Geographic Network Visualisation: A Survey and Taxonomy

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Abstract

Geographic networks such as train networks or trade flows are ubiquitous. Being able to explore and analyse this type of data visually is crucial to obtaining insights from it. Yet, geographic networks data remains challenging to visualise. Various visualisation techniques have been proposed in the growing literature, which this work reviews and structures using a novel visualisation taxonomy. The taxonomy is based on categorising each technique across four facets: how the geographic aspect is represented, how the network aspect is represented, how these two visual representations are integrated, and to what extent it relies on user interaction. Based on the taxonomy, we classify and discuss existing techniques and identify directions for future research. A companion website providing an overview of the collected techniques and their classification is available at sarah37.github.io/geographic-networks.

Table of Contents

Chapter 1

Introduction

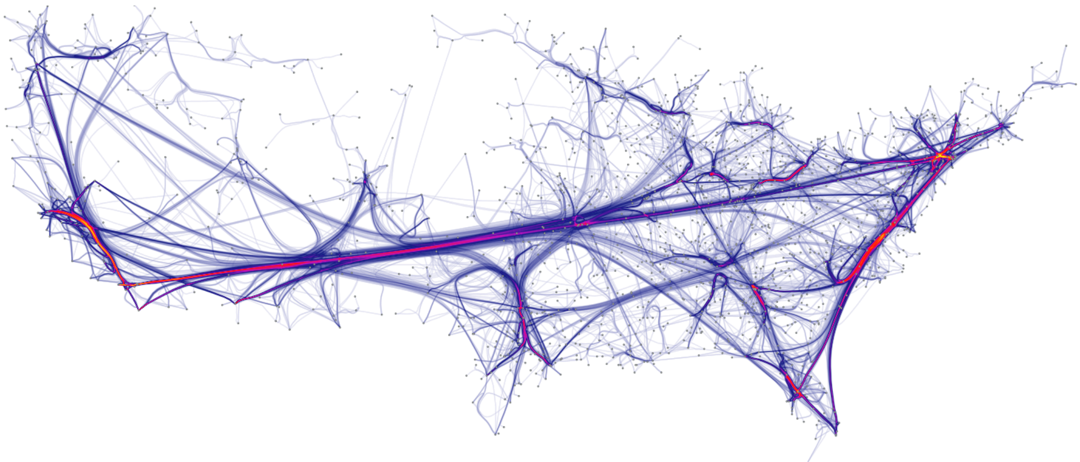


Figure 1.1: Example of a geographic network visualisation — airline connections across the United States, as displayed using force-directed edge bundling [Hv09]

An often-made claim among geographers is that '80% of all data is geographic'. While neither the origin nor the accuracy of this statement is clear [HB13], geographic data certainly is ubiquitous and network data is no exception. Geographic network data describes the relationships between geolocated entities. Examples are airports as connected by commercial flights (Figure 1.1), global trade, or public transport networks. Technological developments have enabled us to collect increasingly precise data, particularly location data. Visualisation is crucial when trying to extract insights from these ever-growing datasets, but continues to be challenging. Even with relatively small networks, overlap and clutter frequently make visualisations difficult to read or even misleading. Also, geographic networks often have irregular densities, and are for example much denser in a city than in its surroundings. A related issue is that node locations can be extremely close or even identical. Likewise, locations or network features can be uncertain. Techniques to address some of these issues have been developed, but there is no one-size-fits-all: it is often not possible to address all issues at once, and there is usually a trade-off between computational complexity and visual quality.

Most geographic network visualisations, such as the one in Figure 1.1, encode the network data as node-link diagrams and variations thereof. A node-link diagram depicts a network as nodes connected by lines, representing the links between the nodes. For a geographic network, the nodes are typically positioned according to their geographic location; optionally superimposed onto a map if the geographic context is not clear from the network display alone. The issue of clutter and overlap is more difficult to address for geographic networks because in geolocated node-link diagrams, nodes cannot simply be repositioned to relieve some of the (edge) overlap. Alternative representations like matrices fail to display the geographic dimension entirely.

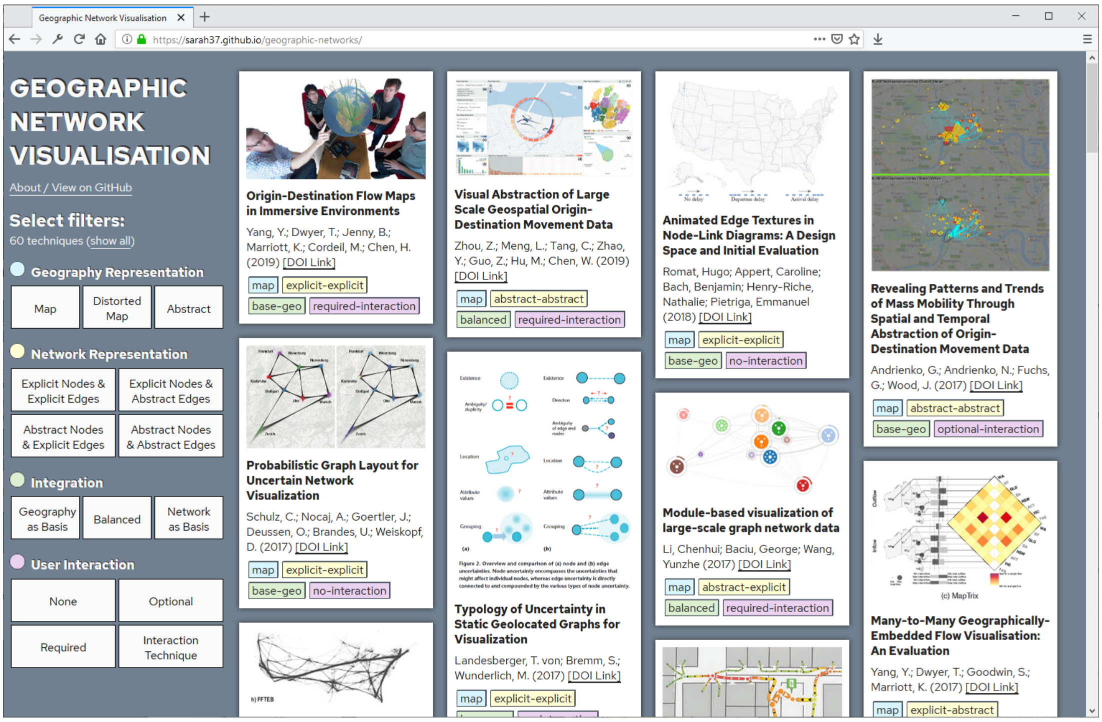


Figure 1.2: Screenshot of the companion website (sarah37.github.io/geographic-networks)

Techniques for geographic network visualisation have been contributed from a variety of fields such as information visualisation, graph drawing and geovisualisation. To date, no comprehensive taxonomy specific to these techniques exists. Accordingly, the contributions of this work are threefold:

1. A novel taxonomy of geographic network visualisation techniques;
2. A compilation of relevant techniques, classified and tagged, accessible through a companion website (Figure 1.2, sarah37.github.io/geographic-networks);
3. The identification of promising directions for future research.

The following chapter begins by providing some background on geographic networks and related surveys. Next, we define geographic network data, its characteristics, and the scope of this survey more precisely and outline the methodology. Then, the taxonomy is presented, and visualisation techniques are discussed in the context of their assigned taxonomy categories. Lastly, the limitations of this work as well as opportunities for future research are discussed, followed by the conclusion.

Chapter 2

Background

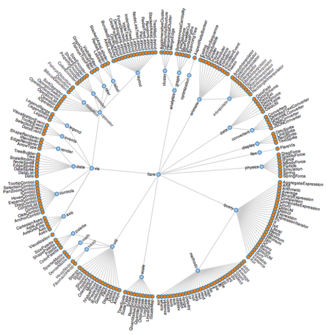
2.1 Graph Drawing and Network Visualisation

Graphs are a useful data model for relational data like networks and flows. Real-world examples of graph data are refugee flows, train networks, or flows of goods between warehouses. In all of these examples, it is important that the geographic aspect be represented in a visualisation – one needs to be able to see where refugees come from and where they go, which places are connected by a train network and how far they are apart, and where the warehouses are located. To model such data as a graph, the entities between which connections or flows exist – countries, train stations, warehouses – are described as *nodes* or *vertices*. The connections between them are called *links* or *edges* [Tru93].

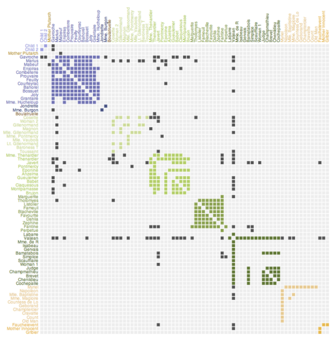
Graphs have traditionally been visualised as node-link diagrams, in which each node is a dot or other symbol, and each link is a line connecting two nodes. Visualisation is an effective tool for exploration and analysis of geographic network data. However, many of the methods developed for graph visualisation in general are not suitable for geographic networks (Figure 2.1). Techniques such as force-directed layouts or radial layouts are based on positioning the nodes in specific ways to reveal different graph characteristics, whereas adjacency matrices, which display the connections as cells in a matrix, are abstracted in a way that removes node positions altogether. Consequentially, the development of visualisation techniques specifically for geographic networks has received increasing attention over the last two decades.

Due to its geographic aspect, contributions to geographic network visualisation have not only come from the graph drawing and information visualisation communities, but also from geography. Geographers were among the first to embrace the

(a) Force-directed node link diagram



(b) Radial graph layout



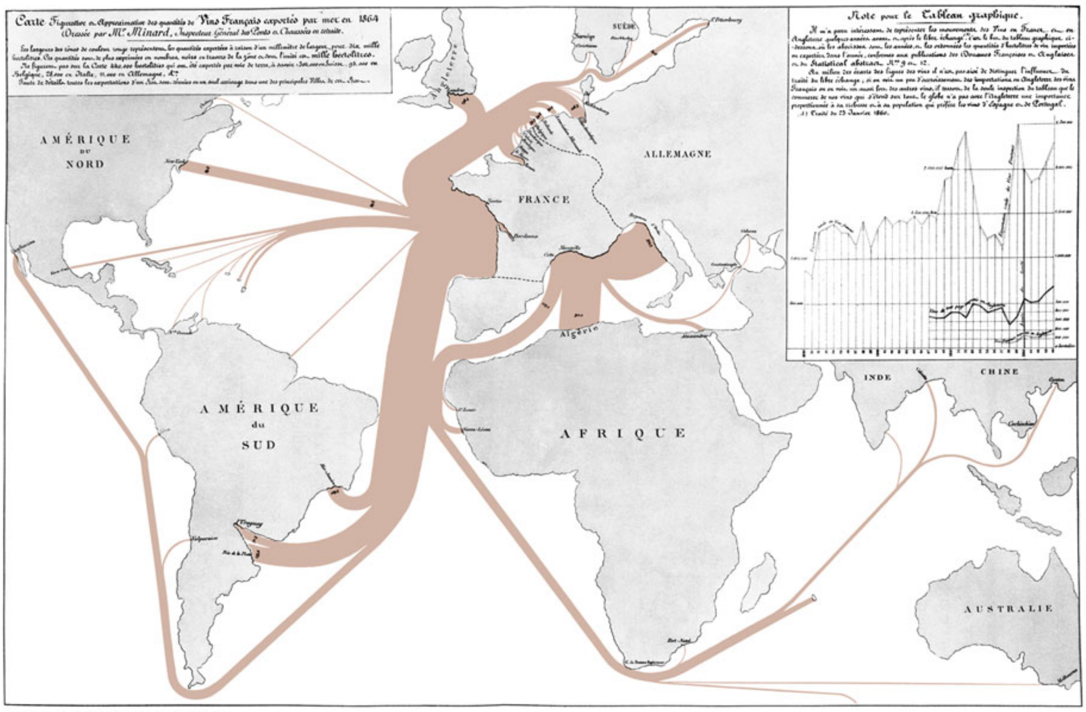
(c) Adjacency Matrix

Figure 2.1: Standard graph visualisations, which are not suitable for geographic networks without extensive modification (Images from [HBO10])

possibilities of using computers to generate visuals. Initially, the main achievements were focused on automation and the use of the computer, not visualisation quality. Tobler's 'Experiments in migration mapping by computer' [Tob87] produced maps that, visually, were of a much lower quality than the hand-drawn flow maps published by Minard over a century earlier in 1845 or the telegraph cable network maps drawn in the early 1900s (Figure 2.2), yet they laid the groundwork for the more sophisticated visualisation techniques introduced in more recent years. In a way, the current challenges are two-fold — using computers to automatically create visualisations of a similar quality as hand-drawn ones, and doing so for ever-growing datasets. Many of the recent methods leverage computers to create visualisations that would be impossible to create manually, for example the variety of edge bundling techniques that have been introduced.

