Multiple coordinated views on massive geo data

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Abstract

Numerous visualization techniques exist for data-driven decision support systems. Those systems primarily used to give guidance in geopolitical decisions often deal with hierarchical and geographical data. There are well-researched data visualizations for both kinds individually. For geographical there are choropleth maps, flow maps, bubble maps and for hierarchical data there are treemaps. To this day however, no appropriate data visualization for hierarchical and geographical information in one view exists. In this thesis, we evaluate coordinated multiple views to combine the capabilities of both data visualizations. We describe a framework to coordinate arbitrary data visualizations in theoretical terms and we give a reference implementation.

1 Introduction

The human brain processes visual information better than it processes text. As a result, the most tangible data analyses usually come with some sort of data visualization. On a computer, the user can interact with the data and explore different levels of granularity. The visualization changes and the user can iteratively perform another interaction. In many cases a great interactivity results in a great user experience.

There is a wide range of options, techniques and implementations for this purpose. Coordinated multiple views are interesting, as they try to make the most out of the various advantages of different visualizations.

Bullshit ahead

This combination may yield a greater value to the user, but it is unclear what kind visualization techniques work best together and for which kind of data. How a user interact with coordinated multiple views and how it differs from the use of single visualizations is another question worth to investigate. In this thesis, we consider the question how a combination of a geographical visualization with a hierarchical visualization performs, for what kind of data this combination is suitable and what interaction patterns apply.

Establish the niche, why is there further research on your topic?

Introduce the current research, what's the hypothesis, the research question?

1.1 Motivation

We create data visualizations of multi-dimensional, hierarchical and geographical data. Namely, we develop RUNDFUNK MITBESTIMMEN which is an application for German citizen to publish which public broadcasts should benefit from their broadcasting fees. The output of this application is a public user ranking and it can be used by broadcasting corporations to evaluate their program. Data visualizations guide media researchers, journalists and the general audience to draw conclusions. In this particular use case, the selection and interaction with the data may happen geographically, but the desired visualization could show e.g. changes over time or relationships within the data.

To explain this a little deeper: Public broadcasting in Germany is organized federally, a German home belongs to the jurisdiction of a public broadcasting corporation. But the produced content can be used all German citizen and it is even required to be free and available to everyone. So this means that e.g. a media researcher might want to select all users from within a certain region, but is actually interested into relationships of broadcasts that are preferred by people from that area.

So the interaction and selection of data should happen in another view than the actual data visualization. Since we deal with geographical data, we use geometry on a map for selection and interaction. For the visualization, we use a different technique, e.g. a tree map if we deal with hierarchical data.

1.2 Problem Statement

2.5D tree maps visualize hierarchical data on a two dimensional canvas and are particularly suitable if the proportions of the data should be emphasized. When dealing with both multidimensional and geographical data, problems arise when features other than geographical features are used as input of the tiling algorithm. Items that should belong together according to their geographic circumstances may be scattered across the 2.5D tree map. This impairs the comprehensibility and complicates the selection of geographical units of items.

A second problem is the coordination of interactions among arbitrary data visualizations. Until today, there is no framework that allows communication between data visualizations of any kind and that simplifies the implementation of coordinated interactions. Neither is there a specification of the interfaces and their requirements, a shared language or a messaging pattern for coordination.

1.3 Research Questions

Based on the preceding problem statement, we take up the following research questions:

1. Are coordinated multiple views an effective way to select data geographically and display it hiearchically and vice versa?

2. Does it significantly improve the comprehensibility and facilitate the understanding of the data in our use case?

3. Is it possible to theoretically describe the substantial characteristics of every interaction?

4. What is the smallest interface possible to connect data visualizations of any kind?

5. How should multiple views be organized and how do they exchange information efficiently?

6. What gives the best user experience: Master- and slave coordinations with one visualization to interact with and another view to show changes or should all views be on an equal footing?

We hypothesize that most of our research questions can be answered positively. The theory of interactions is not very well researched, for this reason we see a great potential. Even if not all visualizations ever to be invented can be coordinated with one common language. Data visualizations share certain characteristics and so should interactions on data visualizations.

1.4 Objectives

To address our research questions we develop a reference implementation of the theoretical framework. This reference implementation gives proof to the feasibility of the specification. We subdivide the development effort into the following work-packages:

1. Basic multiple view layout

   The existing VISUAL ANALYTICS PLATFORM is complemented with a basic coordinated multiple view system. Modules, interfaces and functionalities of the coordinated multiple view system are designed, coordinated and prototypically implemented. In particular, a method for arranging multiple coordinated multiple view widgets in a coordinated multiple view layout and storing coordinated multiple view layouts is developed.

2. Interactions within coordinated multiple views

   We develop linking and interaction mechanisms between 2D maps (for map-based representation) and 2.5D tree maps (for abstract information representation). The functionality includes zoom per object or selection with a bounding box. This creates a powerful selection mechanism, which can be used to select data in map-based representations and highlight the data in the 2.5D tree map.

3. Demonstration and evaluation

   Coordinated multiple view layouts and suitable views are implemented and tested for the selected test data. Based on the test data sets, the coordinated multiple view implementation is examined and evaluated for design criteria [35], general usability aspects [30] and usage for typical visual analytics tasks.

1.5 Methodological Approach

A literature research is used to gather knowledge about the current state of the art with respect to coordinated multiple views. Existing concepts and implementations available on the internet are examined and reused if possible. Interviews of people from the target group are conducted and the define the requirements for the application. A minimal viable product is developed to further validate the user requirements. Also, common user behaviour is observed during user tests. The prototype is continuously developed to allow for further experimentation.

Scenarios While implementing more features, we have two scenarios with different kind of data and different user requirements:

- In our work on the project RUNDFUNK MITBESTIMMEN we design and prototype visualizations for media researchers. We fully control the

database and the database schema as well as on the user facing application on top of it. User requirements are tied to journalists, media researchers, broadcasting corporations. The data has geographical, hierarchical, temporal and correlated characteristics.

- The VISUAL ANALYTICS PLATFORM for administrative data is used as a more general purpose application. There is no single database schema but combatibility with many sources or services. User requirements are potentially unknown and part of the resrach. The usage focuses especially on geographical and hierarchical data.

For the scope of this master thesis we therefore compare implemented visualization and views. How do both approaches differ in development speed, value for the customer? What considerations need to be done regarding the database schema?

What are the areas of research, in which this thesis can be placed into?

1.6 Structure of the Work

In Section 3 we will give an overview on coordinated multiple views and focus on visual analytics as well as massive, geographical data. Existing concepts and implementations of coordinated multiple views are examined and summarized in an overview.

2 Theoretical background

2.1 Data Visualizations

Data visualizations is a means of visual communication and have steadily developed since the 16th century [13]. Otherwise abstract information is visually represented, making complex data more accessible, understandable and usable. Kusinitz [23] explains that the human brain processes visual information 60,000 times faster than text and visual content makes up even 93% of all human communication. The purpose of data visualizations is twofold, according to the Interaction Design Foundation: sense-making and communication. Statistical information is abstract and in data visualization "we must find a way to give form to that which has none."[11]

Data-driven decision support systems are applications to support businesses and organizational decision-making activities in which data visualizations play a key part [24] [28]. Visualizations are an obvious choice for managers who demand a quick overview on performance data. Stephen Few's book "Show me the numbers" was named after the phrase often used by sales managers who can't afford to wade through lengthy reports.

We can expect to see these technologies more in more in business applications. McAfee and Brynjolfsson [27] from the MIT Center of Digital Business showed that organizations driven most by data-based decision making had 4% higher productivity rates and 6% higher profits. However, little research has been done regarding the performance of coordinated multiple views in the field of decision making. There might be a great potential. Back in 1997 Mayer [26] conducted eight studies to compare the effect of using multimedia on university students. The studies showed that when using combined visual and verbal explanations the generation of creative problem solutions increased by an average of more than 50%.

So the application of combined data visualization techniques in decision making seems to be a promising strategy. Nevertheless is is unclear, which visualization techniques are the most suitable to be used in combination. If we know what kind of data we are dealing with, what are the best suited visualization techniques? Let's say we have multidimensional data, is there an order in how people access these multiple dimensions? How do these visualizations perform and what are best practices to be considered for their implementation?

