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Bicentric diagrams: Design and applications of a graph-based relational set visualization technique

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ABSTRACT

In an era where data on social, economic, and physical networks are proliferating at a rapid pace, the ability to understand the underlying complex structural connections, discover prominent entities, and identify clusters is becoming increasingly important. It is also well-established that interactive visualizations can amplify human cognition and augment decision making. Motivated by a practical need articulated by corporate decision makers and limitations of existing visual representations, this research presents our journey in designing and implementing bicentric diagrams, a novel graph-based set visualization technique. A bicentric diagram enables simultaneous identification of sets, set relationships, and set member reach in integrated egonetworks of two focal entities. Our technique builds on the well-established sociological theory of tie strength to visually group and position nodes. We illustrate the broad applicability of bicentric diagrams with examples from four diverse sample domains: university collaboration, technology co-occurrence, health app purchases, and interfirm alliance networks. We assess the value of our technique using an expert-based evaluation approach. The paper concludes with implications and a discussion of opportunities for implementation in real-world decision support settings.

1. Introduction

Humans are visual thinkers [1]. We use visualizations to solve problems, explore opportunities, communicate ideas, recognize patterns, and understand complexity [2]. The foundational challenge in information visualization research is to transform and map raw data into appropriate symbolic and spatial visual representations and couple it with effective and intuitive interaction techniques [3]. It also requires a deep understanding on the user and the task/decision context in which the visualization will be used. Visualization is thus both an art and a science. When done correctly, however, visualizations can significantly amplify human cognition [4].

In an era where data on social, economic, and physical networks are produced at a rapid pace, the ability to visually understand underlying complex structural connections, discover prominent entities, and identify clusters is becoming increasingly important [5,6]. It is thus not surprising to see the research community call for a greater integration of visual network analytics into decision support systems (DSS) [7]. The study of visual decision support is not entirely new. Prior work has incorporated visualization into DSS and evaluated its efficacy in various fields such as personal finance [8], healthcare [9,10], and national power system [11]. More recently, studies have shown the particular value of visual analytics for complex business ecosystem decision making [12,13].

Despite these notable attempts, several important challenges remain. Most network analysis studies still use relatively common visualization layout algorithms, such as circular or force-directed, to represent complex networks [14]. These layouts, however, often result in cluttered representations that are hard to analyze and interpret. The cluttered representation is particularly problematic for large networks because the number of edges increases much faster than the number of nodes. The DSS and information systems literature has recognized and confirmed the importance of representation in managerial problem solving and decision making [15,16]. Existing studies, however, predominantly compare existing classic representations such as table, list, and line chart [17,18]. Novel visual representations for specific types of decision-making problems are rarely developed, despite their importance to problem solving. Motivated by this literature gap and the practical need of corporate executives and investors to map global innovation networks of competing firms, and our discovery of the significant shortcomings of existing visualization techniques to help address questions related to sets (i.e., firm clusters), members of sets, relationships between sets, and reach (i.e., distance from focal node or relationship tier), we designed a visualization layout called the *bicentric diagram*.

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Overlaying two concentric layouts in a clever way, a bicentric diagram fuses ideas from graph and set visualization to depict sets, relationship between sets, and the reach of set members in the integrated egonetworks of two focal entities [19]. The concentric layout is arguably the best layout for depicting an egonetwork [20]. It places the focal node at the center of a set of concentric circles. All neighboring nodes are placed around the circumference of one of the circles based on how many steps they are away from the focal node at the center. Although the concentric layout works well when displaying a single focal node's egonetwork, it falls short when it comes to comparing or merging two focal nodes' egonetworks. A great deal of ambiguity arises when one attempts to portray two egonetworks in the same canvas such as where to place a node that has direct connection to both focal nodes. The bicentric diagram we propose in this paper provides specific visual encodings for simultaneous display of two egonetworks when the interest lies in identifying shared and exclusive components between the two networks.

During our early design discourse [21], it became increasingly evident that analysis of such set-related issues are not just pervasive in business network contexts, but also in sociology, economics, healthcare, politics, and engineering. In social networks, for instance, a researcher may be interested in identifying the overlap and exclusion of friends and acquaintances; in the healthcare context [22], patients may be interested in understanding the co-occurrence structure of drug side effects.