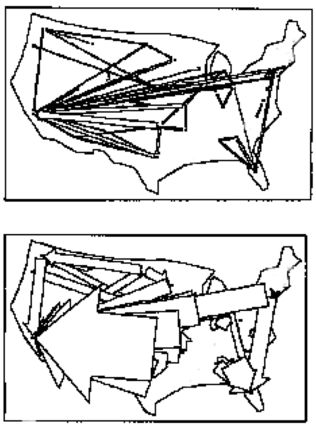
2.2 Related Work

There are a number of related publications that have partly surveyed geographic network visualisation techniques. Rodgers provided a brief overview of the state-of-the-art in geographic network visualisation in 2005, but did not include a comprehensive taxonomy in his overview [Rod05]. More recently, Wolff discussed the use of graph drawing in cartography [Wol13]. Both of these surveys were used for a meta-survey on the visualisation of multi-faceted graph data, in which spatial (including geographic) data is discussed as one possible facet of a multi-faceted graph [HSS15]. The authors of the meta-survey describe geographic network visualisation as a subdomain of cartography and claim that 'most of the literature on (geo)spatial graphs has appeared in

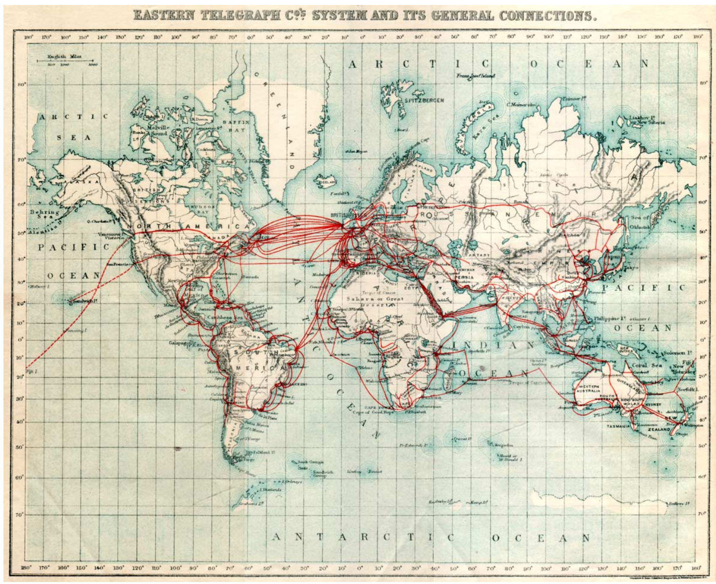


Charles Joseph Minard, *Tableaux Graphiques et Cartes Figuratives de M. Minard, 1845–1869*, a portfolio of his work held by the Bibliothèque de l'École Nationale des Ponts et Chaussées, Paris.

(a) Minard's flow map of French wine exports for 1864 [Min65]



(b) Tobler's US migration flow map from 1987 [Tob87]



(c) Map of the global telegraph network in 1901 [01]

Figure 2.2: Comparison of historic hand-drawn and early computer-generated flow maps

this context' [HSS15, p. 1], an observation that, considering most techniques included in this survey were published in information visualisation venues, cannot be confirmed in this work. The application of visual analytics methods to geographic networks is discussed by Rozenblat and Melançon [RM13], but their focus is not on visualisation methods as such, although they include an overview of edge bundling methods. A more detailed survey of edge bundling, one of the more prominent techniques in geographic network visualisation, is provided in [Zho+13].

Furthermore, there are a variety of surveys covering visualisation techniques for other specific types of graphs and networks, for example dynamic graphs [Bec+14], multivariate networks [Nob+19], trees [Sch11], or multilayer networks [McG+19]. Due to the overlap between types of graphs and variety of different characteristics a graph can have, each of these surveys includes techniques suitable for certain types of geographic networks as well, e.g. dynamic geographic networks.

Chapter 3

Scope and Methodology

This chapter defines our notion of a geographic network more precisely, describes characteristics of network data, specifies the scope of the survey, and reports how relevant publications were obtained and classified.

3.1 Definition: Geographic Network Data

In this survey, geographic network data as well as data that can be modelled as such are considered. Examples of data that can (in most cases) be modelled as geographic network data are origin-destination (OD) data or flow data. Geographic networks in general are not a well-defined concept, and overlap with other concepts such as spatial networks and geolocated graphs. Geographic networks can be seen as a subset of spatial networks, which often are interpreted to include non-geographic networks such as biological ones. The term 'network' as used in 'geographic network' is used here in its colloquial sense and not in the way a network is defined in graph theory. Instead, a relatively broad definition as follows is used:

Geographic network data is any data that can be modelled as a graph $G = (V, E)$, where V is a set of vertices and E is a set of edges, with each edge either being a set of two distinct vertices (undirected graph) or an ordered set of two vertices (directed graphs) and each vertex having an associated geographic location.

The term 'geographic location' is deliberately left vague and should be taken in its wider sense, including for example geographic coordinates, areas, city names, or uncertain locations. To describe the data structure, the terms graph and network are used interchangeably in the following text.

Further elaborating on our notion of what qualifies as a network; flows, trees, origin-destination data, and some types of spatial interaction data are all included since they can be modelled as graphs. However, single-line networks such as route descriptions have not been included despite in theory fitting this definition. Also excluded is movement data, which is often discussed in the context of OD data but cannot be modelled as a graph unless simplified to OD data.

3.2 Data Characteristics

As the definition used in this survey is relatively broad, there is quite some variety in the networks (or graphs), of which the main aspects are outlined in this section. The taxonomy presented in Chapter 4 is a visualisation taxonomy, not taking data types into account. However, since a data visualisation practitioner would typically have a certain dataset or type of data and then try and find the best possible visualisation for it, we additionally classified each technique in the survey as suitable or unsuitable for different types of data based on the characteristics listed here. This classification is available in full in Appendix A and can also be used to filter techniques on the companion website.

Directed and undirected graphs — In an undirected graph, each edge connects two nodes without any associated direction. This can either mean that the connection is truly undirected, or it can mean it goes both directions, such as when describing a railway network where tracks between train stations are used in both directions. In a directed graph, each edge has a direction. An example would be modelling trade of certain goods such that different countries are modelled as nodes, and each flow of goods from one country to another is a directed edge.

Edge weights and attributes — Beyond a direction, edges can have additional attributes. The most common attribute is a weight, meaning that a value is associated with each edge. Edges can also have more complex attributes, making the network a multivariate network. Multivariate networks are surveyed by Nobre et al. [Nob+19].

Dynamic graphs — Graphs can be dynamic, meaning they change over time. Beck et al. present a typology and survey of visualisation techniques for dynamic graphs [Bec+14].

Uncertainty — Uncertainty can manifest in a number of ways in a graph, ranging from uncertainty about whether a node or edge exists at all, to uncertainty about node or edge attributes such as weights.

Node Locations — Node locations can take different forms. They can be point locations, e.g. given by geographic coordinates, or areas, such as continents, countries, or administrative units. Locations can also be uncertain to different degrees.

Geolocated Edges — Edges could be geolocated in addition to the nodes being geolocated. This is the case for example when modelling a rail network as a graph, since the train tracks follow specific paths.

Special Graph Structures — Some networks may have a special graph structure as described in graph theory. A notable structure is the tree, a graph where any two nodes are connected by exactly one path. Planarity, i.e. whether the graph can be drawn such that no two edges overlap, is another important feature.

3.3 Survey Scope

Based on our definition of a geographic network introduced in Section 3.1, we further define the scope of the survey in terms of the papers selected for inclusion in the survey.

In general, we focus on visualisation *techniques*. To qualify for inclusion, a visualisation technique must represent both the geographic and the network aspect of the geographic network. Consequentially, a paper describing a visualisation technique has to either be focused entirely on geographic networks, or, at a minimum, be applicable to geographic networks and demonstrate this with at least one example application. Techniques that can for other reasons be clearly identified as being applicable to geographic networks, e.g. through respecting pre-determined node positions of a non-geographic kind, are included even if there is no geographic example. As such, general purpose network visualisation techniques are not included if they disregard the geographic aspect entirely, even if they can theoretically be applied to geographic networks.

While the focus is on technique papers, several evaluation-, application- or review-focused publications, which nonetheless presented novel visualisation techniques, have been included as well.

3.4 Data Collection

As discussed previously, contributions to geographic network visualisation have come from several scientific fields, the main ones being information visualisation, geovisualisation, and graph drawing. This has resulted in a diverse set of terms being used to describe similar concepts, and relevant papers being spread across many different journals and conferences. Therefore, a systematic two-step approach was followed to retrieve relevant references. Initially, conference proceedings of major conferences in the three aforementioned fields were manually scanned for relevant publications. From the resulting set of references, keywords were extracted, which were then used to search for additional publications in the relevant online libraries. Additionally, references of already retrieved publications were followed.

3.4.1 Initial collection

Proceedings of the following conferences were considered:

- IEEE VIS (InfoVis) (Accessed via [Ise+17])
- ACM CHI (Accessed via [ACM19])
- EuroVis (Accessed via [Wil19])
- PacificVis / APVIS (Accessed via [Pac19])
- Symposium on Graph Drawing (GD) (Accessed via [Spr19])

For each conference, we scanned the proceedings and manually retrieved candidate papers based on their title, resulting in a collection of 191 publications. In a second pass, in which at least the abstract and figures of each paper were examined, this was reduced to 40 publications that fit the scope.

3.4.2 Additions

The major journals such as Computer Graphics Forum, IEEE TVCG and others publish too much for it to be feasible to scan each issue manually. Therefore, to include as many relevant articles from these journals as possible, keyword searches through Google Scholar, the ACM Digital Library, and IEEE Xplore were used to retrieve relevant articles.

Keywords were extracted from the initial, manually selected, set of papers. The search terms are a combination of different terms that are used to describe our notion of a geographic network and different terms used to describe the visualisation aspect. Figure 3.1 shows the keywords and how they were combined in a Boolean search. Unfortunately, this search still turned up relatively many false positives, such as spatial interaction techniques for visualisation in virtual reality, but narrowing it down further would have resulted in missing some papers that are in scope. Similarly to the initial collection described in the previous section, papers were selected for inclusion in a first pass based on title, and a second pass based on examining as much as needed of the paper to decide on inclusion or exclusion.

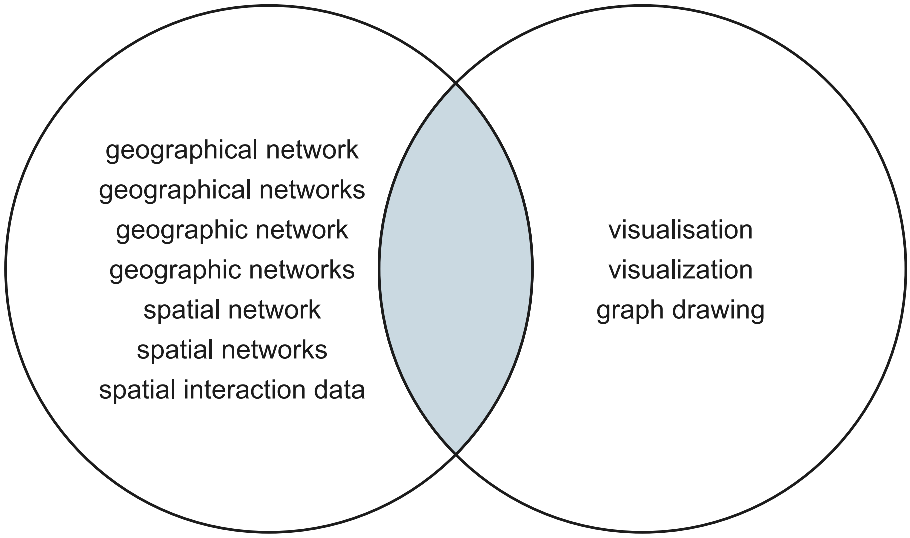


Figure 3.1: Keywords used for retrieving papers

In addition to manual and keyword searches, a number of papers were discovered through following references of some of the already obtained publications. 20 papers were added to the collection, resulting in a total of 60.

