needed.

The initial node arrangements in our Daisy Visualization can be easily modified by simple mouse/touch interactions. The petal's orientation is determined by directional constraints.

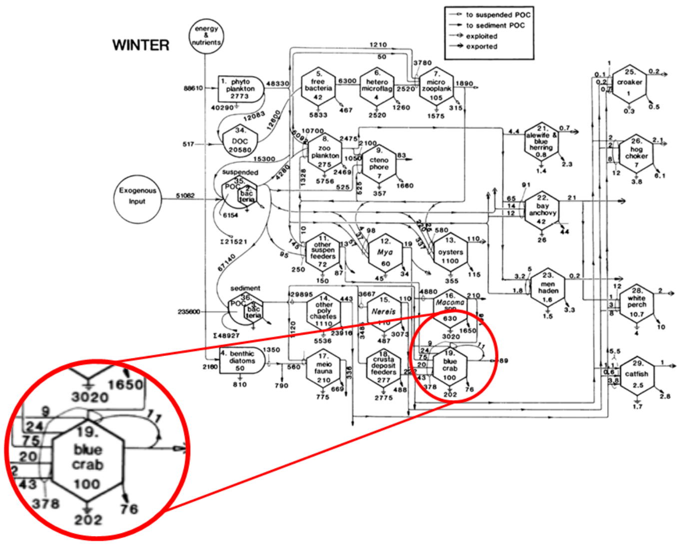


Figure 5.20: There is a cyclic exchange edge for "blue crab" in this ecological network [15].

However, the arrangement of other floral elements (i.e. output and respiration) can be done independent from the petal arrangements. One possibility is to simply orient all of respirations toward one specific direction (e.g. the up vector, to convey the concept of the air). The same approach can be used for outputs by aligning all of their floral elements toward another point (e.g. east). Figure 5.22 left, demonstrates these arrangements for an ecological network. In general, depending on the applications and the type of feature, the alignment of these directions can be determined. But enforcing these constraints in addition to directional and color constraints may create unbalanced floral patterns.

As demonstrated in Figure 5.21-Left, a simple mouse/touch interaction for rotating the floral elements of respirations and outputs can help to improve the balance of the floral pattern in an interactive manner (see Figure 5.22 right). Also, algorithmic methods can be used to create more balanced arrangements for these extra floral elements. For example, one idea is to use the angular range $[\theta_1, \theta_2]$ of the neighbors of the current vertex v (see Figure 5.21-Right). The explementary angle [1] $[\theta_2, \theta_1]$ shows the remaining space around the node v not used by the petals. So, if explementary is large enough, it can be used to

[1] When the sum of two angles is equal to 360^O, each one is called the explementary angle of the other.

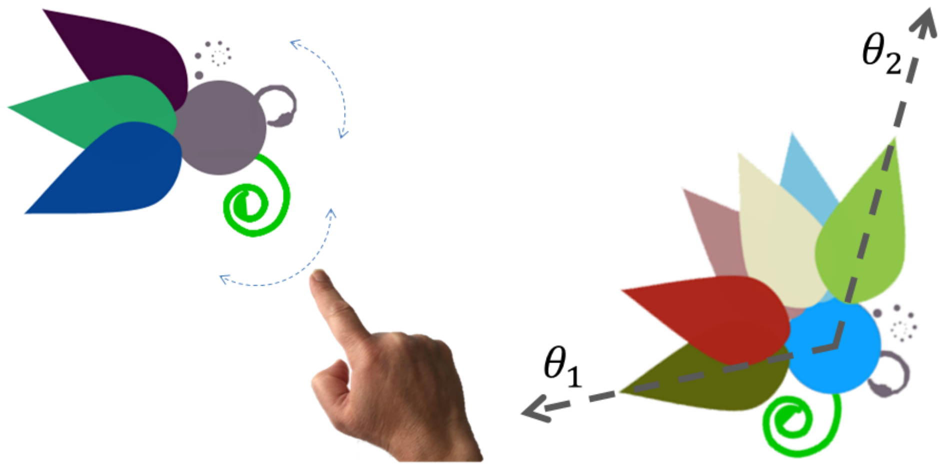


Figure 5.21: Left: The position of cycle and output links can be interactively change. Right: Automatically finding the angular range of the neighbors of the current node, helps to improve the balance of the floral pattern.

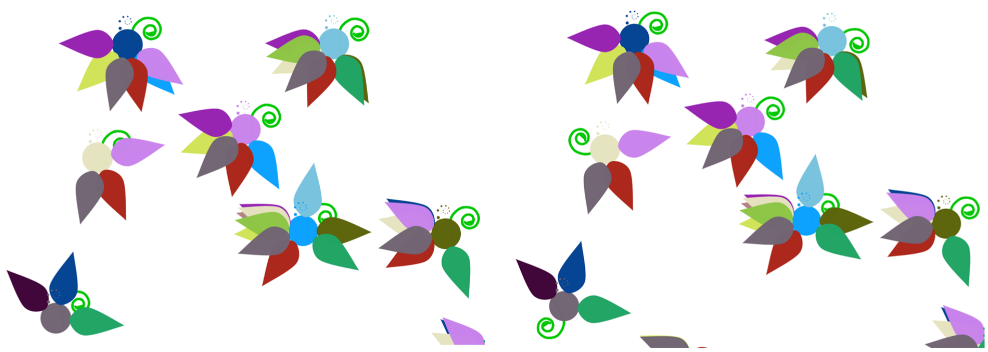


Figure 5.22: Mapping output and respiration edges to different floral elements. When it becomes too crowded (left), we can move these elements (right) in order to have more balance arrangement for daisy flower.

accommodate the respiration and output elements (see Figure 5.21-Right).

5.5 Results and Discussion

We have used Processing 2.12 development environment for prototyping Daisy Visualization. Some of the floral elements (e.g. petals) have been directly coded in this environment. For creating more complex floral patterns (e.g. leaflets and loops), an interactive B-spline curve editor has been used and the resulting curves have been exported to the prototype.

We have access to forty eight ecosystem data files which have been provided to us by Professor Robert Ulanowicz, Chesapeake Biological Laboratory, from the University of Maryland. The number of nodes in these realistic data-sets ranges from five to one hundred twenty five. Thirty four data files contain less than thirty six nodes. In essence, the size of these graphs is not large but their complexity is due to other aspects of the data. Each data file contains the following fields:

- Ecosystem name
- Number of nodes or species in the ecosystem
- List of node labels or the species names
- List of the nodes' weights or species biomass
- List of inputs (index and weight)
- List of outputs (index and weight)
- List of Respirations (index and weight)
- List of exchanges (index of adjacent nodes and the exchange's weight)

Figure 5.23, shows a screen shot of Node-link and Daisy Visualizations, created from one of these networks "Chesapeake Mesohaline ecosystem" with 15 nodes and 71 edges.

The attributes such as node labels and biomass can be shown for the entire network or a set of nodes highlighted interactively (see Figure 5.23).

Figure 5.24, shows a screen shot of Node-link and Daisy Visualizations, created for *Crystal River Creek* ecosystem which has 21 species and 82 exchange edges and 129 edges in total.

These two results show that it is possible to map most of the data-sets to a beautiful Daisy floral pattern. The study we conducted (refer to Chapter 7) also confirms that a large number of participants are strongly in favor of this mapping. Furthermore, Figure 5.25,

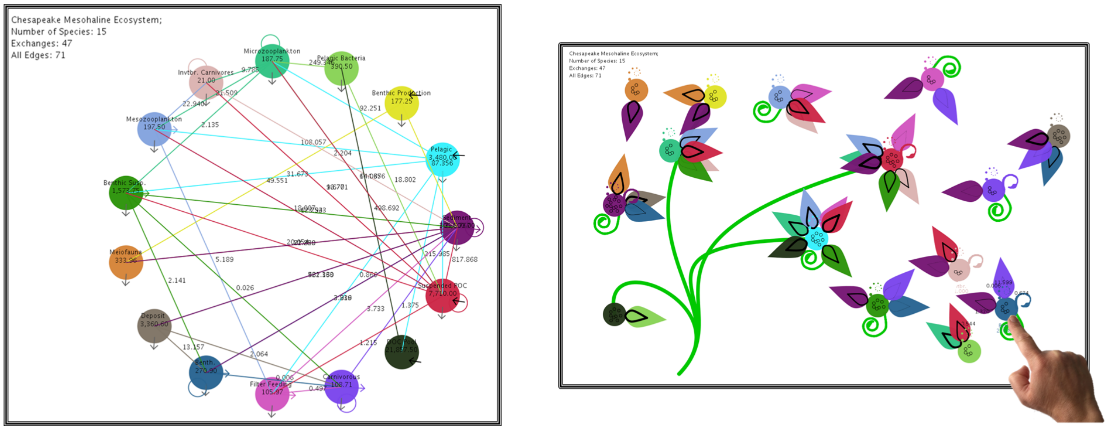


Figure 5.23: Details of ecological network (e.g. input. output, respiration) are mapped to more floral elements. Left: traditional node-link, Right: Daisy Visualization.

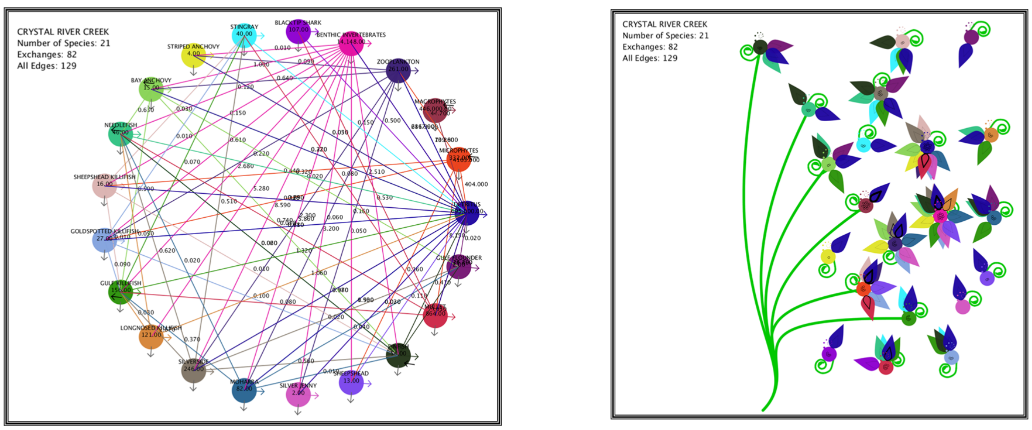


Figure 5.24: Traditional node-link (left) and Daisy Visualization (right) for ecological network of "Crystal Creek River" with 21 species.

shows the food-web network visualized by Daisy layout. This network is a simplified version of Figure 5.24 where all respirations, inputs and outputs are removed.

Compared to Node-Ring, putting edges adjacent to the nodes has provided better flexibility for representing features (e.g. respirations and inputs/outputs). In Daisy Visualization, weights, for node and exchanges, are approximately captured by the flower's size and venation pattern. However, depicting weights of respirations and outputs by the size variation of floral features (e.g. leaflets, pistil) is not a viable solution. These features are relatively small and size variation will be difficult to discern. While, these weights can be interactively shown, a remaining challenge is to do this in a visual manner. In addition, for larger dense

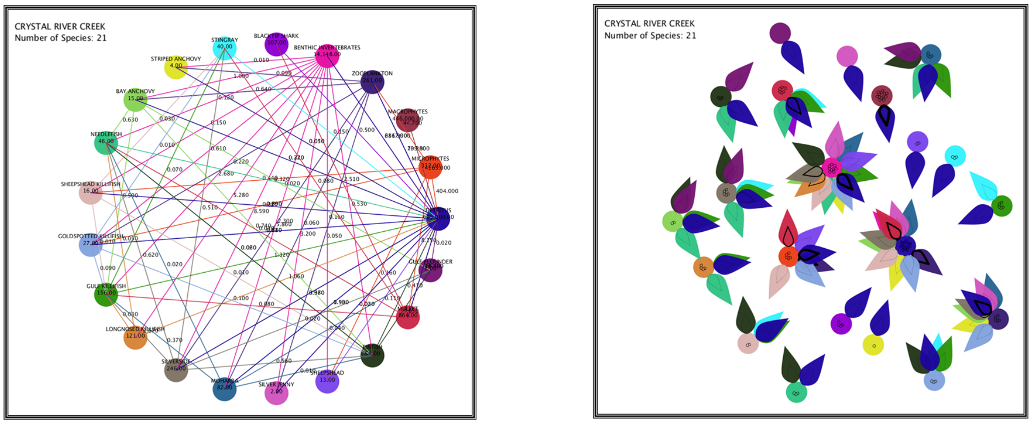


Figure 5.25: Traditional node-link (left) and Daisy Visualization (right) of the food web with 21 species.

graphs (more than fifty nodes) the number of petals per node will be high, which might make it difficult to see the exchange edges. Continuing our journey of alternate aesthetics exploration, we have created another novel visualization which is more successful for ecological networks with larger size, and it is able to depict weights of respirations and outputs in a better way.

5.6 Summary

In this Chapter, we introduced a novel visualization for representing weighted directed graphs with Daisy floral patterns. This visualization represents, each node and all its adjacent edges with aspects of daisy flower patterns. The core of the daisy represents the node, and its petals show the edges connected to that node. We have used this visualization to represent real data-sets of ecological networks and this visualization is capable of representing all types of edges in ecological networks.

Chapter 6

Eco-Spiro Visualization

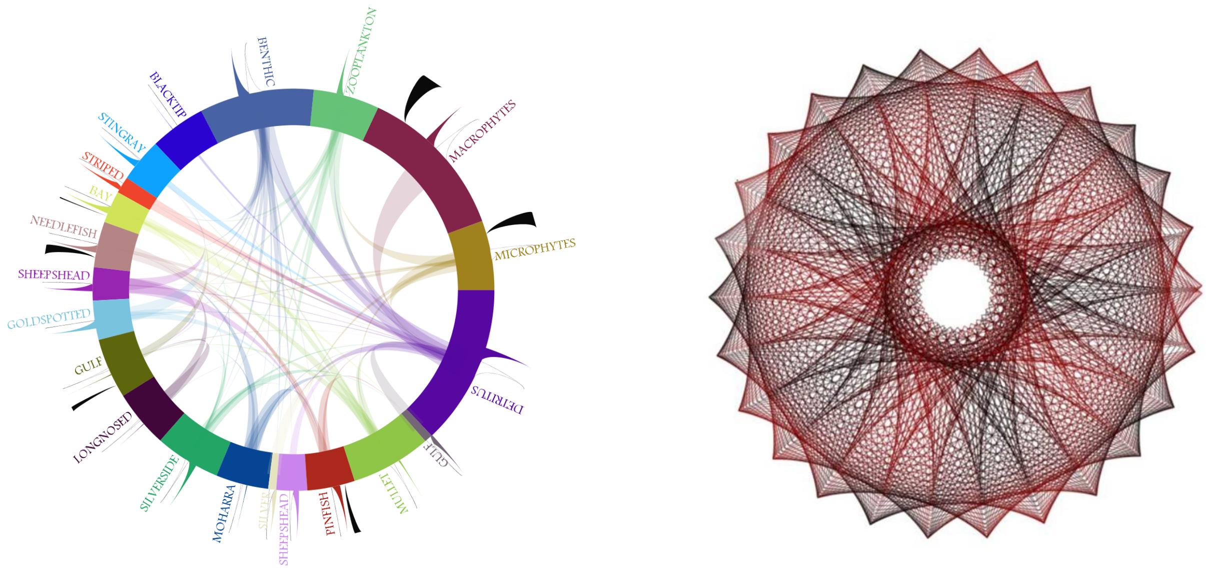


Figure 6.1: Eco-Spiro Visualization of ecological networks, inspired by Spirograph.

6.1 Introduction

In this chapter, we modify Spirograph layout (Section 3.6) to create a novel visualization specifically designed for ecological networks. We have named this visualization *Eco-Spiro* which visualizes the basic network and the associated flow of energy and matter between species, in an ecosystem. In comparison with Daisy and Node-ring, Eco-Spiro can handle more aspects of ecological networks. Furthermore, both the direct and indirect quantities that are commonly required in ecological studies can be supported in this visualization. This chapter is an extension and revision of our published paper: "Spirograph inspired visualization of ecological networks" [42].

As described in Chapter 3, in Spirograph layout, a circular form is used for the space.

In this layout all nodes are arranged on a large circle (boundary circle) which divides the space to the internal and external regions. Edges are drawn as circular arcs either outside or inside of the boundary circle. Therefore, Spirograph provides a natural way to support external and internal edges of ecological networks.

Selection of Spirograph as the underlying layout made it possible to represent the entire ecosystem by a circular shape, defined by the boundary circle (see Figure 6.1). This circle has an organic form providing the impression of a closed ecosystem, which separates the environment into its internal and external spaces. Nodes are represented by arcs on the circle, the lengths of which illustrate the nodes' weights (biomass). We use a thorn shaped Bezier curve [55] for each edge (see Figure 6.1), whose thickness is proportional to the weight of the edge. Therefore, in Eco-Spiro, edges are completely drawn as opposed to Node-ring and Daisy Visualizations. Exports and imports from outside are shown with smaller thorns attached to the outer side of the circle.

The remainder of this chapter is structured as follows. Since Eco-Spiro is designed for visualization of ecological networks, we start with explaining the design challenges for visualizing these networks in Section 6.2. One of the important quantities for ecologist is the throughput of the system, so in Section 6.3 we explain how to find this indirect quantity. Then in regards to the artistic inspiration, a short review of Spirograph patterns can be found in Section 6.4. We continue with details about Eco-Spiro Visualization in Section 6.5, and explain the structure of the data and our implementation in Section 6.6. We also provide a short discussion about this chapter in Section 6.7.

6.2 Design Challenges for Ecological Networks

While it may be tempting to think that traditional graph visualizations would be adequate for ecosystem networks most of the details that are of particular interest to ecologists get suppressed, and as with all graphs the complexity of even small networks becomes visually overwhelming.

Currently variations on flow diagrams as used in computer hardware and software diagrams are being used to represent networks. With these flow-based node-link diagrams, for simple networks, the visual representation is helpful in establishing an overview of the network. Furthermore, it may be possible to capture some of the topological connections (who eats whom) and simple measurements of the flow with other graph visualizations (including Node-Ring and adjacency matrix). However, exploring indirect and more global effects commonly used by ecologists (see Section 6.3 for more details), such as the total amount of flow (throughput) from a node to another, is still challenging [129]. In addition, as the system grows even moderately larger, node-link layout quickly becomes cluttered, making it difficult to answer even simple and direct questions (e.g. discovering all adjacent nodes) (see Figure 2.19) [15].

To create an interactive visualization that addresses some of the challenges faced by ecologists interacting with visualization, we note the following challenges:

1. Providing an impression of a coherent system.

2. Offering a clear delineation of internal and external factors.

3. Representing node and edge weights visually in the layout.

4. Providing a powerful representation of directionality.

5. Offering appropriate interaction techniques via highlighting and filtering, that are linked to common ecosystem questions such as: adjacency for incoming and outgoing connections; and revealing cycles of different lengths.

6. Providing options of exploring network structure independently of weighted network structure.

7. Adding ecosystem specific analysis by making it possible to evaluate and provide indirect exchange quantities using the Leontief matrix.

We consider the above challenges to develop a layout based on Spirograph for visualizing ecosystem.

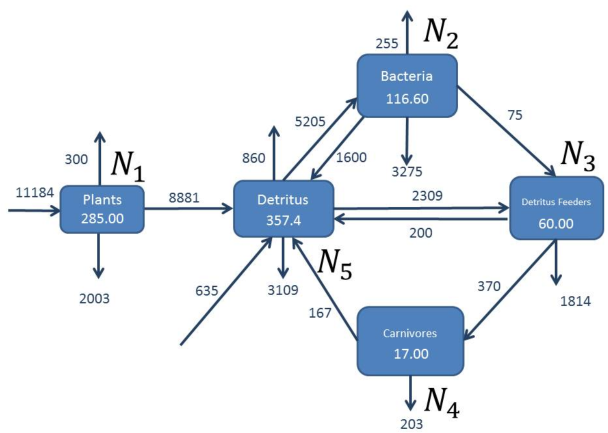


Figure 6.2: Ecological network with five nodes. As shown in Chapter 2 and Chapter 5. Nodes and edges are weighted and edges are categorized into four groups: Exchange, Input, Output and Respiration.

6.3 Indirect Effects in Ecological Networks

As demonstrated in Figure 6.2, an ecological network is a directed weighted graph in which nodes are species and edges represent the energy or material flow in the system. Each node's weight corresponds to the biomass of the associated species and each edge's weight represents the amount of energy that flows between the nodes in the system. There are usually three types of edges in these kinds of networks: exchange, input and output edges. Exchanges are simply edges between nodes. Input edges, enter the system from the outside, and output edges leave the system. In practice it is possible to have multiple types of outputs. In Figure 6.2, there are two types of output edges: energy and respiration (or breathing). In this section, we provide a basic background on indirect effect in ecological network.

Ecological networks are important tools which ecologists use in quantifying the flow of energy/matter in the ecosystem. In order to quantify indirect effects, it is necessary to evaluate and visualize measures beyond the weights of edges. For example, in Figure 6.2, it is important to know the total energy flow from N_1 to N_4. To evaluate this measure, it is necessary to find all pathways from N_1 to N_4, possibly including cycles (e.g. $N_2 \rightarrow N_3 \rightarrow N_5 \rightarrow N_2$). However, even for a moderately sized system (i.e. with 10 to 40 nodes) the network becomes very complex. Therefore, a proper representation of these networks, including the direct and indirect quantities, is required for the study of whole ecosystems [130]. These quantities are usually computed using linear algebra [129][84]. As discussed in Section 2.1, the connectivity of the network can be captured by the adjacency matrix A where:

$$a_{ij} = \begin{cases} 1, & \text{if } i \text{ is connected to } j \\ 0, & \text{otherwise.} \end{cases}$$

For example, if we ignore the input and output edges in Figure 6.2, its adjacency matrix will be:

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 \end{pmatrix}.$$

The inputs and outputs can be included by introducing some extra phantom vertices. As we discussed in Section 2.1, the adjacency matrix has also been used as a layout for general graph visualizations [58] [60] [59].

One can show that the powers of A can be used to calculate the indirect connections between vertices. For example; $A^2(i,j)$ shows the number of paths of length 2 from i to j and similarly $A^3(i,j)$ shows the number of paths of length 3 from i to j. To see the basic reason for this property, consider that (N_i, N_k, N_j) is a path with the length two from N_i to N_j. Consequently, N_i is directly connected to N_k and N_k is directly connected to N_j which means $A(i,k) = A(k,j) = 1$. Therefore, for forming $A^2(i,j)$ when we multiply the row i to the column j, there is a nonzero entry at k. This simple observation can be used to prove the above property using mathematical induction.

In order to include weights, a similar matrix $W_{n\times n}$ is defined where $w_{i,j}$ is the flow exchange from N_i to N_j. For instance, for the network in Figure 6.2, we have:

$$W = \begin{pmatrix} 0 & 0 & 0 & 0 & 8881 \\ 0 & 0 & 75 & 0 & 1600 \\ 0 & 0 & 0 & 370 & 200 \\ 0 & 0 & 0 & 0 & 167 \\ 0 & 5205 & 2309 & 0 & 0 \end{pmatrix}.$$

Similar to the adjacency matrix, $W^3_{i,j}$ shows the flow exchange between N_i and N_j, through paths with the length of three. Therefore, the entire throughput of the network can be found by summing all the powers of W:

$$S = W^0 + W^1 + W^2 + \dots \tag{6.1}$$

However, in cyclic networks W^n does not converge to zero and, therefore S in Equation 6.1 is not well defined. For example, if there is a cycle with a positive total weight, we can achieve any arbitrary large number by repeating this cycle for many times (approaching to infinity). To address this issue, W is normalized such that no entry in the matrix is greater than one. Let $G_{n\times n}$ be defined such that $g_{i,j}$ is the normalized flow from node N_i to the node N_j:

$$g_{i,j} = \frac{w_{i,j}}{E_j + \sum_{k=1}^{n} w_{kj}} \tag{6.2}$$

where E_j is the external input to the node N_j. For the network in Figure 6.2, we have:

$$G = \begin{pmatrix} 0.0 & 0.0 & 0.0 & 0.0 & 0.773 \\ 0.0 & 0.0 & 0.031 & 0.0 & 0.139 \\ 0.0 & 0.0 & 0.0 & 1.0 & 0.017 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.015 \\ 0.0 & 1.0 & 0.969 & 0.0 & 0.0 \end{pmatrix}.$$

Now the summation is well defined as:

$$L = G^0 + G^1 + G^2 + \ldots = [I - G]^{-1} \tag{6.3}$$

where I is the identity matrix and L is called the *Leontief* matrix (See [129] and [69]). In 1973, Wassily Leontief earned the Nobel prize in economics for his input-output model related to L [84]. As an example, for the network in Figure 6.2 we have:

$$L = \begin{pmatrix} 1.0 & 0.933 & 0.933 & 0.933 & 0.933 \\ 0.0 & 1.169 & 0.201 & 0.201 & 0.169 \\ 0.0 & 0.039 & 1.039 & 1.039 & 0.039 \\ 0.0 & 0.018 & 0.018 & 0.018 & 0.018 \\ 0.0 & 1.207 & 1.207 & 1.207 & 1.207 \end{pmatrix}.$$

In this case, the total (direct, indirect) normalized exchange between nodes 2 and 4 is 0.201. In a cyclic network it is possible for entries to be larger than one. In summary, the matrix L provides very useful information for ecologists to study the network [129] [69].

Note that Equation 6.2 is just one of many possible normalization equations. Other possibilities have been discussed in [129].