2.2 Visual Variables

French cartographer Jaques Bertin introduced seven visual varables in 1967 [2]. We can see an example for each in Figure 1. These visual variables are used in

cartography but can also be applied to data visualization in general. Carpendale [6] explains in detail their use in terms of computational information instead of printed cartography. Garlandini and Fabrikant [14] put these visual variables under systematical validation procedures. The authors conclude that the variable size provides the most accurate and efficient performance while the variable orientation provides the least performance.
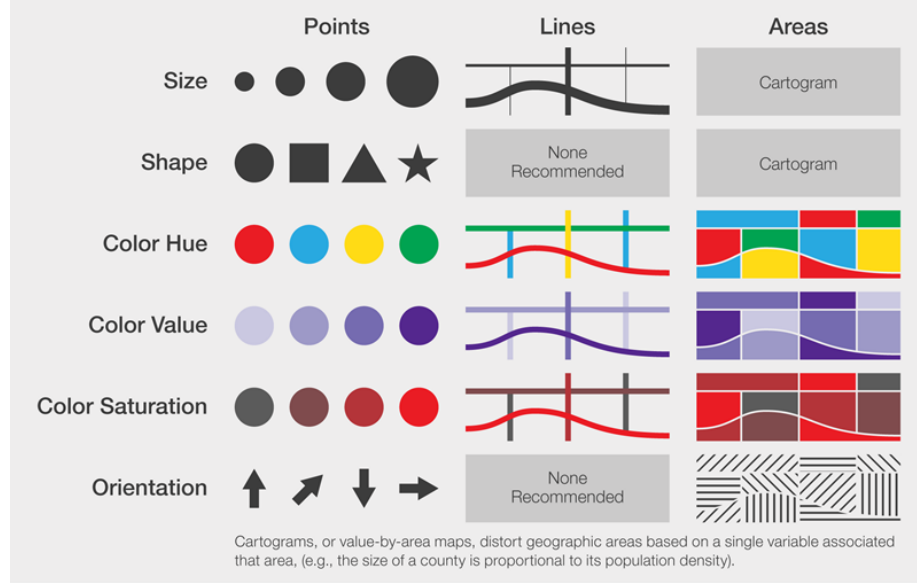

Figure 1: Bertin's [2] original visual variables.

2.3 Treemaps

The visualization of hierarchical data has a long tradition. The traditional representation of a tree is a rooted, directed graph with the root node at the top. An everyday use case is a directory tree example of a file system, e.g. in file browsers or command line utilities like `tree` in UNIX based operating systems. As Shneiderman [32] mentions, this visualization becomes increasingly large when displaying more than one node and soon exceeds the entire screen size. Johnson and Shneiderman [20] proposes the tree map visualization technique, in which each node is a rectangle whose area is proportional to a specified dimension. Rectangles contain sub-branches of the node as tiles, thereby expressing hierarchy information.

We can see an example of an interactive treemap in Figures 2 and 3. German exports are divided in generic groups like "Machines" and "Chemical Products" and include more specific groups like "Cars" and "Packaged Medicaments". The level of hiearchy can be selected with a dropdown menu, so only leaf nodes
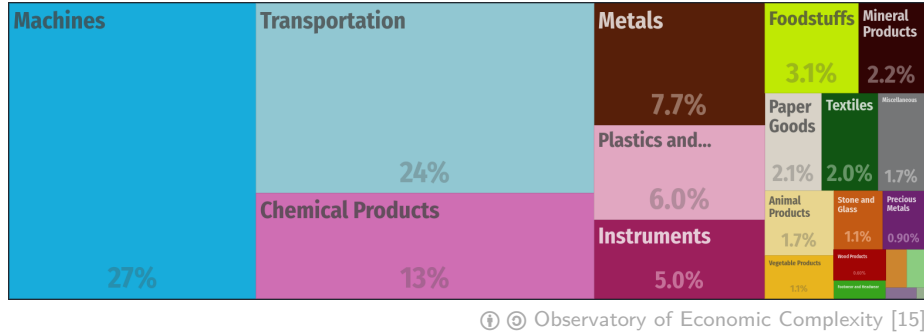
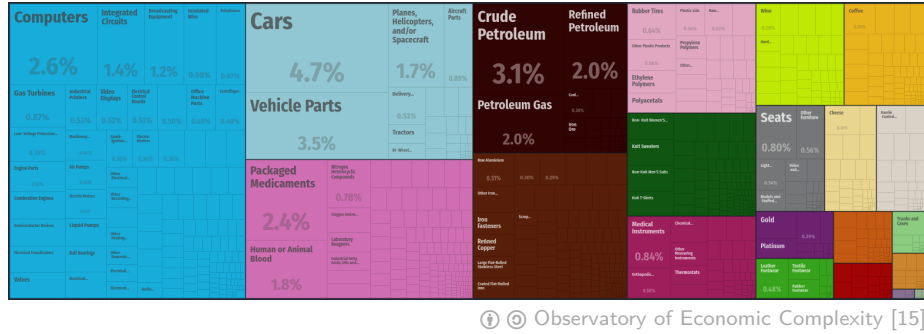Figure 2: First hierarchy level of German exports

Figure 3: Second hierarchy level of German exports

are displayed at a time. Treemaps are space-filling visualizations, i.e. they make 100% use of the available screen size.

Note that as the order and placement of the nodes depends on the value of their specified dimension, geographical units of data may may be placed separately on the treemap.

3D tree maps is a concept introduced by Bladh, Carr, and Scholl [4] in 2004. The authors transfer the concept of tree maps from two dimensional into three dimensional space. They introduce StepTree [4], which is a three dimensional tree map to display a directory layout. It "differs from Treemap in that it employs three dimensions by stacking each subdirectory on top of its parent directory." 3D tree maps are superior to 2D tree maps for tasks with a pronounced topological challenge. User perform significantly better in interpreting the hierarchical structure. However, 3D visualizations also introduce some disadvantages as superimposition of objects and a complex view point navigation.

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2.5D tree map is a term coined by Limberger et al. [25]. A 2.5D tree map emphasizes physical constraints of a 3D tree map, i.e. a 2.5D tree map has all items attached to the ground. We can see an example of a 2.5D tree map in figure 4
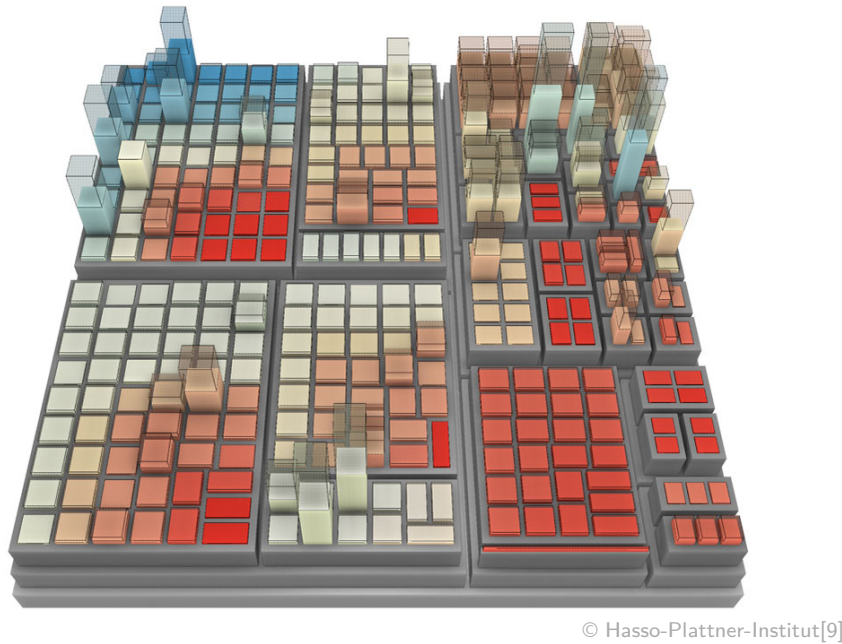
Figure 4: Example of a 2.5D tree map

2.4 Geographical Maps

introduction

Flow maps place stroked lines on top of a geographic map. They often display the flow of goods or the migration of people. As we can see in Figure 5, an early example of a flow map is Charles Minard's depiction of Napoleon's ill-fated march on Moscow in 1861 [7].