The contribution of our study is multifold. To the best of our knowledge, there are no existing techniques that enable simultaneous identification of sets, set relationships, and set member reach in integrated egonetworks of two focal entities. By developing a unique graph-based set visualization technique with broad application appeal, we contribute to information visualization and human–computer interaction in decision making. Moreover, building on the well-established theory of tie strength [23], we classify shared sets in the bicentric diagram into four types: (i) strong/strong, (ii) weak/weak, (iii) strong/weak or weak/strong, and (iv) exclusive-strong or exclusive-weak. This classification enables us to formally characterize the different types of questions one may address with a bicentric diagram. Our implementation of bicentric diagrams also contributes to the decision making and DSS literature. Considering decision making as an iterative multi-step process [24,25], our study focuses on improving the perspective development and synthesis step. Moreover, many comtemporary relational and network decisions involve identification of specific key nodes (e.g. structural holes) and exclusive assets in the overall network [26]. Our novel representation immediately supports such tasks. The DSS community also calls for further work on web-based DSS [25]. Our system is deployed on the web and accessible for a wide range of users, enabling greater democratization of decision making. By considering an appropriate layout and visual encodings, we also contribute to the aesthetic aspect of DSS design [24].

We illustrate the broad applicability of bicentric diagrams with examples from four diverse sample domains: university collaboration, technology co-occurrence, health app purchases, and global strategic alliances network. Lastly, we assess an interactive prototype version of the bicentric diagram using a value-driven expert evaluation approach and discuss opportunities for implementation in real-world settings. Overall, respondents give above-average scores to all surveyed aspects of our system. In particular, we find that survey respondents with higher visualization literacy levels tend to give higher scores to our implementation of bicentric diagrams in performance areas of time reduction, insight generation, and essence extraction. Even respondents with relatively lower visualization expertise give satisfactory scores in most aspects, indicating that experience and expertise are not a strict prerequisite to appreciate the value of our system.

The remainder of the paper is organized as follows. Section 2 provides an overview of the key related literature from information visualization, business analytics, and network analysis. Section 3 explains the detailed machineries of the bicentric diagram. Section 4 showcases various domains where the bicentric diagram can be a useful tool. Section 5 presents our user study that confirms value of the bicentric diagrams in four key performance areas. Section 6 concludes the paper.

2. Related work

In the DSS literature, the decision-making process has been modeled as an iterative process of problem recognition, perspective development, perspective synthesis, actions, and results [24]. The role of DSS is to facilitate human decision-making parts by providing structured views about information pertaining to the decision-making problem space [25]. As more network-centric data emerges, many decision-making contexts are now also network related. Given that the choice of representation of data influences decision-making outcomes [15,16], DSS must take this shift in decision-making contexts into account and novel representations are potentially needed.

Data visualization is a well-established method to support decision making in a wide variety of domains. For instance, a visualization approach was adopted to display geographic distribution and market power structure of the U.S. electric power system [11] and a visualization model of adjacency data illustrated college selection decisions [27]. Recent studies show how visualization affects and supports user decision making in the context of financial services [8] and healthcare delivery [9], respectively. Thanks to technological advancements in personal computers, the role of interactivity in visualizations has been highlighted in the literature. An interactive version of self-organizing map visualizations is shown to reduce the cognitive load during Internet browsing tasks [28] and a suite of interactive visualizations was developed and used to explore auction databases [29]. Departing from the decision-making context, a visualization approach is also shown to be useful in the strategic planning process as well [30].

Pending the nature of the data and use context, many different forms of visual representation and interactions exist [31,2]. Multivariate datasets are often visualized using parallel coordinates, starplots, or glyph-based techniques [32]. Hierarchical data are often depicted using a variety of space-filling techniques, such as treemaps, sunbursts, and circle packing [33,34].

One context in which data visualizations are becoming increasingly pervasive is in the analysis of networks. Virtually any aspect of our economic, technical, and social contexts can be described using networks [35]. Node-link diagrams and adjacency matrices are the preferred visualization method for network and graph data [14]. Such visualizations of network evolution can complement and even enhance the associated statistical analysis [36].

Network visualizations have been used to help identify global supply network risks [20], examine criminal networks [37], and understand the evolution of digital communication networks [38].

Following the recognition that many contexts of decision making involve analysis of networks, recent DSS studies have paid attention to the network perspective [39,20]. However, it is the inherent complexity of network data that often hinders the conversion of data into decision-making insights; this is amplified when the scope and size of the underlying data are large and wide [40,13]. Visualizations can help users overcome this issue by providing a graphical representation of the underlying network data structure [41]. When coupled with interaction techniques, network visualizations can facilitate the knowledge construction and sharing process and provide confirmatory and new insights [42,43]. Visual analytic systems that afford interactive visual exploration and analysis are thus invaluable for supporting decision-making processes.

Real-world networks are often characterized by sets, groups, and clusters. Visualizing sets and set-typed data has also been a topic of substantive interest in the information visualization community [44]. Sets are common data structures in information visualization and are