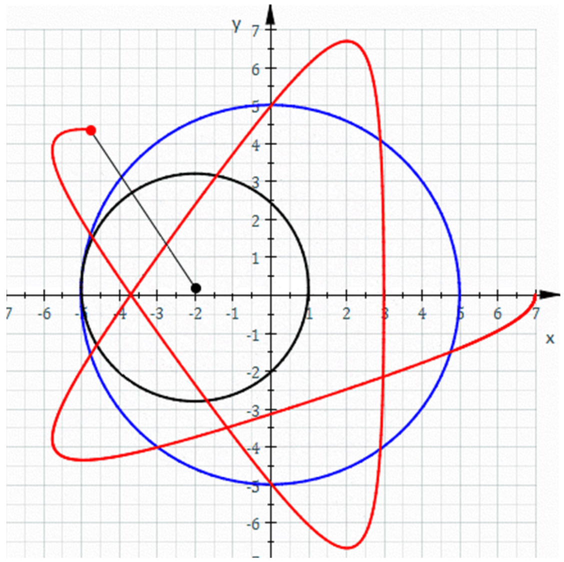


Figure 6.3: Spirograph, creates rolling curves generated by fixing a point on a rolling circle inside another fixed circle [143].

6.4 Spirograph Patterns

Since Eco-Spiro Visualization uses a layout (refer to Section 3.6) inspired by Spirograph patterns, here we provide a short background on these patterns. Spirograph patterns are a fascinating class of curves created using a simple toy containing a set of circular gear-like rings of various sizes. Figure 6.1, right shows an example of Spirograph patterns. A simple web search reveals that there is significant interest in these patterns, as evidenced by many software packages and art galleries of Spirograph patterns [126, 20]. Mathematically the Spirograph creates hypotrochoid curves, which are rolling curves generated by fixing a point on a rolling circle inside another fixed circle (see Figure 6.3).

Spirograph can be modeled as parametric curves which can be created and rendered efficiently in computer graphics. Taking advantage of virtual tools instead of real toys, Glassner in [47] extends Spirograph patterns, by replacing circles to interactive curves (e.g Bezier curves). Such extension enabled him to use other egg-like shapes such as ellipse to create new kinds of patterns.

The visual appeal and elegant geometric description of Spirograph patterns motivated

Lin and Vuillemot to use them for visualizing tweets [85]. In their work, many Spirograph patterns were created by tweaking control parameters in a drawing tool. Then a set of interesting patterns was identified and classified. Interestingly, the distribution of tweets over time was mapped to the petals of selected Spirograph patterns.

Spirograph patterns are only a source of inspiration for our layout and we have not tried to reproduce them exactly. As shown in Figure 3.16, and 3.18-d, the main property of our layout is that it is based on repeating circles and arcs with controlled increments. We do not use the exact mathematical definition of roulette curves but only simple circular arcs.

6.5 Eco-Spiro Visualization

In this section, we introduce our visualization method for ecological networks. In the first sub-section we provide more details about the layout and specific aspects which have been introduced for visualization of ecological networks. Then we introduce Eco-Spiro Visualization and explain the interaction tools provided in this visualization system.

6.5.1 Layout

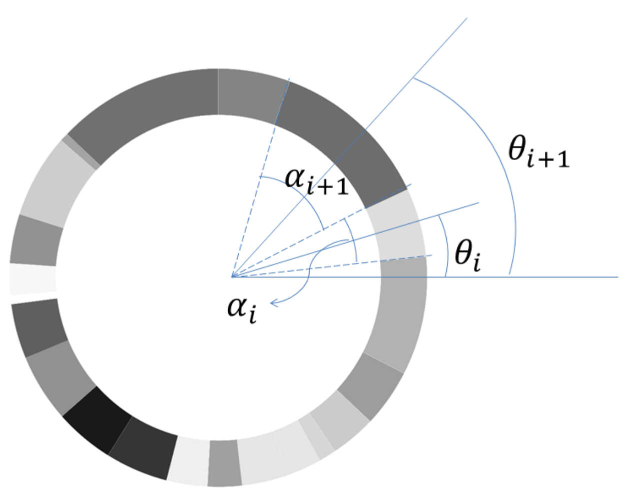


Figure 6.4: α for each arc is proportional to the biomass of the species that it represents.

The layout used for Eco-Spiro is a modification of Spirograph. As discussed in Section 3.6, the boundary circle has an important role for dividing the display space to internal and external. This property can greatly benefit ecosystems as we can enclose the entire ecosystem using this circle. The closed nature of the circle is useful in implying the concept of the "closed" ecosystem. As shown in Figure 6.4, this circle has thickness and each node can be represented as an arc determined by a specific angle proportional to the species' biomass (i.e. the node's weight). Let α_i denote the angle of the arc associated with N_i, which is proportional to N_i's biomass. The order of the nodes is usually the same as that provided in the input file (see Section 6.6). If it is necessary, we reorder the nodes for better distribution. To position the nodes on the circle, we start from a specific angle (say $\theta = 0$). Then we incrementally add new arcs to the end of the previous one (see Figure 6.4). More formally, if θ_i is the angular position for the center of N_i, then:

$$\theta_{i+1} = \theta_i + \frac{1}{2}(\alpha_i + \alpha_{i+1})$$

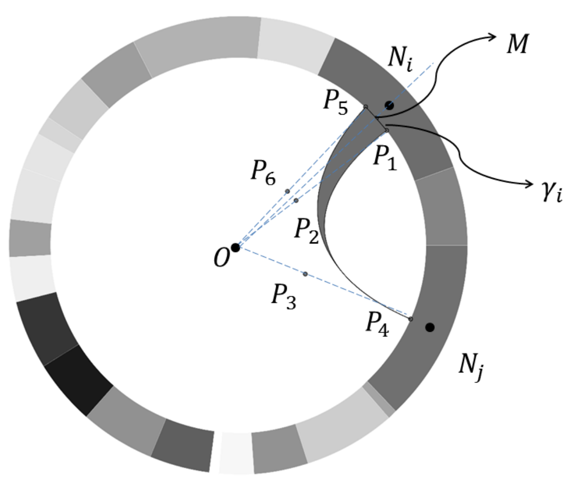


Figure 6.5: Arc point i is the origin of the thorn-shaped edge and arc point j is the destination of that edge.

For the representation of exchange edges, the direction and the weight of each edge should be visible. Therefore, techniques provided in [64] do not work well since they do not consider weight requirement. We have tried several designs for edges. For example, a simple thick line or arrow between nodes is not an aesthetic choice. Our final design is a curved thorn/spike-like shape with variable thickness (see Figure 6.5). Thorns impose a natural direction on edges. The thicker part of the thorn is attached to the source node, and the tip to the destination node. The thickness of the thorn is proportional to the weight of the corresponding edge. The structure of the thorn's curve is defined such that visual similarity (inspired by Spirograph patterns) is established between edges. To accomplish this, the tangent of the curve at source and destination nodes, and the curvature of the thorn are controlled by the center of the ecosystem circle (see Figure 6.5). In our implementation, we have used cubic Bezier curves in order to construct thorns. As demonstrated in Figure 6.5, each thorn consists of three pieces: internal, external and the base. Let the control points of the internal and the external Bezier curves, from N_i to N_j, be represented respectfully by $\{P_1, P_2, P_3, P_4\}$ and $\{P_5, P_6, P_3, P_4\}$. The center of the circle is denoted by O and the weight factor of each edge is denoted by the angle γ_i. P_4 is simply the intersection of ON_j with the internal circle edge. Point M, used in the definition of P_1 and P_5, is determined as the intersection of ON_i with the internal circle edge (see Figure 6.5). Then P_5 and P_1 are defined by adding and subtracting $\frac{\gamma_i}{2}$ to M's angle in the polar coordinates. And finally we define:

$$
\begin{aligned}
P_2 &= \mu O + (1-\mu)P_1, \\
P_6 &= \mu O + (1-\mu)P_5, \\
P_3 &= \mu O + (1-\mu)P_4,
\end{aligned}
$$

where μ is a constant to control the curvature of the thorns. In our implementation we set μ to 0.62 (the golden ratio).

As mentioned in Section 2.4, ecological networks have external edges (input and output edges). In our layout, the outside space of the boundary circle is considered for input and

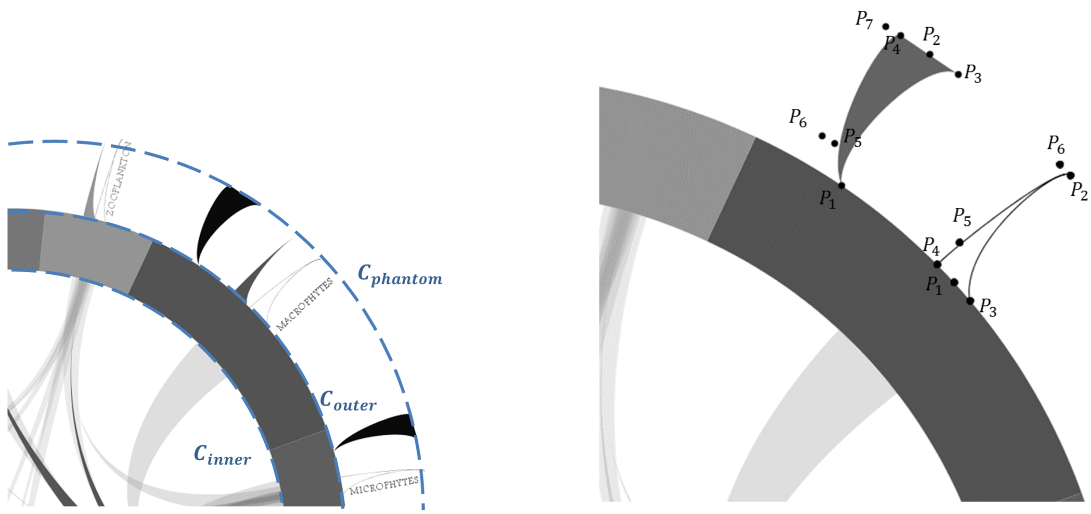


Figure 6.6: Left: External edges. For our implementation, the distance of $C_{phantom}$ and C_{outer} is the same as C_{outer} and C_{inner}. Right: Schematically presented the control points for Bezier curves.

output edges as they show the interaction with the outside of the ecosystem. For these edges we use thorns attached to the outer layer of each node's corresponding arc (see Figure 6.6). To keep the circular form of our design, the length of these thorns is controlled by a larger concentric circle $C_{phantom}$ illustrated in Figure 6.6. This circle is only used for organizing outer thorns and it is not drawn (phantom).

The Bezier curves of the input, output and respiration edges are constructed similarly to the exchange edges. These edges are constructed by two cubic Bezier curves and a line segment. For example for the input edge, as demonstrated in Figure 6.6-Right, the control points are $\{P_1, P_5, P_2, P_3\}$ for the first curve and $\{P_1, P_6, P_7, P_4\}$ for the second curve. As seen in the figure, P_1 is the intersection point of the thorn with the boundary circle. We are free to position this intersection on any place on the arc associated with the corresponding node. Since the center of the arc may be used for displaying the label of that node, we position P_1 slightly off the center. P_4 is on phantom circle, and P_6 and P_7 are used to control the curvature of Bezier curves.

6.5.2 Visualization

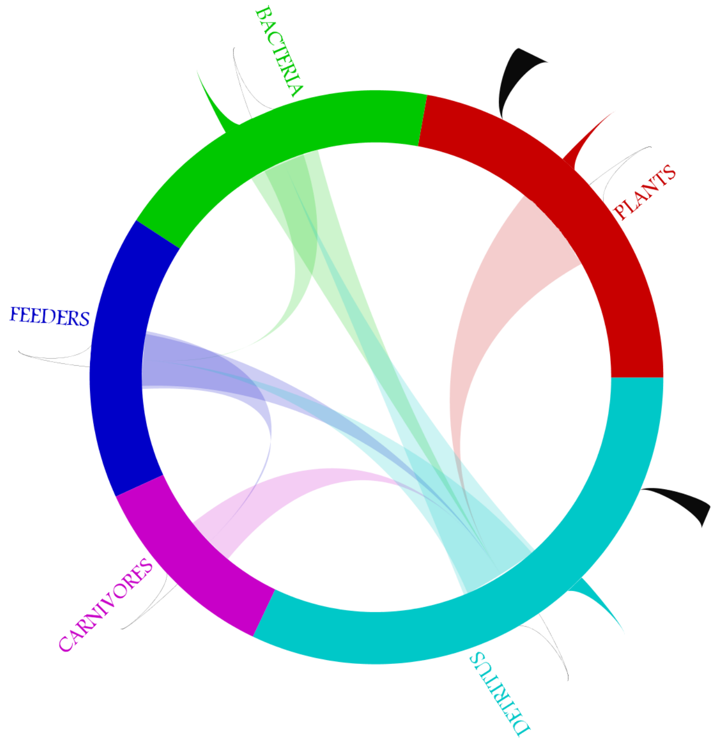


Figure 6.7: Spirograph visualization of the example network in Figure 6.2.

Using the layout described in the previous section, we designed and implemented a visualization prototype for ecological networks. Figure 6.7 demonstrates our result of this visualization for the network in the Figure 6.2. Each node is represented by an arc with a specific color. The angle of the arc is proportional to the node's biomass. Since the biomass numbers' range is wide, a logarithmic mapping is used to normalize the biomass.

As described in the layout of this visualization, edges are presented by thorns whose tip points towards the destination node and whose base identifies the source node. The color of each thorn is chosen to be the same as the source node's color, but it fades on the edge. As demonstrated in Figure 6.7, the weight of an edge is mapped to the thickness of its thorn. Therefore, the edge from “Bacteria” to “Feeder” is smaller than the edge from “Plants” to “Detritus” (see Figure 6.7). Once again, we have used a logarithmic mapping to normalize the range of the edge weights.

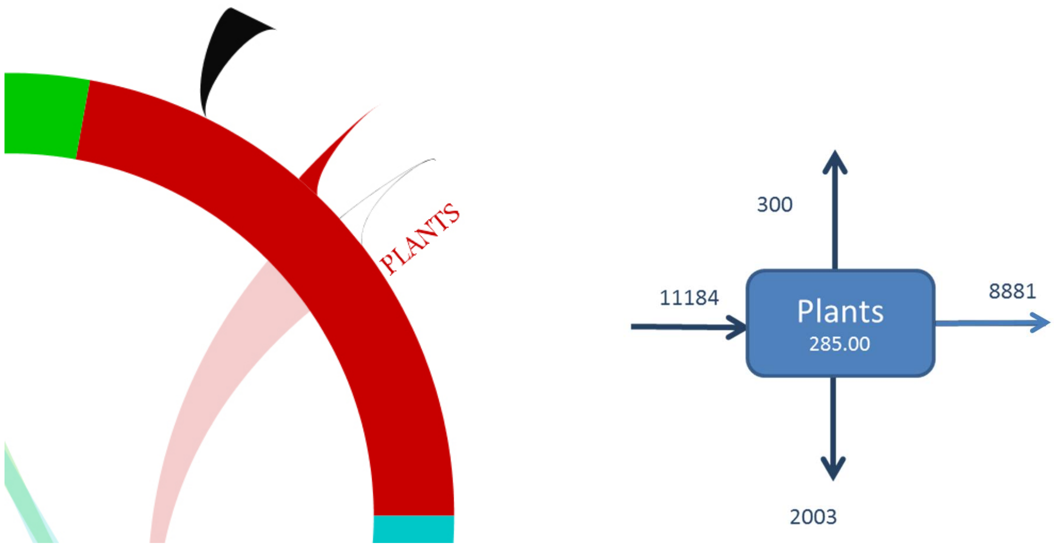


Figure 6.8: The inputs, outputs and respiration edges. For the node "Plants" input is 11184, output is 2003, respiration is 300 and its exchange to other nodes in the network is 8881.

External edges are identified by the directions of the thorns. The inputs are shown in black and the outputs are shown with the same color as their original node. The color of the respirations is white, so that they are distinguishable among other edges (see Figure 6.8).

Interaction

To provide a practical tool for ecologists to achieve their goals from this visualization, we have designed some interaction possibilities.

Ecological networks may contain more than a hundred nodes. In our data-sets, the number of nodes ranges from five to one hundred twenty five. Thirty five data files contain less than fifteen nodes. In essence, the size of these graphs is not large but they are highly complex, due to other aspects of the data. Considering that nodes representing species, have different biomass amounts, presenting the thickness of all edge and node weights is not always practical. Therefore, in these cases the impact of these weights may be optionally ignored. So, one variation of Eco-Spiro Visualization can show all exchange edges with same thickness, and ecologists will have an interactive tool to highlight the amounts of edge weights, according to requested tasks. It is up to the ecologist to decide whether to present

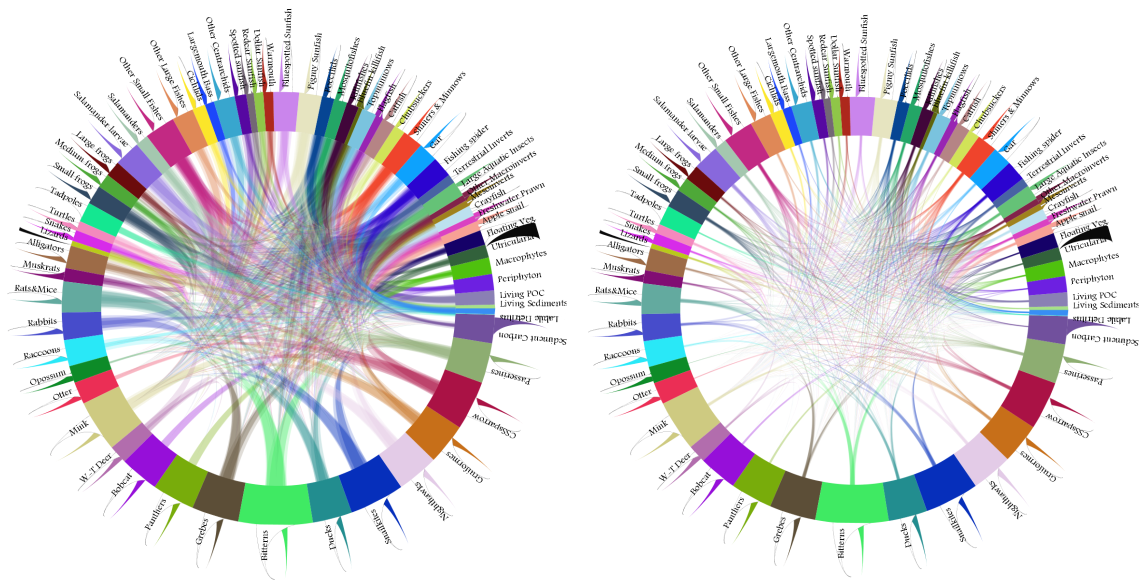


Figure 6.9: The visualization may optionally ignore edge weights. In cases with larger number of nodes, edges weights are visible by selection.

the edges with their weights or not (see Figure 6.9).

Furthermore, in our implementation, when a node is selected with mouse/touch interaction, the node and all outgoing edges are highlighted and their weights are reported with mouse hover (Figure 6.10).

Evaluating and displaying indirect connections and effects (e.g. cycles, cyclic fractions, total exchange) are also important in ecological networks. In our visualization prototype, we have implemented some of these tasks to demonstrate the potential for Eco-spiro Visualization. Figure 6.11 shows how we display multiple cycles.

In the network shown, which has fifteen nodes, there are two cycles that include node “Mesozooplankton”. The left image shows the first cycle and the middle image shows the second cycle. The right image is the view of the network with both cycles highlighted. In path/cycle mode, all regular edges are faded and only the edges of the various cycles are highlighted. Each cycle has its own individual color.

Another important requirement for ecologists is the display of total flow between two nodes. To achieve this, we first evaluate the Leontief matrix from Equation 6.3. Using

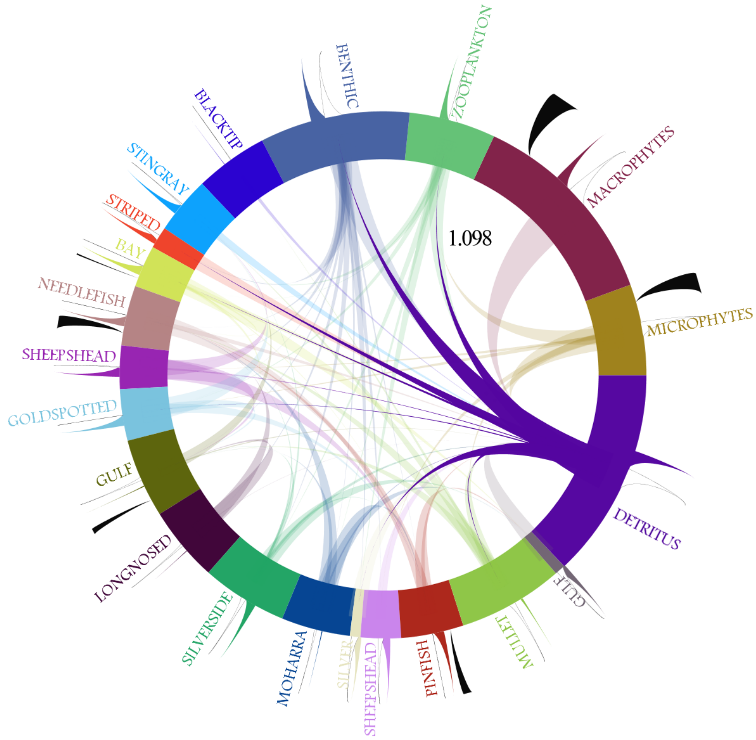


Figure 6.10: Ecological network with twenty one nodes. The node "Detritus" with eight exiting exchange edges is selected .

this matrix, the total exchange between two selected nodes is displayed. Our visualization provides a simple interaction tool for selecting these nodes (see Figure 6.12).

6.6 Implementation and Data

We used Processing 2.12 development environment to implement this visualization tool. We have used the same ecological network data that have been provided for us by Professor Robert Ulanowicz. More detail about the data-sets is provided in Chapter 5.

We have used *Matlab* to compute the Leontief matrix L defined in Equation 6.3 for all the ecosystems. Figure 6.14, shows how L can be used for all flow exchanges.

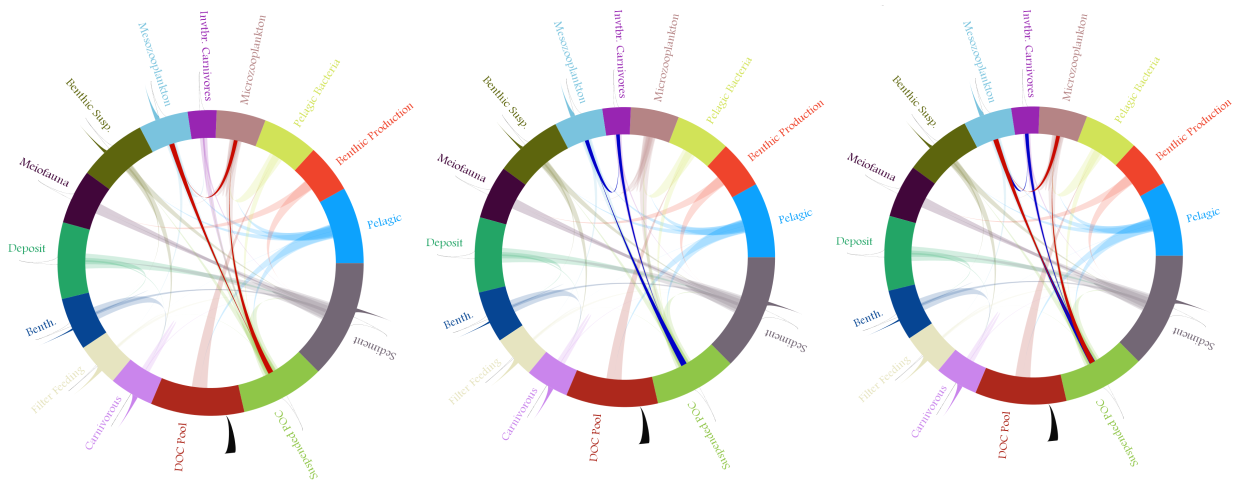


Figure 6.11: Two cycles that include node "Mesozooplankton" are shown. This first cycle is shown in the left image with color red, the second cycle is shown in the middle image with color blue, and the right image shows both cycles together.

6.7 Discussion

Here we discuss our visualization in terms of the design challenges as formulated through discussion with ecologists (Section 6.2).

While each identified ecosystem is naturally embedded in larger ecosystems, maintaining a visual impression of it as a coherent system was deemed important. Since metaphorically, a circle offers both visual containment and a sense of completeness, we chose to work with a circle as our basic structure. Using this circle to hold the nodes contain the internal edges in its interior, and orient the external edges outwards, provides an overview of the system. The ecologists we have worked with told us that this global view of the adjacent nodes is helpful for realizing the overall structure of the network and as requested provides a clear distinction between internal and external energy flows in the system. One comment made about the overall impression of the visualization was "I delight in the lovely organic forms by which the information is conveyed"[1] Matching node and outgoing edges colors is also an appreciated factor. The initial feedback from our ecological team confirms this by saying, "I

[1]quotes in this section are from personal communications (with Mishtu Banerjee) and are used with permission.