Chloropleth maps is a thematic map in which areas are shaded or patterned in proportion to the statistical variable being displayed on the map. A popular use case is the display of population density or per-capita income. We can see an example of a choropleth map in figure 6, showing the percentage of obese population in the US. Choropleth maps are widely popular and likely to understand them. They are very helpful when data is attached to enumeration unites like counties, provinces and countries.

Figure 5: Charles Minard's map of Napoleon's disastrous Russian campaign of 1812. Minard managed to represent six values in two graphical dimensions: The number of Napoleon's troops, the travelled direction and distance, latitude and longitude relative to specific dates and the temperature.
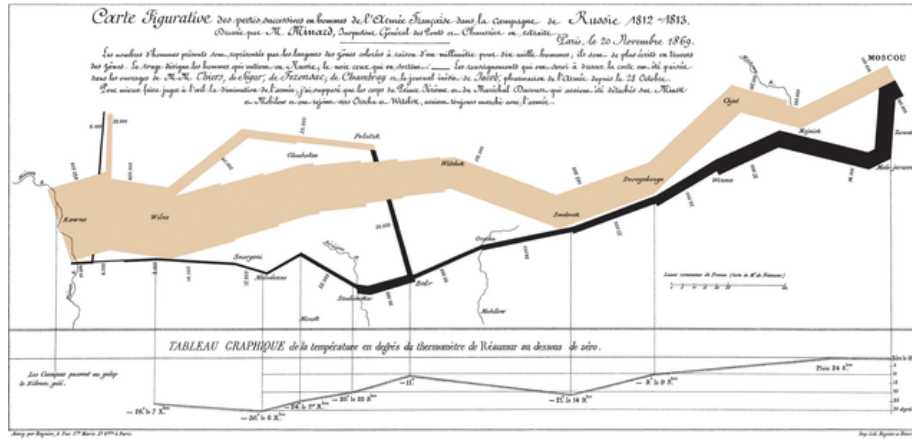
Graduated Symbol Maps is a good alternative to a choropleth maps, as it alleviates one of its downsides: Larger areas may appear more emphasized than smaller ones, thus confounding geographic area with data values. Instead, symbols are placed over the regions of a map. As Heer, Bostock, and Ogievetsky [16] point out, these symbols allow for more visal variables to be visualized, i.e. symbol size, shape and colour.

Cartograms are used to encode a data attribute in the size of an area. For this reason geographic regions in cartograms appear distorted. A common example is to redraw the size of a country based on the the population or gross domestic product of a country. Area cartograms may be contiguous or noncontiguous, depending on the applied layout algorithm.

2.5 Coordinated Multiple Views

According to Roberts [30] coordinated multiple views is just "a specific exploratory visualization technique that enables users to explore their data". Coordinated multiple views are characterized by the fact, that they show multiple views side-by-side. We can see an example in figure 7. It displays an on-time performance of airlines, visualized with the "Crossfilter" javascript library. The user can set the borders of an interval with the mouse in each of the views. The visualization takes the most recent 80 flights from the database that match all given filters. All visualizations are then updated in real time. As we can see in the example in figure 7 there seems to be a correlation of a long delay with a later time of the day.

13
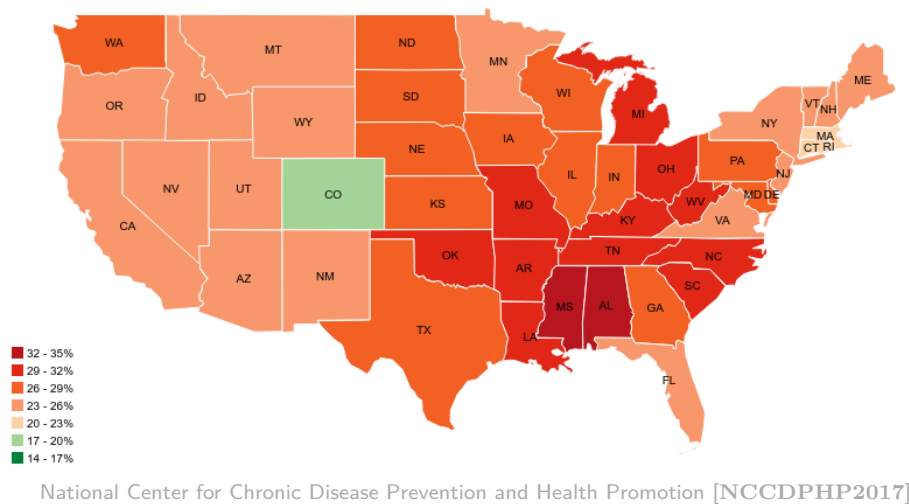
Figure 6: Choropleth Map of Obesity in the United States in 2008. Present of population classified as "obese" (Body Mass Index in excess of 30), by state.

Brushing and Linking   Most multiple coordinated views also provide some kind of brushing technique. "The technique of brushing is the principle approach, where elements are selected (and highlighted) in one display, concurrently the same information in any other linked display is also highlighted."[30]
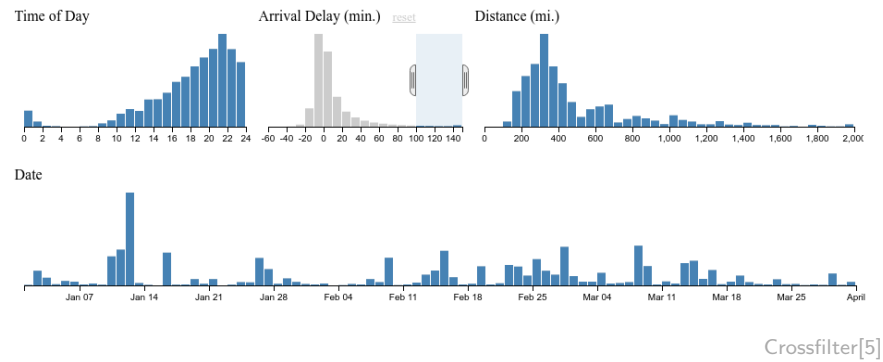
Figure 7: Airline on-time performance: Correlation of time of day with arrival delay. Most recent flight with a delay of more than 100 minutes selected.

3 Related Work

According to Ho [17] interactions are a crucial part of data visualizations, yet most research in the area of data visualization still focuses on visual representations. Roughly speaking, research on interaction falls into these groups: How to categorize interaction techniques? How to find new interaction techniques and apply those to visualizations?

> Give a rough overview of this section

3.1 Categories

Shneiderman [31] classifies interactions into these groups: (1) Gain an *overview* of the entire collection, (2) *zoom* in on items of interest, (3) select an item or group and get *details* when needed, (4) view *relationships* among items, (5) keep a *history* of actions to support undo, (6) allow *extraction* of sub-collections and of the query parameters.

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Two years later, Dix and Ellis [8] identified these categories: (1) *Highlight and focus* particular subsets of the data, (2) instead of displaying everything simultaneously *access extra information* by drilling down the data, (3) zoom in and out to give an *overview and context*, (4) *change parameters* of the *same representation*, e.g. another baseline of a stacked bar char, (5) *change representation* of the *same data* by switching the chart type, (6) *link representations* to determine the relationship between items.

In 2002, Keim [22] comes up with the following classification: (1) Dynamic *projection* to show all combination of data attributes mapped to the axis of a diagram, (2) focus on a smaller subsets by *filtering* out parts of the data, (3) *zoom* into a subset of the data and get a higher level of detail, (4) preserve an overview of the data during drill-down operations is called *distortion* (5) and finally *link and brush* visualizations, to highlight the same data points in multiple visualizations.

The most recent classification was done in 2007 by Yi, Kang, and Stasko [37] listing seven categories: (1) *Select* to mark something as interesting, (2) *explore* to show something else, (3) *reconfigure* to show a different arrangement, (4) *encode* to show a different representation, (5) *abstract/elaborate* show more or less detail, (6) *filter* show something conditionally, (7) *connect* show related items.