3.4.3 Data Analysis

To obtain an initial overview of the different characteristics of geographic network visualisations, we tagged all techniques with a set of preliminary tags, adding new tags flexibly throughout the tagging process. These tags revealed abstraction and distortion as important distinctions between techniques, which is reflected in the taxonomy presented in the following chapter. Additionally, the data type–related tags were expanded into a more complete list of data characteristics and applied to all techniques, available in Appendix A.

Chapter 4

Taxonomy

Conceptually, the geographic and network aspects of a geographic network visualisation can be considered separate. The taxonomy presented here makes use of this idea and classifies each visualisation along four facets — the first two describe the geography and network representation respectively and the third describes how the two representations are integrated. Since interaction can be an important component of a visualisation concept, a fourth facet was added to describe the level of interaction used by the visualisation technique. As such, this taxonomy is a pure visualisation taxonomy, not describing data types or user tasks.

To ensure all possible characteristics are covered, the categories for each facet are based on continuous scales. For each facet, we then determined discrete categories along the continuous scale. Creating a limited number of discrete categories not only facilitates the classification task, but also allows for a clear evaluation of how frequently different categories across facets occur together.

The first two facets are classified along scales based on abstraction. In the context of data, abstraction has been defined as 'the process of hiding detail of data while maintaining [its] essential characteristics' [Cui+06, p. 709]. In addition to hiding data, we also consider distortion a form of abstraction here. For the *geography representation* facet, this results in representations being categorised into the categories *map*, *distorted map*, and *abstract*, each being an increasingly abstract representation of geography. For the *network representation* facet, the classification is two-dimensional, because nodes and edges can show different levels of abstraction. Therefore, node and edge representations are classified as *abstract* or *explicit* respectively, resulting in four categories in total.

The *integration* facet is subdivided based on which representation is dominant —

the visualisation can be dominated by one representation, i.e. be *geography-based* or *network-based*, or be a *balanced* composition of both.

Lastly, the interaction facet is classified based on how much user interaction is required or possible: *none*, some *optional interaction*, or *required interaction*. A fourth category for pure *interaction techniques* that are not visualisation techniques in their own right has been added.

Table 4.1 shows an overview of the facets and categories within, and how the surveyed techniques were classified into them. Figure 4.1 displays the co-occurrence of different categories across facets.

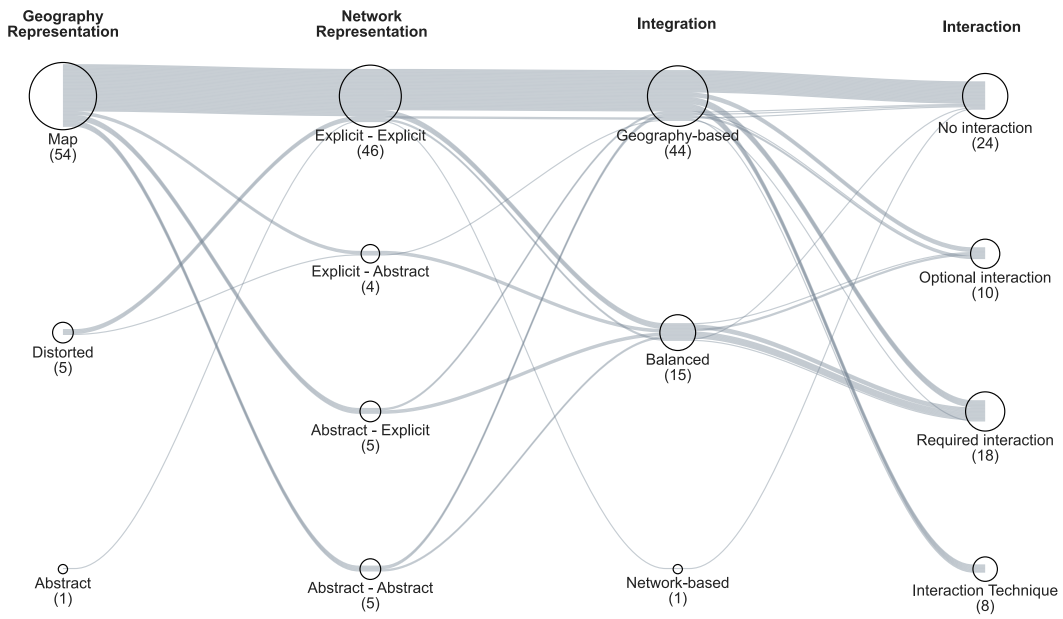


Figure 4.1: Co-occurence of categories across taxonomy facets

Facet	Category	Techniques	#
Geography Representation	Map	[Yan+19], [Zho+19], [Rom+18], [And+17], [Sch+17], [LBW17a], [LBW17b], [Yan+17], [LHT17], [Cor+16], [Bro+16], [KB16], [ITH16], [Zou16], [PHT15], [BS15], [Lu+15], [Bac+15], [GZ14], [DSA14], [EW14], [Rob+14], [NB13], [BBL12], [Pen+12], [Ric+12], [BSV11], [SHH11], [AA11], [Boy+11], [HSS11], [Gan+11], [Luo+11], [GRE11], [LBA10b], [LBA10a], [WDS10], [Hv09], [Mos+09], [Guo09], [Rae09], [Di +09], [Cui+08], [Guo07], [WC07], [Pha+05], [KW05], [WCG03], [BST00], [BW98], [CEH96], [BEW95], [Tob87]	53
	Distorted map	[Bou+16], [WC11], [ASB07], [HMN06], [MG06], [BMS93]	6
	Abstract	[Hen13]	1
Network Representation	Explicit Nodes & Explicit Edges	[Yan+19], [Rom+18], [Sch+17], [LBW17a], [LHT17], [Cor+16], [Bro+16], [KB16], [Zou16], [PHT15], [BS15], [Bac+15], [DSA14], [Rob+14], [Hen13], [NB13], [BBL12], [Pen+12], [Ric+12], [BSV11], [SHH11], [WC11], [HSS11], [Gan+11], [Luo+11], [GRE11], [LBA10b], [LBA10a], [Hv09], [Mos+09], [Rae09], [Di +09], [Cui+08], [WC07], [HMN06], [MG06], [Pha+05], [KW05], [WCG03], [BST00], [BW98], [CEH96], [BEW95], [BMS93], [Tob87]	45
	Explicit Nodes & Abstract Edges	[Yan+17], [Bou+16], [Boy+11], [ASB07], [Guo07]	5
	Abstract Nodes & Explicit Edges	[LBW17b], [ITH16], [GZ14], [EW14], [Guo09]	5
	Abstract Nodes & Abstract Edges	[Zho+19], [And+17], [Lu+15], [AA11], [WDS10]	5
Integration	Geography as basis	[Yan+19], [Rom+18], [And+17], [Sch+17], [LBW17a], [LHT17], [Cor+16], [KB16], [Zou16], [Bou+16], [PHT15], [BS15], [GZ14], [DSA14], [Rob+14], [NB13], [BBL12], [Pen+12], [Ric+12], [BSV11], [SHH11], [AA11], [Gan+11], [GRE11], [LBA10b], [LBA10a], [WDS10], [Hv09], [Mos+09], [Guo09], [Rae09], [Cui+08], [ASB07], [WC07], [MG06], [Pha+05], [KW05], [WCG03], [BST00], [BW98], [CEH96], [BEW95], [BMS93], [Tob87]	44
	Balanced	[Zho+19], [LBW17b], [Yan+17], [Bro+16], [ITH16], [Lu+15], [Bac+15], [EW14], [WC11], [Boy+11], [HSS11], [Luo+11], [Di +09], [Guo07], [HMN06]	15
	Network as basis	[Hen13]	1
Interaction	No interaction	[Rom+18], [Sch+17], [LBW17a], [LHT17], [Bou+16], [PHT15], [BS15], [GZ14], [Hen13], [NB13], [Pen+12], [BSV11], [SHH11], [Gan+11], [LBA10b], [WDS10], [Hv09], [Rae09], [Cui+08], [HMN06], [MG06], [Pha+05], [BST00], [BW98], [Tob87]	25
	Optional interaction	[And+17], [Yan+17], [Cor+16], [Bro+16], [Rob+14], [AA11], [Boy+11], [GRE11], [Guo09], [BEW95]	10
	Required interaction	[Yan+19], [Zho+19], [LBW17b], [KB16], [ITH16], [Lu+15], [Bac+15], [EW14], [BBL12], [WC11], [HSS11], [Luo+11], [LBA10a], [Di +09], [ASB07], [Guo07], [KW05], [CEH96]	18
	Interaction technique	[Zou16], [DSA14], [Ric+12], [Mos+09], [WC07], [WCG03], [BMS93]	7

Table 4.1: Overview of facets, categories, and classification of surveyed techniques

4.1 Geography Representation

This facet describes how the geographic aspect of the network is represented visually. All geography representations can be captured on a scale from most to least abstracted. Regular maps are the least abstract way of representing geography, whereas at the other end of the scale, geographic locations are encoded in very abstract ways that show little relation to the physical location, for example by only loosely sorting countries by continent. Theoretically, this is a continuous scale. Nonetheless, when surveying visualisation techniques, it is useful to classify geography representations into three fixed categories: maps (including both two-dimensional maps and three-dimensional globes), distorted maps, and abstract representations.

It is important to note that *any* map, no matter which map projection is used to create it, introduces some level of distortion. This distortion is inherent to what map projections do: taking a globe and flattening its surface. Since this distortion is unavoidable (with few exceptions as discussed in the following section), it is not taken into account when classifying geography representations — all maps and globes that are not distorted *beyond* what is caused by the map projection are classified into the *map* category.

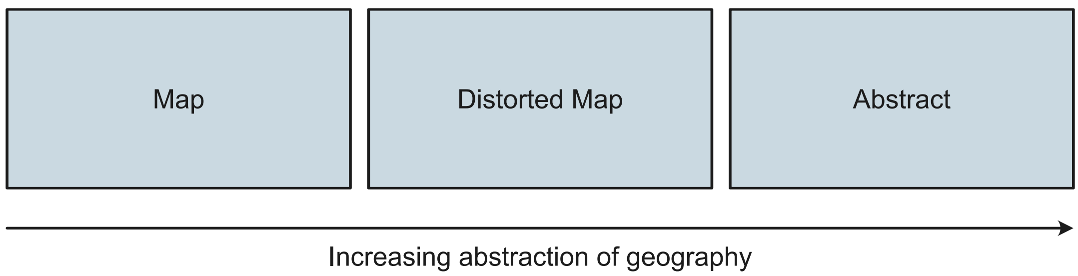


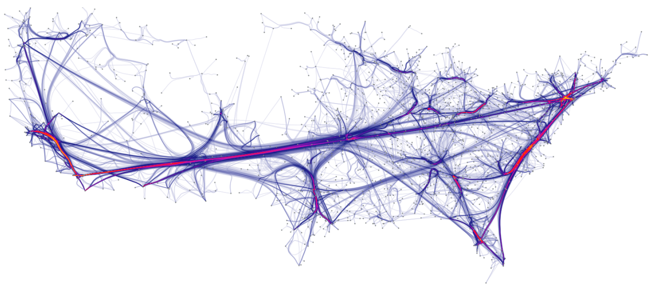
Figure 4.2: Geography representation facet of the taxonomy

4.1.1 Maps

Firstly, there are *maps*, the least distorted category. This includes flat, two-dimensional maps of any projection as well as three-dimensional globe representations. Despite any projection introducing distortion of a different type and magnitude, maps are the most explicit way of representing geography in a visualisation, and due to virtually everyone's familiarity with them also the one that is most easily linked to people's mental map of the world. In some cases, there is no need to display the map explicitly, for example when the network (e.g. of flight paths, Figure 1.1) is so dense that the geographic context is clear without the map.

In geographic network visualisation, flat maps are by far the most frequent geography representation. Examples are maps overlaid with node-link diagrams, flow maps or glyphs, or juxtaposed with a separate network visualisation (Figure 4.3b). In total, 53 out of the 60 surveyed techniques make use of an undistorted map to represent the geography.

