Multi-level tree based approach for interactive graph visualization with semantic zoom

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Abstract. A recent data visualization literacy study shows that most people cannot read networks that use hierarchical cluster representations such as “super-noding” and “edge bundling.” Other studies that compare standard node-link representations with map-like visualizations show that map-like visualizations are superior in terms of task performance, memorization and engagement. With this in mind, we propose the Zoomable Multi-Level Tree (ZMLT) algorithm for map-like visualization of large graphs that is representative, real, persistent, overlap-free labeled, planar, and compact. These six desirable properties are formalized with the following guarantees: (1) The abstract and embedded trees represent the underlying graph appropriately at different level of details (in terms of the structure of the graph as well as the embedding thereof); (2) At every level of detail we show real vertices and real paths from the underlying graph; (3) If any node or edge appears in a given level, then they also appear in all deeper levels; (4) All nodes at the current level and higher levels are labeled and there are no label overlaps; (5) There are no crossings on any level; (6) The drawing area is proportional to the total area of the labels. This algorithm is implemented and we have a functional prototype for the interactive interface in a web browser.

1 Introduction

Every day millions of people use maps to find restaurants, theaters, shops, the best routes to reach them. Google Maps, Apple Maps, OpenStreetMap are only some of the available services that use maps and all of them share in common the standard map interactions via panning and zooming. Panning moves the map in any direction while
keeping it at the same scale. Zooming changes the scale of the visualization by adding or removing details for a specific area. These two interactions are very familiar to people and provide a natural way to interact with large graphs. An important feature of map visualizations is that when zooming in or out, the information density remains roughly the same and the type of information (e.g., cities and roads) is also the same. Graph visualization systems that rely on meta-nodes (or super-nodes, cluster-nodes, etc.) and meta-edges (or edge bundling) violate this principle. With this in mind, we propose the Zoomable Multi-Level Tree (ZMLT) algorithm for map-like visualization of large graphs that is (1) representative, (2) real, (3) persistent, (4) overlap-free labeled, (5) planar and (6) compact:

1. The abstract and embedded trees represent the underlying graph appropriately at different levels of detail (in terms of the structure of the graph and the embedding thereof).
2. Real vertices and real paths from the underlying graph are shown at every level of detail.
3. If any node or edge appears in a given level, then they also appear in all deeper levels.
4. All nodes at the current and higher levels are labeled and there are no label overlaps.
5. There are no crossings on any level.
6. The drawing area is proportional to the total area of the labels.

Formally, given a node-weighted and edge-weighted graph \( G = (V, E) \) we want to visualize \( G \) as a set of progressively larger trees \( T_1 = (V_1, E_1) \subset T_2 = (V_2, E_2) \subset \cdots \subset T_n = (V_n, E_n) \subseteq G \), such that \( V_1 \subset V_2 \subset \cdots \subset V_n = V \) and \( E_1 \subset E_2 \subset \cdots \subset E_n \subset E \). To make the trees representative of the underlying graph we rely on a multi-level variant of the Steiner tree problem [3], where we create the vertex filtration \( V_1 \subset V_2 \subset \cdots \subset V_n = V \) with the most important vertices (highest weight) in \( V_1 \), the next most important vertices added to form \( V_2 \), etc.

A solution to the multi-level Steiner tree problem then creates the set of progressively larger trees \( T_1 = (V_1, E_1) \subset T_2 = (V_2, E_2) \subset \cdots \subset T_n = (V_n, E_n) \subseteq G \) using the most important (highest weight) edges; see Fig. 2. Note that extracting the best tree \( T_i \) that spans vertex set \( V_i \) may require the use of vertices that are not in \( V_i \), which are called Steiner vertices.

Just as in interactive map visualizations, at a minimum level of zoom, only the most important cities and highways are visible, and these are provided by the tree \( T_1 \) in our setting. Increasing the level of zoom brings in new cities and roads, and these are provided by the next tree in the filtration, until the maximum zoom level is reached and the whole maps is shown (the entire underlying graph \( G \), in our setting). The six guarantees above are also embodied in the ZMLT layout, which is implemented and has a functional prototype for the interactive interface in a web browser; see Fig. 1.