> The classifications are all redundant! Explain why and choose one classification for later use

> Give one example for each category of the chosen classification

3.2 Interaction Theory

no section without text

Space-Time Cube Operations is a concept introduced in 2014 by Bach et al. [1] to map temporal data into two dimensional visualizations. Space-time-cubes are used to model two attributes of continuous data with temporal data along a third axis, therefore the name *cube*. While the transformations are rather static it is also possible to introduce activity into the transformations. The authors describe user-independent *animations* and user-controlled *interactions*. E.g. a transformation may display a given slice of the cube. An animation would display one slice at a time and display the next slice every second. Whereas the interaction would show the slice determined by a user-controlled slider. Various transformations and their best use in practice are evaluated in this work. The work focuses on temporal data and otherwise continuous data. Interactions are not seen as an abstract entity, that need to be agnostic of the underlying data structure and visualization. The authors admit "our framework does not provide much guidance for interaction design: the design space for interactive operations has only been partially explored."[1, Other limitations, p. 15]

ITlib[12] is an architecture and a framework of interaction techniques for virtual reality applications, designed to be extensible and flexible. New interaction techniques can easily be added and application specific code is seamlessly integrated. On a low level an interaction technique "is modeled as a set of filters connected in a small data flow"[12, Basic concept, p. 2]. These filters are the smallest process unit in the data flow. Composed of input and output ports, they communicate with other filters, to receive data input from predecessors and send data output to successors. The framework specifies and stores the interaction techniques along with its filters, the execution model and the scene in XML documents. The authors chose XML because it can be parsed easily and they generate code in order to target various virtual reality toolkits and environments.

Even though the system describes interactions in an abstract way, the domain of the framework is clearly the interaction of a human body within a 3D virtual reality. Certain assumptions are made, including the data model, which is the 3D scene, and human computer interaction devices, like the user's hand or the user's head. The goal is not to better understand the data, as the data model in this case is the 3D scene, and not statistical data. Most important, the framework describes interaction techniques for a single viewpoint but not for coordinated multiple views.

Focus+Context Visualization by Bjork, Holmquist, and Redstrom [3] is one of the few formalizations of information visualizations. The authors describe this formalization based on first-level and second-level visualization:

Visualizations   referred to as IV, are triples of a set $[D]$ of underlying data, a visual representation V and I which is the possible interaction or manipulation.

$$IV([D], V, I) \tag{1}$$

If I affects $[D]$ we can manipulate the underlying data set. Examples would be changes in a spreadsheet editor, or a change of the start and end date of an appointment in a calendar. When V is affected by I the user can manipulate IV in order to change the way $[D]$ is represented, e.g. choosing a different level of detail as shown in Figures 2 and 3.

Second-level Visualizations   are information visualizations consecutively applied. The underlying data set $[D]$ of the previous formula is replaced with some information visualization IV, which is compatible with IV'.

$$IV'(IV, V', I') \tag{2}$$

Focus+context visualizations are second-level visualizations. An example given by the authors is the "rubbersheet" visualization, that visually distorts a first-level visualization similar to a magnifier.

4 Use case

4.1 Data Sets

For our uses cases, we have two different data sets: One data set consists of a user ranking of public broadcasting in Germany, i.e. entities, mostly TV and radio broadcasts, are liked or disliked by people. This data is public data and can be used by media researchers of broadcasting corporations but also targets media journalists and the general audience. The other set, called RISO, consists of statistical data from various German administrations and is used by the authorities for urban planning and policy strategies.

Both data sets share some characteristics. The administrative data connects certain features with certain regions of Germany. As Germany is a federal state, larger regions consist of many other smaller regions.

The second one consists of user data that was collected through a web application called RUNDFUNK MITBESTIMMEN.

4.1.1 RISO

The RISO data base is used in by local authorities to get insights about governmental KPIs to assist local and regional decision making. It is a relational database and a part of the data base schema is shown as an ER diagram in figure 8.
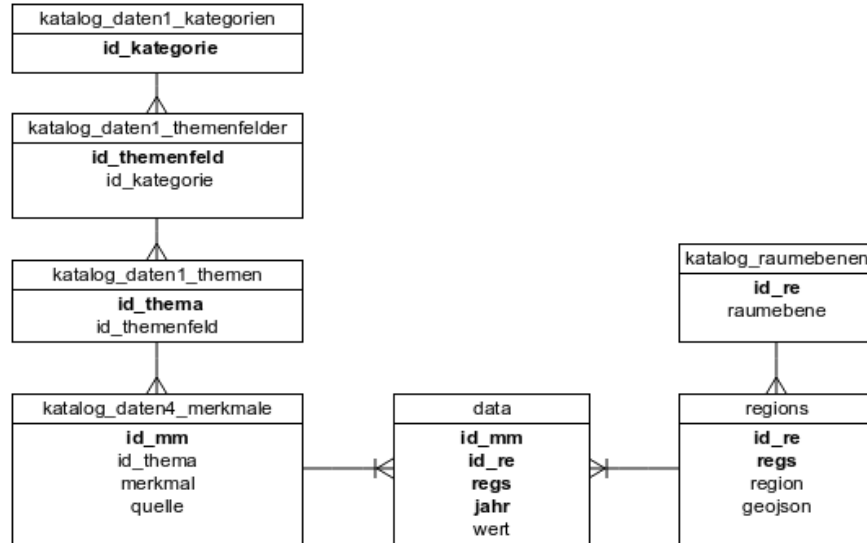

Figure 8: Part of the RISO database schema. Primary keys are set in bold.

The largest table is called `data` with approximately 10,466,600 records, which holds all values along with the survey date.

Features   This data is connected to a feature table through a foreign key called `id_mm`. In the feature table we can find the description for every referenced feature, e.g. population density, working population in agriculture, education spending. The `RISO` system groups all features in a 4-level hierarchy:

1. `katalog_daten_1_kategorien`

2. `katalog_daten_2_themenfelder`

3. `katalog_daten_3_themen`

4. `katalog_daten_4_merkmale`

The actual features table is the last one in the list. At the lowest level within the hierarchy, this is the largest table with 1234 records.

Regions   On the other side, the geographical data is stored in the `regions` table. The geometry data for each region is stored in the `geojson` column and as the name suggests, the data type is a `geojson`. The foreign keys that connect the tables `data` and `regions` are called `id_re` and `regs`. Unlike the feature table, the regions are grouped through the `id_re` that indicates the hierarchy level. So the values of the `id_re` column denominate the level of the hierarchy. E.g. a region with a `id_re` of 1 is a federal state of Germany, a region with id 13 is a constituency. A textual description for the hierarchy level can be found in the `katalog_raumebenen` table in column `raumebene`. Both column `id_re` and `regs` belong to the primary key of the regions table, so there will never be two regions on the same hierarchy level with the same `regs` id.

Characteristics   As we can see, the schema of the `RISO` database follows a rather denormalized approach. The schema does not make a lot of assumptions regarding the input data. It allows to add data of arbitrary size, features and completeness as long as there is some kind of numerical data associated with some kind of geographical unit. This approach is suitable for a data base that incorporates data from different sources, as it is the case with the `RISO` data base.

4.1.2   Rundfunk MITBESTIMMEN

Unlike the `RISO` database, the data base of RUNDFUNK MITBESTIMMEN is used as persistence layer. For that reason the data base schema follows the requirements of a web application in production.

As outlined in Section 1.1 RUNDFUNK MITBESTIMMEN is an evaluation platform for public broadcasting in Germany. First, users vote on broadcasts, i.e. they decide if they want to support broadcast or if they do not want to

support. As a next step, user can define a weighting by distributing a virtual, monthly budget among the chosen broadcasts.

Figure 9 shows the data base schema of the application. A `user` is connected to `broadcast` through a `selection`. If the `user` supports some a broadcast, the `response` on the given `selection` will be 'positive'. If the `user` does not wish to support a `broadcast`, the `response` will be 'neutral'. The `user` can allocate virtual money to supported broadcasts. The money will be stored in the column `amount` of the `selection`. The sum of all amounts for one user will never exceed the virtual budget of 17.50€.
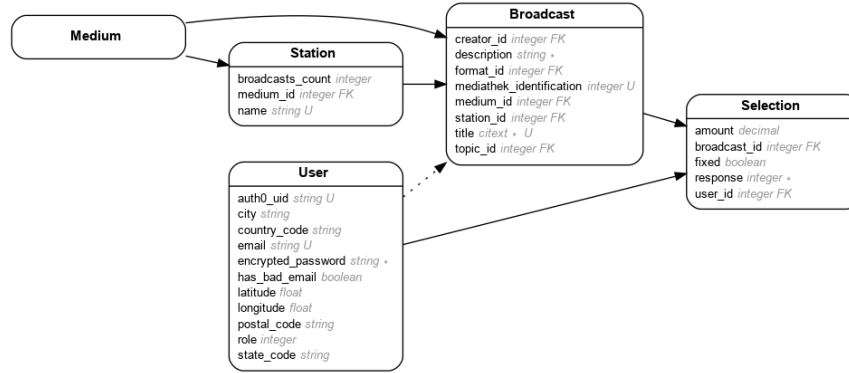

Figure 9: Database schema of the RUNDFUNK MITBESTIMMEN app

Features We have both numerical as well as nominal features. A numerical feature could be the number of supporters from an area in Germany. A nominal feature could be a list of the most supported broadcasts from an area in Germany. Numerical and nominal features can be combined, so we could request for every region, a distribution of the desired expenditure for radio, TV, online and other broadcasts.