(a) Spiral tree flow map [BSV11]



(b) Edge bundling [Hv09]

Figure 4.3: Visualisations based on maps

Within the map category, the three-dimensional globe is somewhat of a special case — when shown on a screen, it is essentially just another map projection, albeit one where only half the world is visible at a time. However, when shown in 'true' 3D, for example in a virtual reality environment or as a physical globe, it is much less distorted than could be achieved with a flat map. In terms of human perception, globes have been shown to lead to a more accurate assessment of area size as compared to the commonly used Mercator projection [Bat09]. When showing networks as node-link diagrams on a globe, there is another difference to flat maps: Links can be drawn along the geographically shortest path, whereas on a flat map, they cannot cross 180° longitude since that is where the globe is 'cut' to obtain a flat map.

Geographic network visualisation methods using three-dimensional globes mostly add the network representation onto the globe in the shape of a node-link diagram, although a variety of link types are used — straight [CEH96], bundled [LBA10a] or arcs [KB16; Yan+19] (Figure 4.4). In a more unusual technique introduced by Alper et al. [ASB07], the globe itself is used to visualise network characteristics by means of distortion (Section 4.1.2).

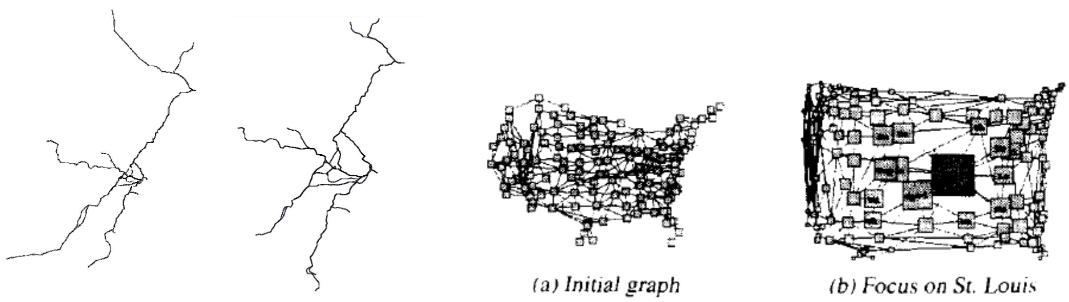
(a) 3D Edge Bundling [LBA10a]   (b) Flow map in virtual reality [Yan+19]

Figure 4.4: Visualisations based on three-dimensional globes

4.1.2 Distorted Maps

The second category is the *distorted map*. This includes any visualisation that is still recognisable as a map but distorted beyond the distortion introduced by the map projection.

In the surveyed techniques, three main ways of using distortion can be identified: Firstly, distortion is frequently introduced by shifting nodes in a node-link diagram in order to increase the legibility of the diagram. An example of this is centrality-based scaling [MG06], where the underlying geography is distorted such that dense areas in the network are enlarged compared to sparser areas, while preserving edge orientation as much as possible (Figure 4.5a).

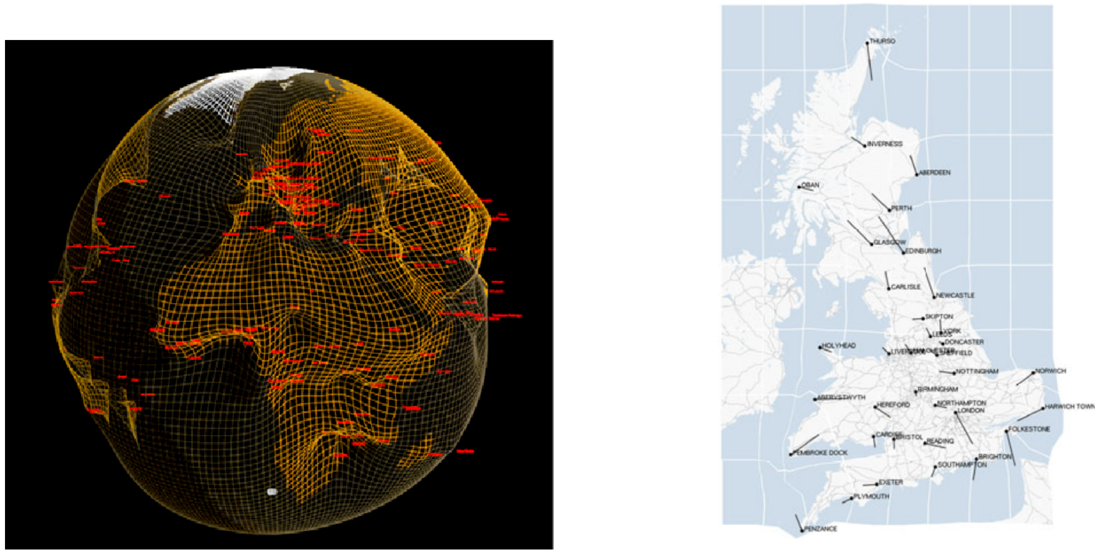


(a) Centrality-based scaling [MG06]   (b) Fisheye lens [BMS93]

Figure 4.5: Two examples of displaying a geographic network with distorted geography

Secondly, distortion can be used as an interactive navigation aid, for example using a fisheye lens [BMS93] to enlarge areas of interest to the user (Figure 4.5b), or through a custom scaling method specifically for metro maps [WC11].

Lastly, distortion can also be used not in the context of making a visualisation more legible, but instead as a visualisation method itself. Alper et al. introduce a method to distort a globe to represent a geographic network [ASB07]. A similar technique for flat maps exists as well [Bou+16] (Figure 4.6).



(a) 3D globe deformation [ASB07]

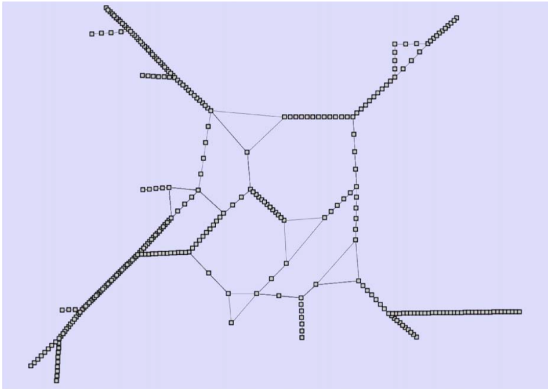
(b) 2D map deformation [Bou+16]

Figure 4.6: Deformed maps

A notable application of distorted maps are metro maps. Metro map layout is a well-researched problem in graph drawing. The idea that for the use case of a metro map — deciding which trains or buses to take, where to change, and finding the fastest route — passengers do not need to know the precise geography of the transport network. Giving people a rough idea of where things are is sufficient, and it allows for the creation of a schematic map that is much easier to read than a map showing the true geography of the transport network. This was first realised by Henry Beck, who created the London Underground map in 1933. Nowadays, a number of methods have been proposed to automate the drawing of metro maps, and to facilitate navigating large metro maps interactively (Figure 4.7) [HMN06; WC11].

4.1.3 Abstract Representations

Finally, there are *abstract* geography representations. An abstract geography representation is one where the geography *is* shown in the visualisation — otherwise it would outside the scope of this survey — but in an abstract way where no map is recognisable.



(a) Automatic metro map layout [HMN06]

(b) Focus+Context metro map [WC11]

Figure 4.7: Metro maps

There is one main advantage to abstract representations — using maps or distorted maps extremely limits the options for the network layout, at least for designs where the network representation is superimposed onto the geography. In many cases, the network topology is more important than where exactly nodes and edges are located. For these cases, abstract ways of representing the geographic aspect are preferable.

In spite of the advantages, only one technique that falls into this category has been found in the literature; a node-link diagram where the nodes are positioned in a circle, approximately positioned and grouped based on their geographical location. Bundled edges are drawn between the nodes inside the circle (Figure 4.8) [Hen13].

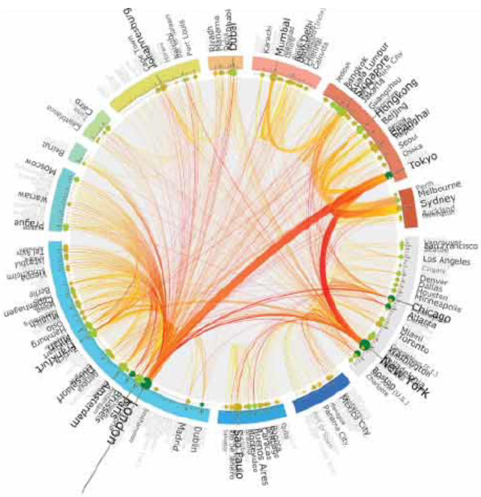


Figure 4.8: Radial geographically ordered network layout [Hen13]

4.2 Network Representation

The second facet of the taxonomy describes how the network topology of the data is represented visually. As with the geography facet, the classification is based on levels of abstraction. However, since a network consists of nodes and edges, which can have different levels of abstraction, it is not possible to classify along just one axis. Therefore, we classify along two axes: Node abstraction and edge abstraction. Despite abstraction being a continuous scale, we introduce two discrete categories of *explicit* and *abstract* encodings for nodes and edges respectively, the combinations of which result in four categories in total, as shown in Figure 4.9.

The implication of this choice of categories and category names is that node-link diagrams are classified as the least abstract, most explicit representation for a network. This is certainly a premise that could be challenged. However, beyond being the de facto standard for network visualisation, node-link diagrams do directly encode the (mathematical) components of a graph – nodes and edges – as dots and lines, which could be seen as the most explicit encoding possible.

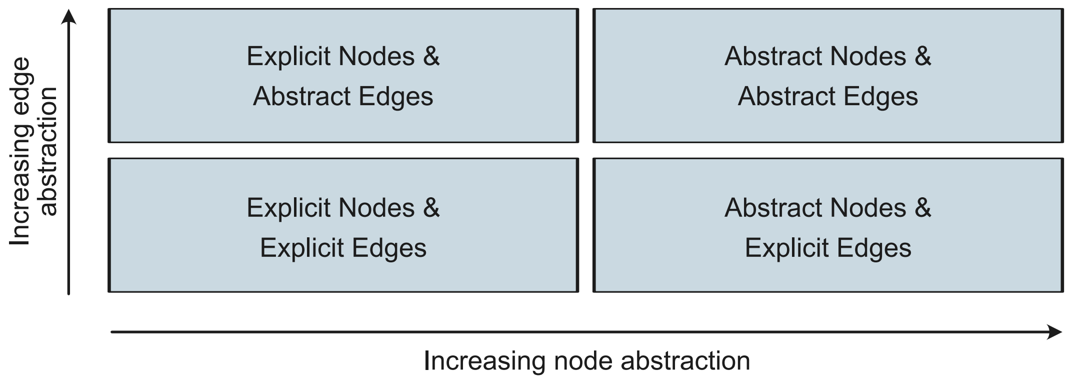


Figure 4.9: Network representation facet of the taxonomy

The line between *abstract* and *explicit* encodings is drawn based on the visual representation of individual nodes and edges. If each individual node or edge is displayed as its own entity (such as a dot or a line), it is classified as *explicit*. Another way of looking at it is whether it is theoretically possible to extract the precise network data from the visualisation, not taking into account practical issues due to potential overlap and clutter. If this is not possible, and nodes or edges are aggregated or otherwise abstracted, the technique is classified as *abstract*. The assessment of abstraction level is done separately for nodes and edges. However, aggregated nodes automatically lead to aggregated edges. Therefore, any edge abstraction that is purely a result of node abstraction is not taken into account in the assessment of whether the edges are visualised in an *abstract* or *explicit* way.

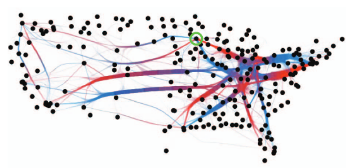
4.2.1 Explicit Nodes & Explicit Edges

The majority of the surveyed techniques explicitly encode both nodes and edges and as such, display the network as (a variation of) a node-link diagram, such as the examples shown in Figure 4.3. Since straight-line node-link diagrams suffer from clutter and overlap even with relatively small datasets, a variety of techniques have been proposed to mitigate this issue. Edge bundling [e.g. Hv09; LHT17; PHT15; Pen+12; Gan+11; LBA10b] and edge routing [BS15] are methods to improve static displays. A more complete overview of edge bundling techniques is provided by Zhou et al. [Zho+13]. Using a three-dimensional globe instead of a flat map is another way of reducing edge crossings [CEH96; Yan+19; KB16]. Lambert et al. combine these two approaches in a 3D edge bundling technique [LBA10a].