The rest of this paper is organized as follows: In Section 2 we describe related work, in Section 3 we give the details of ZMLT and in Section 4 we describe the visualization.
tool to navigate and interact with the output of ZMLT. In Section 4.2, we compare the results of our approach to existing techniques. We conclude in Section 5.

2 Related Work

Large Graph Visualization: Most graph layout algorithms use a force-directed or a stress model and provide a single static drawing. The force-directed model works well for small graphs, but does not scale for large networks. Speedup techniques employ a multi-scale variant or use parallel computation as in VxOrd. GraphViz uses the force-directed method sfdp that combines the multi-scale approach with a fast $n$-body simulation. Stress minimization was introduced in the more general setting of multidimensional scaling (MDS) and has been used to draw graphs as early as 1980. Simple stress functions can be efficiently optimized by exploiting fast algebraic operations such as majorization. Modifications to the stress model include the strain model, PivotMDS, COAST, and MaxEnt. Although these algorithms are fast and produce good drawings of regular grid-like graphs, the results are not as good for dense, or small-world graphs.

Graph layout algorithms are provided in libraries such as GraphViz, OGDF, MSAGL, and VTK, but they do not support interaction, navigation, and data manipulation. Visualization toolkits such as Prefuse, Tulip, Gephi, and yEd support visual graph manipulation, and while they can handle large graphs, their rendering often does not: even for graphs with a few thousand vertices, the amount of information rendered statically on the screen makes the visualization unusable.

Multi-Level Visualization: Research on interactive multi-level interfaces for exploring large graphs includes ASK-GraphView, topological fisheye views, and Grokker. Software applications such as Pajek for social networks, and Cytoscape for biological data provide limited support for multi-level network visualization. Zinsmanier et al. proposed a technique to deal with visual clutter by adjusting the level of detail shown, using node aggregation and edge bundling. Most of these approaches rely on meta-vertices and meta-edges, which make interactions such as semantic zooming, searching, and navigation counter-intuitive, as shown by Wojton et al. This work confirms that people have difficulty reading graph layouts that use hierarchical cluster representations (via high-level meta-nodes and meta-edges) such as “super-noding” and “edge bundling.” Other studies that compare standard node-link representations with map-like ones show that map-like visualizations are superior in terms of task performance, memorization and engagement. GraphMaps visualizes a graph using the map metaphor and provides different zoom levels, driven by an embedding of the entire underlying graph. GRAM also visualizes a graph using the map metaphor and provides different zoom levels but neither GraphMaps nor GRAM guarantees all six of our desirable properties. For example, GRAM does not provide consistency or planarity. GRAM provides a button to show or hide the edges of the shown graph but the first option does not show the structure of the graph and the second one leads to a hairball; see Fig. 3.

Overlap Removal and Topology Preservation: In theory, vertices are usually treated as point objects, but in practice, vertices are labeled and these labels must be shown in
the layout. Overlapping labels is a major problem for most graph layout algorithms, and it severely affects the usability of the visualization. The standard approach to dealing with this problem is post-processing of the layout where node positions are perturbed to remove label overlaps. This usually results in significantly modified layout with increased stress, larger drawing area, and with the introduction of crossings even when the starting vertex configuration is crossings-free.

A simple solution to remove overlaps is to scale the drawing until the labels no longer overlap. This approach works on every layout and is straightforward, although it may result in an exponential increase in the drawing area. Marriott et al. [47] proposed to scale the layout using different scaling factors for the $x$ and $y$ coordinates. This reduces the overall blowup in size but may result in poor aspect ratio. Gansner and North [35], Gansner and Hu [31], and Nachmanson et al. [50] describe overlap-removal techniques with better aspect ratio and modest additional area. However, none of these approaches (except the straightforward scaling), can guarantee that no crossings are added when starting with a crossings-free input.

Post-processing a layout while preserving the topology of the input layout is a difficult task. Pred [9] is a post-processing force directed algorithm applied on a given layout that aims to improve layout quality metrics while preserving the number of crossings. Impred [60] is an improved version that speeds-up the force computation and provides better results. This algorithm is not designed to remove the node overlaps but, with some appropriate modifications described in Section 3.4, it can be used for that purpose, while ensuring that the number of crossings remains unchanged.