Regions RUNDFUNK MITBESTIMMEN stores the geometry for each region in `geojson` files. These files hold a `FeatureCollection`. Every `Feature` is a region, the identifier is stored as a property. We merge the geometry data with features for every request. To be precise: We get all the user data, group it by the identifier `state_code` and merge it with the geometry in the `geojson`.

Characteristics The data base schema is a result of the specific requirements of the persistence layer. Changes in the source code may require a migration of the data base schema.

However, we can ask a lot of questions already with common data base queries or standard data analysis tools:

1. How does the actual support of a broadcast compare to the average support of a broadcast?

2. What are the most popular broadcasts in Berlin?

3. What is the desired ratio of genres of supported broadcasts? How important is education compared to sport?

4. How does the support of a broadcast change over time?

5. According to the user ranking, which broadcasts are similar to each other?

4.2 Existing Interactions

We will now classify the implemented interactions of our two applications according to the classification by Yi, Kang, and Stasko [37] in Section 3.1.

In our visual analytics platform possible interactions can be categorized into the classes *select*, *explore*, *reconfigure*, *encode* and *filter*. As seen in figure 10 the user can *select* one item in the view by clicking on it. The user can reveal a tooltip showing the item properties by hovering with the mouse on the item, which is another *selection*. The user can *explore* the map in the usual manner: If the user drags with the mouse on the map, a panning operation is performed with the viewpoint focused on Germany, i.e. the camera moves around like a turntable. The zoom factor can be changed by scrolling on the canvas of the map. *Encode* and *reconfigure* techniques are performed through the menu on the left side: Under the "features" tab, the user can *reconfigure* different data sets and the displayed diagram, e.g. a tree map visualization based on the geometry shape, cubes or voronoi regions. The tab "Dimensions" allows the user to *encode* properties of a data set to visual attributes, e.g. the height, color and texture of an item. The tab "Filter" can be used to reduce the displayed data set along a range of continuous values. Figure 11 shows the range of visible values in the left menu. When the user drags the slider, the items in the map on the right side are updated interactively.

4.3 Planned Interactions

We have a focus on coordinated multiple views consisting of a tree map and a geographical map. Let's have some examples how an interaction between a 2.5D tree map and a 2D map might work:

1. User selects a feature set from the drop down in the menu. This will trigger a *Reconfigure* interaction. A data set consisting of all features and their ids, geometries and metadata is transferred. The receiving components are both the 2.5D tree map and the 2D map which will rerender the entire visualization.
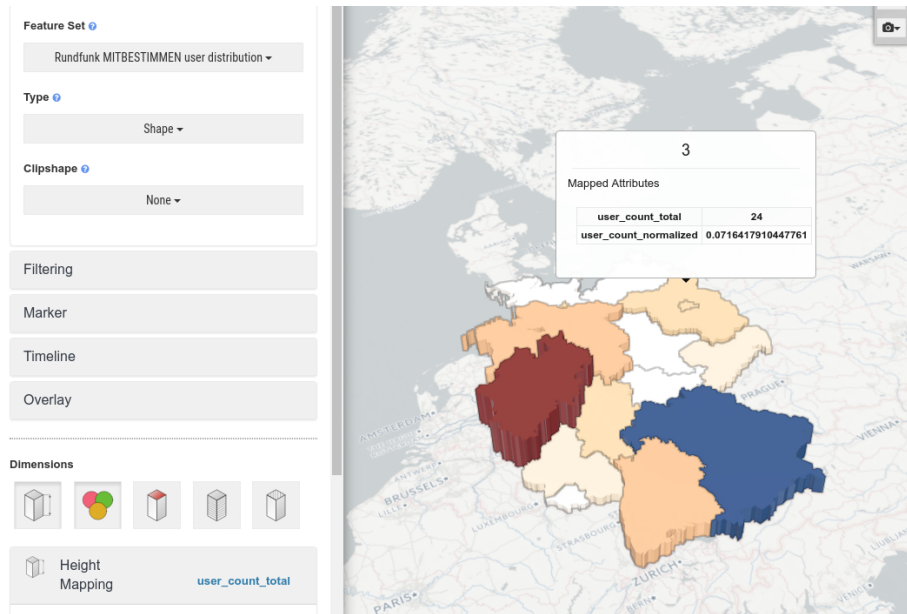
Figure 10: Items can be highlighted with a click, Bavaria is currently high-lighted. A mouse over reveals a tooltip showing item properties. The menu on the left side allows to change the data set and the specific base visualization.

2. User hovers with a mouse over a polygon in the 2D map. This will trigger a *Select* interaction. The data is a single feature id that will be transferred to the 2.5D tree map, which will change the color of an box.

3. Rotate or zoom the 2.5D tree map. This will also rotate or zoom the 2D map. The interaction would fall into *Explore* and the shared information is the orientation of the camera and the zoom level.

4. A click in the 2.5D tree map will trigger an *Explore* interaction. The data is a single feature id sent to the 2D map. The map will center the viewport on the center of geometry of the respective feature.

5. The user selects many features at once in the 2D map by dragging a rectangle. The ids of all features within the rectangle are sent to the 2.5D tree map. All features will be highlighted with a different color, which is therefore a *Select* interaction.

6. *Reconfigure* the layouting of the 2.5D tree map by choosing a different hierarchy level. This increased granularity may lead to an increased granularity in the 2D map, e.g. show postal codes instead of federal states. The changed data are additional items, that are nested in the former items.

7. *Encode* the 2.5D tree map by a different attribute mapping like color,
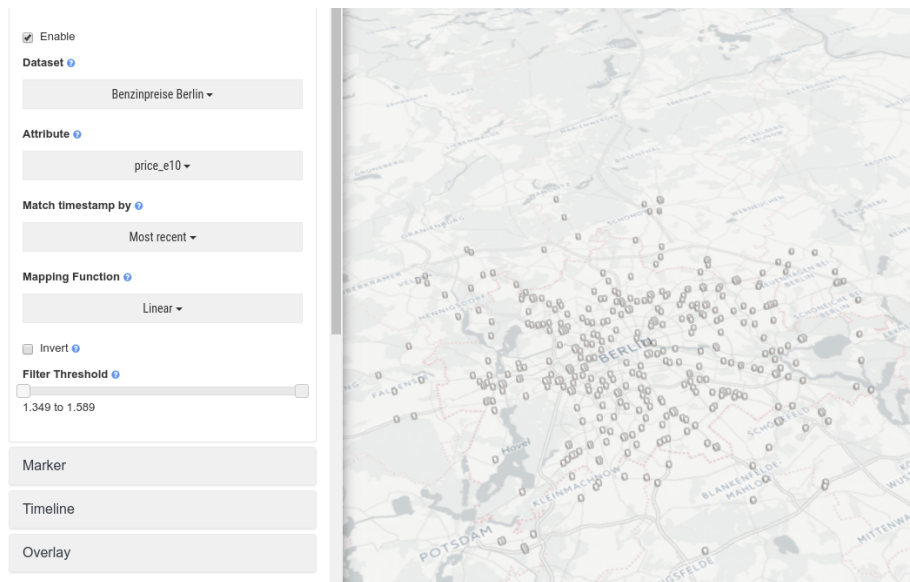
Figure 11: Only gas stations with a price for E10 within 1.349 Euro and 1.589 Euro are displayed in the map

> height or texture. If the 2D map has no geometry data that defines the shape of a feature, it can also display a larger point marker.

8. Apply a *Filter* and reduce the data set by choosing only items with metadata beyond a certain treshold. The reduced data leads to a full re-render of all data visualizations. The message contains the updated item list

9. Show a *Connect* by highlighting boxes of the same subtree in the 2.5D tree map. The respective connected items would be highlighted in the 2D map as well. Here the data is a relation between items.