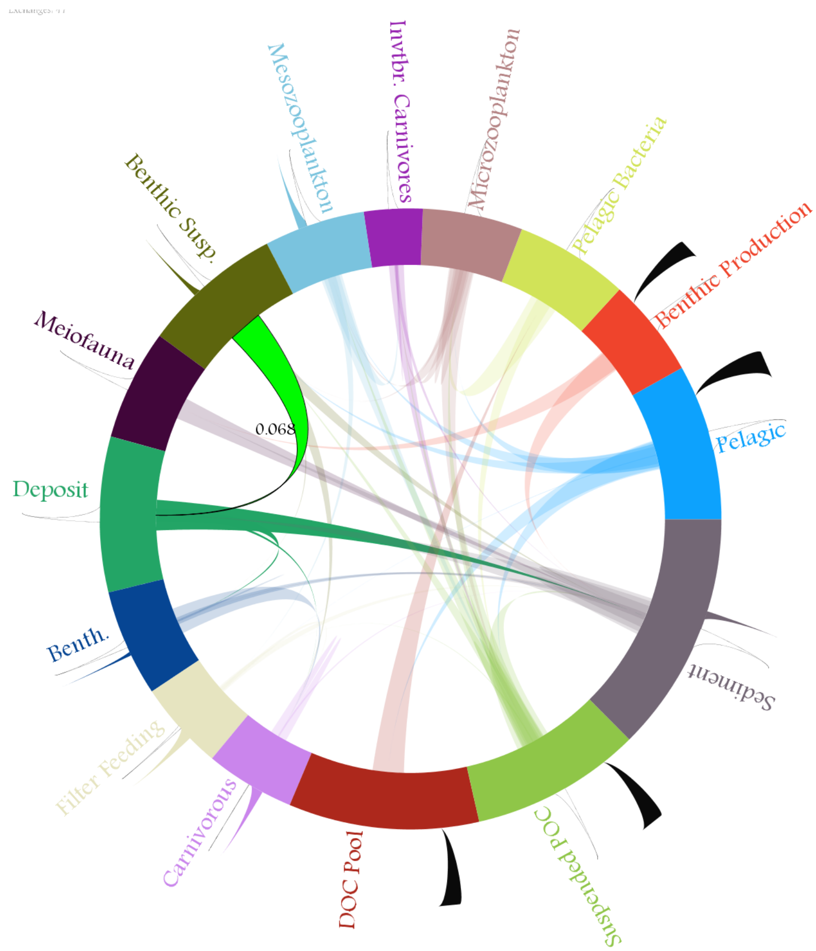


Figure 6.12: Energy/matter flow from node "Benthic Susp" to the node "Deposit". These two nodes are not directly connected, but there is an energy flow between them through the network.

like the colorful nature of the graphics it gives a good idea of adjacency".

Our visualization is able to present all node and edge weights by mapping them into graphical values: nodes are sized proportional to their biomass; and the wide end of the edge thorn is proportional to its weight. Also using the thorn or spike-shaped edges maintains clear visual directionality while reducing the clutter that caused by arrow heads. On the other hand, if desired, the ecologists can use the system with no edge weights, especially while working with larger ecological networks, perhaps to only consider connectivity.

As always in visualization, scalability is an issue. However, perhaps in part due to the complexity of ecosystems in general, it appears that often small ecosystems are studied. For

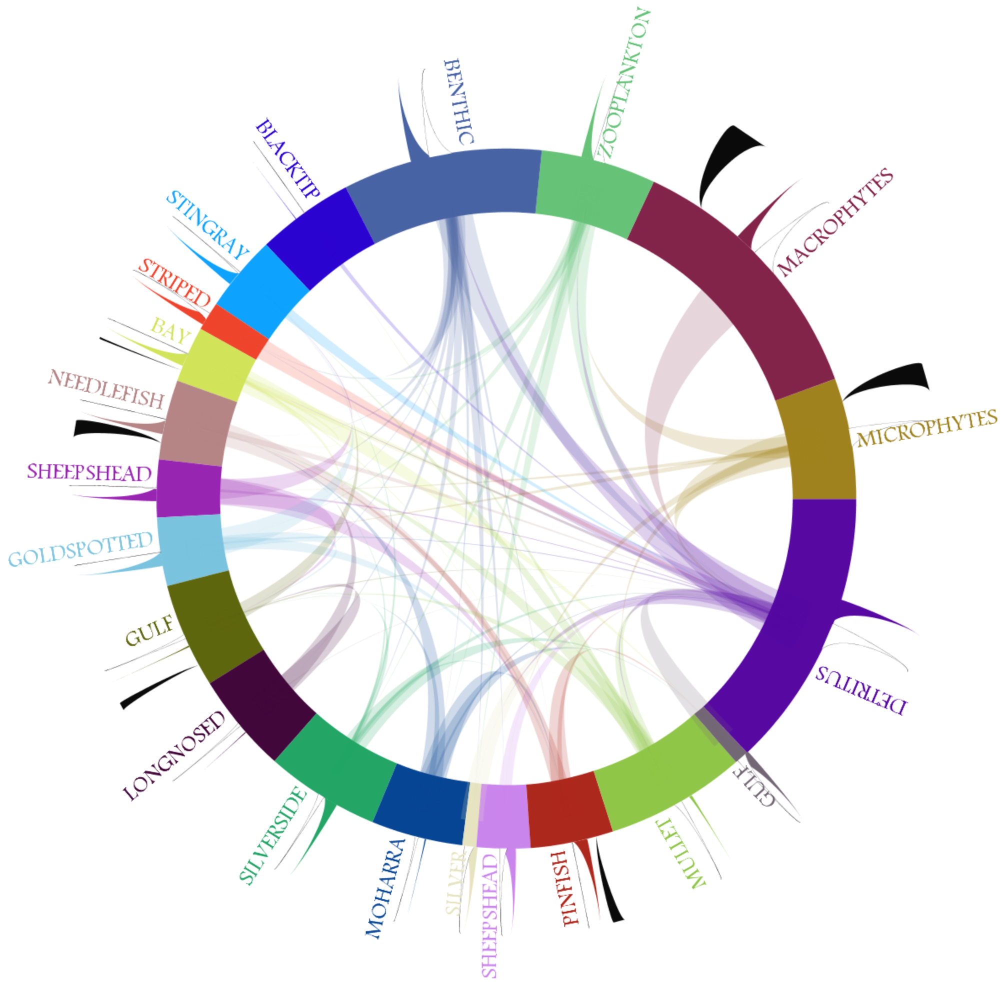


Figure 6.13: Crystal River Creek, an ecological network with 21 nodes.

example, from forty-eight ecosystem data-sets thirty five data-sets contain less than fifteen nodes. We recognize that our visualization is best suited for ecosystem data sets in these size ranges and would be challenged to display more than a few hundred nodes. There are other scalability issues, for example, since the weight of the nodes are spread across a large range of sizes with some extremely small and some very large, it can become challenging to create a data consistent display in which all nodes are visible. While these issues present interesting future challenges, our visualization is successful with our current data sets.

Our prototype visualization offers interactive tools for exploring ecological networks including highlighting, and various types of selections and filtering. These interactions are

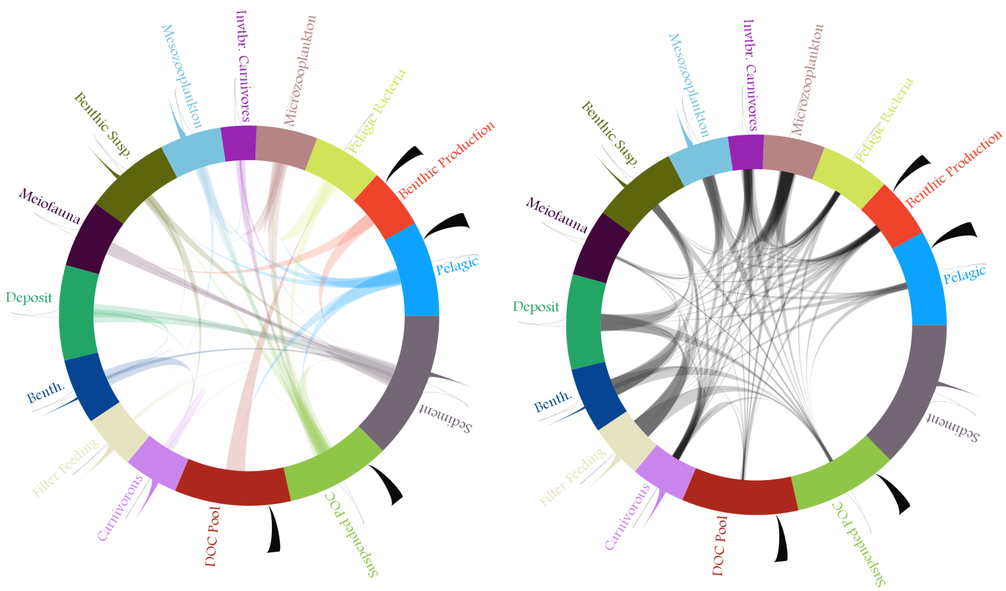


Figure 6.14: Left image, an example network with fifteen nodes, all exchange edges are displayed. Right image, the same example with fifteen nodes, instead of exchange edges, the total energy/matter flow between nodes are presented.

continually being refined through closer collaboration with ecologists and inclusion of more detailed descriptions of their task requirements. For example, this visualization tool currently includes indirect exchanges of energy, which is an important requirement for studying ecological networks [129]. Our collaborating ecologist team has reiterated the same point noted in [130]. We have addressed the issue of indirect exchange in our visualization, the discussion of which is provided in Section 6.5. For example, our tool shows cycles [130] and the total exchange of energy/matter between species.

We conducted a formal evaluation of Eco-Spio visualization, which is discussed in Chapter 7. The goal of this evaluation was to capture participants' feedback about the design decisions that we made for Eco-Spiro Visualization. Their feedback is very helpful for further improvement of the system.

6.8 Summary

In this chapter, we have presented Eco-Spiro Visualization, a tool specifically designed for representing ecological networks. Eco-Spiro uses a circle as the basic layout structure to provide an impression of the coherent system. While nodes are colored distinctly, edges are colored to match the node from which they emanated. This provides clear visuals of single level links. The circle layout also provides structure to visually present a clear delineation of internal and external factors. Nodes are angularly sized proportionally to their biomass and similarly edge widths are set by their weights. The tapered edges provide a representation of directionality. In addition, Eco-Spiro Visualization offers basic interaction techniques for highlighting and filtering that are linked to common ecosystem questions. These questions include showing adjacency for incoming and outgoing connections.

Including ecosystem specific analysis makes it possible to show such factors as indirect exchange quantities using the Leontief Matrix [129, 84].

Chapter 7

Evaluation and Discussion

In this Chapter, we describe the study conducted to asses our three novel graph visualizations. The goal of this study was to get feedback about the design of layouts used in these three visualizations. Our objective is to find out how our design decisions are perceived by our participants. We also collected useful feedback about participants' overall opinions about our designs.

We first describe the goals and other common aspects for our conducted studies in Section 7.1. Then we explain those parts of the procedure which are common between these three evaluations in Section 7.2. In Section 7.3 we gathered demographic information about our participants. Following that we report detail of each evaluation in separate sections. Section 7.4 contains details of evaluating Node-Ring Visualization. Section 7.5, explains the evaluation of Daisy Visualization, and Section 7.6 contains details about evaluating Eco-Spiro Visualization.

7.1 Goals

In this thesis, three new graph layouts and their applications to graph visualization are presented. These layouts have been inspired by decorative artworks and patterns, personally selected from different types of aesthetics. The mapping and visual encoding from the pattern to the graph is the outcome of several iterations. Also, there are several possibilities for particular aspects of each mapping (e.g. node weight, edge weight, directional versus symmetric arrangements). These graph layouts are all quite different from previous graph layouts. Since our purpose is to open up new avenues of exploration in graph layout possibilities, and it has been shown that rigorous comparison studies tend to favor the familiar *usability harmful*, we chose to run studies that explored people's reactions to these layouts. In our studies we were interested in what people think about the layouts in general and about specific design decision, in particular. Consequently, the main goal of our studies is to evaluate the layouts and the details of the visual encodings which we used in our graph visualizations. In our prototypes, we support some basic interactions, but evaluating these interactions is not the focus of our current study. Learning from these studies, we can potentially improve the layouts and the visual encodings that have been chosen. Such improved methods may be used for creating complete graph visualizations equipped with well-designed interactions and advanced techniques such as clustering, focus+context, and filtering (see Section 2.3). Developing such interactive graph visualizations is out of the scope of this thesis and left for future work. Therefore, the goals of our studies are to learn more about participants' responses to:

1. whether they find the layout (mapping) understandable,
2. what their preferences on specific design decisions are, and
3. what their general impression of the overall design are.

We approach to the first goal by asking our participants to perform some common tasks in graph visualization. As discussed in Section 1.4, adhering a given aesthetic may conflict with the mapping, being understandable. In other words, when designing our layouts, we often have to satisfy more constraints, due to adherence to the selected aesthetic, than common conventional layouts. Consequently, for the first goal, we have not tried to discover if a person's performance for a particular task is faster or slower. Instead we are interested in whether the mappings still support task comprehension. Thus we asked participants to perform common tasks using our visualization and we observed how these tasks can be done in our visualizations. This stage of our study also helps participants to better understand the layout and basics of our visual encodings. For the second goal, we simply asked our participants to compare different design decisions.

The intent of the third goal is to learn more about how the personal aesthetic choices, in our art inspired visualizations, are perceived by participants. We have had some initial feedback about the overall design of Eco-Spiro Vis from the ecologists we have worked with (refer to Section 6.7). One of their comments was: "I delight in the lovely organic forms by which the information is conveyed"[1] . This is a very interesting feedback reflecting the personal feeling of a domain expert. This kind of feedback is important, supportive and valuable. We wanted to explore this type of response further to understand more about people's response to the use of these aesthetic choices, including responses that may not be trigged or framed with specific tasks and/or questions. Instead, for receiving this type of qualitative feedbacks, we use an open ended semi structured interview with questions about the general impression and overall design.

7.2 Procedure

In this section, we provide the common aspects of the procedure used in all three studies. Our initial intention was to only evaluate Daisy and Eco-Spiro Visualizations. We started this with eight participants. Later, we realized that it is better to take the advantage of the setup and the procedure of the study to get feedback on Node-Ring as well. Therefore, we added Node-Ring Visualization in the evaluation and continued with eleven more participants. We also tried to reach out to our first eight participants and invited them for Node-Ring study. However, just five of them had time to come again and participate in Node-Ring evaluation. Therefore, we had sixteen participants evaluating Node-Ring Visualization and nineteen participants evaluating both Daisy and Eco-Spiro Visualizations.

In our study, after a short training session, the participants were asked to perform some common graph exploration tasks using our visualizations. We then got their evaluation and

[1]quotes in this section are from personal communications (with Mishtu Banerjee) and are used with permission.

feedback using questionnaire and interview.

The recruiting process was done through poster announcements at public places at the University of Calgary, sending email to mailing groups, and through word of mouth. See Appendix B for these recruitment announcements. Participants were asked to fill out a consent form which indicates their agreement to their opinions and feedback used in the future publications, as well as allowing for study sessions to be video recorded. Participants were also asked to indicate if they give us permission to use the video recording of the interview in publications. A sample of the consent form is also included in Appendix B.

Participants were then asked to fill a pre-questionnaire form regarding their demographic information. This pre-questionnaire includes questions about their age, gender, and their level of familiarity with data visualization. The pre-questionnaire is included in Appendix B.

We then provided a short training session with the help of a slide show presentation and live demo. In this presentation, our visualizations and the detail of their visual encodings were introduced. Slides of this presentation are included in Appendix B. Following the training session, we asked participants to perform a list of common graph exploration tasks (e.g. topology based tasks and attribute based tasks). For selecting the common tasks in graph visualization, we followed the classification that is provided in [82, 56]. The complete list of these tasks is provided in the following sections. Participants were requested to use our interactive visualization prototypes for performing these tasks. They were also asked to think aloud during performing tasks.

After finishing this stage, we requested the participants to fill a post-questionnaire regarding the visualization. This questionnaire includes questions about the visual encodings and participants' feedback about each design decision (refer to Appendix B for the post-questionnaire). In the final stage, we had a short interview with the participants and asked about their general impressions and overall feedback about the presented visualization. Participants' feedback is collected in Appendix A.

Participants had the choice to stop after each visualization's training session, and perform the tasks and fill post-questionnaire for that visualization, and then move to the next one, or have two or all three visualizations' training sessions first and then move to the tasks and post-questionnaire. This decision was made because there was no intention for comparing accuracy or speed of task performance. Three participants decided to have all three visualization training session together and start the tasks session and pos-questionnaire afterward. While 16 participants decided to have training, tasks and post-questionnaire for each visualization separately.

7.3 Participants

As explained in previous section, in these evaluations, nineteen participants were recruited for Daisy and Eco-Spiro evaluations and sixteen of them also participate in Node-Ring evaluations. These people ranged from 18 to 45 years old; both males and females; some students were from the University of Calgary; some work in the field of design; and some work in computer industry outside of the university.

More specifically, thirteen females and six males were recruited in these studies. Six participants aged from 18 to 25 years old, nine from 26 to 35, and four from 36 to 45. None of them were color blind. Three participants were undergraduate students, eight were Master students and eight were PhD students. Three participants were from art and design, one from medicine, one from molecular biology, four from engineering and ten from computer science.

Four participants had more than three years training, working or active interests in *Designing Artistic Patterns*; four had less than one year, and eleven had no experience in this field. Seven participants had more than three years training, working or active interests in *Graphs and Networks*; eight had one or two years, and four had no experience in this field.

Just two participants had about two years of training, working or active interests with

Ecological Networks, and the rest had no experience in this field.

Four participants reported a frequent use (more than a few times a week) of *data visualization systems, including viewing visualizations on the web*, while five reported few times a month, seven reported few times a year and three reported that they did not use them at all. Six participants reported few times per month they use *systems involving weighted directed graphs*, nine reported that few times per year and four reported that they did not use them at all. Six participants reported that they use *aesthetically pleasing visualization systems* few times per month, six reported few times per year and seven participants reported that they do not use them at all.

Three of our nineteen participants could not attend the second session for evaluating Node-Ring. These three participants were females who work outside of the university.

7.4 Evaluation of Node-Ring Visualization

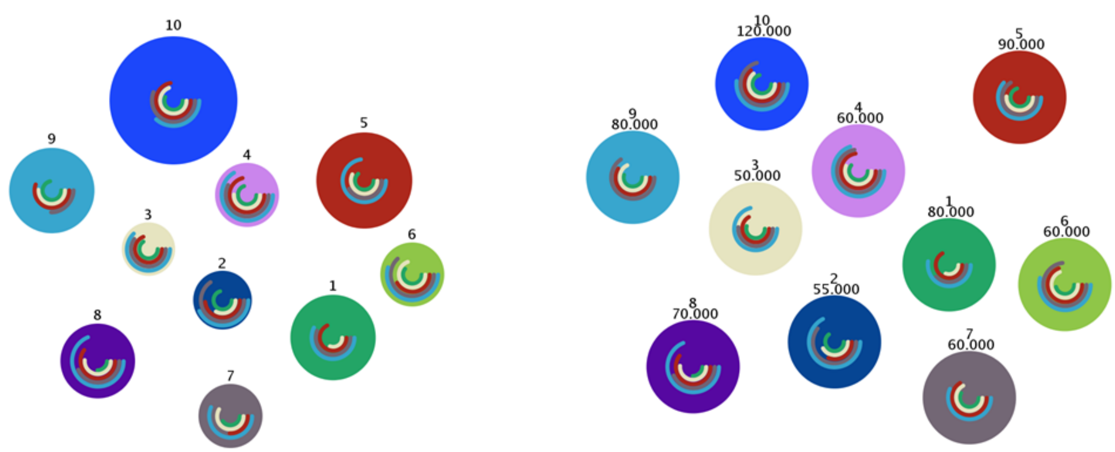


Figure 7.1: Two variations of Node-Ring Visualization for evaluation.

As discussed in Section 7.1, we intended to verify whether Node-Ring layout is understandable. Also, we wanted to get participants' feedback on visual encodings and design decisions. Representing weight and direction of edges (refer to Section 4.3) are important design decisions specific to Node-Ring.

7.4.1 Participants

As discussed in Section 7.3, we had 16 participants for this evaluation. These people ranged from 18 to 45 years old, and there were ten female and six male participating in this evaluation. See Section 7.3, for more details on participants demographics.

7.4.2 Setup

Participants were asked to complete the tasks on a computer system and then fill a paper-based questionnaire. The evaluation of Node-Ring Visualization was performed on desktop system with the use of mouse and keyboard for interaction. Participants had access to two screens during the navigation/interaction. Each screen has been used to display one of two design variations of Node-Ring Visualization for mappings of node's weights (see Section 4.3, also Figure7.1).

1. How many outgoing edges does node 1 have?
2. Which nodes are connected to node 8?
3. Between outgoing edges from node 8, which one is heaviest? Which one is lightest?
4. Is there an edge from node 3 towards node 4? Is there an edge from node 4 towards node 3?
5. Between nodes 2 and 9, which node has more outgoing edges?

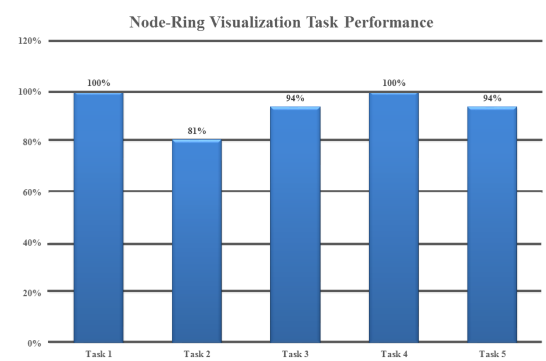


Figure 7.2: Task list for evaluating Node-Ring Visualization and the result of performance is presented. The y axis shows the accuracy of tasks for all participants.

7.4.3 Procedure and Analysis

As discussed in Section 7.2, we started with the learning session using a slide presentation. After that, we asked our participants to perform some tasks using our Node-Ring Visualization prototype for a graph with fifteen nodes (see Figure 7.1). These tasks, framed as questions, are

- Task 1: How many outgoing edges does node 1 have?
- Task 2: Which nodes are connected to node 8?
- Task 3: Between outgoing edges from node 8, which one is heaviest? Which one is lightest?
- Task 4: Is there an edge from node 3 towards node 4? Is there an edge from node 4 towards node 3?
- Task 5: Between nodes 2 and 9, which node has more outgoing edges?

Four of these tasks were inquiries about the graph connectivity and one was about the relative weights of the nodes. As shown in Table 7.2-Right, the accuracy (performances) of these tasks respectively are $100\%, 81\%, 94\%, 100\%, 94\%$.

We also asked our participants to evaluate design decisions in Node-Ring Visualization. The list of questions is provided in Table 7.1.

We have collected results of participants' response to these questions and assembled them into the chart shown in Table 7.2. More specifically feedback from 16 participants about our design decisions are as follows:

1. The idea of using color for mapping direction: 9 strongly agree, 5 agree, 2 neutral.
2. Replacing edges with rings: 2 strongly agree, 8 agree, 5 neutral, 1 disagree.
3. Mapping edge weights to the angular size of the rings (see Figure7.3): 8 strongly agree, 6 agree, 2 neutral.
4. Mapping edge weight to thickness of the rings (see Figure7.3): 1 strongly agree, 2 agree, 4 neutral, 6 disagree, 3 strongly disagree.

Please evaluate the following design decisions using the provided charts.

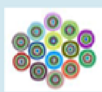
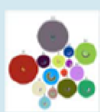
		Strongly disagree				Strongly agree
	The idea of using color for mapping direction	☐	☐	☐	☐	☐
	The idea of replacing edges with rings	☐	☐	☐	☐	☐
	Mapping edge weights to angular amount of the rings.	☐	☐	☐	☐	☐
	Mapping edge weights to the thickness of the rings.	☐	☐	☐	☐	☐
	Using random color pallet	☐	☐	☐	☐	☐
	Using color pallet from well-known paintings.	☐	☐	☐	☐	☐
	Mapping node's weight to the size of the circle	☐	☐	☐	☐	☐
	Highlighting outgoing edges for the selected node.	☐	☐	☐	☐	☐

Table 7.1: Post-questionnaire for evaluating Node-Ring Visualization.

5. Using random colors (see Figure7.4): 2 agree, 6 neutral, 6 disagree, 2 strongly disagree.

6. Using color palette from well-known paintings (see Figure7.4): 6 strongly agree, 4 agree, 4 neutral, 1 disagree, 1 strongly disagree.

7. Mapping node's weight to the size of the circle: 7 strongly agree, 5 agree, 3 neutral, 1 disagree.

8. Highlighting outgoing edges for a selected node: 13 strongly agree, 2 agree, 1 neutral.

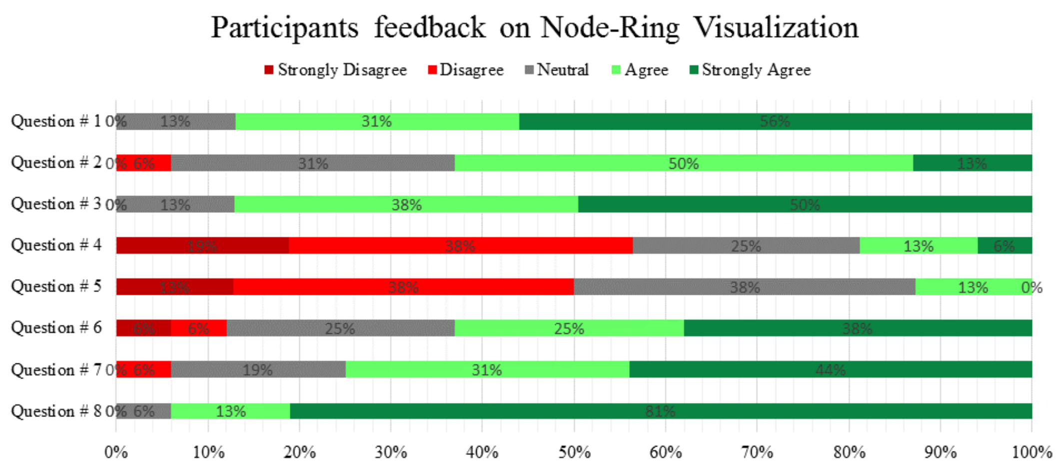


Table 7.2: Participants feedback about Node-Ring Visualization.