**Steiner Trees:** The Steiner tree problem is one of Karp’s original 21 NP-Complete problems [41]. A polynomial time approximation scheme exists if the underlying graph is planar [10], but not for general graphs [19]. More importantly, the Steiner tree can be efficiently approximated within a factor of $\ln 4 + e < 1.39$ [16]. In the vertex-weighted Steiner tree problem, the cost of the tree is determined by the weights of the vertices included in the solution (rather than the weights of the edges). This version of problem is also NP-hard [49] but can be approximated within a logarithmic factor [37, 42]. The classic Steiner tree problem has also generalized to a multi-level setting [6, 17, 20], where the terminals appear on different levels and must be connected by edges of appropriate levels, as described in the introduction. In particular, Ahmed et al. [3] showed that the standard (edge-weighted) Steiner tree problem can be efficiently approximated
to within a constant factor. Similarly, Darabi et al. [21] described a multi-level version of the vertex-weighted Steiner tree, and showed that it can be approximated as well as the single-level version.

3 The Zoomable Multi-Level Tree Drawing Algorithm

As discussed in the previous section, there are many graph drawing algorithms and systems, and there is also a great deal of work on visualizing trees; see Treevis.net [57] which summarizes more than 300 techniques. However, none of these can guarantee the six desirable layout properties that we need: representative, real, persistent, overlap-free labeled, planar and compact. For example, sfdp [40] produces great drawings but cannot guarantee that trees are drawn without crossings. Other algorithms designed specifically for crossing-free tree layouts (e.g., Walker, orthogonal, radial, hierarchical) do not produce representative views of the underlying graph, as they impose a layer-by-layer visualization in graphs where there is no such structure. Such algorithms are also not designed for labeled data. In order to guarantee overlap-free labeled layouts, these algorithms require significant scaling and this violates the compactness property; see Fig. 4.

![Fig. 4: Layouts of a the large tree $T_8$ that is used as a running example in this paper, produced by several dedicated tree drawing algorithms in Tulip [5].](image)

With this in mind, we designed the Zoomable Multi-Level Tree (ZMLT) algorithm that guarantees all six of the desired properties. We begin with an overview of ZMLT as a block diagram shown in Fig. 5.

The input of this algorithm is a weighted graph with non-negative weights on edges and nodes and the general framework consists of the following steps:

1. **Layered tree extraction**: Given weighted graph, extract a set of trees that are persistent, real and representative of the graph.
2. **First-layer drawing**: Draw the first (smallest) tree in a planar fashion.
3. **Improve**: Improve the quality of the produced drawing while maintaining planarity.
4. **Remove overlap**: Remove label overlaps while maintaining planarity and aiming for compactness.
5. **Augment**: Add to the current tree the forest of subtrees needed to obtain the next (larger) tree, while maintaining palarity.
6. Repeat steps 3-5 until the last layer is reached.

7. **Extract subtrees**: Extract the layouts of all trees $T_1, T_2, \ldots$ from the drawing of the final tree that spans all the vertices of the graph.

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**Fig. 5**: ZMLT framework to extract and compute layouts for the multi-level tree hierarchy (left) and a table of notation used (right).

### 3.1 Layered tree extraction

**Input**: Weighted graph $G$

**Output**: Set of trees $\{T_1, \ldots, T_n\}$ such that $T = T_1 \subset T_2 \subset \cdots \subset T_n$

**Module**: Multi-level Steiner tree extraction algorithm

This module deals with the construction of the (abstract) multi-level tree from the given weighted graph. We use a **multi-level vertex-weighted Steiner tree (MVST)** [21], defined and discussed in the Introduction. For our purposes, we are interested in the maximum weight Steiner tree, as nodes and edges with high weights are important and should be present on the high levels in the multi-level hierarchy. While the Steiner tree problem usually asks for the min cost tree, this is easy to fix by simply choosing the reciprocal of the weights (assuming all weights are positive and greater than 1). Note that the multi-level Steiner tree step above results in the creation of abstract (not yet drawn) trees. Before starting the actual layout computation, we preprocess the nodes and the edges. First, we assign different font sizes to the vertex labels, depending on the level they belong to. Second, we eliminate vertex and edge weights.