What are the key interactions in our use case?

5 Analysis

In this section, we list several interaction examples in singular views as well as in multiple views. We list the expected data structure of each visualization and the respective dependent and independent visual variables according to [2]. In addition we classify each interaction according to Yi, Kang, and Stasko [37]. Finally, we describe the relevant subject of the interaction. I.e. what would be exchanged, if the interaction should be mirrored in an entirely different visualization on the underlying data set.

The goal of this procedure is to abstract and deduce the essential characteristics of any interaction, to pave the way for a formalized language of coordinated multiple views.

Bullshit ahead

5.1 Free visual variables allow for interaction effects

In order to communicate the interaction to the user, the effect of the visualization must be communicated back to the user by a visual change. Data visualizations have *dependent* and *independent* visual variables, see 2.2. Dependent variables are those that are tied to a data attribute. These constrained visual attributes are unavailable while independent visual variables are therefore available to be used for a visual feedback of an interaction.

5.2 List events as candidates for interaction triggers

Interaction can be triggered by any input of a human-computer-interaction device, like the keyboard or the mouse. Because users are in the habit of expecting certain interactions to be triggered from certain events, we also have constraints here. E.g. the viewpoint in geographical maps is moved by mouse drag events and the zoom level is controlled by the mouse wheel. So we should not use those already occupied events as triggers for our coordinated interactions. Nevertheless, consistency in user interfaces is crucial for great user experience, because users can reuse the learned knowledge. Therefore, we need to list all availabe events as candidates and connect them to our interactions in a preferrably consistent manner.

On the other hand, we might have special controls in visualizations, in order to change the encoding. E.g. a 2.5D tree map shows a menu where the user can define how attributes are mapped to visual variables.

5.3 Singular Visualization Interactions

The data visualization catalogue by Severino Ribecca list many of the most used data visualizations[29]. Let's pick some of those and derive a number of possible interactions.
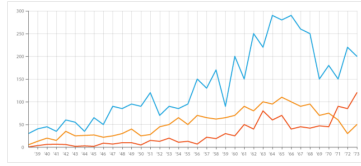
(a) Line diagram

Figure 12: Line charts are used to display trends

Figure 13: Interactions for line charts

Select	Highlight a data point (id of data point)
Select	Highlight a data series (id of data series)
Encode	Change colours of data series (data series $\rightarrow$ colour)
Filter	Restrict interval on x-axis (filter function of data attribute)
Filter	Hide a data series (id of data series)

Line diagrams Line diagrams are multiple sets of data, displayed along the x-axis. They are used to display quantitative value over a continuous interval or time span. It is possible to highlight an entire series of data or just a feature within that series.

Data structure	Tabular data, many data sets as series.
Dependent visual attributes	Position, orientation, texture.
Independent visual attributes	Color, shape, size.

Bar charts and multiset bar charts Bar charts and multiset bar charts show one or many attributes per feature along an axis. They have in common that they encode the data attribute into the height of the eponymous bars. Colors might be used to better distinuish between the different data attributes. Features can be arbitrarily ordered along the axis, although multiset bar charts group features along a series of categories.
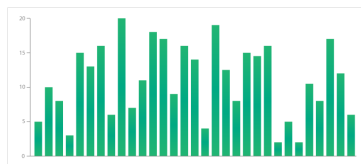
(a) Bar chart
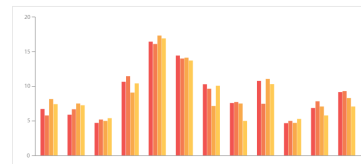
(b) Multiset bar chart

Figure 14: A multiset bar charts is a variation of a bar chart

26

Figure 15: Interactions for bar charts

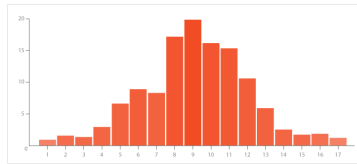|	
Select	Highlight a bar (id of data point)
Encode	Change colours of data series (colours → data series)
Reconfigure	Sort by attribute (data attribute)
Reconfigure	Drag bars to reorder data series (ordered list of ids of data points)
Filter	Hide a data series (id of data series)

Figure 16: A histogram is a bar chart over a continuous interval

Therefore, bar charts need to be initialized with the set of features and their values as well as the groups of features for the multiset bar chart. The supplied colours would colour each feature in a group in turn. The set of possible ineractions include the highlighting of features, the reordering of features and a change in encoding of colour values.

Data structure	Tabular data, many data sets as series
Dependent visual attributes	Size, orientation.
Independent visual attributes	Position, colour, shape, texture.

Histograms visualise the distribution of data over a continuous interval or certain time period. A special type is the population pyramid, which is a pair of back-to-back histograms, one for each sex. The difference of histograms to bar charts lies in the type of data itself, not the representation. Therefore these charts need to be initialized with the same data and the same interactions can be applied.

Data structure	Tabular data, many data sets as series
Dependent visual attributes	Size, orientation, position.
Independent visual attributes	Color, shape, texture.

Bubble charts and scatter plots Bubble charts are popular choices to display a distribution of features. The chart is initialized with coordinates for each feature, a colour and a size in case of a bubble charts. Possible interactions include the highlighting of features, a different colour encoding, a reconfiguration to map another attribute to size. Bubble charts may show only a window of the available data and allow to zoom in, zoom out or move the window along the axes.
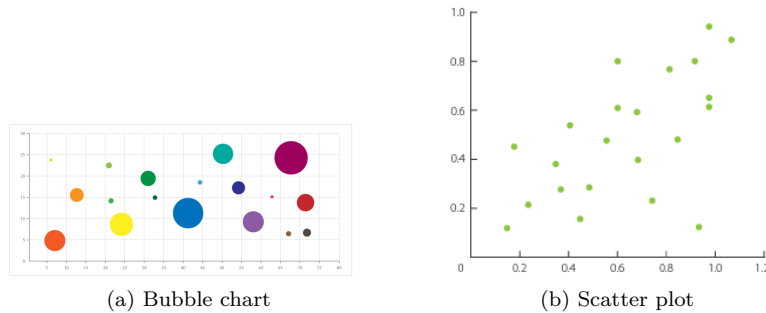
(a) Bubble chart
(b) Scatter plot

Figure 17: Bubble charts and scatter plots are similar regarding interactions

Figure 18: Interactions for bubble charts

Select	Highlight a bubble (id of data point)
Explore	Zoom in, zoom out (width and height of window)
Explore	Move viewport position (x- and y-coordinates of viewport)
Encode	Change mapping of colour to category (data series → colour)
Encode	Change colour function (function value → colour)
Encode	Change data attribute to colour (data attribute)
Encode	Change data attribute to size
Reconfigure	Sort by attribute (data attribute)
Reconfigure	Drag bars to reorder data series (ordered list of ids of data points)
Filter	Hide a data series (id of data series)

Data structure	Tabular data, single data set with x- and y-coordinates
Dependent visual attributes	Size, position.
Independent visual attributes	Color, shape, texture, orientation.

Stacked bar charts Unlike a multi-set bar graph which displays their bars side-by-side, stacked bar graphs segment their bars of multiple datasets on top of each other. A baseline, as shown in figure 19 might be modeled as two back-to-back multi-set bar graphs. A reordering would e.g. move one data set from the left side to the right side. Possible interactions include the highlighting of a feature, a change of color mapping, reordering of the baseline.

Data structure	Tabular data, multiple date sets as series
Dependent visual attributes	Size, shape, orientation.
Independent visual attributes	Color, position, texture.

Hierarchical visualizations Treemaps are great to show hierarchical data without ever exceeding the availabe screen. Each feature is a assigned a rectangle according to a layouting algorithm. Unlike a tree map a hiearchical ring diagram or sunburst diagram shows each level of the tree as a series of rings.