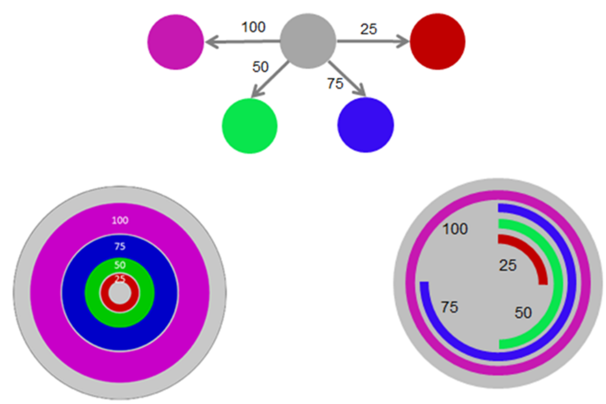


Figure 7.3: Two variations of mapping edge weights in Node-Ring Visualization.

Finally, for receiving qualitative feedback for overall design, we asked the following open ended question: "Please describe what you learned or found interesting about Node-Ring Visualization for weighted directed graphs during this session. There is no wrong answer". A box approximately the size of one third of the page was provided for answering this question. After filling this form, during a short interview, we asked the same question and gave a chance to the participants to express their feedback freely in narrative way. We have extracted the written and oral comments (from the captured video) and reported them in Appendix A. In the next section, we provide the result of this part too.

Figure 7.4: Left: random color palette for Node-Ring. Right: color palette extracted from "Silent Flowers" by Hundertwasser.

7.4.4 Results and Discussion

From the task performance results, we wanted to have a better sense whether the layout is understandable or not. We did not intend to use an accurate quantity to measure tasks performance, as we only studied one example graph with a small number of nodes. But as evidenced in Table 7.2, the performance result gives a good sense that our participants generally understood the layout and the concept of implicit connectivity using of the rings. The average percentage of these tasks is around %95. It seems that finding the incoming edges for each node is harder (%81) than finding the outgoing ones. This was somehow expected as a consequence of the nested definition. It did seem to be easier to find all nodes (large circles) with a certain color than finding all rings with a certain color inside of all nodes.

The questionnaire results (Table 7.2) clearly shows that the mapping edge weight to the angular size of the ring is better received than mapping weight to the thickness of the rings. Furthermore, the same results show that participants were in favor of using the color palette from Hundertwasser's painting than the random color palette. The idea of mapping node's weight to the size of the circle also received positive feedback. The idea of highlighting outgoing edges for the selected node(s) seems to be strongly well received by participants.

The participants were very supportive of the idea of color coding nodes and edges (Question 1) however they only moderately supported the idea of replacing edges by rings inside of the node (Question 2).

The written and oral comments about the general impression (refer to Appendix A for all comments) could be categorized to the followings:

- Perceiving the personal aesthetics: "clean and clear", "simple, minimal" , "love Hundertwasser's works", "use of arc is nice", "nice look", "tidy and clear", "cleaner", "arcs are nice", "using color to represent connections was interesting", "looks nice and colorful", "mapping node's weight to its size is nice and visual", "good for outgoing edges", "it is more artistic to efficient visualization"

- Supportive: "using arc is useful", "uncluttered", "less cluttered" (two comments), "mapping edges to arc is smart", "easy to find outgoing edges", "good for outgoing edges", "edge mapping quickly represents the connections they are more visual than click on the node", "good to have the option of selecting and moving nodes", "showing detail if necessary", "it was hard at the beginning but got easier when you get used to it"

- Critiques and suggestions: "not showing incoming edges", "weak for incoming edges", "better to show incoming edges too", "sometimes confusing to keep track on edges until you click on them", "not scalable", "not easy to scale", "fail for more nodes", "contrasts between colors are problem", "does not give you the whole perspective of data", "it is more artistic to efficient visualization", "hard to see understand the weight of edges".

According to these comments, in summary Node-Ring is nice, clean, clear, uncluttered and good for outgoing edges. On the other hand, it is not scalable, contrast between colors is difficult, weak for overview, and weak for incoming edges.

The issue of incoming edges was also captured from the questionnaire. This issue can be simply addressed by a simple interaction that highlighting *incoming edges* for each node. Our prototype originally, only supported highlighting outgoing edges. Now it is clear that we need to change this interaction and also show incoming edges.

The scalability is a more fundamental issue. There are a limited number of distinguishable colors to use for coding the nodes. Essentially, Node-Ring is better for smaller graphs. To address the salability for slightly larger graphs, in addition to a better color assignment, we can use other rendering attributes such as patterns, shades and textures for drawing the nodes. However, this is also not scalable to larger graph. A better solution is to use this layout in combination with the traditional layouts. For example, the default visualization could be Node-Ring (colorful and clean) but the traditional form of edges (line/curve) can be displayed on-demand for selected group(s) of nodes.

7.5 Evaluation of Daisy Visualization

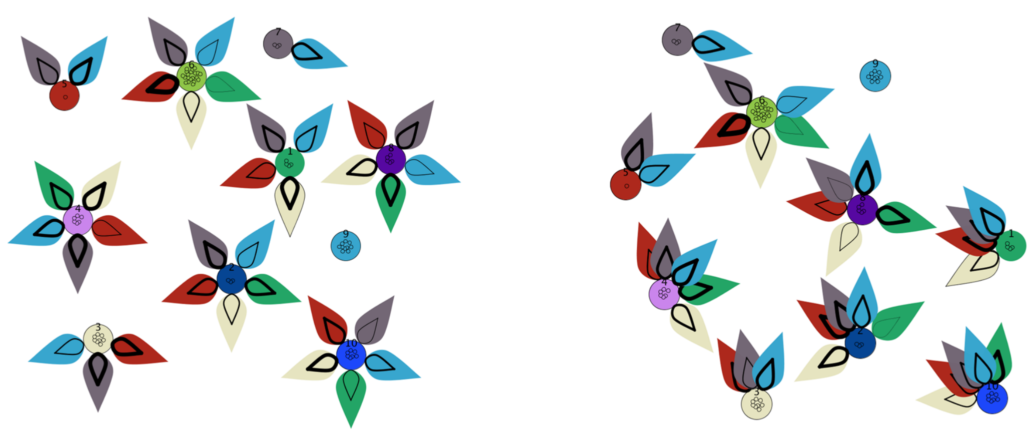


Figure 7.5: These two arrangements were presented to participants (left: symmetric, right: directional) and they are asked to perform tasks on them.

We need to verify whether Daisy layout is understandable, compare its design decisions (e.g. symmetric versus directional arrangements) and get the general impression of the overall design (refer to Section 5.3).

7.5.1 Participants

As discussed in Section 7.3, we had 19 participants for this evaluation. These people ranged from 18 to 45 years old, and there were thirteen female and six male participating in this evaluation. See Section 7.3, for more details on participants demographics.

7.5.2 Setup

Participants were asked to complete the tasks on a computer system and to fill a paper-based questionnaire. The computer setup for evaluating Daisy Visualization was a Microsoft Surface Pro with windows 8 OS using touch/stylus-pen interactions.

7.5.3 Procedure and Analysis

As discussed in Section 7.2, we started with a learning session through a slide presentation describing the basics of this layout and also both symmetric and directional arrangements (see Figure 7.5). We gave participants the opportunity of playing with both arrangements in an interactive environment. For doing this, we first asked them to do the simple task of arranging daisy flowers, using pen/touch, in such a way that nodes do not overlap. The average time they spent to perform this task for the same graph in Figure 7.5 was less than two minutes. After finishing their initial task, we asked them to perform the main tasks (some of the participants interestingly spent extra time to play and have fun with the design!). To reduce the workload of our participants, we asked them to perform the remaining tasks using only their preferred arrangement. We have tried to select a short list of tasks related to the connectivity of the graph and the visual encoding of weights:

- Task 1: Which node is the heaviest node in the graph?
- Task 2: What is the weight of node 1?
- Task 3: Which outgoing link from node 6 is the heaviest?

- Task 4: Which nodes are connected to node 9?
- Task 5: Compare node 6 to node 10, which one is heavier?

As summarized in Figure 7.6-Right, the accuracy (performances) of these tasks respectively are: $98\%, 100\%, 68\%, 74\%, 95\%$.

1. Which node is the heaviest node in the graph?
2. What is the weight of node 1?
3. Which outgoing edge from node 6 is the heaviest?
4. Which nodes are connected to node 9?
5. Compare node 6 to node 10 which node is heavier?

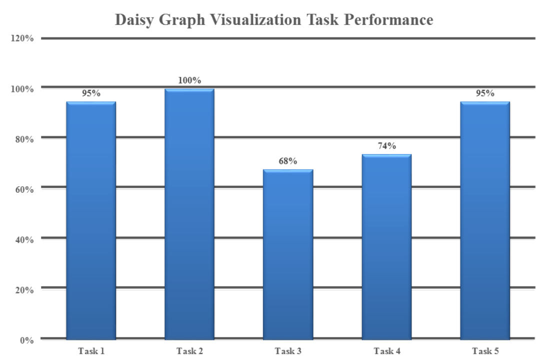


Figure 7.6: Task lists for evaluating Daisy Visualization and the results of the study performed on Daisy Visualization. The y axis shows the accuracy of tasks for all participants.

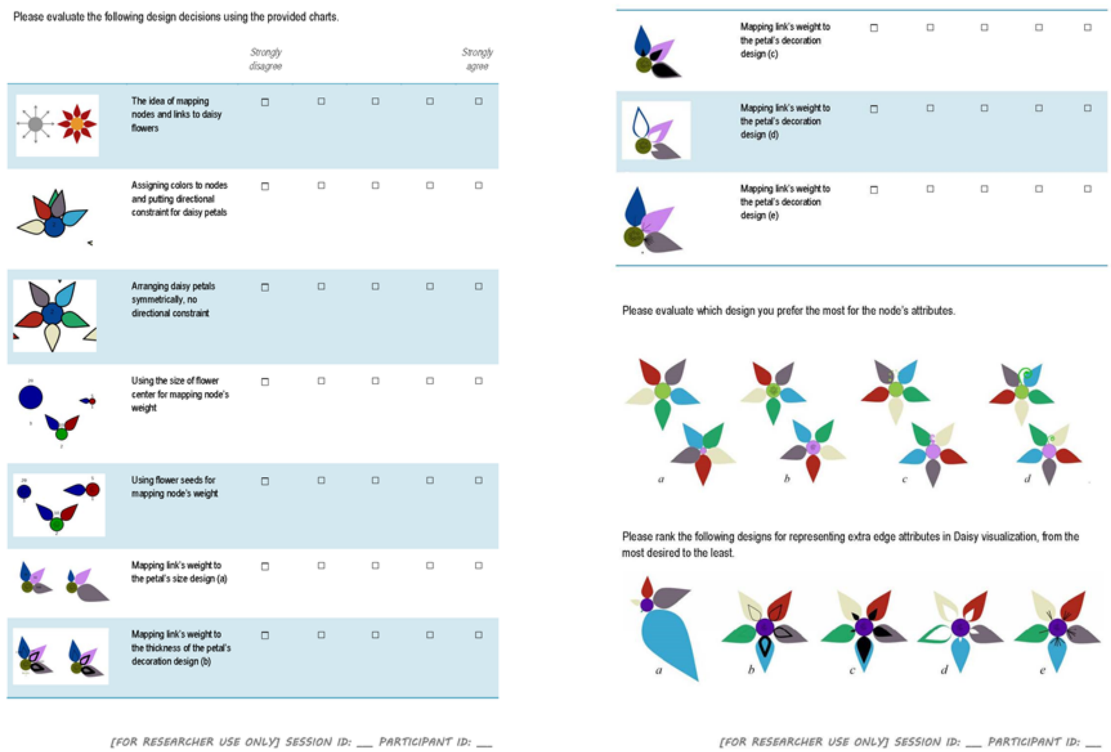
After finishing the tasks, we asked our participants to evaluate various design decisions for Daisy Visualization using a list of questions. This list is presented in the Table 7.3. We have collected the results of participants' response to these questions and assembled them into the chart shown in Table 7.4.

More specifically feedback from 19 participants about our design depictions are as follows:

1. Mapping nodes and edges to Daisy flowers: 10 strongly agree, 8 agree, 1 neutral.

2. Assigning colors to nodes and putting directional constraint for daisy petals (see Figure 7.7, left): 9 strongly agree, 6 agree, 3 neutral, 1 disagree.

3. Arranging daisy petals symmetrically (See Figure 7.7, right): 5 strongly agree, 5 agree, 2 neutral, 5 disagree, 2 strongly disagree.


Please evaluate the following design decisions using the provided charts.

	Strongly disagree				Strongly agree
The idea of mapping nodes and links to daisy flowers	☐	☐	☐	☐	☐
Assigning colors to nodes and putting directional constraint for daisy petals	☐	☐	☐	☐	☐
Arranging daisy petals symmetrically, no directional constraint	☐	☐	☐	☐	☐
Using the size of flower center for mapping node's weight	☐	☐	☐	☐	☐
Using flower seeds for mapping node's weight	☐	☐	☐	☐	☐
Mapping link's weight to the petal's size design (a)	☐	☐	☐	☐	☐
Mapping link's weight to the thickness of the petal's decoration design (b)	☐	☐	☐	☐	☐
Mapping link's weight to the petal's decoration design (c)	☐	☐	☐	☐	☐
Mapping link's weight to the petal's decoration design (d)	☐	☐	☐	☐	☐
Mapping link's weight to the petal's decoration design (e)	☐	☐	☐	☐	☐

Please evaluate which design you prefer the most for the node's attributes.

a b c d

Please rank the following designs for representing extra edge attributes in Daisy visualization, from the most desired to the least.

a b c d e

[FOR RESEARCHER USE ONLY] SESSION ID: __ PARTICIPANT ID: __

[FOR RESEARCHER USE ONLY] SESSION ID: __ PARTICIPANT ID: __

Table 7.3: Post-questionnaire for evaluating Daisy Visualization.

4. Using the size of the flower center for mapping node's weight (See Figure 7.8, left): 8 strongly agree, 4 agree, 6 neutral, 1 disagree.

5. Using flower seeds for mapping node's weight (a) (See Figure 7.8, right): 5 strongly agree, 5 agree, 2 neutral, 7 disagree.

6. Mapping edge weight to the petal's size (See Figure 7.10-a): 1 strongly agree, 5 agree, 5 neutral, 6 disagree, 2 strongly disagree.

7. Mapping edge's weight to the thickens of the petal's venation droplet (b) (see Figure 7.10-b): 6 strongly agree, 4 agree, 3 neutral, 6 disagree.

8. Mapping edge's weight to the droplet size (c) (see Figure 7.10-c): 4 strongly

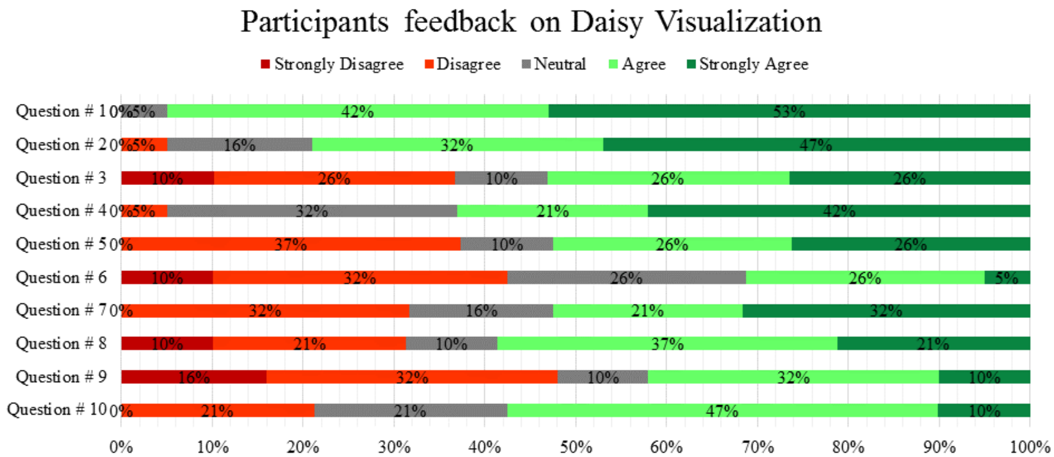


Table 7.4: Participants feedback about Daisy Visualization.

agree, 7 agree, 2 neutral, 4 disagree, 2 strongly disagree.

9. Mapping edge's weight to the droplet whose size is inverse proportional to the weight (d) (see Figure 7.10-d): 2 strongly agree, 6 agree, 2 neutral, 6 disagree, 3 strongly disagree.

10. Mapping edge's weight to the petal's venation lines (e) (see Figure 7.10-e): 2 strongly agree, 9 agree, 4 neutral, 4 disagree.

In the same questionnaire, we also provided four different floral designs for representing node's attributes (see Figure 7.9), and ask our participants to choose one as their desired design. The result shows that 10 participants picked the design (b), 5 picked the design (a), 3 picked the design (c), 1 picked the design (d) for representing node's attribute.

And finally, our participants were asked to select their favorite from our five different designs for representing edge's weight (see Figure 7.10). The result shows that 6 people chose the design (c), 5 the design (e), 4 the design (b), 3 the design (d) and 1 person selected the design (a) as their most desired design.

Similar to Node-Ring, to receive qualitative feedback for overall design, we asked the following open ended question: "Please describe what you learned or found interesting about Daisy Visualization for weighted directed graphs during this session. There is no wrong

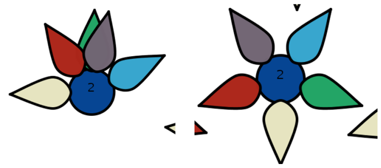


Figure 7.7: Left: Arrangement based on the directional constraint. Right: symmetric arrangement of petals.

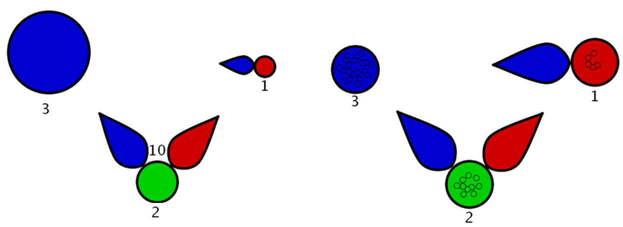


Figure 7.8: Mapping node's weight; Left:to the size of the flower; right to the number of the flower seeds.

answer". A box was provided for answering this question. After filling this form, during a short interview, we asked the same question and gave a chance to the participants to express their feedback freely in narrative way. We have extracted the written and oral comments (from the captured video) and reported them in Appendix A. In the next section, we provide the result of this part too.

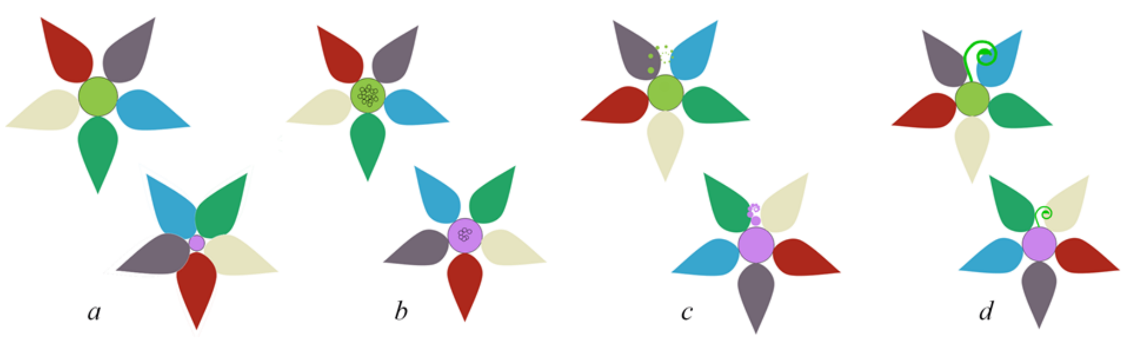


Figure 7.9: Four different designs for representing node's attributes in Daisy Visualization.

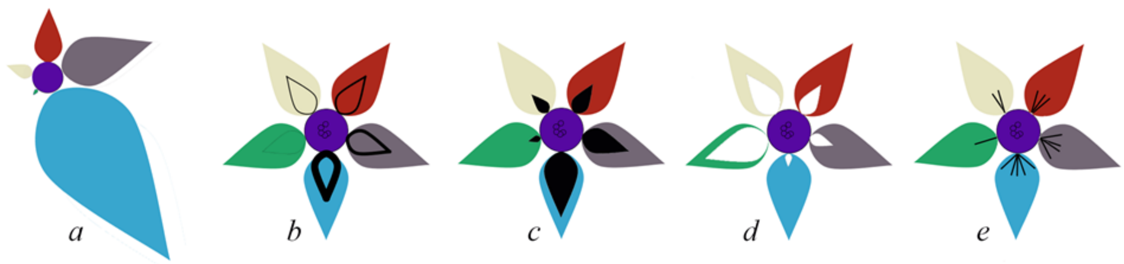


Figure 7.10: Mapping edge weight to daisy petals with five different designs.

7.5.4 Results and Discussion

As explained before, we are interested to know whether the layout is understandable and verify the design decisions. These aspects are captured through the analysis of the questionnaire after finishing the tasks. Our intended purpose for performing the tasks was to help participant to understand the basic layout and a specific subset of visual encodings and make them ready to fill the questionnaire. In addition, their performance can be used as a rough indicator to see if they understand the layout.

According to the results from the initial task (see Figure 7.5), ten participants preferred the first type of Daisy Visualization because the orientation of petal can help them to see the destination node. Also, they liked the effect that when they move a node, its petals, and petals of its adjacent flowers, rotate to maintain the directional constraint. On the other hand, nine participants liked the second type where daisy petals are arranged symmetrically. They found the petal/node color coding sufficient to find the destination nodes and preferred to have a more symmetric design. Also, they preferred the symmetric arrangement because petals overlapping is less. They also mentioned that the overall presentation of Daisy Visualization looks closer to the Daisy floral patterns when petals are arranged symmetrically.

The written and oral comments about the general impression (refer to Appendix A for all comments) could be categorized and summarize as follow:

- Perceiving the personal aesthetics: “appealing”, “interesting”, “less dunting”

, “colorful and organized look of natural forms”, “when all edges that are connected to one node are in same color they all pop out in my eyes”, “looks very cool”, “very pleasing”, “appealing to look at and interact with”, “interesting, nice and tidy arrangement of nodes”, “moving petals are enjoyable”, “it is interesting I haven’t seen anything like this before”, “it is interesting”, “the dynamic change of petals is interesting”, “it tries to have all features of graphs and look better”, “interesting”, “it is joyful, I like to keep playing with daisies” .

- Symmetric versus directed petal arrangements: “I prefer the symmetric model and follow just the colors”, “I liked the symmetric one it has less overlaps”, “I like the symmetric arrangements because I have freedom of moving them”, “the directional encourage deeper understanding of the visualization”, “I prefer non symmetric one”, “I prefer directional constraint one because it has more room to move nodes”, “I liked the directional constraint because moving petals is interesting touch”, “I prefer non-symmetric model easier to locate the nodes”, “symmetric model seems confusing”, “symmetric model is better when you want to see all nodes and non-symmetric model is better when you want to focus of directions”, “I liked the non-symmetric one”, “to see edge weights symmetric one is better and to see directions non-symmetric one is better”,

- Supportive: “the design choices for mapping is really smart”, “easy to see relative differences in weight of nodes and edges”, “it simplifies the visualization”, “I like the use of stem even for the selected node”, “it is clear with no edge crossing”, “easy to identify heavier nodes and edges”, “this color coordinating of edges with nodes is novel and helps to extract the connections”, “the elimination of overlapping is interesting”, “easy to see incoming edges and find the heaviest edge”, “the stem works well for ecological network”, “the use of stem for source of energy is good".

- Critiques and suggestions: "showing the proportional difference node size is better but to showing the numerical difference the flower seeds are better", "for someone with engineering background it is hard to switch to these new models", "It will be good to teach kids", "hard to see the edge weights", "a legend is needed for describing the attributes", "the flower seeds are not easy to see", "the stem works well for ecological network but not for selected node", "the use of stem for source of energy is good but not for the selected node".

These comments are very interesting and positive. In summary, our participants consider Daisy Vis to be interesting, appealing, pleasing, colorful and eye-popping which has smart design choices for simplifying the graph visualization. They were also supportive of its no edge cluttering effect, the use of the stem for the source of energy in ecosystems, and the color encoding.

In regards to comparison of the two arrangements, our participants were divided. Almost half (to be more accurate slightly less than half) of the participants preferred to use symmetric arrangement. The reasons provided for this choice are: it creates less petals overlap, it is easier to see the edge's weight, nodes can be moved freely, and relying on colors is enough for finding the connections. On the other hand, some other participants preferred the non-symmetric (directional constraint) arrangement. We found their reasons interesting: emphasizes on the direction helps for finding connections, it feels more enjoyable and interesting, and connections can be seen easier.

Some of our participants raised the issue of not seeing weights clearly. But this is not specific to our design decision. Any visual coding of the weights has the same problem. In essence, it is hard to recognize the exact numeric values from a visual encoding of those measures. This encoding gives only a visual clue for the relative differences (as correctly captured by some of our participants). A simple touch/mouse interaction can reveal the exact numeric attributes of the selected nodes. However, we intended to not disturb the beauty of the pattern with extra numbers/labels.

In summary, the result of this study can be used to narrow down some of the possible choices for encoding weights and attributes (see Table 7.4). For encoding edge weight, it seems that the resizing petals (see Figure 7.10) is not a reasonable choice in compare with the other possibilities (see the same figure). Also, it seems for the node weight, there is a strong preference to use flower seeds. Notice that in practical applications we may have multiple attributes for nodes and edges. This is clearly the case of ecological networks. Therefore, we may have to use many of the possibilities to encode multiple attributes. For such cases, perhaps a good strategy is to assign more desired encodings to more frequent attributes.

Unfortunately, based on the results of this study, it is hard to finalize our decision for using symmetric or directional arrangements. Perhaps providing both options is a fair decision.