**Rationale**: The multi-level Steiner tree approach used in this module ensures the representative property, as important vertices and edges belong to the higher levels. Further, the multi-level Steiner tree approach guarantees the real property as real vertices and real paths are represented in every tree. Finally, this approach also guarantees the persistent property, as by construction we have that $T_1 \subset T_2 \subset \cdots \subset T_n$.

Differentiating the font sizes helps identify the more important vertices even on deeper levels when there is a mix of nodes from different levels. We associate with each label the enclosing rectangle and these are used compute and remove overlap in later stages. We forget the weights from this point onward since they already played their role in the extraction of the multi-level Steiner tree.

### 3.2 First-layer drawing

**Input**: $T_1$

**Output**: Planar $\Gamma(T_1)$

**Module**: Crossing free drawing algorithm.
The input at this step is the tree at the first layer of the hierarchy, namely $T_1$. Here the desired output is a planar drawing of the unweighted, unlabeled tree. Algorithms that guarantee a planar drawing of $T_1$ and do not impose additional features (such as hierarchical visualization) are suitable for this module.

**Rationale:** Here we aim to compute a representative layout for $T_1$ while ensuring the planar property.

### 3.3 Drawing-improvement

**Input:** $\Gamma(T_i)$.

**Output:** Improved $\Gamma(T_i)$.

**Module:** Modified ImPred algorithm.

This module improves the drawing of $\Gamma(T_i)$, the output of the previous step. The algorithm used for this module is ImPred [60], a force directed algorithm that aims to improve the layout of a drawing without changing the number of crossings in the input layout. To preserve the number of crossings of the input drawing, this algorithm uses three forces: (i) node-to-node repulsion force ($F_r$), (ii) edge attraction force ($F_a$), (iii) node-to-edge repulsion force ($F_e$). The last force prevents a vertex from crossing any edge and ensures that no crossing is removed or added. We modified the desired edge-length distances in order to have longer edges at higher level trees and shorter edges for lower level trees.

**Rationale:** This step is particularly meaningful from $T_2$ and deeper, when an already drawn high-level tree $T_i$ is combined with forest of subtrees from the next level to obtain $T_{i+1}$. As we will see in Step 3.5 (Augment layer), forest of subtrees is drawn in a sub-optimal way in order to ensure that it can be added while guaranteeing planarity. This makes the drawing improvement stage essential in the multi-level layout pipeline.

### 3.4 Remove label overlap

**Input:** $\Gamma(T_i)$

**Output:** $\Gamma(T_i)$

**Module:** Modified ImPred algorithm in remove overlap mode.

In this module we add labels and remove overlaps. We do this by adding another Label-to-Label-repulsion (llrep) force to ImPred. As in other force-directed algorithms, this force uses a repulsion force parameter $\delta$. At each iteration we compute llrep$_{uv}$ for every pair of vertices $u$ and $v$ as follows. Let $(x_u, y_u)$ and $2w_u, 2h_u$ be the coordinate, box width, and height of a vertex $u$, respectively. Let $(x'_u, y'_u)$ be the new force of $u$. This repulsion force is zero when vertices $u$ and $v$ do not overlap each other i.e., $w_u + w_v - abs(x_u - x_v) < 0$ or $h_u + h_v - abs(y_u - y_v) < 0$. Otherwise the force is applied in the direction of the line through the vertices $(x'_u, y'_u) = (-\delta, s*(x_u - \delta - x_v))$ and $(x'_v, y'_v) = (\delta, s*\delta + y_u - y_v)$, here $s = \frac{y_v - y_u}{x_v - x_u}$. Note that this approach reduces label overlap iteratively. In our experiments all overlap can be removed, but we also post-process by scaling in order to guarantee that there are no overlapping labels.

**Rationale:** ImPred, with the additional Label-to-Label-repulsion force, works best locally. Thus the progressive multi-layer drawing algorithm has a good chance of removing overlaps without needing to resort to scaling.
3.5 Augment-layer

**Input:** $\Gamma(T_i), F_{i+1}$.

**Output:** Preliminary drawing of tree $T_{i+1}$.

**Module:** Monotone drawing algorithm to add the forest.

![Diagram](image)

Fig. 6: Augmentation: $\Gamma(T_i)$ is augmented with $\Gamma(F_{i+1})$ to obtain $\Gamma(T_{i+1})$. In this example, the common vertex of $T_i$ and $F_{i+1}$ is shown as a square. Each subtree rooted in the common vertex (enclosed by dotted gray region) is drawn in monotone way and placed in the cones of $\Gamma(T_{i+1})$ around the common vertex, based on the size and width of the cones. If crossings occur the subtree is scaled down until there are no crossings.