Directed data is often displayed as a flow map. Flow maps, having first been introduced by Charles Minard in 1845, are not a new invention. However, until recently, they had to be hand-drawn to obtain legible results. First attempts at using computers to draw flow maps were made by Tobler in the late 1980s [Tob87]. Since then, a number of techniques [e.g. NB13; BSV11; Pha+05] have been developed to automate the layout of flow maps such that the different flows are routed and bundled in an aesthetically pleasing as well as legible manner. Divided edge bundling is a technique that somewhat blurs the line between flow maps and edge bundling techniques [SHH11]. Examples of edge bundling, flow maps, and divided edge bundling are shown in Figure 4.10.

(a) Fast Fourier Transform Edge Bundling [LHT17]

(b) Flow map with stub bundling [NB13]



(c) Divided edge bundling [SHH11]

Figure 4.10: Visualisations with explicit node and edge encodings

For smaller, less dense graphs, connections can be displayed more clearly by ensuring edges are clearly visible as separate lines, which can be achieved by bending them, for example using Bézier curves [BW98], which can be further spread out using angle constraints where the edges connect to the nodes [BST00]. More recently, a technique to spread out edges around a globe has been introduced [KB16].

For localised dense areas in an otherwise sparse graph, e.g. a transport network that is much denser in the city than its surroundings, centrality-based scaling has been shown to be an effective distortion technique [MG06].

For graphs with additional edge attributes more complex than weights or directions, different modifications to the edges have been proposed, such as animated [Rom+18] or patterned edges [Cor+16].

Specifically for dynamic geographic networks, animated node-link diagrams or small multiples can be used [BBL12]. Another alternative is the use of a space-time cube in the context of the GeoTime system [KW05].

Lastly, node-link diagrams have been adapted to visualise uncertainty in the underlying graph data. Landesberger et al. present a typology of uncertainty visualisation in the content of geographic networks. Schulz et al. introduce a technique that first decomposes the uncertain graph into its possible instances, then creates a visualisation from these [Sch+17]. Uncertainty visualisation is also discussed in more detail in Section 6.2.

There are many more versions and modifications of node-link diagrams which are discussed in other sections, such as user interaction and navigation techniques (Section 4.4.4), metro maps (Section 4.1.2), node-link diagrams as one part of a composite visualisation (Section 4.4.3), or non-geolocated node-link diagrams (Section 4.1.3).

4.2.2 Explicit Nodes & Abstract Edges

Techniques in this category explicitly show the nodes of the network, but use abstract means of showing the connections between them.

The distorted globe technique by Alper et al. shows the node locations on a globe, distorting the globe such that nodes are closer together the more closely linked they are, without showing edges as arcs or similar [ASB07]. A similar technique on a flat map has been introduced by Bouts et al. [Bou+16].

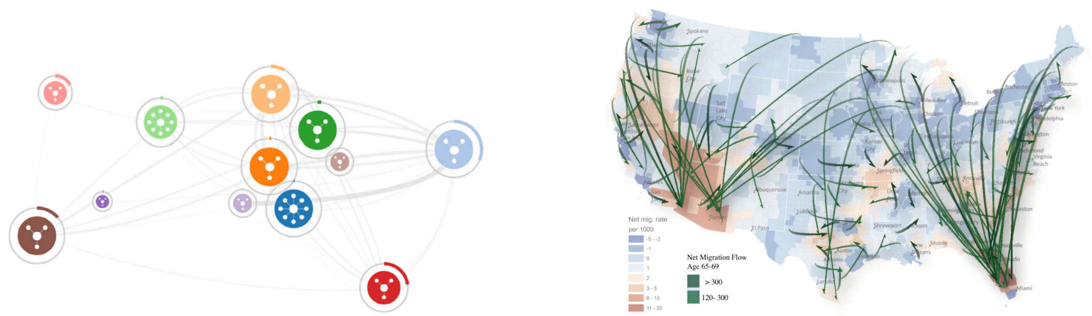
Flowstrates is a technique for dynamic flow data which can be split into a bipartite graph. The flows are displayed using two maps, one for origins and one for destinations. The two maps are linked through a heatmap showing the flows between the linked locations over time. The example used by them are refugee flows, which change over time, and often go from one region of the world to another [Boy+11]. For many-to-many flow data, Yang et al. introduce MapTrix, a technique that shows a matrix with a 45° rotation, rows and columns connected to their associated location on two juxtaposed maps [Yan+17]. As such, Flowstrates and MapTrix both employ the same basic concept of inserting a graph representation in between two maps showing origins and destinations (Figure 4.11).

(a) Flowstrates [Boy+11]

(b) MapTrix [Yan+17]

Figure 4.11: Visualisations with explicit nodes and abstract edges

4.2.3 Abstract Nodes & Explicit Edges



(a) Module-based network visualisation: Clusters are replaced by aggregate symbols [LBW17b]

(b) Smoothed flow data: Flow patterns are extracted and shown without fixed node locations [GZ14]

Figure 4.12: Visualisations with abstract nodes and explicit edges

The opposite approach is abstracting the nodes but not the edges. The most commonly used node abstraction method is aggregation, thereby simplifying the network structure while still showing overall trends. Nodes can be aggregated into a predetermined number of areas [Guo09], or partitioned more flexibly, either through user interaction [EW14], by algorithmically identifying clusters [LBW17b], or by dropping fixed node locations altogether and instead extracting inherent flow patterns (Figure 4.12) [GZ14].

The ‘connection barchart’ takes a different approach and instead separates displaying the distribution of the nodes from displaying the connections, indicating the number of connections on both parts of the visualisation [ITH16].

4.2.4 Abstract Nodes & Abstract Edges

Finally, there are representations where neither nodes nor edges are encoded explicitly. The techniques in this category, although few, are rather diverse in their approach. Interestingly, all of them have been published in the context of visualising origin-destination data and focus on showing directions.

Andrienko et al. developed a technique that at first glance, seems to show a regular flow map, yet not only makes use of nodes aggregated into areas, but also of partitioned trajectories such that flows are only drawn between neighbouring areas [AA11]. The remaining techniques make use of entirely different visual representations: There are glyphs that show movements over time [And+17], a dashboard-type visualisation using a variety of different visualisations [Zho+19], and the OD-wheel, which combines a circular and a linear display to show movement patterns over time.

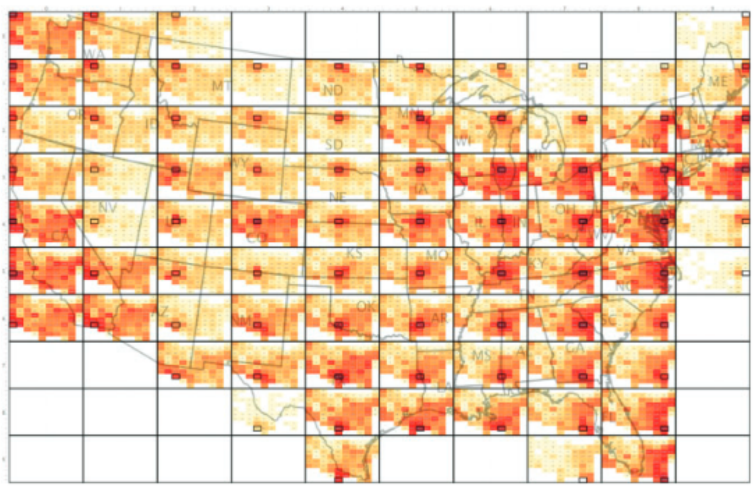


Figure 4.13: OD Map [WDS10]

Possibly the best example of a visualisation fitting this category is the OD map, which uses spatially ordered small multiples, each a smaller map, to show origin-destination flows between all regions of a larger area (Figure 4.13) [WDS10]. This technique stands out in that it does not apply any kind of generalisation to achieve the visual result.

4.3 Integration

The third facet, *integration*, describes how the different geography and network representations are integrated into one visualisation. This can be done in a multitude of ways, which we have classified into three categories ranging from most geography-focused to most network-focused, as illustrated in Figure 4.14. This classification is essentially a simplification of the approach taken by Hadlak et al. [HSS15]. In addition to distinguishing between the visualisation being based on either of the two facets, or being balanced, they also differentiate between spatial and temporal compositions. This difference has been dropped for this taxonomy, sacrificing some level of detail for the purpose of more effectively comparing classification across facets.

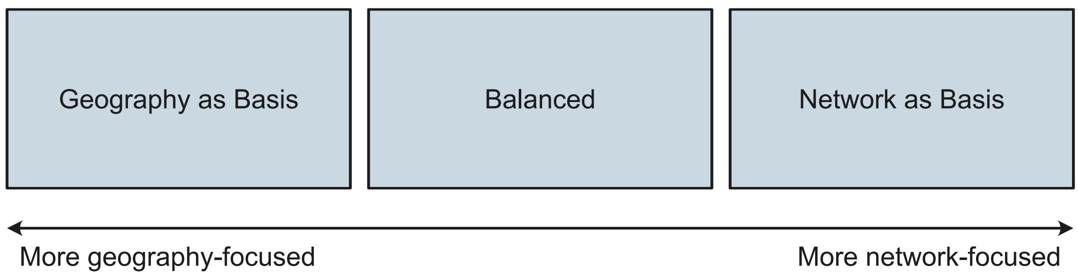


Figure 4.14: Integration facet of the taxonomy

4.3.1 Geography as Basis

The majority (43 out of 60) of the surveyed visualisation techniques use the geography representation as their basis. Among these, the most common implementations are those with undistorted maps as their base, and network representations with explicit nodes and edges superimposed onto them. This includes node-link diagrams with the nodes positioned according to their geographic locations, either with straight lines or using edge bundling or routing, and flow maps, as shown in Figures 4.3 and 4.10. There are also several techniques targeted at reducing clutter on the overlaid node-link diagrams or flow maps through generalising the network data by aggregating nodes

[Guo09; GZ14; AA11]. As a more abstract variation on this theme, Andrienko et al. have proposed a technique that uses glyphs on a map to indicate the direction and intensity of flows [And+17].

However, there are also a number of techniques that do not follow this pattern: OD maps (Figure 4.13) use a map as their basis, but instead of superimposing a node-link diagram, the network representation is 'nested' into the map itself [WDS10].This is a highly abstracted network representation combined with an explicit geography representation.

Again, the two techniques based on deforming the surface of a globe [ASB07] or a map [Bou+16] stick out as well. Here, the nodes are less abstracted, but the geography is distorted as an abstract way of displaying the connections (Figure 4.6a).

4.3.2 Balanced Integration

A *balanced* integration is one where neither geography nor network are clearly dominant. In the 15 techniques classified into this category, this is achieved through two main approaches: One option is to use a node-link diagram, but instead of positioning the nodes entirely based on their geolocation, determining their position based on a combination of clear network display and approximate geolocation. The most prominent example of this are metro map layouts as shown in Figure 4.7 and discussed in Section 4.1.2. A variation on this is the module-based approach by Li et al., who aggregate parts of the network into groups, which are represented by symbols at the approximate location of the nodes contained within (Figure 4.12a) [LBW17b]. Yet another approach is the use of large map insets to accommodate denser areas of the network, turning the map into somewhat of a patchwork so that it cannot be classified as a geography-based technique anymore (Figure 4.15).