7.6 Evaluation of Eco-Spiro Visualization

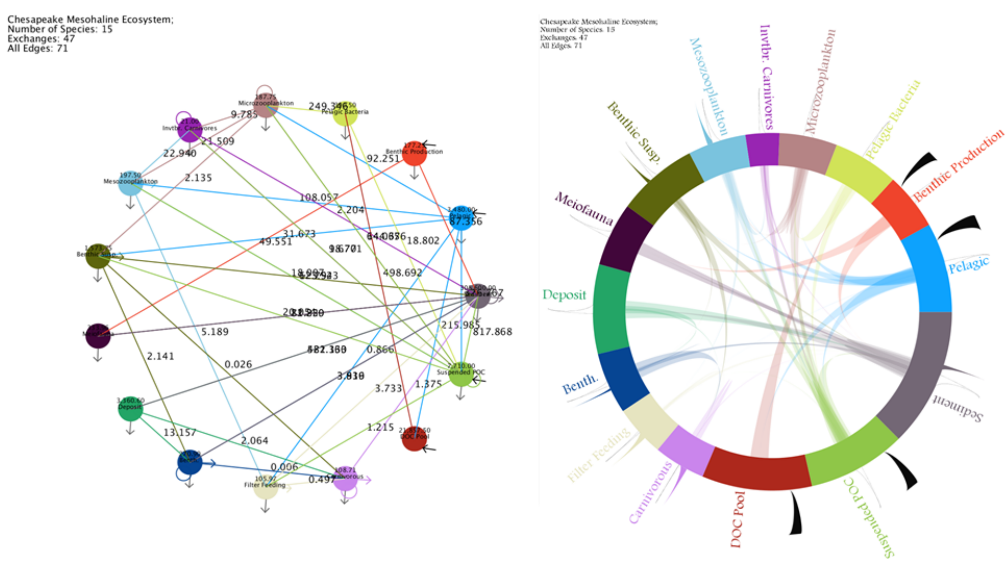


Figure 7.11: The setup for evaluation of Eco-Spiro Visualization.

Our study for Eco-Spiro is generally similar to other studies which are discussed in this chapter. Since this visualization has been designed for representing ecological networks (in its general form), we were particularly interested to evaluate the specific aspects and design decisions related to these networks (e.g. inputs, outputs, respirations and exchanges) (refer to Section 6.5).

7.6.1 Participants

We had 19 participants for this study too. These people ranged from 18 to 45 years old, and there were thirteen female and six male participating in this evaluation. Refer to Section 7.3, for more details on participants demographics.

7.6.2 Setup

Participants were asked to complete the tasks on a computer and to fill a paper-based questionnaire. The evaluation of Eco-Spiro Visualization was performed on desktop system with mouse and keyboard interactions. They had access to two screens during the navigation. As shown in Figure 7.11, one screen was set to show ecological network with the traditional node-link visualization, and the other one for displaying the same network with Eco-Spiro Visualization. In the traditional node-link visualization of ecological network, we depicted details of data with simple texts and lines.

7.6.3 Procedure and Analysis

In this evaluation, we asked our participants to perform some tasks with Eco-Spiro Visualization prototype. We requested them to use the traditional graph representation, side by side, as their reference (see Figure 7.11). Both Eco-Spiro Visualization and the traditional graph visualization were interactive. In the traditional model participants can select a node and move it to have a better view of its links. Also in Eco-Spiro, they were able to select a node to highlight its connections. Colors of the nodes are matched in both visualizations. For example when *Pelagic* is represented with blue in the traditional model, it appears with the exact same color in Eco-Spiro model (see Figure 7.11). In the training session, we clarified for the participants that the goal is not to compare these two visualizations but to focus on the design decisions in Eco-Spiro. Then, we asked them to answer some questions while working with the system. Based on the categorization introduced in [82], we tried to select a short list of tasks that are a combination of topology based and attribute based tasks:

1. Task 1: Find the node with the most number of outgoing exchanges. How many are they?

2. Task 2: Is there an edge between *Micro-zooplankton* and *Meiofauna*?

3. Task 3: Which node has no respiration edge?

4. Task 4: Name two nodes of the ecosystem which do not have any output link,

5. Task 5: Name two nodes which receive energy from outside of ecosystem.

The performance result of these tasks is reported in the Figure 7.12. As summarized in this table, the accuracy of these tasks respectively are: $74\%, 100\%, 100\%, 96\%, 100\%$.

1. Find the node with most outgoing exchange edges. How many are they?
2. Is there a link between *Micro-zooplankton* and *Meiofauna*?
3. Which node has no Respiration edge?
4. Name two nodes of the ecosystem which do not have any Output link.
5. Name two nodes which receive energy from outside of ecosystem.

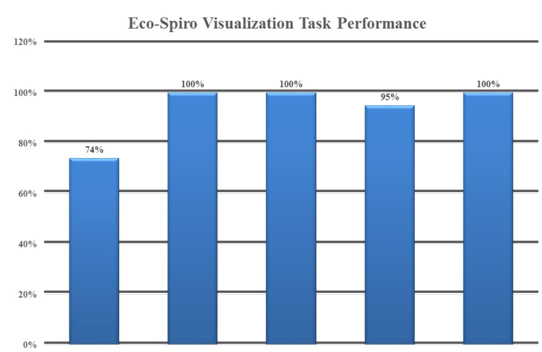


Figure 7.12: Task list for evaluating Eco-Spiro Visualization and the result of performance is presented. The y axis shows the accuracy of tasks for all participants.

We also asked our participants to evaluate several of the design choices and decisions related to Eco-Spiro Visualization. The list of these questions is presented in Table 7.5. The result collected from this evaluation is gathered in the Table 7.6.

Please evaluate the following design decisions using the provided charts.

	Strongly disagree				*Strongly agree*
The idea of dividing the space into internal and external	☐	☐	☐	☐	☐
Using spike shapes for directed edges rather than arrowhead links	☐	☐	☐	☐	☐
Mapping species biomasses with angular amount of the arc section	☐	☐	☐	☐	☐
Fading the color of the exchange links, inside the circle.	☐	☐	☐	☐	☐
Assigning color to each node	☐	☐	☐	☐	☐
The arrangement of labels	☐	☐	☐	☐	☐
The query chart on the top left corner, indicating the size of the network	☐	☐	☐	☐	☐

Table 7.5: Post-questionnaire for evaluating Daisy Visualization.

These questions and feedback from our 19 participant are as follows:

1. Dividing the space into internal and external: 14 strongly agree, 5 agree.
2. Using spike shapes for directed edges rather than arrowhead links: 8 strongly agree, 6 agree, 4 neutral, 1 disagree.
3. Mapping species' biomass to angular size of the arc section: 10 strongly agree, 4 agree, 4 neutral, 1 disagree.
4. Fading the color of exchange links: 10 strongly agree, 5 agree, 1 neutral, 3 disagree.
5. Assigning color to each node: 17 strongly agree, 1 agree, 1 neutral.

6. The arrangement of labels: 8 strongly agree, 7 agree, 1 neutral, 1 disagree, 2 strongly disagree.

7. The query chart, indicating the size of the network: 9 strongly agree, 3 agree, 2 neutral, 3 disagree, 2 strongly disagree.

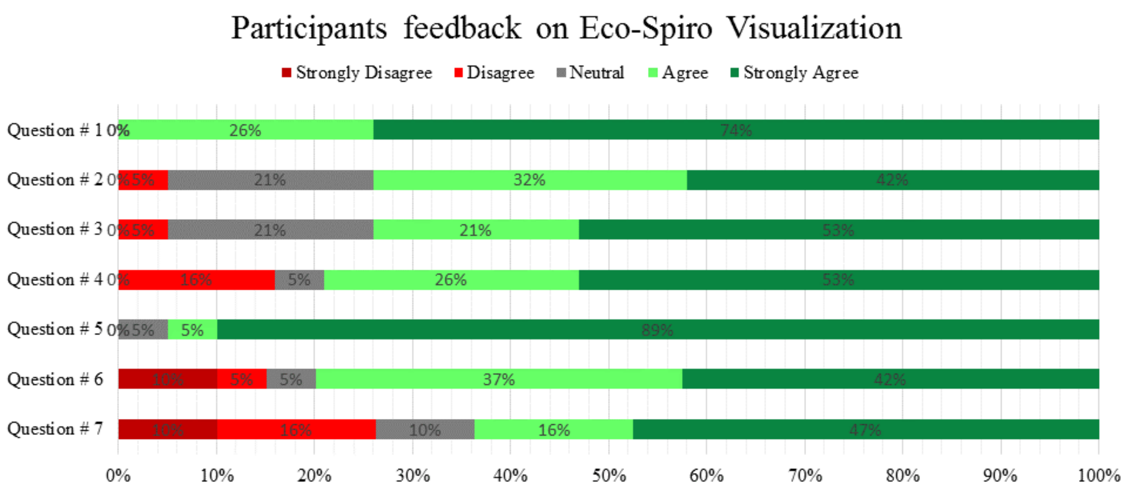


Table 7.6: Participants feedback about Eco-Spiro Visualization.

Similar to other studies, we asked the following open ended question: “Please describe what you learned or found interesting about Eco-Spiro Visualization for weighted directed graphs during this session. There is no wrong answer”. After filling the provided form, during a short interview, we asked the same question and gave a chance to participants to express their feedback freely in narrative way. As other studies, we have extracted the written and oral comments (from the captured video) and reported them in Appendix A.

7.6.4 Results and Discussion

There are two groups of tasks. The first group(internal) is related to exchange relationships inside the ecosystem (tasks 1 and 2), and the second group (external) is about the relationship between ecosystem and its outside (external). The results show that the external tasks were easier for participants. All three questions were answered very accurately

$(100\%, 95\%, 100\%)$. It seems that separating the space into internal and external and encoding the output, the input and the respiration edges in different ways are good reasons for this perfect performance. This has been confirmed in our post-questionnaire as well. For the first group of tasks (1 and 2), the performance of the task 1 is low. It seems that our participants had problems in finding the number of outgoing exchanges. On the other hand, they were able to check accurately whether two given nodes are adjacent or not.

The results of the questionnaire (see Table 7.5) are generally very supportive of our decisions. The distribution of the answers to the question 7 is more scatted and less supportive (5 disagree in total), however this question is about the query chart which is not a fundamental feature of our Eco-Spiro Visualization.

The written and oral comments about the general impression (refer to Appendix A for all comments) could be categorized to the followings:

- Perceiving the personal aesthetics: "very appealing", "it is aesthetically pleasing and readable", "aesthetically pleasing", "enjoyed colors and shapes", "looks nice", "looks modern and appealing", "beautiful", "interesting visualization".

- Supportive: "input arrows are visible", "I like the input/output connections and separating the space more clear than traditional one", "less cluttered", "not as cluttered as traditional one", "able to discern information very quickly", "readable", "less cluttered", "I like the input edges", "fading is smart", "it is interesting that all nodes and edges between them are inside the system", "I like the idea of separating space", "I like it when you can see all nodes and connections in only one frame", "highlighting the selected node is useful", "it is easy to find input/outputs".

- Critiques: "some middle connections are not visible", "hard to read labels upside-down I refer all of them horizontal", "it is hard to see the loop links", "hard to see the end of exchange edges", "I didn't like respiration edges", "hard to see the end of edges", "not easy to see the end of exchange edges", "hard to see exchange edges when their weight is low", "didn't like the input black edge", "not easy to see the end and the weight".

- Suggestion: "expand the selected node and show all exchange edges beside each other so it is easier to see their weights", "I think using green for input energy and black for wasting is better", "labels are hard to read upside-down".

According to these comments, in summary Eco-Spiro is appealing, aesthetically pleasing, nice, modern and beautiful. Its input and output edges are very clear, less cluttered and it is readable. Once again, the idea of separating the space is supported.

On the other hand, a common and frequent issue raised by many participants is the visibility issue of the end of the exchange edges. We guess one of the source of this problem is the faded colors of the edges. As possible solutions to this issue, one may tweak the coloring of the exchange edges. Also, the thickness of the spikes can be increased near to the destination node. The downside of these color and shape tweaking is that they may impact the overall design and the appeal of Eco-Spiro.

As suggested by one of the participants, it is very interesting to use a focus+context technique designed especially for this layout. We have left this as an opportunity for future work.

7.7 Summary

The timing and design of an evaluation is important. Though usability evaluations with precise measures (like time and accuracy), have an important role in improving interfaces, it has been noted that running these studies at early stages limits the creativity of the design process [51]. Therefore, in order to improve our three visualizations, we first needed to better understand people's responses. The next step would be to add interactive exploration tools based on the expert needs of ecologists, which would require a second round of interviews. We recognize that the study described in this chapter is only a first step in a full evaluation process.

In this chapter we presented the outcome of the study that we conducted for evaluating three novel graph visualizations. Participants' feedback support the overall design for all three visualizations. Furthermore, they provided us with useful comments about our design decisions, which we will use to improve the design of these visualizations.

Chapter 8

Conclusion and Future Work

In this thesis, three novel graph layouts and their applications to graph visualization have been presented. These layouts were inspired by decorative artworks and patterns, personally selected from different types of aesthetics. Through our exploration, we have shown that any intriguing pattern, mesmerizing ornament or exciting art piece could be used as the source of inspiration for new layouts. On the other hand, we have discussed the difficulties for creating a mapping between the input graph and the selected pattern. To create this mapping, we have used a design process involving several design iterations for each visualization.

The first graph visualization introduced in this thesis is Node-Ring. The layout used for Node-Ring was inspired by Australian dot painting and Hundertwassers paintings. In this visualization, concentric circles are used for an implicit representation of edges (i.e. information about edges are included without explicitly drawing them as links). Node-Ring is a clean and nit representation and can reduce the issue of edge congestion in small size graphs. Also, it can be combined with node-link for larger graphs.

Daisy Vis is our second graph visualization, inspired by ornamental patterns of daisy flowers. In this visualization, nodes, edges and other features of data are mapped to some floral elements. More specifically, nodes are replaced by a colored circle as the flower's center and edges by petals of that flower. Petals can be arranged in two different ways. In the first arrangement (i.e. directional constraint) the direction of each petal points to the destination node. In the second arrangement, we distribute petals symmetrically around the node. For the second arrangement (symmetric), we need to use a specific color coding where the color of the petal is the same as the color of the destination node. We have used Daisy Vis for visualizing ecological networks of real ecosystem data-sets. We have extended the initial visual encoding of this visualization to support specific attributes of ecological networks (e.g. input/ouput edges, respiration).

Our third graph visualization is Eco-Spiro specifically designed for ecological networks. The layout used for this visualization is a modification of Spirograph, which is another novel graph layout introduced in this thesis. Spirograph is a circular layout using a circle (the boundary circle) for placing nodes. Edges in Spirograph are mapped to arcs connecting nodes. This circle has an organic form for showing the closeness of ecosystem and for separating the environment into its internal and external spaces. Eco-Spiro visualizes both the direct and indirect quantities related to the flow of energy and matter between species in an ecosystem.

To evaluate our novel graph visualizations, we conduct three studies. The main goals of these studies are to evaluate the overall designs of our layouts and the design decisions for each visualization. In general, based on the feedback from participants, they liked the idea of representing graph with decorative patterns. They mentioned it is more interesting and in most cases even more clear that traditional representations. Some of our design decisions received extra positive feedback, like replacing edges with colored rings in Node-Ring, or mapping edge weights inside daisy petals in Daisy, and specially the idea of separating space into internal and external in Eco-Spiro Visualization for representing ecological network.

In summary, this thesis offers several contributions. One of these contributions is to frame a methodological approach for turning artistic patterns to new graph layouts for novel graph visualizations. We have also designed three new graph layouts: Node-Ring, Daisy, and Spirograph. We have used these layouts for prototyping three visualizations with basic interactions. Particularly, we have used Spirograph layout for creating Eco-Spiro, a visualization tool for Ecological networks that provides interactions tuned to ecosystems, calculates and displays indirect effects of ecosystem dynamics. Also, our conducted studies provide valuable insights and feedback on the proposed graph visualizations.

8.1 Future Work

There are several possible future directions for this work. Developing a complete graph visualization based on each of our three prototypes is one of these possibilities. In essence, we have introduced alternatives for node-link and adjacency matrix layouts. Many graph visualizations are based on these two traditional layouts. Currently, there are several state-of-the-art graph visualization systems by which advanced techniques such as clustering, focus+context, and filtering are employed. After the success of our visualization prototypes and the valuable feedback from our studies, it will be interesting to explore the use of our alternative layouts in combination with traditional layouts to develop advanced graph visualizations with similar features. The resulting hybrid graph visualizations may address the scalability issue and could be compared, using appropriate evaluations, with conventional graph visualizations.

The scalability issue has a more noticeable impact on Node-Ring. There is a limited number of distinguishable colors to use for coding of nodes. It is possible that a hybrid layout equipped with advanced visualization techniques could be the ultimate solution for this issue. However, it is also possible to incrementally improve Node-Ring. One can explore various color palettes to find one with more noticeable differences. In addition to a better color assignment, other rendering attributes such as patterns, shades and textures can be employed for drawing the nodes.

We used ecological networks as a practical use case for this thesis. Starting with other use cases like genomic data [125] or social networks [115], and applying the same design process could potentially create new insights for developing new layouts or improving the current layouts. Ecological networks, even for a small sized system, are usually very complex. Several indirect quantities (e.g. trophic level) are usually needed and could potentially be evaluated and displayed in the visualization tool. Currently, as a proof-of-concept, in our prototype we only display one of these quantities (throughput). Using a simple m-file of

Matlab, we compute throughput from Equation 6.3 and save the resulting matrix as a part of the data-set. A complete visualization for an ecosystem might do this on-fly within the visualization system. Additionally, interactions for ecological networks should be designed based on the needs and requirements of ecosystem experts/scientists.

Finding the position of nodes in Daisy Vis is currently done in an interactive manner. For a specific network, a good arrangement of nodes and other attributes (e.g. respiration) can be saved and re-used later. This interactive approach may be challenging for larger graphs. Nodes have different degrees and their positions also can change the direction of petals. A possible avenue for future research is to model the arrangement to an optimization problem. Although, the optimization techniques used in graph drawing [30] maybe useful here, Daisy Visualization arrangement seems to be a much more complex problem. The existence of several types of attributes, the impact of petals' direction and the degree of nodes can visually impact the arrangement and therefore could be included in the optimization model.

8.2 Summary

In Summary I have learned that many intriguing patterns, mesmerizing ornaments or exciting art pieces can be a source of inspiration for new layouts. The contribution of this thesis can be summarized as follows:

1. A design process to turn artistic patterns to new graph layouts for novel graph visualizations.

2. Node-Ring Visualization , inspired from Hundertwasser's contrasting colorful circle patterns and Australian aboriginal dot paintings.

3. Daisy Visualization, inspired from daisy ornamental decorative patterns.

4. Eco-Spiro Visualization, inspired from Spirograph patterns, and designed specifically for visualizing ecological networks.

5. Empirical response to design decisions for each of the three introduced visualizations.

Also limitations can be categorized as follows:

1. Node-Ring and Daisy Visualizations are designed based on color coding nodes with contrasting and distinguishable colors, which makes them hard to scale for larger graphs [142].

2. The well-known problem in organizing labels [44] occurs in all three visualizations but is particularly noticeable in Eco-Spiro Visualization, where sometimes labels are shown upside-down.

3. In ecological network it is possible to have loop edges, which are not well designed in the Eco-Spiro Visualization.

4. The learning curve for all three of these visualization needs to be considered.

5. The choice of aesthetic patterns was personal. Thus it is possible that patterns which were selected might not be acceptable by participants.

Furthermore, here are several possible future directions for this research:

1. Developing a complete graph visualization based on each of our three prototypes would be an interesting challenge. This might be approached by combining them with traditional graph layouts and developing advanced graph visualizations with integrated features.

2. In Node-Ring Visualization, in addition to a better color assignment, other rendering attributes such as patterns, shades and textures could be employed for drawing the nodes.

3. Other cases like genomic data or social networks can be used in application of any of the three visualizations.

4. The indirect quantities in ecological network could be included for visualization in Node-Ring and Daisy Visualizations.

5. Other indirect quantities of ecological network could be visualized in Eco-Spiro Visualization.

6. Based on ecologists needs other interactive tools for exploring and analyzing ecosystem could be provided in each of these visualizations.

7. The arrangement of nodes and their various attributes may be modeled through applying an optimization approach.

Bibliography

[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; 1969 :https://www.flickr.com/photos/gandalfsgallery/10165932273/.

[4] Quran khodava. In *Kian ketab publisher*, Tehran, Iran, 1999. Kian Ketab.

[5] James Abello, Stephen G. Kobourov, and Roman Yusufov. Visualizing large graphs with compound-fisheye views and treemaps. In *Proceedings of the 12th international conference on Graph Drawing*, GD'04, pages 431–441, Berlin, Heidelberg, 2004. Springer-Verlag.

[6] James Abello, Frank Van Ham, and Neeraj Krishnan. Ask-graphview: A large scale graph visualization system. *Visualization and Computer Graphics, IEEE Transactions on*, 12(5):669–676, 2006.

[7] Haleh Alemasoom, Faramarz F. Samavati, John Brosz, and David Layzell. Interactive visualization of energy system. In *International Conference on Cyberworlds (CW) 2014*, pages 229–236. IEEE Computer Society, Oct 6-8 2014.

[8] Stefano Allesina and Mercedes Pascual. Food web models: A plea for groups. *Ecology Letters*, 12(7):652–662, 2009.

[9] Basak Alper, Benjamin Bach, Nathalie Henry Riche, Tobias Isenberg, and Jean-Daniel Fekete. Weighted graph comparison techniques for brain connectivity analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 483–492. ACM, 2013.

[10] Answers.com. Paisley. http://www.answers.com/topic/paisley-1#cite-note-GH-1, September 2009.

[11] Daniel Archambault, Tamara Munzner, and David Auber. Topolayout: Multilevel graph layout by topological features. *Visualization and Computer Graphics, IEEE Transactions on*, 13(2):305–317, 2007.

[12] Fred Attneave. Symmetry, information, and memory for patterns. *The American journal of psychology*, pages 209–222, 1955.

[13] David Auber. Tulipa huge graph visualization framework. In *Graph Drawing Software*, pages 105–126. Springer, 2004.

[14] Benjamin Bach, Emmanuel Pietriga, Ilaria Liccardi, and Gennady Legostaev. Ontotrix: a hybrid visualization for populated ontologies. In *Proceedings of the 20th international conference companion on World wide web*, WWW '11, pages 177–180, New York, NY, USA, 2011. ACM.

[15] Daniel Baird and Robert E Ulanowicz. The seasonal dynamics of the chesapeake bay ecosystem. *Ecological Monographs*, 59(4):329–364, 1989.

[16] Michael Balzer, Oliver Deussen, and Claus Lewerentz. Voronoi treemaps for the visualization of software metrics. In *Proceedings of the 2005 ACM symposium on Software visualization*, pages 165–172. ACM, 2005.

[17] Vladimir Batagelj, Franz J. Brandenburg, Walter Didimo, Giuseppe Liotta, Pietro Palladino, and Maurizio Patrignani. Visual analysis of large graphs using (x,y)-clustering

and hybrid visualizations. *IEEE Transactions on Visualization and Computer Graphics*, 17(11):1587–1598, November 2011.

[18] Giuseppe Di Battista and Fabrizio Frati. A survey on small-area planar graph drawing. *CoRR*, abs/1410.1006, 2014.

[19] Paola Bertolazzi, Giuseppe Di Battista, Giuseppe Liotta, and Carlo Mannino. Upward drawings of triconnected digraphs. *Algorithmica*, 12(6):476–497, 1994.

[20] Spirache Bogdan. Guilloche generator 1.0, March 2015.

[21] John Adrian Bondy and Uppaluri Siva Ramachandra Murty. *Graph theory with applications*, volume 290. Macmillan London, 1976.

[22] Rita Borgo, Johannes Kehrer, David H Chung, Eamonn Maguire, Robert S Laramee, Helwig Hauser, Matthew Ward, and Min Chen. Glyph-based visualization: Foundations, design guidelines, techniques and applications. *Eurographics State of the Art Reports*, pages 39–63, 2013.

[23] Gilles Brassard and Paul Bratley. *Fundamentals of algorithmics*, volume 133350681. Prentice Hall Englewood Cliffs, 1996.

[24] M Burch, H Schmauder, A Panagiotidis, and D Weiskopf. Partial link drawings for nodes, links, and regions of interest. In *Information Visualisation (IV), 2014 18th International Conference on*, pages 53–58. IEEE, 2014.

[25] Nick Cawthon and Andrew Vande Moere. The effect of aesthetic on the usability of data visualization. In *Information Visualization, 2007. IV'07. 11th International Conference*, pages 637–648. IEEE, 2007.

[26] Fan Chloe. Spark: Visualizing physical activity using abstract ambient art, 2014.

[27] William S Cleveland and Robert McGill. Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American statistical association*, 79(387):531–554, 1984.

[28] Christian Collberg, Stephen Kobourov, Jasvir Nagra, Jacob Pitts, and Kevin Wampler. A system for graph-based visualization of the evolution of software. In *Proceedings of the 2003 ACM symposium on Software visualization*, pages 77–212. ACM, 2003.

[29] Willem C de Leeuw and Jarke J van Wijk. A probe for local flow field visualization. In *Visualization, 1993. Visualization'93, Proceedings., IEEE Conference on*, pages 39–45. IEEE, 1993.

[30] G. Di Battista, P. Eades, R. Tamassia, and I.G. Tollis. *Graph Drawing: Algorithms for the Visualization of Graphs.* Prentice-Hall, 1999.

[31] Giuseppe Di Battista, Peter Eades, Roberto Tamassia, and Ioannis G Tollis. Algorithms for drawing graphs: an annotated bibliography. *Computational Geometry*, 4(5):235–282, 1994.

[32] Sergey N Dorogovtsev and Jose FF Mendes. Evolution of networks. *Advances in physics*, 51(4):1079–1187, 2002.

[33] Peter Eades and Xuemin Lin. Spring algorithms and symmetry. *Theoretical Computer Science*, 240(2):379–405, 2000.