This step adds to $T_i$ the vertices and edges of the forest $F_{i+1}$, so that $T_i \cup F_{i+1} = T_{i+1}$. The goal of this module is to start with a good layout of $T_i$ and initial layouts of the forest $F_{i+1}$ and create a planar drawing of $T_{i+1}$.

A monotone drawing of a tree is a straight-line drawing such that, for every pair of vertices, there exists a path that monotonically increases with respect to some direction [4]. Since a monotone drawing of a tree is always a planar drawing, we use it to add the drawing of $\Gamma(F_{i+1})$ to $\Gamma(T_i)$ yielding $\Gamma(T_{i+1})$.

Forest $F_{i+1}$ is made of trees rooted in vertices of $T_i$ and those are the only vertices in common between $F_{i+1}$ and $T_i$. The common vertices define where the rooted trees should be placed in the input drawing. Each such subtree is placed in the middle of the cone defined by two consecutive edges around the common vertex, in decreasing order by size of the tree and the size of the cone. After placing the monotone drawing of the subtree a crossing check is performed. If a crossing is generating by this placement, the subtree is scaled down. This process continues until adding the subtree creates no crossings and until all components of the forests are placed; see Fig. 6.

**Rationale:** The main objective here is to combine $T_i$ with $F_{i+1}$ and obtain a planar drawing of $T_{i+1}$. The improvement of the layout and overlap removal are performed in other steps.

3.6 Extract subtrees

**Input:** $\Gamma(T_n)$, all edges

**Output:** $\Gamma(T_1), \ldots, \Gamma(T_n), \Gamma(G)$

**Module:** Adding edges.
This step actually computes the drawings for all the trees in the multi-level hierarchy. We simply extract from \( \Gamma(T_n) \) the layouts for all subtrees \( \Gamma(T_1), \ldots, \Gamma(T_n) \). We also generate the layout for the entire graph, \( \Gamma(G) \), by adding to \( T_n \) all the edges of \( G \).

4 Interactive Web Browser Interface and Prototype

In this section we describe a functional browser interface and a prototype deployment of ZMLT with a specific dataset.

4.1 Web Browser Interface

The output the algorithm contains the positions of all the nodes in all the trees, as well as in the underlying graph. We modify the node-link representation into a map-like one using GMap [30]. Finally we extract GeoJSON files and use openlayers to display the data in the browser. We briefly describe the process.

Node Clustering: By default, we use MapSets [43] to cluster the graph and show the clusters as contiguous regions on the map, although other GMap [30] options are also available.

Generating Map Layers: GeoJSON [15] is a standard format for representing simple geographical features, along with their non-spatial attributes. We split all geometric elements of the map into nodelayer, edgelayer, clusterlayer. Each of the map layers is composed of many attributes. For example, nodelayer contains node-ID, coordinates, font-name, font-size, height, width, label and weights for all nodes.

JavaScript Application: For rendering and visualizing the map layers we use openlayers, a JavaScript library for displaying map data in the browser. This visualization requires additional work to show the map elements in a multi-layer fashion. Node attributes, edge attributes and zoom level is used to determine the appropriate levels in the multi-level visualization.

Interactions: As an interactive visualization tool, we enable panning and zooming, as well as clicking on nodes and edges; see the Fig. 7.

4.2 Prototype ZMLT Deployment

In this section we show the results of our technique applied to the GRAM Topics Network [14]. This network is a weighted topic graph extracted from Google Scholar with 5947 nodes and 26695 edges. We used the ZMLT algorithm with 8 levels, determined by vertex weights. Tree \( T_1 \) contains the heaviest 5% of the vertices, tree \( T_2 \) contains the heaviest 15% of the vertices, and so on until tree \( T_8 \) which contains all vertices.
The exact percentages used are (5, 15, 30, 40, 60, 70, 85, 100). All vertices are labeled using 8 different font sizes. The vertices in tree $T_1$ have font size 30, the vertices in tree $T_2$ have font size 25, and so on until tree $T_8$ where vertices have font size 8. The exact font sizes are (30, 25, 20, 15, 12, 10, 9, 8). The prototype is available here: http://uamap-dev.arl.arizona.edu:8086/zmlt.html

4.3 Evaluation

We compare ZMLT to a simpler implementation relying on off-the-shelf tools using several quality metrics.