(a) Stacked bar chart

(b) Stacked bar chart with baseline
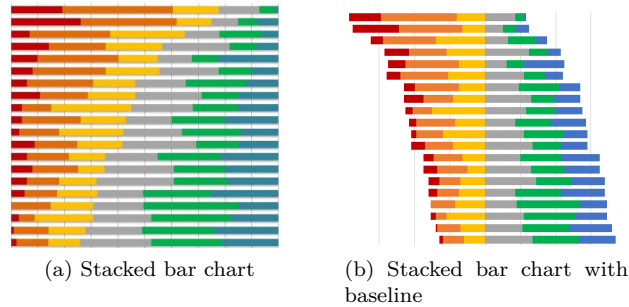
Figure 19: Stacked bar charts can be ordered along a baseline or stretch to 100% width to show the percentage-of-the-whole of each group
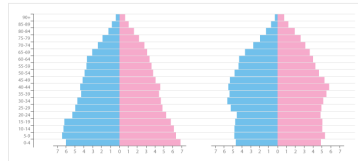
Figure 20: A population pyramid can be modeled as a stacked bar chart

Figure 21: Interactions for stacked bar charts

Select	Highlight a bar (id of data point)
Encode	Change mapping of category to colour (data series → colour)
Reconfigure	Sort by attribute (data attribute)
Reconfigure	Reorder Y axis (ordered list of ids of data points)
Reconfigure	Sort stacking order by attribute (data attribute)
Reconfigure	Specify the stacking order data series (ordered list of ids of data series)
Reconfigure	Specify a negative data series (list of ids of data series)
Filter	Hide a data series (id of data series)

(a) Tree map

(b) Sunburst diagram

Figure 22: Tree maps and sunburst diagrams are ideal to show hierarchies

Figure 23: Interactions for hierarchical visualizations

Select	Highlight a feature (id of data point)
Explore	Use another node as root of the visible tree (id of data point)
Encode	Change mapping of category to colour (data series → colour)
Reconfigure	Change data attribute used for layouting (data attribute)
Reconfigure	Sort by attribute (data attribute)
Reconfigure	Specify order (ordered list of ids of data points)
Abstract/Elaborate	Specify maximum depth of visible tree (number of levels)

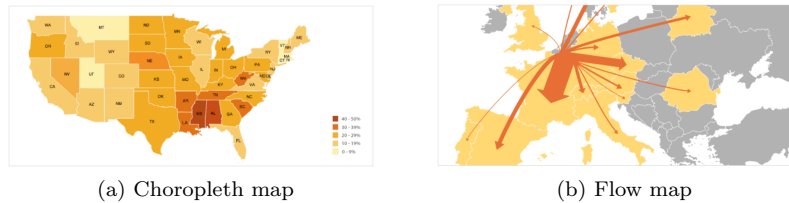(a) Choropleth map   (b) Flow map

Figure 24: Choropleth maps focus on a density while flow maps show a migration of data

Therefore, both tree map and ring diagram need the feature set as a tree, with each node having a data attribute for layouting. Every node may be assigned a color. As we are describing hierarchies, the maximal depth of tree may be increased or decreased. Again, interactions could include a highlighting of features and a change of color encoding. Both visualizations may show only a subtree. E.g. a click on a box in the treemap opens another treemap focused on the subtree. Similarly a click on a slice of the ring would surround the most external ring with the children of the feature.

Data structure	Tree, each feature has a value for layouting.
Dependent visual attributes	Position, Size, shape, orientation.
Independent visual attributes	Color, texture.

Geographical Data Choropleth maps and flow maps are specialized diagrams focused on geographical data. Size, position and shape of a feature is defined by the geometry data of a feature. In choropleth maps the color of each feature is based on a data attribute. Flow maps may display connections between features, a data value defining the size of each arrow.

Data structure	Graph data with edges, each feature has geometry data.
Dependent visual attributes	Position, Size, shape, orientation.
Independent visual attributes	Color, texture.

Figure 25: Interactions for geographical visualizations

|	
Select	Highlight a feature (id of data point)
Explore	Move viewport (latitude and longitude of viewport)
Explore	Zoom in, zoom out (zoom factor)
Encode	Change shape of marker (data id → shape)
Encode	Change mapping of category to colour (data series → colour)
Encode	Change colour function (value → colour)
Encode	Change data attribute used for colour (data attribute)
Connect	Show relations of a feature (id of data point)
Abstract/Elaborate	Change granularity of displayed regions (number of levels)

(a) Calendar (b) Gantt chart
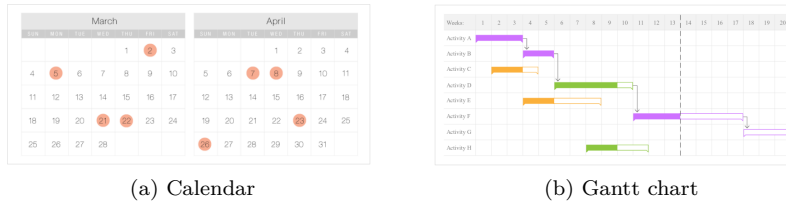
Figure 26: Similar to a calendar, a gantt chart shows activities and the progress along a time line

Activity diagrams   In activity diagrams, each feature is represented as a rectangle, with the duration of the activity mapped to size and position. Calendars and gantt charts could not only read the data from the data source, but also add new features to the data set or update metadata of a feature, e.g. the progress of the activity.

Data structure	Temporal data, each feature has a time interval.
Dependent visual attributes	Position, Size, orientation.
Independent visual attributes	Color, shape, texture.

5.4   Multiple View Interactions

Detail view

Figure 27: Interactions for temporal visualizations

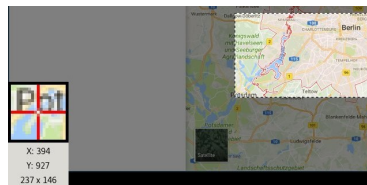|	
Select	Highlight a feature (id of data point)
Explore	Show a different period of dates (start and end datetime)
Explore	Show a different time interval (start and end hour)
Encode	Change color of categories or activities (data series → colour)
Encode	Change data attribute used for colour (data attribute)
Filter	Remove a calendar or a category (id of data series)

Figure 28: The screenshot-tool "shutter" shows a magnified detail view of the area around the mouse cursor in the lower right corner of the screen

6 Concept

Based on the findings in Section 5 we specify a formal language and a framework for coordinated multiple views in this section. Our approach involves the definition of the terminology and the basic components of the framework. The first component is the shared data model on which all visualizations must agree on. We formalize each interaction from Section 5 as a mathematical function and group these functions together if they have the same input and output. As a last step, we specify the communication pattern of the formalized language.

6.1 Terminology

no section without text

6.1.1 Trigger and Effect

We introduce two new terms: *trigger* and *effect*.

As we have seen in Section 5 every interaction is started by a user action. The user e.g. clicks on a shape in the view, hovers over an area, selects an item from a dropdown menu, turns around a mobile device, speaks into the microphone or makes a particular gesture. If the event of action is handled by a view and causes an interaction, we call this handling a *trigger*. Every view is responsible of its *triggers*. These are implementation details and are not shared by other views.

In order to be perceivable by the user, the interaction must have some visual effect, i.e. a change in the visual representation of the data. Examples are: A change of colour of a selected bubble, a movement of the viewpoint, a rearrangement of attributes in a parallel plot or a higher level of detail in a 2.5D tree map. Every view is responsible of its visual *effects*. Those are implementation details as well and they are not shared by other views. Obviously visual effects are not shared, as it depends on the visualization if visual variables are constrained or available to express a visual effect.

In singular visualizations, interactions consist of at least of a trigger and an effect:

$$I(T, E) \tag{3}$$

The meaning of the interaction in a singular view can be implicit. E.g. hovering over a geographic area changes the background colour of the polygon and the user can identify the interaction as a *highlighting*. Note that this implicit meaning must be explicit in coordinated multiple views so that other views are able to understand it.

6.1.2 Interaction type

The aforementioned explicit meaning of the interaction is the smallest unit of information of the interaction. This meaning is shared among multiple views, it is agnostic of how the interaction is implemented. Therefore the meaning is

shared between multiple views. We call this meaning the *interaction type*. Some examples of interaction types include: Highlighting, Deletion, Point-of-Interest, Filtering, Reordering, Re-encoding. Interaction types can be classified with the interaction categories of Yi, Kang, and Stasko [37].

Note that different information visualizations implement an interaction types in a different way or maybe not at all:

E.g. a bubble chart might encode a certain data attribute to the colour of a bubble. Therefore the colour would not be changed for an interaction of type *Highlighting* but the texture of the bubble.

A user may perform an interaction of type *Reordering* on the series of a stacked bar chart. This can have no effect on a coordinated scatter plot, as the position of each data point depends on its dimension.