[34] Herbert Edelsbrunner and Raimund Seidel. Voronoi diagrams and arrangements. *Discrete & Computational Geometry*, 1(1):25–44, 1986.

[35] Markus Eiglsperger, Martin Siebenhaller, and Michael Kaufmann. An efficient implementation of sugiyama's algorithm for layered graph drawing. In *Graph Drawing*, pages 155–166. Springer, 2005.

[36] Ahmed Elgammal, Ramani Duraiswami, David Harwood, and Larry S Davis. Background and foreground modeling using nonparametric kernel density estimation for visual surveillance. *Proceedings of the IEEE*, 90(7):1151–1163, 2002.

[37] Sacha Epskamp, Angélique O.J. Cramer, Lourens J. Waldorp, Verena D. Schmittmann, and Denny Borsboom. qgraph: Network visualizations of relationships in psychometric data. *Journal of Statistical Software*, 48(4):1–18, 5 2012.

[38] Ozan Ersoy, Christophe Hurter, Fernando Paulovich, Gabriel Cantareiro, and Alex Telea. Skeleton-based edge bundling for graph visualization. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2364–2373, December 2011.

[39] Katayoon Etemad, Dominikus Baur, John Brosz, Sheelagh Carpendale, and Faramarz F. Samavati. Paisleytrees: A size-invariant tree visualization. *EAI Endorsed Transactions on Creative Technologies*, 14(1), 10 2014.

[40] Katayoon Etemad and Sheelagh Carpendale. Shamsehtrees: Providing hierarchical context for nodes of interest. In Craig S. Kaplan and Reza Sarhangi, editors, *Proceedings of Bridges 2009: Mathematics, Music, Art, Architecture, and Culture*, pages 293–300. Tarquin Books, 2009.

[41] Katayoon Etemad, Sheelagh Carpendale, and Faramarz Samavati. Node-ring graph visualization clears edge congestion. *Proceedings of the IEEE VIS Arts Program (VISAP)*, pages 67–74.

[42] Katayoon Etemad, Sheelagh Carpendale, and Faramarz Samavati. Spirograph inspired visualization of ecological networks. In *Proceedings of the Workshop on Computational Aesthetics*, pages 81–91. ACM, 2014.

[43] Katayoon Etemad, Faramarz F Samavati, and Przemyslaw Prusinkiewicz. Animating persian floral patterns. In *Proceedings of the Fourth Eurographics conference on*

Computational Aesthetics in Graphics, Visualization and Imaging, pages 25–32. Eurographics Association, 2008.

[44] Jean-Daniel Fekete and Catherine Plaisant. Excentric labeling: dynamic neighborhood labeling for data visualization. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, pages 512–519. ACM, 1999.

[45] Emden R Gansner and Stephen C North. An open graph visualization system and its applications to software engineering. *Software Practice and Experience*, 30(11):1203–1233, 2000.

[46] Mohammad Ghoniem, Jean-Daniel Fekete, and Philippe Castagliola. On the readability of graphs using node-link and matrix-based representations: a controlled experiment and statistical analysis. *Information Visualization*, 4(2):114–135, 2005.

[47] Andrew Glassner. Around and around [computer graphics]. *Computer Graphics and Applications, IEEE*, 24(2):98–108, March 2004.

[48] Liang Gou and Xiaolong (Luke) Zhang. Treenetviz: Revealing patterns of networks over tree structures. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2449–2458, December 2011.

[49] GraphicsKeeper. Colorful floral pattern. http://graphicskeeper.com/vector/colorful-floral-pattern/respond. Accessed: 2015-03-08.

[50] Jeremy Gray. Henri poincaré and the disc model of non-euclidean geometry. *Worlds Out of Nothing: A Course in the History of Geometry in the 19th Century*, pages 273–289, 2007.

[51] Saul Greenberg and Bill Buxton. Usability evaluation considered harmful (some of the time). In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 111–120. ACM, 2008.

[52] Carl Gutwin and Chris Fedak. A comparison of fisheye lenses for interactive layout tasks. In *Proceedings of the 2004 Graphics Interface Conference*, pages 213–220. Canadian Human-Computer Communications Society, 2004.

[53] N. Hamekasi, F. F. Samavati, and A. Nasri. Interactive modeling of muqarnas. In *Proceedings of the International Symposium on Computational Aesthetics in Graphics, Visualization, and Imaging*, CAe '11, pages 129–136, New York, NY, USA, Aug 5-7 2011. ACM.

[54] Nader Hamekasi and Faramarz Samavati. Designing persian floral patterns using circle packing. In *GRAPP/IVAPP*, pages 135–142. Citeseer, 2012.

[55] Donald Hearn and M Pauline Baker. *Computer graphics*, volume 11. Prentice Hall Upper Saddle River, 1997.

[56] Jeffrey Heer, Stuart K Card, and James A Landay. Prefuse: a toolkit for interactive information visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 421–430. ACM, 2005.

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

[58] Nathalie Henry and Jean-Daniel Fekete. Matrixexplorer: a dual-representation system to explore social networks. *IEEE Transactions on Visualization and Computer Graphics*, 12(5):677–684, September 2006.

[59] Nathalie Henry and Jean-Daniel Fekete. Matlink: enhanced matrix visualization for analyzing social networks. In *Proceedings of the 11th IFIP TC 13 international conference on Human-computer interaction - Volume Part II*, INTERACT'07, pages 288–302, Berlin, Heidelberg, 2007. Springer-Verlag.

[60] Nathalie Henry, Jean-Daniel Fekete, and Michael J. McGuffin. Nodetrix: a hybrid visualization of social networks. *IEEE Transactions on Visualization and Computer Graphics*, 13(6):1302–1309, November 2007.

[61] Ivan Herman, Guy Melançon, and M. Scott Marshall. Graph visualization and navigation in information visualization: A survey. *IEEE Transactions on Visualization and Computer Graphics*, 6(1):24–43, January 2000.

[62] Lars Erik Holmquist and Tobias 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.

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

[64] Danny Holten and Jarke J Van Wijk. Force-directed edge bundling for graph visualization. In *Computer Graphics Forum*, volume 28, pages 983–990. Wiley Online Library, 2009.

[65] Danny Holten and Jarke 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.

[66] Ellis Horowitz and Sartaj Sahni. *Fundamentals of data structures*. Pitman, 1983.

[67] Adriana Iamnitchi, Matei Ripeanu, and Ian Foster. Small-world file-sharing communities. In *INFOCOM 2004. Twenty-third AnnualJoint Conference of the IEEE Computer and Communications Societies*, volume 2, pages 952–963. IEEE, 2004.

[68] Paul Jacobsthal. Early celtic art. *The Burlington Magazine for Connoisseurs*, pages 113–127, 1935.

[69] Sven Erik Jorgensen and Brian Fath. *Encyclopedia of Ecology, Five-Volume Set*, volume 1. Newnes, 2008.

[70] Dieter Jungnickel and Tilla Schade. *Graphs, networks and algorithms*. Springer, 2008.

[71] Wassily Kandinsky. *Concerning the spiritual in art*. Courier Corporation, 2012.

[72] Craig S Kaplan et al. Computer generated islamic star patterns. In *Bridges: Mathematical Connections in Art, Music, and Science*, pages 105–112. Tarquin Publications, 2000.

[73] Craig S Kaplan et al. Metamorphosis in eschers art. In *Bridges Leeuwarden: Mathematics, Music, Art, Architecture, Culture*, pages 39–46. Southwestern College, 2008.

[74] Craig S Kaplan and David H Salesin. Escherization. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 499–510. ACM Press/Addison-Wesley Publishing Co., 2000.

[75] Craig S Kaplan and David H Salesin. Islamic star patterns in absolute geometry. *ACM Transactions on Graphics (TOG)*, 23(2):97–119, 2004.

[76] Matthew Kaplan and Elaine Cohen. Computer generated celtic design. *Rendering Techniques*, 3:9–19, 2003.

[77] Kinjart. Stomping grounds, in deviant art. 2011 :http://kinjart.deviantart.com/art/stomping-grounds-208538959/. https://www.flickr.com/photos/gandalfsgallery/10165932273/.

[78] D Knuth. *Computer and Typesetting Series, Vol. C: The METAFONT Book*. Addison Wesley 1986b, ISBN 0-201-13444-6, 1986.

[79] Kurt Koffka. *Principles of Gestalt psychology.* Routledge, 2013.

[80] Martin Krzywinski, Jacqueline Schein, İnanç Birol, Joseph Connors, Randy Gascoyne, Doug Horsman, Steven J Jones, and Marco A Marra. Circos: an information aesthetic for comparative genomics. *Genome research*, 19(9):1639–1645, 2009.

[81] Cris Kuhlemeier. Phyllotaxis. *Trends in plant science*, 12(4):143–150, 2007.

[82] Bongshin Lee, Catherine Plaisant, Cynthia Sims Parr, Jean-Daniel Fekete, and Nathalie Henry. Task taxonomy for graph visualization. In *Proceedings of the 2006 AVI workshop on BEyond time and errors: novel evaluation methods for information visualization*, pages 1–5. ACM, 2006.

[83] Michael D Lee, Marcus A Butavicius, and Rachel E Reilly. Visualizations of binary data: A comparative evaluation. *International journal of human-computer studies*, 59(5):569–602, 2003.

[84] Wassily Leontief. Input-output analysis. *The new palgrave. A dictionary of economics*, 2:860–64, 1987.

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

[86] Jingwan Lu, Connelly Barnes, Connie Wan, Paul Asente, Radomir Mech, and Adam Finkelstein. Decobrush: Drawing structured decorative patterns by example. In *ACM Transactions on Graphics (Proc. SIGGRAPH)*, Aug 2014.

[87] Sean Lynch, Jonathan Haber, and Sheelagh Carpendale. Colourvis: Exploring colour in digital images. *Computers and Graphics*, 36(6):696–707, 2012.

[88] Hosseinali Machiani. *Design and Tazhib(in Persian)*. Yassavoli Press, Tehran, Iran, 2000.

[89] Joseph Brendan Manning. Geometric symmetry in graphs. 1990.

[90] Guy 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.

[91] Miriah Meyer, Tamara Munzner, and Hanspeter Pfister. Mizbee: a multiscale synteny browser. *Visualization and Computer Graphics, IEEE Transactions on*, 15(6):897–904, 2009.

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

[93] Stefaner Moritz. Wel-formed eigenfactor, 2014.

[94] Tamara Munzner. *Visualization Analysis and Design*. CRC Press, 2014.

[95] Petra Neumann, M Sheelagh T Carpendale, and Anand Agarawala. Phyllotrees: Phyllotactic patterns for tree layout. In *EuroVis*, volume 6, pages 59–66. Citeseer, 2006.

[96] Petra Neumann, Annie Tat, Torre Zuk, and M Sheelagh T Carpendale. Keystrokes: Personalizing typed text with visualization. In *EuroVis*, volume 43, page 2007, 2007.

[97] Robert T Paine. Food web complexity and species diversity. *American Naturalist*, pages 65–75, 1966.

[98] Andrea Palladio. *The four books of architecture*, volume 1. Courier Corporation, 1965.

[99] Alex Pang et al. Visualizing uncertainty in geo-spatial data. In *Proceedings of the Workshop on the Intersections between Geospatial Information and Information Technology*, pages 1–14, 2001.

[100] JinKyu Park, EenJun Hwang, and Yunyoung Nam. Utilizing venation features for efficient leaf image retrieval. *Journal of Systems and Software*, 81(1):71–82, 2008.

[101] Romualdo Pastor-Satorras and Alessandro Vespignani. Epidemic spreading in scale-free networks. *Physical review letters*, 86(14):3200, 2001.

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

[103] Ronald M Pickett and Georges G Grinstein. Iconographic displays for visualizing multidimensional data. In *Proceedings of the 1988 IEEE Conference on Systems, Man, and Cybernetics*, volume 514, page 519, 1988.

[104] Frédéric JAM Poirier and Hugh R Wilson. A biologically plausible model of human radial frequency perception. *Vision research*, 46(15):2443–2455, 2006.

[105] 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, Nov 2007.

[106] Przemyslaw Prusinkiewicz and Aristid Lindenmayer. *The algorithmic beauty of plants*. Springer-Verlag New York, Inc., New York, NY, USA, 1996.

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

[108] Helen C Purchase, Christopher Pilcher, and Beryl Plimmer. Graph drawing aesthetics created by users, not algorithms. *Visualization and Computer Graphics, IEEE Transactions on*, 18(1):81–92, 2012.

[109] Casey Reas and Ben Fry. Processing: programming for the media arts. *AI and SOCIETY*, 20(4):526–538, 2006.

[110] Patrick Riehmann, Manfred Hanfler, and Bernd Froehlich. Interactive sankey diagrams. In *Information Visualization, 2005. INFOVIS 2005. IEEE Symposium on*, pages 233–240. IEEE, 2005.

[111] Timo Ropinski, Steffen Oeltze, and Bernhard Preim. Survey of glyph-based visualization techniques for spatial multivariate medical data. *Computers & Graphics*, 35(2):392–401, 2011.

[112] Bahador Saket, Carlos Scheidegger, and Stephen Kobourov. Towards understanding enjoyment and flow in information visualization. *arXiv preprint arXiv:1503.00582*, 2015.

[113] Manojit Sarkar and Marc H Brown. Graphical fisheye views of graphs. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 83–91. ACM, 1992.

[114] Mario Schmidt. The sankey diagram in energy and material flow management. *Journal of industrial ecology*, 12(1):82–94, 2008.

[115] John Scott. *Social network analysis*. Sage, 2012.

[116] T. Skog, S. Ljungblad, and L.E. Holmquist. Between aesthetics and utility: designing ambient information visualizations. In *Information Visualization, 2003. INFOVIS 2003. IEEE Symposium on*, pages 233–240, Oct 2003.

[117] Douglas R Smith. The synthesis of lisp programs from examples: A survey. *Automatic program construction techniques*, pages 307–324, 1984.

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

[119] Andre Suslik Spritzer and Carla Maria Dal Sasso Freitas. Design and evaluation of magnetviz-a graph visualization tool. *Visualization and Computer Graphics, IEEE Transactions on*, 18(5):822–835, 2012.

[120] Chris Stolte, Diane Tang, and Pat Hanrahan. Polaris: A system for query, analysis, and visualization of multidimensional relational databases. *Visualization and Computer Graphics, IEEE Transactions on*, 8(1):52–65, 2002.

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

[122] Avneesh Sud, Danyel Fisher, and Huai-Ping Lee. Fast dynamic voronoi treemaps. In *Voronoi Diagrams in Science and Engineering (ISVD), 2010 International Symposium on*, pages 85–94. IEEE, 2010.

[123] Ardeshir Mojarrad Takestani. *The Art of Tazhib(in Persian)*. Soroush Press, Tehran, Iran, 2006.

[124] Roberto Tamassia. On embedding a graph in the grid with the minimum number of bends. *SIAM Journal on Computing*, 16(3):421–444, 1987.

[125] Helga Thorvaldsdottir, James T. Robinson, and Jill P. Mesirov. Integrative genomics viewer (igv): high-performance genomics data visualization and exploration. *Briefings in Bioinformatics*, 2012.

[126] Beddard Tom. Guilloche pattern generator, April 2014.

[127] Christian Tominski, Petra Schulze-Wollgast, and Heidrun Schumann. 3d information visualization for time dependent data on maps. In *Information Visualisation, 2005. Proceedings. Ninth International Conference on*, pages 175–181. IEEE, 2005.

[128] Christopher W Tyler. *Human symmetry perception and its computational analysis.* Psychology Press, 2002.

[129] Robert E Ulanowicz. Quantitative methods for ecological network analysis. *Computational Biology and Chemistry*, 28(5):321–339, 2004.

[130] Robert E. Ulanowicz. *Circumscribed Complexity in Ecological Networks*. Wiley VCH Verlag GmbH and Co. KGaA, 2013.

[131] Gol va boteh. Gol va boteh, March year = 2015, url = `http://shs.farhang.gov.ir/fa/product/view/244/929`.

[132] Frank van Ham, Hans-Jörg Schulz, and Joan M Dimicco. Honeycomb: Visual analysis of large scale social networks. In *Human-Computer Interaction–INTERACT 2009*, pages 429–442. Springer, 2009.

[133] Frank Van Ham and Jarke J van Wijk. Interactive visualization of small world graphs. In *Information Visualization, 2004. INFOVIS 2004. IEEE Symposium on*, pages 199–206. IEEE, 2004.

[134] Christophe Viau, Michael J. McGuffin, Yves Chiricota, and Igor Jurisica. The flowvizmenu and parallel scatterplot matrix: Hybrid multidimensional visualizations for network exploration. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):1100–1108, November 2010.

[135] Fernanda Viégas and Martin Wattenberg. 9 luscious. *Net Works: Case Studies in Web Art and Design*, page 104, 2012.

[136] Fernanda B Viégas and Martin Wattenberg. Artistic data visualization: Beyond visual analytics. pages 182–191, 2007.

[137] Cristbal Vila. Snakes: an animated film based on a woodcut by m.c. escher, 2015.

[138] T. von Landesberger, A. Kuijper, T. Schreck, J. Kohlhammer, J.J. van Wijk, J.-D. Fekete, and D.W. Fellner. Visual analysis of large graphs: State-of-the-art and future research challenges. *Computer Graphics Forum*, 30(6):1719–1749, 2011.

[139] Matthew O Ward. A taxonomy of glyph placement strategies for multidimensional data visualization. *Information Visualization*, 1(3-4):194–210, 2002.

[140] Matthew O Ward. Multivariate data glyphs: Principles and practice. In *Handbook of Data Visualization*, pages 179–198. Springer, 2008.

[141] Colin Ware. *Visual thinking: For design*. Morgan Kaufmann, 2010.

[142] Colin Ware. *Information visualization: perception for design*. Elsevier, 2012.

[143] Wikipedia. Hypotrochoid, March 2015.

[144] Wikipedia. Seven bridges of königsberg, 2015.

[145] Robin J Wilson. An eulerian trail through königsberg. *Journal of graph theory*, 10(3):265–275, 1986.

[146] Michael T Wong, Douglas E Zongker, and David H Salesin. Computer-generated floral ornament. In *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 423–434. ACM, 1998.

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

[148] Xianfeng Zhang and Micha Pazner. The icon imagemap technique for multivariate geospatial data visualization: approach and software system. *Cartography and Geographic Information Science*, 31(1):29–41, 2004.

Appendix A

Participants' Feedback

A.1 Node-Ring Visualization

- Participant 4: "The use of the arc segments was a very interesting concept but it would be hard to find the exact weight of the outgoing edges. Another thing I find interesting was the lack of links, which cleared up the diagram. The use of colors is appealing."

- Participant 5: "Much better than traditional, shows more info if necessary."

- Participant 6: "I find the concept behind visualization like using arc and nodes size very useful. The only thing that I found a little confusing was finding incoming edges. It works well for outgoing edges and there should be a way to easily find incoming edges. Something like a right click that switch between outgoing and incoming links."

- Participant 7: "I loved Hundertwasser's coloring, I like the simple and uncluttered appearance. I liked this one, how minimal it is in compare with other ones."

- Participant 8: "Look of edges is nice make. graph feels less cluttered. Seems strong for outgoing edges, week for analyzing/exploring incoming edges. Seems like this will not work well for more than ten nodes, too easy to mix up colors."

- Participant 9: "The option for moving was very good in terms of comparing nodes. Also clicking gives you option for make outgoing edges visible which was good specially if you are beginner. It was hard at the beginning but when you get used to it, it is easier and cleaner. The option of selecting and moving nodes makes it easier to understand. The decision for mapping edges to arcs and their weight to angular size of the arc is smart. "

- Participant 10: "I learned that the weight of the outgoing edges are represented by the length of arcs. using colors to represent connections was interesting. In order to see the weight of links it was good to look at the arc lengths but to find out how many outgoing link one node has it was easier to select the node and see the links."
- Participant 11: "Looks nice, a colorful pattern is always good to use with such things. Would fail for too many nodes though. Arcs are nicely rendered. Edge visualizations give quick feedback on connections. Small arcs might be difficult to see. To find the connections it is faster to click and see the links, but rings are more visual."
- Participant 12: "I like how outgoing connections were not there until clicked on. It made it less cluttered. I like the different mode sizes to demonstrate weighting. Color coding was also helpful. Circle line were clear than flower."
- Participant 13: "I got the same feel as the symmetric flower model. This one looks cleaner. If I had to rank them I would say: spiral graph non-symmetric flower node-ring symmetric daisy. I think it can not be scaled to larger graphs. I would be better if there is a way to show incoming edges too. "
- Participant 14: "It seems to be a more artistic visualization, than an efficient one, compared to the previous two. It is sometimes confusing to keep track of the links unless you click on nodes. Is it for larger graphs? "
- Participant 15: "The idea is generally good but it needs more elaboration regarding rings."

- Participant 16: “I think when we give weight to nodes and draw them in different sizes, it can make confusion for the size or the number of links shown inside. For example between two nodes with same number of links inside, the smaller node will look like a node with more links as it is full. Also similar to Daisy graphs understanding the connection using the colors is hard.”

- Participant 17: “The interesting point is that you don’t need to track the connections between different nodes to figure out which one is heavier. But still I think contrast between different colors might be an issue for this visualization.”

- Participant 18: “It is so tidy and clear which is a good advantage of this visualization. And it is easy to get information from it. But, it doesn’t give a general perspective of the whole data. You can use the design of Eco-Spiro, and put all links on one circle and map their weight to the angular size of the section of the circle. This one does not give the whole perspective of data, where the Eco-Spiro does have this ability. ”

- Participant 19: “easy to find which node has the most number of outgoing links.”

A.2 Daisy Visualization

- Participant 1: “It is very appealing to look at and seems more interesting and less daunting than the original one from which it was derived. It is very easy to see relative differences in weight of the nodes and their connections. It is also easy to find connections between nodes. The symmetric one is a lot easier to manage because of the coloring. I didn’t need the directional constraint to find the connections. Putting dots inside nodes as flower seeds in flower cores made it easier to distinguish the weight of the node. As well as the thickness of the lines inside petals to see the weight of the links."

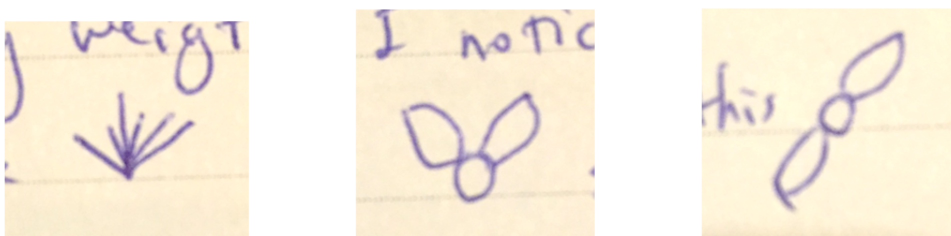
- Participant 2: "colors are key to make connection among elements. I liked the organized look of natural forms of the flowers rather than directional petals. It is easier to comprehend the relationship of the colors of the flowers and flower petals when they are symmetrical. I prefer the symmetric model, the directed constraint model is a little messy for me. So just using colors to follow the links is enough for me, because when all connections to one node have the same color as their destination node, all will pop out in my eyes and I can see them easily, and I do not need the directional hint for that."

- Participant 3: "I learned we can use colors or some specific elements to show weight and direction. I prefer the directional constraint model because there is more room to move the nodes, or add some labels or numbers in that area."

- Participant 4: "The visualization itself is very cool and I liked how a multitude of data is represented through the different channels of information in the vis. The movement of petals was an interesting touch and I found that having both color and direction helped me to find these directed links much faster than having it spaced out symmetrically.

- Participant 5: "I am not very organized, I have to be quick so symmetric is faster for me. In the non-symmetric model people will miss overlaps. But non-symmetric daises are more live. Daisy visualization is very good for kids because they look interesting, participants "

- Participant 6: "I liked the way it simplifies graph visualization. I liked the symmetric concepts because of the freedom it provides but I preferred other ways for representation of outgoing weight. The line thickness was not my favorite, instead I preferred (Figure A.1, a) way because of its accuracy. One minor thing that I noticed is that the flowers are not symmetrically arranged, for example (Figure A.1, b) should be like (Figure A.1, c), but if the flower with most node is symmetrical and others are loosing petals respect to that, it is fine, specifically for counting. Using stems in this visualization is not very clear, unless there is a special meaning for that. For example if they used for incoming energy source that should be fine, but for a node that should look like others, it you remove the links and replace them with stems, then it will be confusing. "



a *b* *c*

Figure A.1: Participant's feedback and suggestions for Daisy visualization.

- Participant 7: "Aesthetically pleasing. More difficult when petals overlap. color differences easy to pick out. I preferred the flower seed's circle to be filled. The selected design for representing weights of edges is easier to see the size difference but less aesthetical than the filled versions. The stems look like they fit well with the design of ecological network. But if it is for arbitrary use, it is better to have a reason to make one node look different than others. For example if the node is the selected node."

- Participant 8: "Appealing visualization, for the look at and interact with. The directional model " forces" interaction to read the vis likely, good way to encourage deeper understanding of the visualization. Would have preferred use of black to instead be a more saturated or darker color of same hue. Should the order of color petals be the same in every case? ordered by weight instead?”

- Participant 9: “I like the use of stem for selected node. For the weight of the links I prefer the one that heavier links have more black hachure in the petal. The idea of moving the nodes and have the petals moving was more enjoyable. So I prefer the non-symmetric model than the symmetric model. The design choices for mapping are really smart. I prefer mapping node’s weight to the core size rather than the number of flower seeds.”

- Participant 10: “The interesting feature comparing to standard graph representation is the nice and tidy arrangement of the nodes. That is, the edges do not have intersection with each other. Also identifying heavier nodes and edges is easier than than the standard representation. Symmetric model is easier than non-symmetric model when you want to see all nodes and links with their weights. The non-symmetric one is better to follow the direction of the links.”