The second option to achieve a balanced visualisation is to juxtapose and link two or more visualisations — at least one geography-based and one network-based. Several techniques with varying degrees of integration between their components have been proposed. MapTrix [Yan+17] and Flowstrates [Boy+11] use two maps connected through a matrix and heatmap respectively to show the network (Figure 4.11). Hadlak et al. propose a system that displays the network as a standard node-link diagram, but lets the user open up different kinds of visualisations like matrices on demand [HSS11]. Van Den Elzen and Van Wijk propose a technique that juxtaposes a detailed node-link diagram with a more abstract diagram, which can be adapted by the

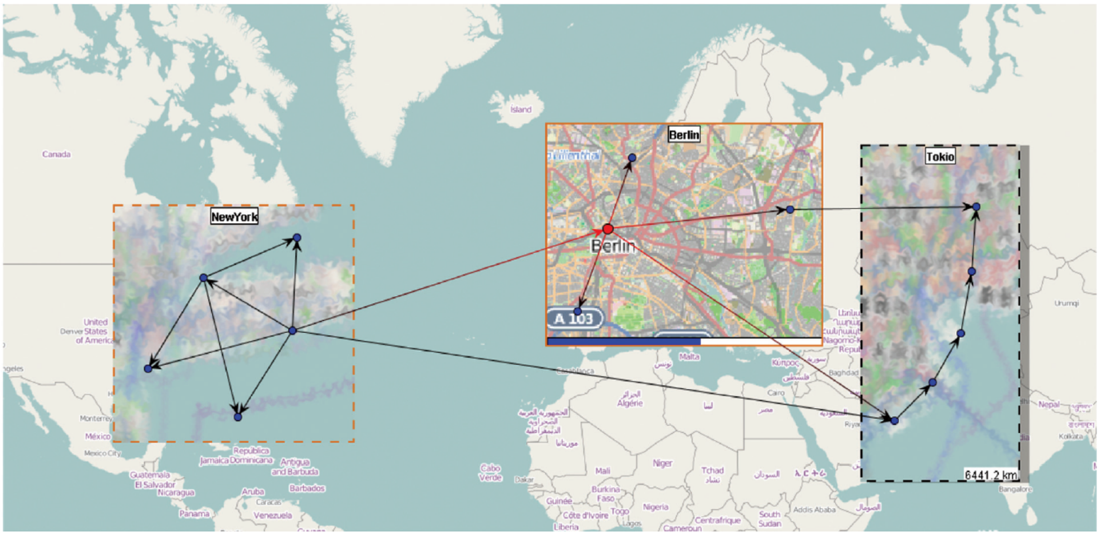


Figure 4.15: Large map insets are used to accommodate denser areas of the network [Bro+16]

user through selecting regions of interest in the detail view, discussed in more detail in section 4.4.3 [EW14]. Other examples of multiple juxtaposed visualisations are the OD-Wheel [Lu+15] and the connection bar chart [ITH16].

4.3.3 Network as Basis

The third option is to use the network as the basis for the visualisation, i.e. to represent the network topology first, then add the geographic aspect. Just like the *abstract* category in the *geography representation* facet, only one technique fits this category: the circular, geographically ordered node-link diagram by Hennemann (Figure 4.8) [Hen13].

4.4 Interaction

The fourth and final facet of the taxonomy is *interaction*, describing to what extent a technique relies on user interaction. This facet is somewhat separate from the three others in that it does not describe the structure of the visualisation. Nonetheless, interaction can be an important component of visualisation techniques, which is why it is included as a fourth facet. Techniques are classified on a scale from most to least interactive, split into four discrete categories. Techniques can have no interaction at all, some optional interaction, required interaction, or be pure interaction techniques that are not visualisation techniques as such (Figure 4.16).

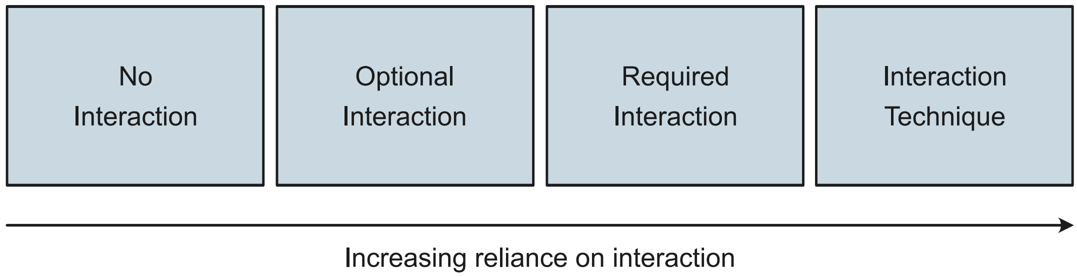


Figure 4.16: Interaction facet of the taxonomy

4.4.1 No Interaction

Many techniques do not make use of interaction at all. However, this does not necessarily mean they are static — some techniques make use of animation, which does not require user interaction, but it does require the visualisation to be shown on a screen or similar medium that supports displaying animated graphics.

This category includes most edge bundling and flow map layout techniques as well as OD maps [WDS10], static metro map layouts [HMN06], and other graph layout techniques. An example of a non-interactive technique that uses animation is the use of animated edge textures [Rom+18].

It is important to note that interaction not being part of the technique does not imply it is not possible or potentially useful. The creators of the SideKnot edge bundling technique for example explicitly discuss the possibility of integrating the technique with the EdgeLens interaction technique [Pen+12; WCG03].

4.4.2 Optional Interaction

Optional interaction describes techniques that are usable as static techniques, but can be used to create interactive visualisations or benefit from being enhanced with interaction techniques.

Many techniques, despite being static at their core, benefit from ‘superficial’ types of interaction such as highlighting components when selected. These types of interaction do not change the structure or data that is being shown, but for example adapt colour or opacity to make it easier for the user to extract insights.

Another type of optional interaction is when techniques are designed such that they can be used to create a static display, but can also be used to create an interactive display that allows the user to interactively adapt the visualisation, e.g. by changing the scale of parts of or the whole visualisation, filtering for a subset of the data, or expanding and collapsing parts of the visualisation.

Both Flowstrates [Boy+11] and MapTrix [Yan+17] include superficial as well as more involved interactive features, yet both can be used to generate a static image that could e.g. be included in a printed report as well. Similarly, some spatial generalisation techniques [Guo09; AA11; Cor+16] can be used to create one-off generalisations for a display at a specific size and scale, but are also computationally efficient enough to be used as part of an interactively scalable map or other visualisation that automatically updates the level of generalisation based on the zoom level.

4.4.3 Required Interaction

More and more techniques are intended to be used on electronic devices and as such rely on user interaction to be usable at all. These have been categorised as *requiring interaction*.

In three-dimensional displays, e.g. if a three-dimensional globe is chosen as the geographic representation [CEH96; ASB07; LBA10a; Yan+19], or in the GeoTime system [KW05] which uses a space-time cube, user interaction is at a minimum required to navigate 3D space through rotation, panning and zooming. Most interactive visualisations are displayed on a simple screen, limiting interaction modalities to using a mouse or touch screen. Virtual reality has been explored as an option [Yan+19].

As a way of dealing with large datasets, many techniques also let the user select regions of interest that are then shown in a separate visualisation. Some techniques implement this such that that the user is presented with an abstract overview and can select what part of the network to expand or show in a more detailed, separate visualisation (Figure 4.17) [HSS11; LBW17b]. Others take the opposite approach and initially present the user with a detailed, possibly cluttered, visualisation, from which they can select regions of interest that are then visualised in a more abstract, overview-type visualisation (Figure 4.18) [EW14].

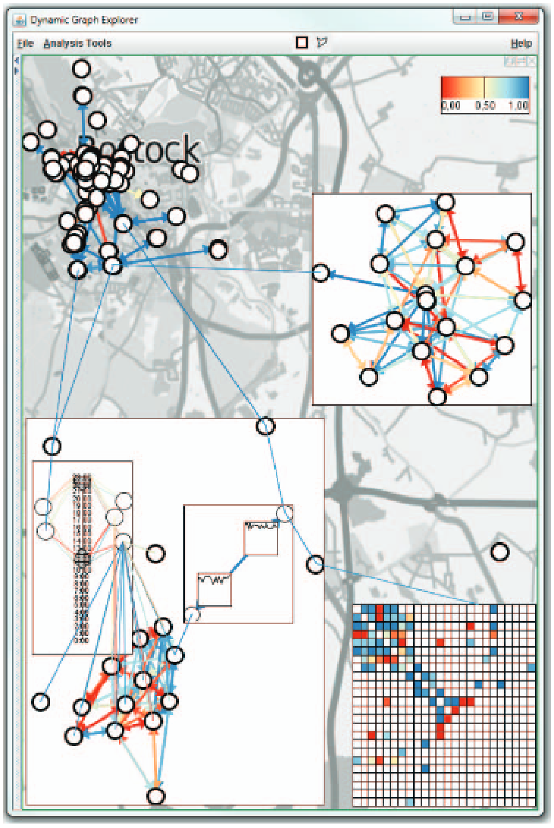


Figure 4.17: In Situ exploration of large dynamic networks [HSS11]

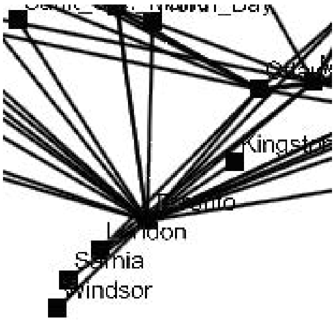
Figure 4.18: Juxtaposed detail and overview views, adaptable by the user [EW14]

4.4.4 Interaction Techniques

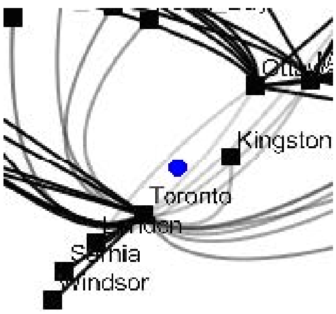
Classified as interaction techniques are all those techniques that can be applied to an existing geographic network visualisation, but that are not visualisation techniques in their own right.

Applying a fisheye lens to the graph was an early attempt at using distortion to improve the readability of a network [BMS93]. EdgeLens [WCG03] and 3DArcLens [DSA14] are two more sophisticated techniques that distort the edges only, allowing the user to dynamically move edges out of the way to see what is underneath (Figure 4.19). There are also methods not based on lenses: Interactive link bundling [Ric+12] lets the user create bundles and move edges aside. Link plucking [WC07] lets the user drag groups of edges to the side.

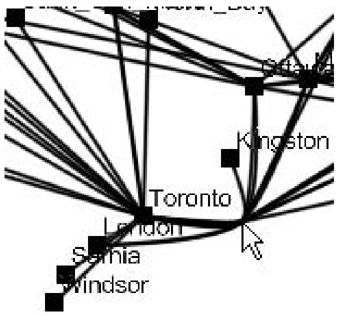
Lastly, there are the *Link Sliding* and *Bring & Go* techniques focused on navigation. With these techniques, the user can bring all connected nodes closer to a node of interest, then select one to go to that node, or alternatively use the mouse to slide along a link [Mos+09]. Another navigation method are small map insets shown on the sides of the map, which can be selected to move to those nodes [Bou+16]. Note that despite the similar use of insets, this technique has a very different purpose to the larger inset technique discussed in Section 4.3.2.



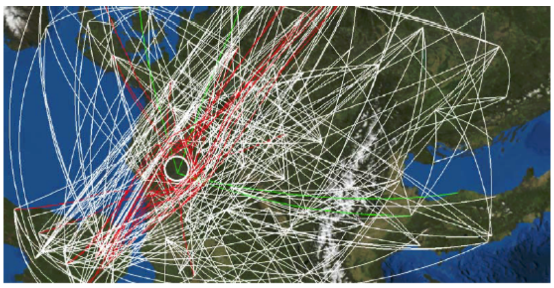
(a) Original graph [WCG03]



(b) EdgeLens [WCG03]



(c) Edge Plucking [WC07]



(d) 3DArcLens [DSA14]

Figure 4.19: Interaction Techniques

Chapter 5

Data Characteristics

We introduced several special characteristics that geographic network data can have in Section 3.2. In this chapter, we provide a brief overview of how well supported the different data types are by the surveyed techniques. Each technique was coded on a scale from 0 to 2 for each data type, where 0 is *not supported*, 1 describes techniques that support the data type in some cases or would need minor modifications to support it, and 2 is *fully supported*. Table 5.1 shows an overview of how many techniques supported each data type. The full coding for individual techniques is available in Appendix A.