**Direct Approach:** Our goals of ensuring planarity and labeling all vertices at the current and higher levels without overlaps can be achieved using the off-the-shelf **Circular Layout** offered by yED. This algorithm produces layouts that emphasize group and tree structures within a network drawing trees in a radial tree layout fashion [62]. We produced this layout by drawing $T_8$ using the Circular Layout with BCC Compact and the “consider node labels” feature. Then we extracted the subtrees of the hierarchy. In the following we call this procedure **Direct Approach**.

**Quality Metrics:** ZMLT uses the graph weights only for the extraction of the trees. As both the direct approach and ZMLT draw unweighted trees, then we use the following three (unweighted) metrics:

- **Edge length uniformity (EU)** evaluates the normalized standard deviation of edge lengths in the layout;
- **Stress (ST)** captures how well the geometric distances in the layout between pairs of vertices reflect their graph-theoretic distances in the graph;
- **Blank space (BS)** measures the ratio between the sum of the areas of labels and the area of the drawing.

These metrics have been used in many prior graph drawing studies [12, 23, 25, 34, 44, 46, 52]. Given $\Gamma$, a straight-line drawing of graph $G$, EU and ST are defined as follows:

$$EU(\Gamma) = \sqrt{\frac{1}{|E|} \sum_{e \in E} (l_e - \bar{l})^2}$$

$$ST(\Gamma) = \frac{1}{|V|^2} \sum_{i,j \in V} w_{ij} (\|p_i - p_j\| - d_{ij})^2$$

where $l_e$ is the length of edge $e$, $\bar{l}$ is the average length of all edges, $p_i$ and $p_j$ are the coordinates of vertices $i$ and $j$ in $\Gamma$, $d_{ij}$ is the graph theoretic distance between vertices $i$ and $j$ in $G$ and $w_{ij} = d_{ij}^{-2}$.

**Results:** Figure 8 shows the layouts of each layer computed by the direct approach while Fig. 9 shows the layouts produced by our technique. Even though details are impossible to see, some significant differences stand out visually. For example, in order to achieve compact layout, the direct approach wraps the trees around in a spiral fashion, which is not a good representation for the underlying graph. There are also very large differences in the lengths of the edges produced by the direct approach.

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3 All metrics are available at https://github.com/felicedeluca/graphmetrics
Fig. 8: Tree hierarchy drawn with the Direct Approach.

Fig. 9: Tree hierarchy drawn with ZMLT.
The metric analysis in Table 1 confirms the observations above. The table reports the values for the three measures computed on each of the 8 trees (representing the graph on different level of detail). Low values in all metrics (EU, ST, BS) correspond to better results and ZMLT has lower values in every table entry.

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Direct Approach

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ZMLT

Table 1: Metric-based layout evaluation of the Direct Approach and ZMLT.

5 Conclusions and Future Work

We presented ZMLT, a multi-level graph visualization approach based on the map metaphor which guarantees that the layout has the following properties: (1) representative, (2) real, (3) persistent, (4) labeled overlap-free, (5) planar and (6) compact. ZMLT extracts from a given graph a multi-level tree using a multi-level Steiner tree approach which are used to provide semantic zooming for interaction with the underlying graph. code for extracting the multi-level tree, generating layouts, measuring quality, and the interactive visualization system are available at https://github.com/enggical/mlgd. The prototype is available here: http://uamap-dev.arl.arizona.edu:8086/zmlt.html.

There are several natural directions for future work. To leverage the map metaphor better, we would like to represent edges and paths in a way that more closely resembles a road-network. Defining *highwayness* and optimizing it will likely lead to better visualization and interaction. ZMLT currently relies on multi-level trees, but perhaps a better approach would be use a multi-level graph spanner (sparse subgraphs that approximately preserve shortest path distances).

References