- Participant 11: “Color coordinating edges with nodes is novel and aids data extraction. A legend would be necessary to describe the meaning of attributes. For representing proportional difference in nodes weight it is better to use node size for the weight of the node, while for representing the numerical difference the flower seed mode works better. I preferred the one with directional constraints.”

- Participant 12: “In the non-symmetric one, the direction responsiveness was weak. This is interesting, I haven’t seen anything like this before.”

- Participant 13: “I liked the non-symmetric one, since it let me rearrange them to get the best fill. while in the symmetric one, rearranging seemed useless and arbitrary. It is easier to see links weights on the symmetric model, but the non-symmetric is easier to find which node is connected to which."

- Participant 14: "I liked the way the petals rotated to face the destination node in non-symmetric model. The block dots inside the cores are hard to track in some dark background colors.

- Participant 15: "The dynamic change of petal's direction was interesting and it can be useful in data visualization.

- Participant 16: "Daisy visualization tries to have all features of traditional graphs and also have a better look. I think they can be useful for kids or maybe people who do not have engineering or science background. For me as I am used to see the graphs in their traditional way, it is hard to understand this model. Specially the symmetric one because I expect to see the links to be directed to the node. I should add that maybe for certain concepts that colors can be mapped to each node and there is a good meaning behind it, colors can help people to recognize the nodes, but without such mapping it was hard for me to understand."

- Participant 17: "I found the elimination of overlaps very interesting, but I think this is a little confusing for the weigh of petals. It took me some time to realize which one is heaviest."

- Participant 18: "I prefer Non-Symmetric method because it is easier to locate the nodes. And I think size of the links are a little big comparing to the size of the nodes. The only problem is the overlapping the petals. The symmetric mode looks confusing because the petals are point to a direction that is not correct."

- Participant 19: "They are aesthetic. It is easy to find incoming links. It is easy to find heaviest edge. I liked the symmetric one better because the other one has more overlaps."

A.3 Participants' Feedbacks on Eco-Spiro Visualization

- Participant 1: "The input arrow are very visible. The model is also very appealing with its bright colors. However, some of the connections within the model are hard to read because of the thinness of the line (ie. Micro-zooplankton). The external ecosystem data was very easy to read. I like the input/output connection designs. Separating the space and putting the input/ouputs outside of the circle helps to understand what is going on."

- Participant 2: "I found it unclear comparing it to the Daisy but more clear than the traditional one. It is hard to read labels upside down. I prefer to see all of them horizontal. Some of the internal connections that are not connected to anywhere are confusing. It looks like these are the cycle/loop connections, which are connected to the original node. This was not as user friendly as Daisy visualization. The form of the links that changes from original node towards the destination node makes it easier to see the direction. "

- Participant 3: "I learned how to show a subject with color and line. Eco-Spiro is easier to read than the traditional model. There are many overlapping in the traditional model."

- Participant 4: "The visualization is easy to read and I found that I was able to discern information very quickly as opposed to the original graph. I found the thorn like very interesting as they were not as cluttered as in traditional links that uses the same width."

- Participant 5: “It is more interesting. Separating outgoing and incoming was nice. color coding was nice. I like circle idea for connecting ecosystem.”

- Participant 6: “I found the visualization aesthetically pleasing and readable. I was wondering if there is more quantitative indication for weights of links. It looks great but not sure about the fading color of exchange links. It makes it hard to see them specially close to destination node, and fading make it hard to distinguish between the weights of the links.”

- Participant 7: “Aesthetically pleasing design. Lots of connections. Easy to see which node had more/fewer exchange connections. The traditional model is too cluttered and hard to see. The traditional model looks so overwhelming, while the Eco-Spiro one shows it well and you don’t feel overwhelmed. Since the links are separated it is easier to see for example how many exchange links one node has in Eco-Spiro, but not as easy in the traditional mode. It is hard to see the loop links in the Eco-Spiro model. Maybe if the end of the exchange link was a bit thicker, it would be more readable. ”

- Participant 8: “I wonder about separating where exchange links leave/enter each node. Also hard to judge amount of links due to overlap. If distribute around the node section this could be more clear. Enjoyed the transparency and link shape.”

- Participant 9: “It was hard to see where the link goes (the destination node), so it was hard to find which node has more outgoing exchange links. Maybe adding the number of links to the selected node can help. I like the incoming links the black ones, but the respiration links that are white is not easy to see on the white background. Fading the links are smart, it reduces the clutter. You can try and use mono-colors and shades in this one.”

- Participant 10: “I found interesting: that the nodes and links that belong to the system itself are all shown inside a circle. However, the environment links are shown outside of the circle. This make me to distinguish both inside links and outside links, easier. I found it confusing, but it is good to separate the links.”

- Participant 11: “A legend describing attributes would be helpful, as would a way to visualize the numeric values if needed. Nice coding of internal connections. Ensure the minimum width to not lose the edge. It might be helpful to have the external links gradient color rather than solid color to more emphasize the direction of the link.”

- Participant 12: “The exchange connections looked nice, but it wasn’t always clear where they are going. I liked how input/output was done.”

- Participant 13: “This design looks modern and appealing. But I see two problems within: 1) Node’s name are written diagonally and it is hard to read the ones that are upside down. 2) Finding the interconnections can be hard specially if the weight is low. I did not notice the query until I was pointed to it.”

- Participant 14: “The visualization is beautiful! Except the input (black) links which I think are not great harmony with the rest of the graph. It’s a bit hard to keep track of link weights, especially when they are almost equal, or when they are small, and not visible.”

- Participant 15: “Inside the shape is a little confusing due to several directions. Except that the rest is ok. It might be better if you expand the selected node and separate the outgoing exchange links of that node, so they do not overlap each other.”

- Participant 16: “The concepts here are much more connected to traditional graphs and easier for me to understand. I like this one more than Daisy Visualization.”
- Participant 17: “I can see all of the nodes in only one frame with a colorful border. This makes the visualization very interesting.”
- Participant 18: “It gives a good visual aspect of general idea in visualization. The highlighting feature is quite useful. I think using color green for input energy from outside is better. Also using black for showing the waste of energy might be better. It will be better to see the amount of weight for exchange link of the selected node. Some labels are hard to see, because they are upside down.”
- Participant 19: “It is easy to find node’s attributes, like Input, Output and Respiration.”

Appendix B

Documents

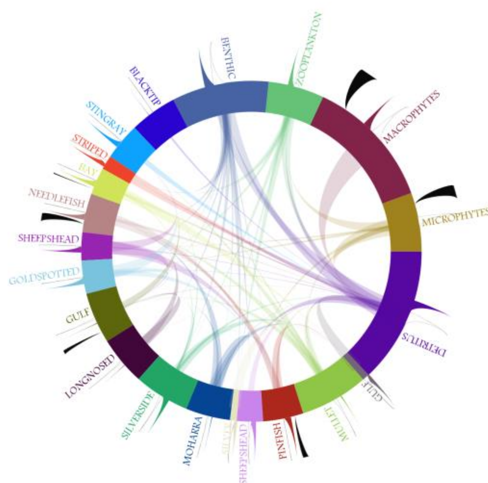
1. Recruitment
2. Consent Form
3. Pre-Questionnaire
4. Node-ring visualization Post Questionnaire
5. Daisy visualization Post Questionnaire
6. Eco-Spiro visualization Post Questionnaire
7. Training Session Slides

UNIVERSITY OF CALGARY

DEPARTMENT OF COMPUTER SCIENCE

RECRUITMENT NOTICE

UNDERSTANDING RESPONSE TO COMPUTING TECHNOLOGIES



We are looking for individuals to participate in a computing technology study. We are graduate students and researchers from the University of Calgary seeking to understand how people respond to computing technologies in order to inform the design of future computing technologies.

If you are over 18, not color-blind, and would like to participate, please contact us using the information below! In addition, if you have friends or colleagues who you believe might also be interested in participating in this research, we would be grateful if you were to talk to them about this research opportunity and/or forward them this notice with information about our study. Thanks so much for your help!

There will be cash remuneration for study participants in the range of $20.

Contact/Questions: Katy

This study has been approved by the University of Calgary's Conjoint Faculties Research Ethics Board.

UNIVERSITY OF CALGARY

Name of Researcher, Faculty, Department, Telephone & Email

Sheelagh Carpendale - Professor Department of Computer Science	Katayoon Etemad– PhD Candidate Department of Computer Science

Supervisor:

Dr. Sheelagh Carpendale, Department of Computer Science

Title of Project:

Understanding Response to Computing Technologies

Sponsor:

N/A

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study:

The purpose of this study is to improve our understanding of how people respond to computing technologies in order to inform the design of future computing technologies.

What Will I Be Asked To Do?

If you agree to participate in this study, you will be asked to participate in the following different research activities:

1. You will be asked to complete a short questionnaire about your experience of interactive computing systems and your background. This questionnaire should take no more than 10 minutes to complete.
2. You will be asked to interact with a set of computing technologies in a directed or undirected way. A researcher will observe, take notes, and videotape you while you do this; your actions may be logged automatically by the system in order to measure the technology's impact on task performance. During this time, you will be asked questions about the computing technology and your experience.
3. After completing the study, you will be asked to participate in a post-study interview about your experience in the study, provide some additional background about your experience with our computing technology and any further thoughts. This may include a short questionnaire. This interview should last approximately 30 minutes.

This whole process was designed to last no longer than approximately 90 minutes. However, should you wish to discuss a topic longer than the allotted time or think that you have any insights that are important to the research, feel free to talk about it.

Your participation in this research is voluntary. You may refuse to participate altogether or in part. You may decline to answer any or all questions. You may withdraw from participation in this study at any time without penalty or loss of benefits.

What Type of Personal Information Will Be Collected?

Should you agree to participate, we would ask to videotape and audiotape you during the study and a post-study interview. Other than these video and audio recordings, no other personal identifying information (such as your name) will be associated with the data collected in this study. By default, in all written publications and presentations based on this research, you will remain anonymous and your comments from the interviews will be referred to either using a participant number or a pseudonym.

In order to better communicate the results of this research in written publications and presentations, it may be helpful to share video (or still photographs from the video) of you in the study. If you grant us permission to share video (or still photographs from the video) of yourself in an interview, in written publications or presentations of this research, there is a chance that you may be recognized and so we cannot guarantee your anonymity. We will never, however, reveal your name in association with your image.

Please note that, where intended reporting of photographed or videotaped images includes public display, the researchers will have no control over any future use by others who may copy the images and repost them in different formats or contexts, including online.

Please indicate your preference to the following statements:

I grant permission for video (or still photos from the video) of me to be shared in publications or presentations of this research: Yes: ___ No: ___

I grant permission for the researchers to contact me at the following email address for a follow-up interview:

Email: ____ Yes: ___ No: ___

Are there Risks or Benefits if I Participate?

There are no known harms or risks associated to the participation in this study.

There is also no cost in your to participation of this study and you will receive $___ for participation.

What Happens to the Information I Provide?

Participation in this research is completely voluntary and confidential. You are free to discontinue participation at any time during the study. Any information you contribute up to the point at which you choose to discontinue your participation will be retained and used in the study. No one except we, the researchers, will be allowed to see or hear any personally-identifiable information unless you have given permission for us to share video or photographs of you in this study in publications or presentations of this research. The audio/video tapes, questionnaires and interview data will be kept on password-protected university computers or in a locked cabinet only accessible by the researchers. The data will be stored for five years, after which it will be permanently erased.

Signatures (written consent)

Your signature on this form indicates that you 1) understand to your satisfaction the information provided to you about your participation in this research project, and 2) agree to participate as a research subject.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature ____Date: _______________

Researcher's Name: (please print) ____

Researcher's Signature: ____Date: ________________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Sheelagh Carpendale
Department of Computer Science

Katayoon Etemad
Department of Computer Science

If you have any concerns about the way you've been treated as a participant, you may contact a Research Ethics Analyst.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

UNIVERSITY OF CALGARY

DEPARTMENT OF COMPUTER SCIENCE

PRE -SESSION QUESTIONNAIRE

UNDERSTANDING RESPONSE TO COMPUTING TECHNOLOGIES

Demographic Information

This information is collected for demographic purposes only. All questions are optional.

Age: ☐ 18-25 ☐ 26-35 ☐ 36-45 ☐ 46-55 ☐ 56-65 ☐ 66 or older

Gender: ☐ Male ☐ Female

Are you currently a student? ☐ Yes ☐ No

If you are a student, please indicate your ***current level of education****. If you are not a student, please indicate the* ***highest level of education*** *you have* ***completed****:*

☐ High school or equivalent
☐ Vocational/technical school (2 year)
☐ Some university
☐ University graduate (4 year)
☐ Master's degree
☐ Doctoral degree (PhD)
☐ Professional degree (MD, JD, etc)
☐ Other ____________________

What is your field of study or expertise, or area of work and experiment?

____

Are color-blind? ☐ Yes ☐ No

*Please indicate the **approximate length of time you have trained, worked, or had an active interest in the following areas:***

	none	*< 1 year*	*1 – 2 years*	*3 – 4 years*	*5 + years*
Design Aesthetic Patterns	1	2	3	4	5
Graphs or networks	1	2	3	4	5
Weighted Graphs	1	2	3	4	5
Directed Graphs	1	2	3	4	5
Ecological networks	1	2	3	4	5

*Please indicate approximately **how often** you use following technologies. Place a checkmark on the most suitable choice:*

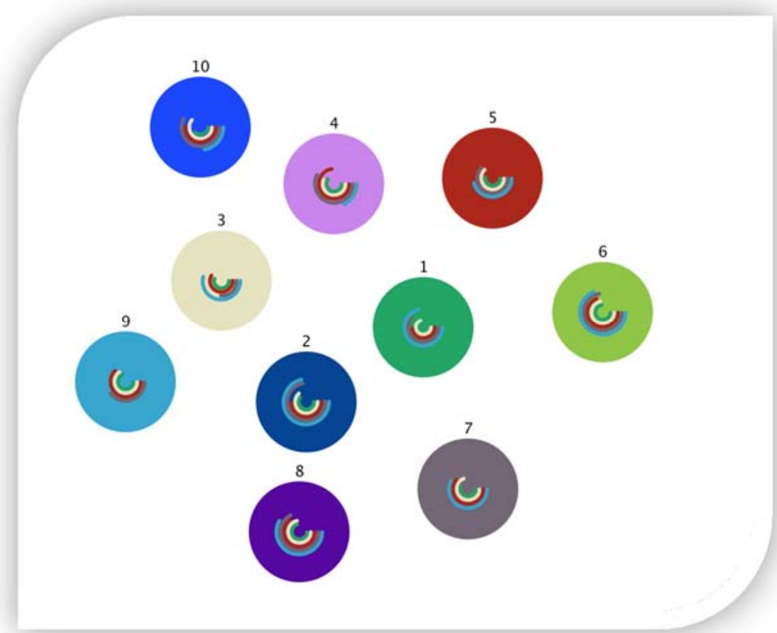
	never	*a few times a year, or sporadically*	*a few times a month*	*a few times a week*	*almost every day or more*
Data visualization systems, including viewing visualizations on web	1	2	3	4	5
Systems involving weighted directed graphs	1	2	3	4	5
Aesthetic visualization systems	1	2	3	4	5

UNIVERSITY OF CALGARY

DEPARTMENT OF COMPUTER SCIENCE

POST-SESSION QUESTIONNAIRE

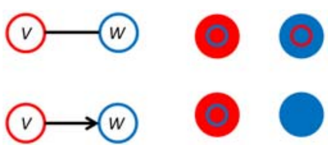
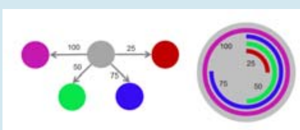
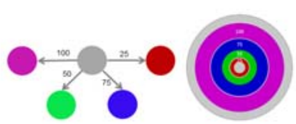
UNDERSTANDING RESPONSE TO COMPUTING TECHNOLOGIES



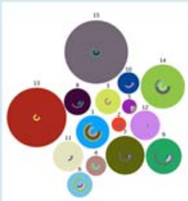
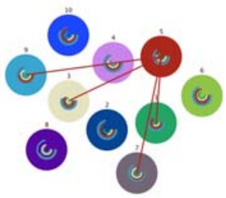
Please describe what you learned or found interesting about Node-Ring Visualization for weighted directed graphs during the session. (There is no wrong answer)

[FOR RESEARCHER USE ONLY] SESSION ID: ___ PARTICIPANT ID: ___

Please evaluate the following design decisions using the provided charts.

		Strongly disagree				*Strongly agree*
	The idea of using color for mapping direction	☐	☐	☐	☐	☐
	The idea of replacing edges with rings	☐	☐	☐	☐	☐
	Mapping edge weights to angular amount of the rings.	☐	☐	☐	☐	☐
	Mapping edge weights to the thickness of the rings.	☐	☐	☐	☐	☐
	Using random color pallet	☐	☐	☐	☐	☐
	Using color pallet from well-known paintings.	☐	☐	☐	☐	☐

[FOR RESEARCHER USE ONLY] SESSION ID: ___ PARTICIPANT ID: ___

	Mapping node's weight to the size of the circle	☐	☐	☐	☐	☐
	Highlighting outgoing edges for the selected node.	☐	☐	☐	☐	☐

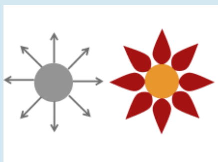
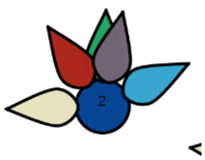
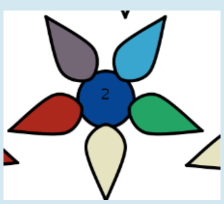
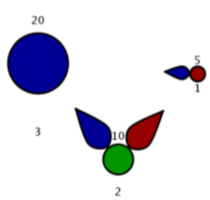
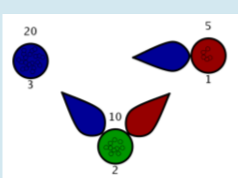
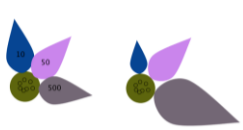
DEPARTMENT OF COMPUTER SCIENCE

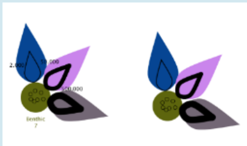
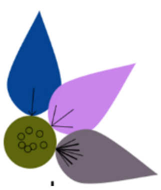
POST-SESSION QUESTIONNAIRE

UNDERSTANDING RESPONSE TO COMPUTING TECHNOLOGIES

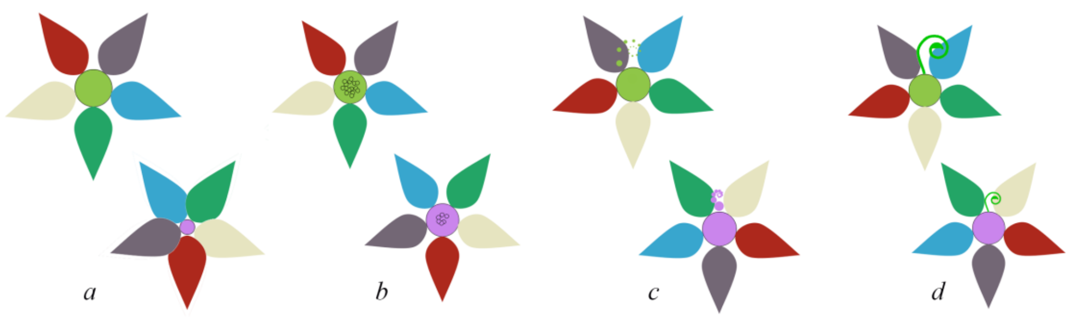
Please describe what you learned or found interesting about Daisy Visualization for weighted directed graphs during the session. (There is no wrong answer)

Please evaluate the following design decisions using the provided charts.

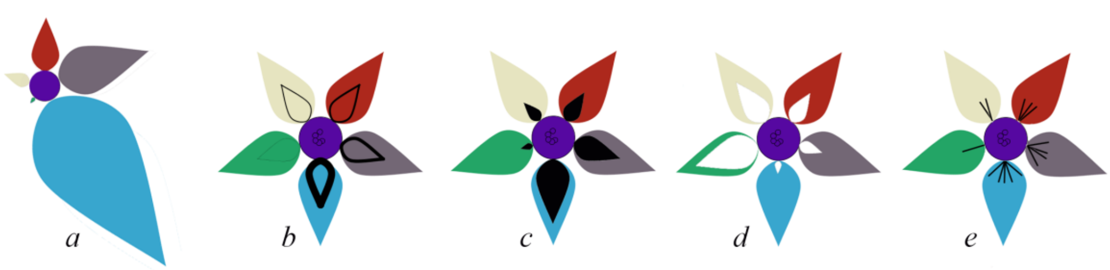
		Strongly disagree				*Strongly agree*
	The idea of mapping nodes and links to daisy flowers	☐	☐	☐	☐	☐
	Assigning colors to nodes and putting directional constraint for daisy petals	☐	☐	☐	☐	☐
	Arranging daisy petals symmetrically, no directional constraint	☐	☐	☐	☐	☐
	Using the size of flower center for mapping node’s weight	☐	☐	☐	☐	☐
	Using flower seeds for mapping node’s weight	☐	☐	☐	☐	☐
	Mapping link’s weight to the petal’s size design (a)	☐	☐	☐	☐	☐

	Mapping link's weight to the thickness of the petal's decoration design (b)	☐	☐	☐	☐	☐
	Mapping link's weight to the petal's decoration design (c)	☐	☐	☐	☐	☐
	Mapping link's weight to the petal's decoration design (d)	☐	☐	☐	☐	☐
	Mapping link's weight to the petal's decoration design (e)	☐	☐	☐	☐	☐

Please evaluate which design you prefer the most for the node's attributes.



Please rank the following designs for representing extra edge attributes in Daisy visualization, from the most desired to the least.

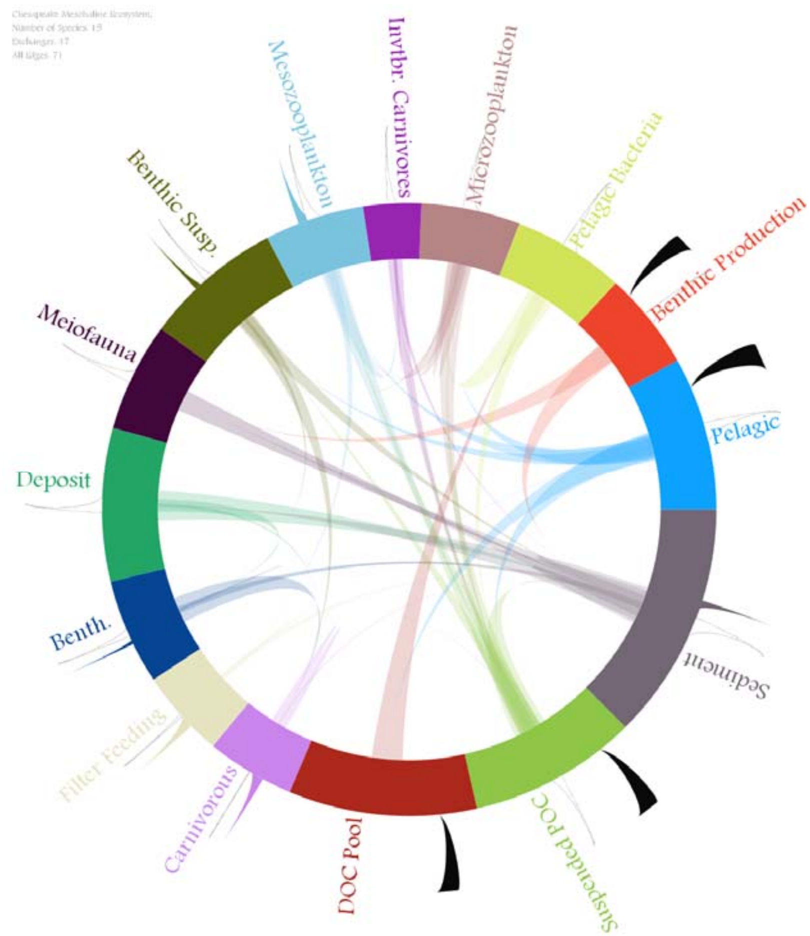


UNIVERSITY OF CALGARY

DEPARTMENT OF COMPUTER SCIENCE

POST-SESSION QUESTIONNAIRE

UNDERSTANDING RESPONSE TO COMPUTING TECHNOLOGIES



Please describe what you learned or found interesting about Eco-Spiro Vis during the session. (There are no wrong answers)

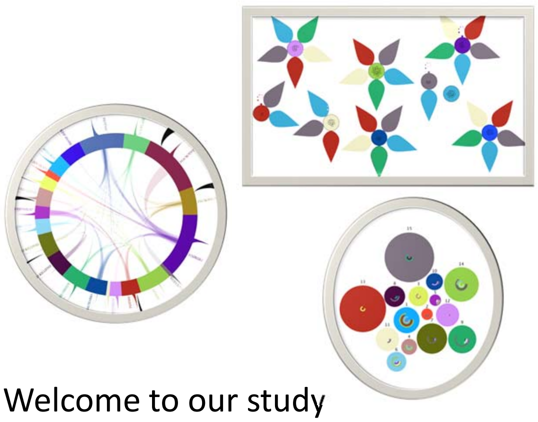
....

....

....

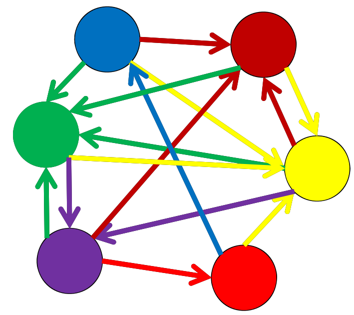
....