Data Type	Fully supported	Partly supported	Not supported
Directed graphs	40 (66.7%)	4 (6.7%)	16 (26.7%)
Undirected graphs	37 (61.7%)	4 (6.7%)	19 (31.7%)
Weighted edges	36 (60%)	7 (11.7%)	17 (28.3%)
Edges with additional attributes	14 (23.3%)	8 (13.3%)	38 (63.3%)
Edges without attributes	54 (90%)	0 (0%)	6 (10%)
Dynamic graphs	12 (20%)	1 (1.7%)	47 (78.3%)
Exact point locations	57 (95%)	0 (0%)	3 (5%)
Area locations	20 (33.3%)	15 (25%)	25 (41.7%)
Uncertain locations	4 (6.7%)	3 (5%)	53 (88.3%)
Uncertain graphs	3 (5%)	3 (5%)	54 (90%)

Table 5.1: Support for different data types

In general, most data types are well-supported, in particular both directed and undirected graphs as well as weighted edges and those without any attributes, which are supported by 60% or more of the surveyed techniques. Regarding geographic locations, point locations are supported by most techniques, although a third of the techniques also support area-type locations. Several techniques are suitable for networks with additional edge attributes and dynamic graphs respectively. Despite recent increased interest in uncertainty visualisation, networks with uncertain locations or an uncertain graph structure are not currently well supported.

Chapter 6

Discussion and Open Challenges

This taxonomy and classification of surveyed techniques has allowed us to obtain an overview of the field, based on which we can discuss the main research trends, challenges, and directions for future research.

Not taking interaction into account, there are 36 possible combinations of the different categories across facets of the taxonomy. Some combinations are extremely common, such as *Map* $\times$ *Explicit Nodes & Explicit Edges* $\times$ *Geography as basis*, which contains nearly all edge bundling techniques as well as flow map layout techniques, whereas some other combinations have no associated techniques at all. However, the precise number of techniques included in a particular category should not be taken as a direct proxy for how well-researched that area is. In the case of edge bundling for example, by far not all techniques are included, and other surveys exist that cover these specific techniques in a more comprehensive manner.

6.1 Network-focused Techniques

Considering that many contributions have come from geography, it is unsurprising that most techniques are map-based and dominated by the geography rather than the network topology. This comes with several caveats – all maps distort the actual geography, a consequence of flattening a globe into a flat map, no matter which projection is used. Using three-dimensional globes, particularly in a virtual reality environment, partly addresses this issue, but virtual reality is not always accessible. An additional issue is the visual dominance of long links. A connection across continents is not necessarily more important than a local link (often quite the opposite), yet takes up much more space simply due to the geographic context, potentially covering shorter links as a side-effect. This is further aggravated through certain geographic projections that do not preserve distance.

A promising way of addressing this are techniques that focus first and foremost on the network topology, integrating references to the geographic context after the fact. Relating this back to the taxonomy, these would be techniques falling into the *balanced* and *network-based* categories of the *integration* facet, and in particular also techniques that use an *abstract* geography representation.

There is a large unexplored design space of juxtaposed and linked visualisations where the network can be represented in a clearer way than when superimposed on a map and as such restricted by its geography. A network-focused approach can resolve issues with clutter and overlap, and help reveal network characteristics that would otherwise remain hidden. It can also potentially deal better with nodes occupying the same or very close positions, or nodes without an associated location. MapTrix and Flowstrates are examples of techniques in this space. Hybrid approaches in terms of positioning, such as the approach taken in metro maps, are another way of giving more importance to the network topology. Hennemann's proposal of a geographically ordered radial chart also makes use of hybrid positioning. It is clear that there is much opportunity for novel techniques to be developed in this direction.

6.2 Dealing with Special Data Characteristics

Geographic network visualisations should ideally cover a large variety of data characteristics that can occur in geographic network data. Some are specific to the geographic aspect: identical, very close, or missing node positions; irregular network densities; and uncertain locations. Other characteristics are also relevant for network visualisation more broadly, such as dynamic networks. Not all of these issues have been adequately addressed through visualisation techniques yet.

Irregular network density — This issue is created through nodes having predetermined positions that are independent from the graph structure. Irregular density is mainly an issue if the network is visualised as a node-link diagram with nodes positioned according to their geographic location. However, since the majority of techniques included in this survey take such an approach, it is a relevant issue. One solution is using distortion to increase the size of dense areas, for example through centrality-based scaling [MG06] or using a fisheye lens [BMS93]. Metro map layouts [HMN06] address this issue as well and could potentially be applied to non-transport networks as well. Interactive techniques that let the user view separate visualisations for subgraphs are also a possible solution [HSS11]. The problem can of course also be avoided altogether by representing the network in a manner that does *not* position nodes based on their geographic location, e.g. an adjacency matrix or a radial layout where the geography is represented in another way.

Identical, close, or missing node positions — This issue overlaps with irregular densities to an extent, so many of the solutions suggested there apply here as well. However, neither identical nor missing node positions are addressed in any technique, except for those that do not use the exact geographic locations. Distortion can mitigate close node positions, but not identical or missing ones. Accordingly, this is a problem deserving of further attention.

Uncertainty — Visualising uncertainty in networks is a growing field of research. For networks in general, Landesberger et al. have proposed a taxonomy for uncertainty in geolocated graphs [LBW17a], and identified many approaches to visualising uncertainty that have not been explored or tested yet. Most of the examples provided in their paper are not specifically targeted at geographic networks, instead focusing either on non-geographic graph data or non-network geographic data. An example of a technique created and tested specifically with geographic uncertain networks is the 'probabilistic graph layout', a quite complex technique that first decomposes the uncertain graph into its possible instances, then uses node splatting and edge bundling to create the final visualisation [Sch+17]. Clearly, there is a need for a larger variety of techniques for more different use cases here; in particular there is a lack of techniques usable for data exploration.

Dynamic Networks — As already observed by Beck et al. [Bec+14], dynamic geographic or geolocated networks remain an underexplored research direction. Few techniques have been introduced despite dynamic geographic networks being commonplace in the real world. A technique specifically developed for dynamic geographic networks is Flowstrates [Boy+11]. Animated edges can also be used to animate changes over time [Rom+18].

6.3 Task & Data Taxonomies

The taxonomy proposed in this dissertation is purely a visual one. In addition to classifying techniques in this visual taxonomy, we applied data coding to describe the suitability of each technique for different data types. The companion website also allows for filtering the results by compatibility with different data characteristics. However, these data type categories were determined relatively ad-hoc, loosely based on existing network data taxonomies.

Data as well as task taxonomies exist for network and graph data, but none have been proposed specifically for geographic network data. Particularly a task taxonomy specific to geographic network visualisations would be beneficial to create in the future. While general network task taxonomies such as [Lee+06] apply in part, there are a number of modifications and additions required to account for tasks arising from the geographic aspect of the network.

Task taxonomies are extremely useful for evaluation, especially in the context of standardising evaluation somewhat across papers that propose new visualisation techniques [KK17]. Although evaluation methods were not a focus of this work, it is obvious that the approaches taken in most publications are relatively lightweight; often just case studies, sometimes small user studies. The tested tasks are predominantly rather basic, with more complex tasks rarely being evaluated. Even when there is a stronger focus on evaluation, comparison across publications is practically impossible due to the lack of standardisation.

Establishing a task taxonomy for geographic network visualisation could therefore be beneficial in two distinct ways: Firstly, to standardise evaluation and allow for comparison across technique papers, and secondly to characterise systems in terms of task support, thus allowing for more informed technique selections for applications.

Chapter 7

Conclusion

This dissertation presented a novel taxonomy and survey showing the state-of-the-art and historic context of geographic network visualisation. To this end, the term *geographic network* was defined to include any kind of geolocated relational data, such as geolocated directed or undirected graphs, certain types of flow or origin-destination data, and more. Visualisation techniques from the information visualisation, cartography, and graph drawing communities were surveyed and classified into a taxonomy created for this purpose. The taxonomy uses the four facets *geography representation*, *network representation*, *integration* and *interaction* and their associated subcategories to classify the surveyed techniques. Like this, we have structured the design space for geographic network visualisations, by providing a structured overview of existing techniques.

We have shown the variety in the techniques already out there and can conclude that many of the possible use cases for geographic network visualisation are already covered. However, it has also become clear that the majority of techniques are based on the relatively straightforward approach of superimposing a node-link diagram or flow map on a geographic map. In this context, edge bundling and automatic flow map layouts are well-researched areas.

Several opportunities for new techniques to be created have become apparent. Many of the issues associated with geography networks, such as overlap and clutter, similar or missing node positions, and variation in graph density have never been fully resolved. In many scenarios, more abstract visualisations that do not directly encode nodes and edges, or only show some indication of the geographic location rather than the precise location on a map, might be preferred. Therefore, non-map-based techniques or techniques that integrate the geography and network representations in other ways, although relatively rare in the literature, are a promising approach that can potentially provide a clearer view of certain network characteristics than geolocated node-link diagrams.

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Appendix A

Table of surveyed techniques

On the following pages, a table of all papers included in the survey and their classification is provided. Data types were coded as follows:

- A value of 2 means the technique fully supports this data type.
- A value of 1 means the technique partly supports this data type, for example only in some situations or with some minor modifications.
- A value of 0 means the technique does not support this data type.
- The data types are:
  - **directed** graph data
  - **undirected** graph data
  - graphs with **weighted edges**
  - graphs with **edge attributes**
  - graphs with **no edge attributes**, except optionally weights
  - **dynamic**, i.e. time-varying graphs
  - graphs where the nodes have **point locations**
  - graphs where the nodes have **area locations**
  - graphs where the nodes have **uncertain locations**
  - **uncertain graph** data, in which structural aspects of the graph itself are uncertain

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
2019	Yang, Y.; Dwyer, T.; Jenny, B.; Marriott, K.; Cordeil, M.; Chen, H.	Origin-Destination Flow Maps in Immersive Environments	[Yan+19]	evaluation	map	explicit-explicit	base-geo	required-interaction	2	1	1	0	2	0	2	1	0	0
2019	Zhou, Z.; Meng, L.; Tang, C.; Zhao, Y.; Guo, Z.; Hu, M.; Chen, W.	Visual Abstraction of Large Scale Geospatial Origin-Destination Movement Data	[Zho+19]	application	map	abstract-abstract	balanced	required-interaction	2	0	2	0	2	0	2	0	0	0
2018	Romat, Hugo; Appert, Caroline; Bach, Benjamin; Henry-Riche, Nathalie; Pietriga, Emmanuel	Animated Edge Textures in Node-Link Diagrams: A Design Space and Initial Evaluation	[Rom+18]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	2	2	1	2	1	0	0
2017	Andrienko, G.; Andrienko, N.; Fuchs, G.; Wood, J.	Revealing Patterns and Trends of Mass Mobility Through Spatial and Temporal Abstraction of Origin-Destination Movement Data	[And+17]	technique	map	abstract-abstract	base-geo	optional-interaction	2	0	2	0	2	2	2	0	0	0
2017	Schulz, C.; Nocaj, A.; Goertler, J.; Deussen, O.; Brandes, U.; Weiskopf, D.	Probabilistic Graph Layout for Uncertain Network Visualization	[Sch+17]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	0	0	2	2
2017	Landesberger, T. von; Bremm, S.; Wunderlich, M.	Typology of Uncertainty in Static Geolocated Graphs for Visualization	[LBW17a]	typology	map	explicit-explicit	base-geo	no-interaction	2	2	2	2	2	0	2	0	2	2
2017	Li, Chenhui; Baciu, George; Wang, Yunzhe	Module-based visualization of large-scale graph network data	[LBW17b]	technique	map	abstract-explicit	balanced	required-interaction	0	2	0	0	2	0	2	1	0	0
2017	Yang, Y.; Dwyer, T.; Goodwin, S.; Marriott, K.	Many-to-Many Geographically-Embedded Flow Visualisation: An Evaluation	[Yan+17]	technique	map	explicit-abstract	balanced	optional-interaction	2	0	2	0	2	0	2	1	1	1
2017	Lhuillier, A.; Hurter, C.; Telea, A.	FFTEB: Edge bundling of huge graphs by the Fast Fourier Transform	[LHT17]	technique	map	explicit-explicit	base-geo	no-interaction	2	2	0	2	2	0	2	0	0	0
2016	Cornel, D.; Konev, A.; Sadransky, B.; Horváth, Z.; Brambilla, A.; Viola, I.; Waser, J.	Composite Flow Maps	[Cor+16]	technique	map	explicit-explicit	base-geo	optional-interaction	2	0	2	2	0	0	2	1	0	0