[FOR RESEARCHER USE ONLY] SESSION ID: ___ PARTICIPANT ID: ___

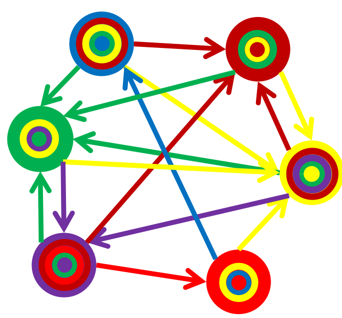


Welcome to our study

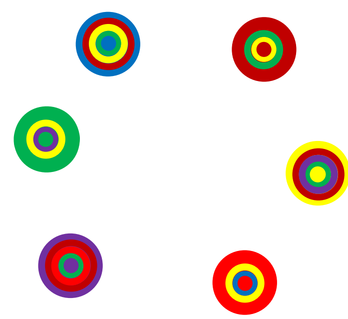
Node-Ring Visualization



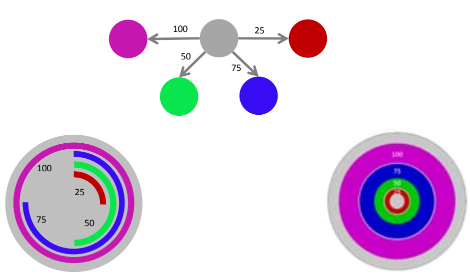
Node-Ring Visualization



Node-Ring Visualization

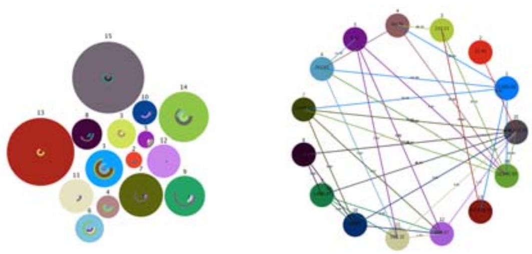


Node-Ring Visualization



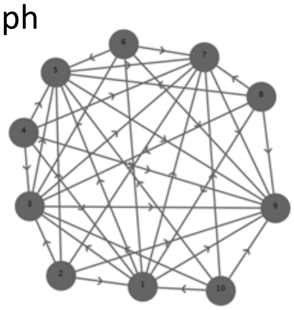
City View by Friedensreich Hundertwasser 1994

Node-Ring Visualization

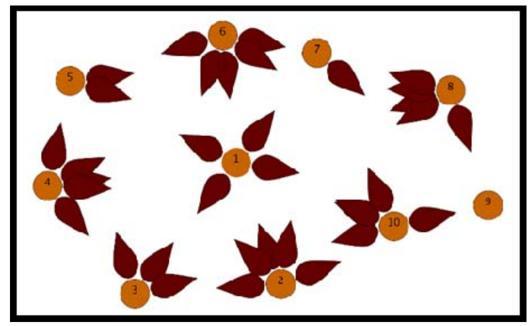


Daisy Visualization

Directed graph

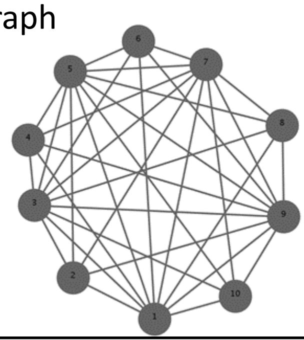


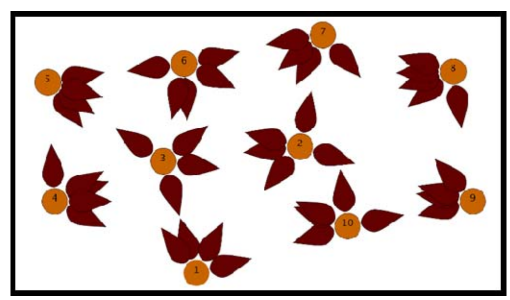
Daisy visualization of directed graph

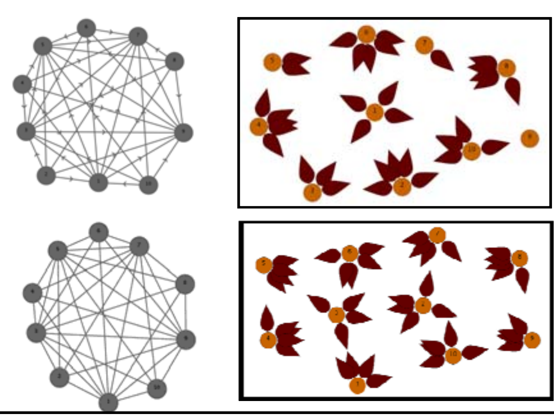


Daisy Visualization

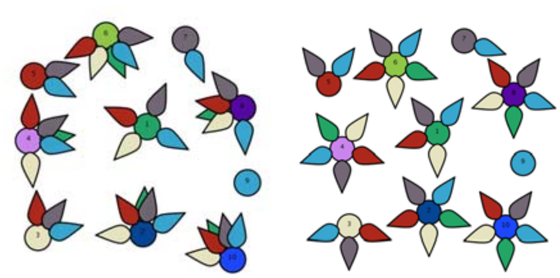
Undirected graph



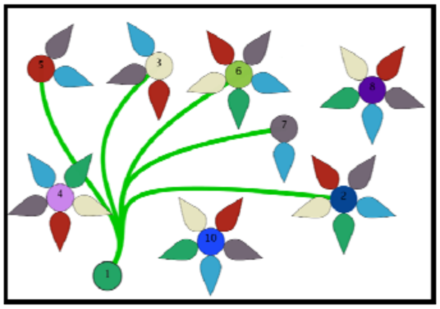




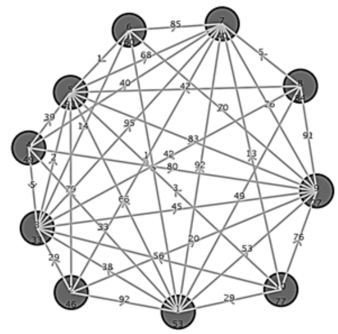
Color and Directional constraint



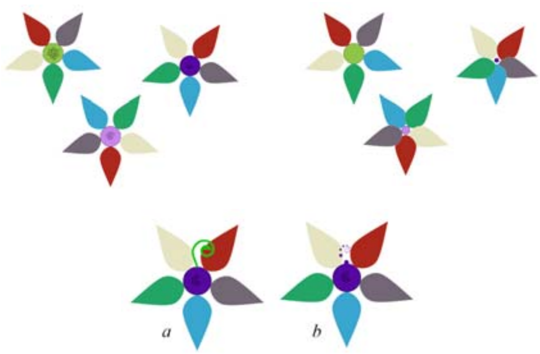
Floral overview



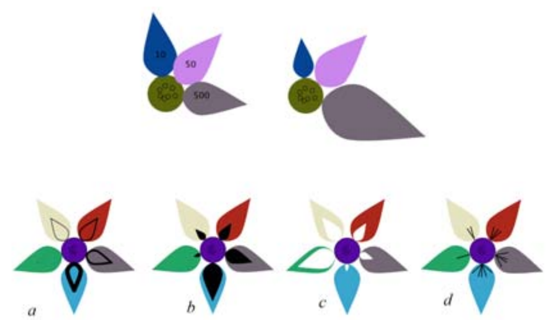
Weight



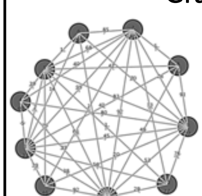
Node’s attributes

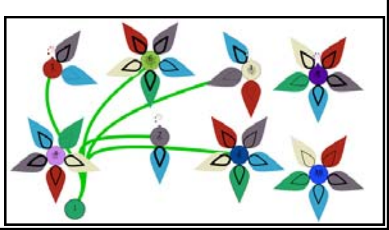


Link’s attributes

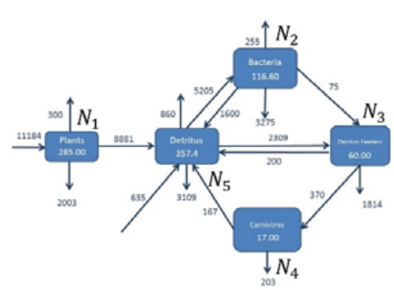


City/road example

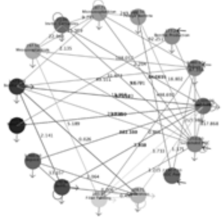




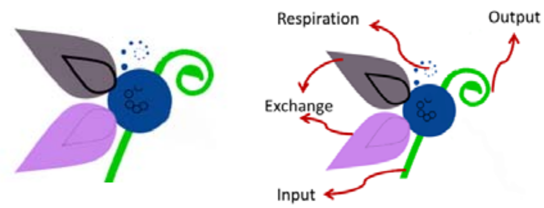
Ecological network



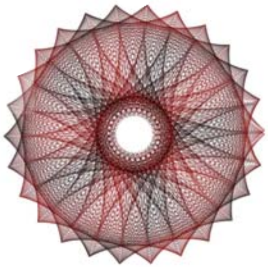
Daisy vis for ecological network

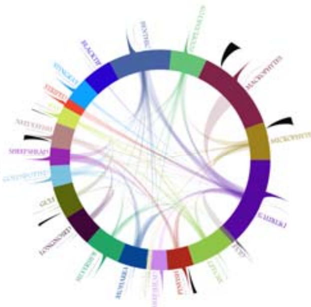


More details

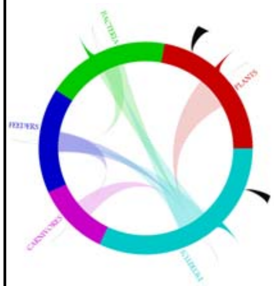


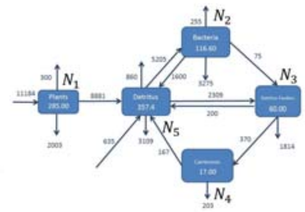
Eco-Spiro Vis

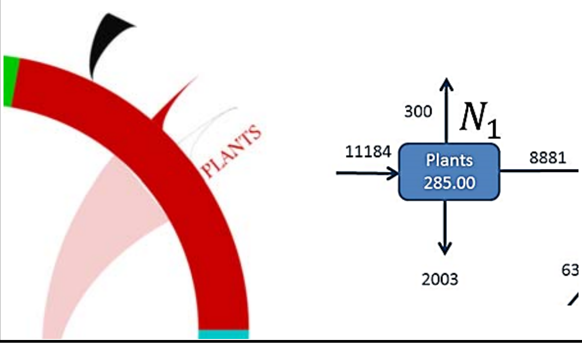




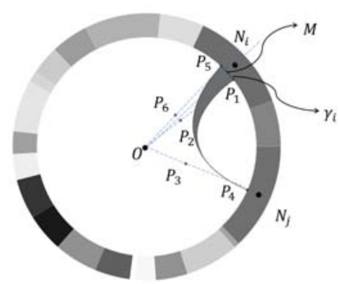
Node-link comparison



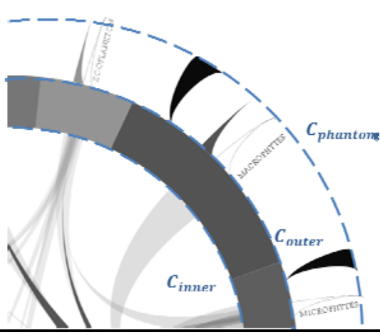


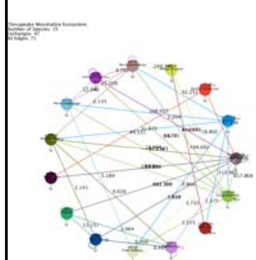


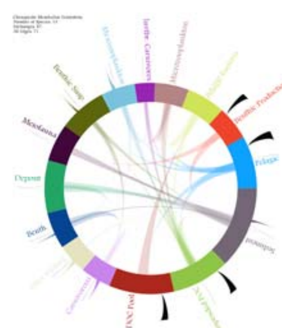
Exchange edges



Outside transactions







Please evaluate the following design decisions using the provided charts.

	Strongly disagree				*Strongly agree*
The idea of dividing the space into internal and external	☐	☐	☐	☐	☐
Using spike shapes for directed edges rather than arrowhead links	☐	☐	☐	☐	☐
Mapping species biomasses with angular amount of the arc section	☐	☐	☐	☐	☐
Fading the color of the exchange links, inside the circle.	☐	☐	☐	☐	☐
Assigning color to each node	☐	☐	☐	☐	☐
The arrangement of labels	☐	☐	☐	☐	☐
The query chart on the top left corner, indicating the size of the network	☐	☐	☐	☐	☐

Appendix C

User Manuals

Here we provide a short description of each prototype describing their state at the time this document was written. This is includes, for each of them, their basic interactions. Note that these three visualizations are in their early stages and their interfaces are not finalized. Note that all images of these three visualizations that are used in this thesis have been generated from these three prototypes.

The current visualizations are designed for representing ecological networks. The structure of input file for these networks is as following:

- Ecosystem name
- Number of nodes or species in the ecosystem
- List of node labels or the species names
- List of the nodes' weights or species biomass
- List of inputs (index and weight)
- List of outputs (index and weight)
- List of Respirations (index and weight)
- List of exchanges (index of adjacent nodes and the exchange's biomass)

A text file including this information, with ".DAT" format is entered in the body of the program. The prototype inputs the text file and converts the included information into several arrays. Data that are stored in these matrices are used later for the visualization. The name of the ecosystem and the dimension of arrays is determined from the beginning of the file. First a one dimensional array of strings is created for storing the labels of the nodes. Another one dimensional array is created for storing the biomass for each node. Then a two dimensional array is created for storing the adjacency matrix of the network. This array is defined to store all relationships between nodes, including inputs, outputs, respirations and exchanges. Next, all this information is used in the visualization.

Any data, which can be converted into adjacency matrix as explained above, can be used as input for each of the following visualizations.

C.1 Node-Ring Graph Visualization

Node-ring visualization is designed for representing dense, weighted and directed graphs. These graphs have more edges than nodes, and all edges are weighted and directed. Nodes are presented by colored circles and directed edges are presented are shown as colored rings inside their source nodes. The color of each ring shows the destination of the edge that is represented.

A list of information about the ecosystem is presented with Node-Ring and will appear on the top left corner of the screen, showing ecosystem's name, the number of species, and the number of exchange edges that exist in the food web of that ecosystem.

C.1.1 Showing Outgoing Edges:

When a person selects one node, with **Left Mouse Clink** all outgoing edges from that node become highlighted. This feature helps people understand the layout (See Figure C.1).

C.1.2 Showing Incoming Edges:

When a person selects one node, with **Right Mouse Clink** all incoming edges to that node become highlighted (See Figure C.2). This feature helps people understand the layout.

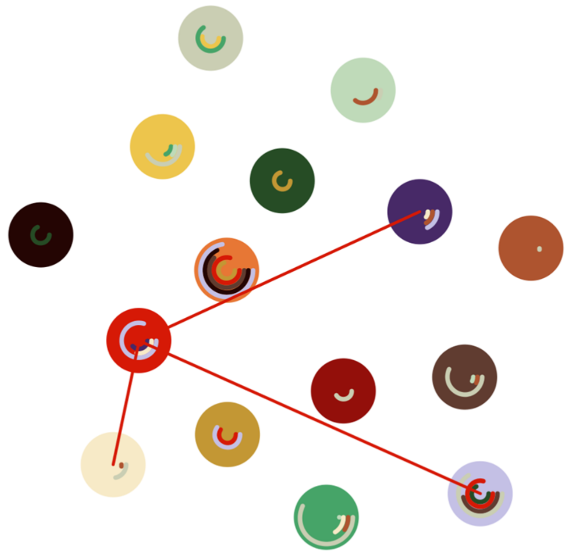


Figure C.1: Left mouse click highlights the outgoing edges from the selected node.

C.1.3 Reviewing Data Details:

When a person presses "q" on the keyboard, it triggers a query of all nodes' labels and weights, and highlighted edges' weights become visible (See Figure C.3).

C.1.4 Moving Nodes:

When a person presses "s" on the keyboard, positions of nodes will be saved on a file "position.txt". In the second run of the program when "r" is pressed on the keyboard, nodes will move and re-arranged, with animation to the positions that are saved in "position.txt" file (See Figure C.4).

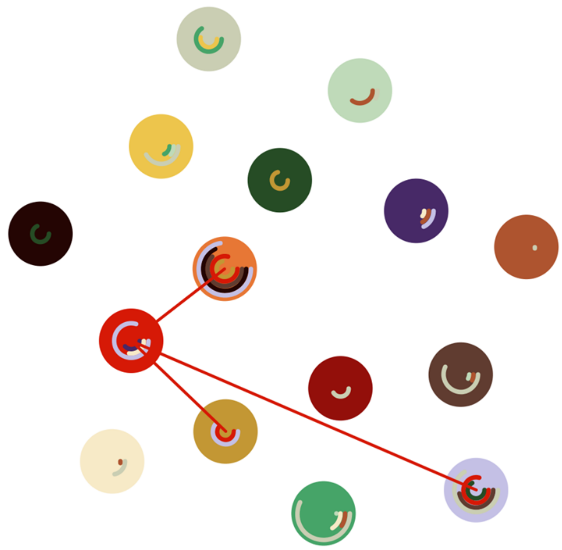


Figure C.2: Right mouse click highlights the incoming edges to selected node.

C.2 Daisy Visualization

Daisy Visualization design is inspired by ornamental patterns of daisy flowers. In this visualization, nodes, edges and other features of data are mapped to floral elements. More specifically, nodes are replaced by a colored circle as the flower's center and edges by petals of that flower.

A list of information about the ecosystem that is presented with Daisy visualization, will appear on the top left corner of the screen, showing ecosystem's name, the number of species, the number of exchange edges and the number of all edges that exist in that ecosystem.

C.2.1 Reviewing Data Details:

When a person presses "q" on the keyboard, it triggers a query of all nodes' labels and weights, and edges' weights become visible (See Figure C.5).

C.2.2 Moving Nodes:

When a person presses "s" on the keyboard, positions of nodes will be saved on a file "position.txt". In the second run of the program when "r" is pressed on the keyboard, nodes

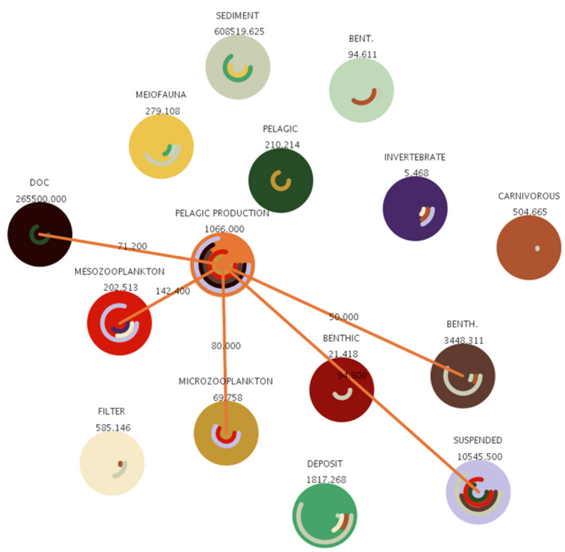


Figure C.3: Nodes labels and biomass and edge weights are highlighted when "q" is pressed on the keyboard.

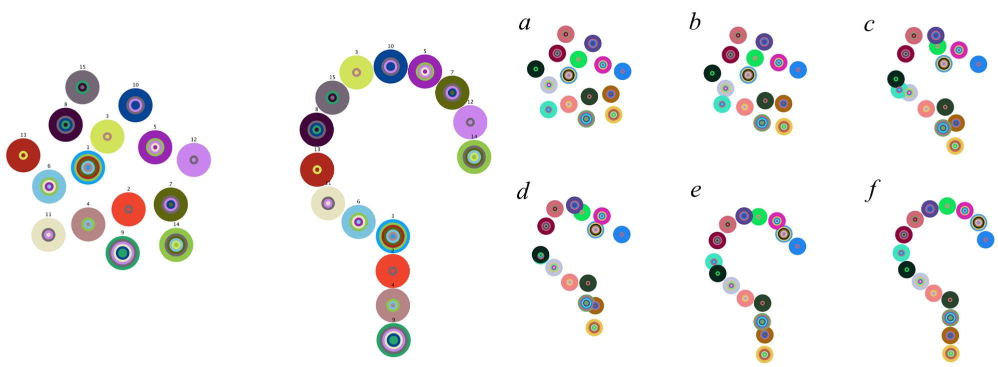


Figure C.4: Position of the nodes can be saved on an external file, and can be uploaded for later use in animation mode.

will move and re-arranged, with animation, to the positions that are saved on "position.txt" file (See Figure C.6).

C.2.3 Moving Individual Elements:

The arrangement of output and loop edges, or stigma and septal of daisy flower, can be changed simply by touching and moving them (See Figure C.7).

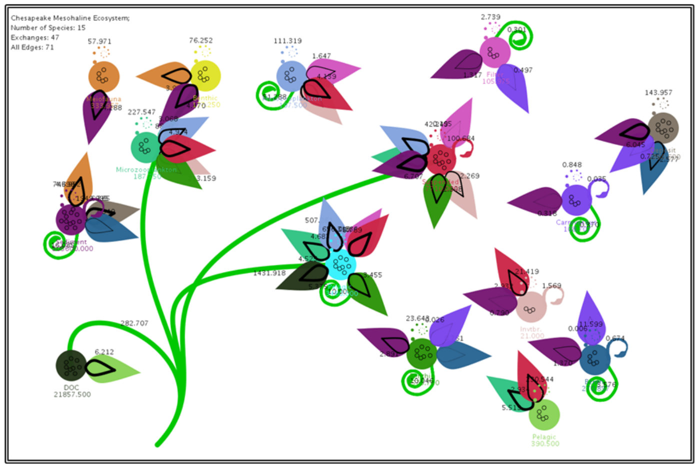


Figure C.5: Nodes labels and biomass and edge weights are made visible after “q” is pressed on the keyboard.

C.3 Eco-Spiro Visualization

Eco-Spiro visualization is specifically designed for ecological networks. The layout used for this visualization is a modification of Spirograph, which is a circular layout using a circle (the boundary circle) for placing nodes. Edges in Spirograph are mapped to arcs connecting nodes. This circle has an organic form for showing the closeness of ecosystem and for separating the environment into its internal and external spaces.

A list of information about the ecosystem that is presented with Eco-Spiro visualization, will appear on the top left corner of the screen, showing ecosystem’s name, the number of species, the number of exchange edges and the number of all edges that exist in that ecosystem.

C.3.1 Selecting One Node:

When a person clicks on one node on the circle, all exchange edges from that node become highlighted (See Figure C.8).

When a person selects one node using **Left Mouse Click** + pressing “2” on the keyboard,

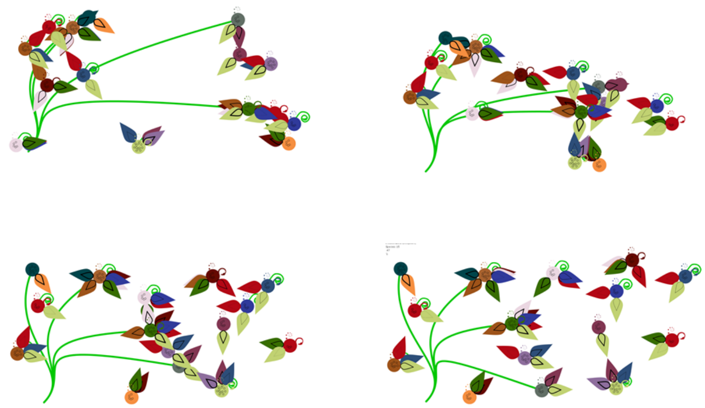


Figure C.6: Positions of nodes can be saved and used for animation.

Figure C.7: Output and loop edges can move using mouse/touch interaction.

and then selected second node using **Left Mouse Click** + pressing “3” on the keyboard, the amount of energy that indirectly, flows from one to another becomes highlighted (See Figure C.9).

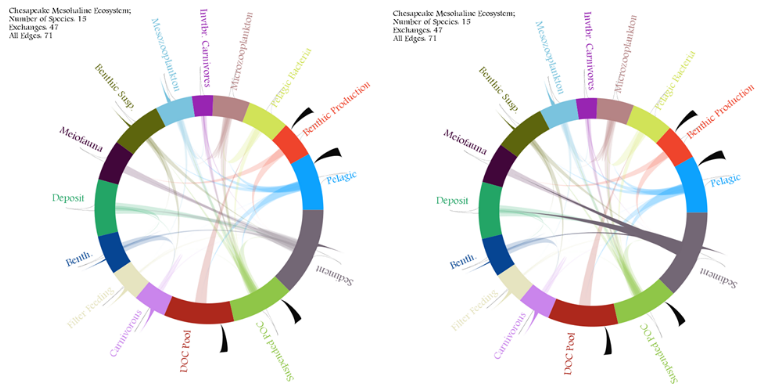


Figure C.8: When one node is selected all outgoing exchange edges from that node become highlighted.

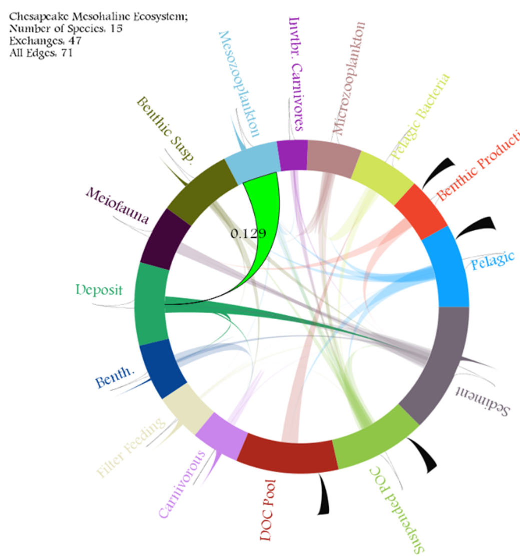


Figure C.9: Using mouse click and pressing “2” and “3” on the keyboard, the amount of indirect energy between two nodes becomes highlighted.