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
2016	Brodkorb, Felix; Kuijper, Arjan; Andrienko, Gennady; Andrienko, Natalia; von Landesberger, Tatiana	Overview with details for exploring geo-located graphs on maps	[Bro+16]	technique	map	explicit-explicit	balanced	optional-interaction	2	2	1	0	2	0	2	1	0	0
2016	Kaya, Berkay; Balcisoy, Selim	Multi-Resolution Visualisation of Geographic Network Traffic	[KB16]	technique	map	explicit-explicit	base-geo	required-interaction	2	1	2	0	2	2	2	0	0	0
2016	Ibarra, J. C.; Triana, J. A.; Hernández, J. T.	Visualization of origin-destination matrices using a connection barchart and coordinated maps	[ITH16]	technique	map	abstract-explicit	balanced	required-interaction	2	0	2	0	2	0	2	0	0	0
2016	Zou, Lingbo	A Dynamic Approach for Visualizing Local and Global Information in Geo-spatial Network Visualizations	[Zou16]	technique	map	explicit-explicit	base-geo	interaction-technique	1	2	0	0	2	0	2	1	0	0
2016	Bouts, Q. W.; Dwyer, T.; Dykes, J.; Speckmann, B.; Goodwin, S.; Riche, N. H.; Carpendale, S.; Liebman, A.	Visual Encoding of Dissimilarity Data via Topology-Preserving Map Deformation	[Bou+16]	technique	distorted	explicit-abstract	base-geo	no-interaction	0	2	2	0	2	0	2	0	0	0
2015	Peysakhovich, V.; Hurter, C.; Telea, A.	Attribute-driven edge bundling for general graphs with applications in trail analysis	[PHT15]	technique	map	explicit-explicit	base-geo	no-interaction	2	2	2	2	0	0	2	0	0	0
2015	Bouts, Q. W.; Speckmann, B.	Clustered edge routing	[BS15]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	2	0	0	0
2015	Lu, M.; Wang, Z.; Jie Liang; Xiaoru Yuan	OD-Wheel: Visual design to explore OD patterns of a central region	[Lu+15]	technique	map	abstract-abstract	balanced	required-interaction	2	0	2	2	0	2	2	1	0	0
2015	Bach, Benjamin; Riche, Nathalie Henry; Fernandez, Roland; Giannisakis, Emmanoulis; Lee, Bongshin; Fekete, Jean-Daniel	NetworkCube: bringing dynamic network visualizations to domain scientists	[Bac+15]	application	map	explicit-explicit	balanced	required-interaction	2	2	2	2	2	2	2	2	0	0
2014	Guo, D.; Zhu, X.	Origin-Destination Flow Data Smoothing and Mapping	[GZ14]	technique	map	abstract-explicit	base-geo	no-interaction	2	0	2	0	2	0	2	2	0	0

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
2014	Debiasi, A.; Simões, B.; Amicis, R. De	3DArcLens: A technique for the exploration of geographical networks	[DSA14]	technique	map	explicit-explicit	base-geo	interaction-technique	2	2	1	1	2	0	2	1	1	1
2014	Elzen, S. van den; Wijk, J. J. van	Multivariate Network Exploration and Presentation: From Detail to Overview via Selections and Aggregations	[EW14]	technique	map	abstract-explicit	balanced	required-interaction	2	0	2	2	2	0	2	1	0	0
2014	Robson, C; Harris, N; Barr, S; James, P	Dynamic Visualisation of Complex Spatial Infrastructure Networks	[Rob+14]	technique	map	explicit-explicit	base-geo	optional-interaction	2	0	2	1	0	2	2	0	0	0
2013	Hennemann, Stefan	Information-rich visualisation of dense geographical networks	[Hen13]	technique	abstract	explicit-explicit	base-net	no-interaction	2	1	2	2	0	0	2	2	2	0
2013	Nocaj, Arlind; Brandes, Ulrik	Stub Bundling and Confluent Spirals for Geographic Networks	[NB13]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	0	2	0	0	2	0	0
2012	Boyandin, Ilya; Bertini, Enrico; Lalanne, Denis	A Qualitative Study on the Exploration of Temporal Changes in Flow Maps with Animation and Small-Multiples	[BBL12]	evaluation	map	explicit-explicit	base-geo	required-interaction	2	0	2	0	2	2	2	2	1	1
2012	Peng, D.; Lu, N.; Chen, W.; Peng, Q.	SideKnot: Revealing relation patterns for graph visualization	[Pen+12]	technique	map	explicit-explicit	base-geo	no-interaction	2	2	2	0	2	0	2	1	0	0
2012	Riche, Nathalie Henry; Dwyer, Tim; Lee, Bongshin; Carpendale, Sheelagh	Exploring the Design Space of Interactive Link Curvature in Network Diagrams	[Ric+12]	technique	map	explicit-explicit	base-geo	interaction-technique	2	2	0	0	2	0	2	1	0	0
2011	Buchin, K.; Speckmann, B.; Verbeek, K.	Flow Map Layout via Spiral Trees	[BSV11]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	0	2	0	0	2	0	0
2011	Selassie, D.; Heller, B.; Heer, J.	Divided Edge Bundling for Directional Network Data	[SHH11]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	0	2	0	2	1	0	0
2011	Andrienko, N.; Andrienko, G.	Spatial Generalization and Aggregation of Massive Movement Data	[AA11]	technique	map	abstract-abstract	base-geo	optional-interaction	2	0	2	0	2	0	2	0	0	0
2011	Boyandin, Ilya; Bertini, Enrico; Bak, Peter; Lalanne, Denis	Flowstrates: An Approach for Visual Exploration of Temporal Origin-Destination Data	[Boy+11]	technique	map	explicit-abstract	balanced	optional-interaction	2	0	2	1	0	2	2	2	0	0
2011	Hadlak, S.; Schulz, H.; Schumann, H.	In Situ Exploration of Large Dynamic Networks	[HSS11]	technique	map	explicit-explicit	balanced	required-interaction	2	2	2	2	2	2	2	2	2	2

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
2011	Gansner, E. R.; Hu, Y.; North, S.; Scheidegger, C.	Multilevel agglomerative edge bundling for visualizing large graphs	[Gan+11]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	2	0	0	0
2011	Wang, Y.; Chi, M.	Focus+Context Metro Maps	[WC11]	technique	distorted	explicit-explicit	balanced	required-interaction	0	2	0	0	2	0	2	0	0	0
2011	Luo, Wei; MacEachren, Alan M.; Yin, Peifeng; Hardisty, Frank	Spatial-social Network Visualization for Exploratory Data Analysis	[Luo+11]	application	map	explicit-explicit	balanced	required-interaction	0	2	2	0	2	0	2	2	0	0
2011	Ghani, S.; Riche, N. Henry; Elmqvist, N.	Dynamic Insets for Context-Aware Graph Navigation	[GRE11]	technique	map	explicit-explicit	base-geo	optional-interaction	2	2	2	1	2	0	2	0	0	0
2010	Lambert, Antoine; Bourqui, Romain; Auber, David	Winding roads: Routing edges into bundles	[LBA10b]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	2	2	0	0
2010	Lambert, A.; Bourqui, R.; Auber, D.	3D Edge Bundling for Geographical Data Visualization	[LBA10a]	technique	map	explicit-explicit	base-geo	required-interaction	0	2	0	2	2	0	2	0	0	0
2010	Wood, Jo; Dykes, Jason; Slingsby, Aidan	Visualisation of Origins, Destinations and Flows with OD Maps	[WDS10]	technique	map	abstract-abstract	base-geo	no-interaction	2	0	2	0	2	0	2	2	0	0
2009	Holten, Danny; Wijk, Jarke J. Van	Force-Directed Edge Bundling for Graph Visualization	[Hv09]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	2	0	0	0
2009	Moscovich, Tomer; Chevalier, Fanny; Henry, Nathalie; Pietriga, Emmanuel; Fekete, Jean-Daniel	Topology-aware Navigation in Large Networks	[Mos+09]	technique	map	explicit-explicit	base-geo	interaction-technique	2	2	1	1	2	0	2	1	0	0
2009	Guo, D.	Flow Mapping and Multivariate Visualization of Large Spatial Interaction Data	[Guo09]	technique	map	abstract-explicit	base-geo	optional-interaction	2	2	2	2	2	0	2	2	0	0
2009	Rae, Alasdair	From spatial interaction data to spatial interaction information? Geovisualisation and spatial structures of migration from the 2001 UK census	[Rae09]	application	map	explicit-explicit	base-geo	no-interaction	2	2	2	0	2	0	2	2	0	0
2009	Di Giacomo, Emilio; Didimo, Walter; Liotta, Giuseppe; Palladino, Pietro	Visual Analysis of One-to-Many Matched Graphs	[Di +09]	technique	map	explicit-explicit	balanced	required-interaction	0	2	2	1	2	0	2	2	0	0

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
2008	Cui, W.; Zhou, H.; Qu, H.; Wong, P. C.; Li, X.	Geometry-Based Edge Clustering for Graph Visualization	[Cui+08]	technique	map	explicit-explicit	base-geo	no-interaction	0	2	0	0	2	0	2	1	0	0
2007	Alper, Basak; Sümengen, Selçuk; Balcisoy, Selim	Dynamic visualization of geographic networks using surface deformations with constraints	[ASB07]	technique	distorted	explicit-abstract	base-geo	required-interaction	0	2	2	0	2	2	2	0	0	0
2007	Guo, D.	Visual analytics of spatial interaction patterns for pandemic decision support	[Guo07]	application	map	explicit-abstract	balanced	required-interaction	2	1	2	1	2	2	2	2	0	0
2007	Wong, Nelson; Carpendale, Sheelagh	Supporting Interactive Graph Exploration Using Edge Plucking	[WC07]	technique	map	explicit-explicit	base-geo	interaction-technique	2	2	1	0	2	0	2	2	0	0
2006	Hong, Seok-Hee; Merrick, Damian; do Nascimento, Hugo A. D.	Automatic visualisation of metro maps	[HMN06]	technique	distorted	explicit-explicit	balanced	no-interaction	0	2	0	0	2	0	2	0	0	0
2006	Merrick, Damian; Gudmundsson, Joachim	Increasing the Readability of Graph Drawings with Centrality-based Scaling	[MG06]	technique	distorted	explicit-explicit	base-geo	no-interaction	0	2	1	0	2	0	2	0	0	0
2005	Doantam Phan; Ling Xiao; Yeh, R.; Hanrahan, P.	Flow map layout	[Pha+05]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	0	2	0	2	2	0	0
2005	Kapler, Thomas; Wright, William	GeoTime Information Visualization	[KW05]	technique	map	explicit-explicit	base-geo	required-interaction	2	2	1	1	2	2	2	0	0	0
2003	Wong, N.; Carpendale, S.; Greenberg, S.	Edgelens: an interactive method for managing edge congestion in graphs	[WCG03]	technique	map	explicit-explicit	base-geo	interaction-technique	1	2	0	0	2	0	2	0	0	0
2000	Brandes, Ulrik; Shubina, Galina; Tamassia, Roberto	Improving angular resolution in visualizations of geographic networks	[BST00]	technique	map	explicit-explicit	base-geo	no-interaction	1	2	0	0	2	0	2	0	0	0
1998	Brandes, Ulrik; Wagner, Dorothea	Using Graph Layout to Visualize Train Interconnection Data	[BW98]	technique	map	explicit-explicit	base-geo	no-interaction	1	2	0	0	2	0	2	0	0	0
1996	Cox, Kenneth C.; Eick, Stephen G.; He, Taosong	3D Geographic Network Displays	[CEH96]	technique	map	explicit-explicit	base-geo	required-interaction	0	2	0	0	2	2	2	0	0	0
1995	Becker, Richard A.; Eick, Stephen G.; Wilks, Allan R.	Visualizing network data	[BEW95]	technique	map	explicit-explicit	base-geo	optional-interaction	2	2	2	2	2	0	2	2	0	0
1993	Brown, Marc H.; Meehan, James R.; Sarkar, Manojit	Browsing Graphs Using a Fisheye View (Abstract)	[BMS93]	technique	distorted	explicit-explicit	base-geo	interaction-technique	2	2	2	2	2	0	2	2	0	0

Year	Author	Title	Reference	Paper Type	Geography Rep.	Network Rep.	Integration	Interaction	directed	undirected	weighted edges	edge attributes	no edge attributes	dynamic	point locations	area locations	uncertain locations	uncertain graph
1987	Tobler, Waldo R.	Experiments in migration mapping by computer	[Tob87]	technique	map	explicit-explicit	base-geo	no-interaction	2	0	2	0	2	0	2	2	0	0