6.1.3 Interaction subject

The interaction *type* is not sufficient enough to describe an interaction. We must define what data or meta-data is affected by the interaction. E.g. when a user moves the mouse cursor on a line in the line diagram, that could highlight the *data point* under the cursor as well as the entire *data series*. Therefore we call the object affected of an interaction the interaction *subject*. A subject can be a data point, a list of data points, a position of the viewpoint, a certain order of attributes or a mapping of attributes to visual variables.

Interaction type and interaction subject are interrelated in the same way like the name and the list of arguments of a function signature.

6.1.4 Application context

A developer may want to have many *select* interactions. E.g. the user desires to select a detail view of an item under the mouse cursor from a previously selected set of already highlighted items. Therefore we allow for a user-defined *application context*. The application context describes the interaction in the context of a task or an intention that is intrinsic to the application the interaction happens in.

6.1.5 Message

A message is the information that is send from one view to another in order to coordinate an interaction. It contains everything necessary to ensure the interaction is reflected in the other view.

6.2 Formalization of an interaction

We formalize an interaction I as follows:

$$I(T, M(AC, IT, F(IS)), E) \qquad (4)$$

For a trigger T, an application context AC, an interaction type IT, a function definition F, an interaction subject IS and the effect E. The part of the interaction which is shared among multiple views is the application context AC. The function definition F is defined by the view at runtime. E.g. when a parallel plot rearranges the list of attributes, the exact order will be determined by the view itself, during the handling of the drag-and-drop action.

6.3 Framework

no section without text

6.3.1 Shared data model

To account for the various data structures, we use an abstract data model that is powerful enough to include tabular, hierarchical and relational data. You can see a class diagram in figure 29.

The *entity* class is used to model the smallest distinguishable unit. All entities can be identified and retrieved via the *id*. An entity is defined to be any object that can have data attached as *attribute*.

While entities describe what an object *is*, an *attribute* describes what it *has*.

An entity can have arbitrary many attributes and each value can be accessed by the name of the attribute. So if you want to get the *latitude* value of an entity, you can retrieve the value with a call to the named attribute *latitude*.

Entities can also be *series* of other entities. A series contains an ordered list of contained entities. As series can also contain other series, so we can model a hierarchy relation.

There is always one particular series without a parent. This is the root node of the hierarchy. If we just want to display tabular data, we just have one or two levels of hierarchy. E.g. one level of hierarchy for a histogram and two levels of hierarchy for a stacked bar chart.

Other relations than hierarchical relations can be modeled as a *relation* entity. It represents a directed edge in a graph and must have incoming and outgoing entity. Since every *relation* is an *entity* as well, we can add *attributes* to the relation. These attributes may describe e.g. the weight of an edge in a flow map.

6.3.2 Predefined Interaction Types

It turns out that we can describe the types of an interaction as a mathematical function. These functions operates on the ids of *entities*, *series*, and *relations*
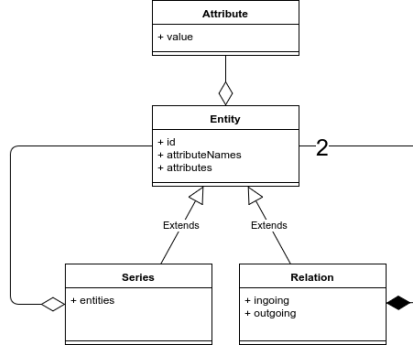
35

Figure 29: A data structure for tabular, hierarchical and relational data

or their respective *attributes*. The name of the function is the *type* of the inter-
action and the function domain being the *subject* of the interaction. Thus, we
can describe interaction through a change of its semantic but we ignore imple-
mentation details of specific visualizations.

These function are derived from specific interactions of the examples in Sec-
tion 5.4. Domain and codomain of these functions refer to the objects defined
in the data model in Section 6.3.1. To declare the functions explicitly, we define
a couple of sets:

1. $\mathbb{E} : \mathbb{E} \subseteq \mathbb{N}$

   The set of ids of all entities in our subject space.

2. $\mathbb{A} : \mathbb{A} \subseteq \sum^*$

   The set of names of all attributes in our shared data model. Attributes
   are the exact same thing as the dimensions of the underlying data set.

3. $\mathbb{D}$

   The set of possible data values of any attribute in our subject space. Those
   values could be e.g. numbers, strings, ordinal values, dates or geometries.

4. $\mathbb{C} : \{(r, g, b) \in \mathbb{C} | r \in \mathbb{R} \wedge g \in \mathbb{R} \wedge b \in \mathbb{R}\}$

   The set of colours, we assume a triple of R, G and B values.

5. $\mathbb{V}$

   The set of visual variables position, size, orientation, texture, colour and
   shape, as described in Section 2.2. Elements of this set include the name
   for $x - axis$ and $y - axis$ as well as the name of shapes. Thus, an *en-
   coding* interaction can change the mapping of a data attribute to another
   coordinate axis.

The following is a list of functions describing the types based on the afore-
mentioned sets:

1. $Highlight : \varnothing \to \mathcal{P}(\mathbb{E})$

   A $Highlight$ is a function without arguments returning a subset of highlighted entities.

2. $FilterById : \varnothing \to \mathcal{P}(\mathbb{E})$

   The $FilterById$ function takes no arguments and returns a subset of entities that are used as input for the visualization.

3. $FilterByValue : \mathbb{D}^* \to \{\bot, \top\}$

   The $FilterByValue$ function takes an ordered list of data values and returns whether or not the associated entity should be part of the visualization input.

4. $FilterAttributes : \varnothing \to \mathbb{A}^*$

   The $FilterByAttributes$ returns an ordered list of attributes names. Retrieving the values of an entity in order produces the input that can be used as input for the $FilterByValue$ function.

5. $Focus : \varnothing \to \mathbb{E}$

   The $Focus$ function returns a single id of the entity that should be in the center of the viewpoint. Different visualizations can have different interpretations of the semantic: A geographical map will move the viewpoint position on the geometric center of the focused entity. Hierarchical visualizations, e.g. tree maps or sunburst maps, may choose the focused entity to be the root node of the currently displayed subtree.

6. $Extent : \varnothing \to \mathcal{P}(\mathbb{E})$

   This function returns a subset of entities that must be within the current boundaries of the diagram window. Again, different visualizations can have different interpretations of the semantic: In scatter plots and geographical visualizations the set may be used to implicitly derive the zoom level. It can also be used to implicitly derive the maximum depth of the currently visible subtree in a tree map.

7. $ColourById : \mathbb{I} \to \mathbb{C}$

   A colour function assigns each entity, data series or relation to a color.

8. $ColourByValue : \mathbb{D} \to \mathbb{C}$

   A colour function assigns a continuous value to a color. This function can be used by e.g. choropleth maps for the background color of regions.

9. $ColourAttributes : \varnothing \to \mathbb{A}^*$

   The ordered list of names of attributes used as input for the $ColourByValue$ function.

10. $Reorder \rightarrow \mathbb{E}^*$

    The *Reorder* function defines how a subset of entities should be ordered. Note that not the entire collection of entities need to be ordered. This sequence will be used in bar charts to order bars along the x-axis or stacked bar charts, to order the stacking of data series.

11. $Sort : \left(\mathbb{D}^* \times \mathbb{D}^* \right) \rightarrow \mathbb{R}$

    This sort function will return a continuous value based on an arbitrary long list of pairs of data values. It's an implicit order function based on one or many data attributes and returns a negative value if the first element is orderd before the second element.

12. $SortAttributes : \varnothing \rightarrow \mathbb{A}^*$

    The ordered list of names of attributes which will be used as input for the *Sort* function.

13. $ReorderAttributes : \varnothing \rightarrow \mathbb{A}^*$

    This ordered list of attributes define in which order visualizations display many coordinate axes. E.g. a parallel plot can reorder the attributes along the x-axis.

14. $Encode : \mathbb{A} \rightarrow \mathbb{V}$

    The *Encode* function can be used to change any mapping of attribute to any visual variable. E.g. bar charts can change the attribute mapped to the *height* of bars. Histograms and scatter plots can change the name attribute that is mapped along the *x-axis*. Bubble charts can encode a different data attribute in the *area* of the bubbles. A specialized version of this function may return the attribute that is used for the layout algorithm in tree maps.

Let's have some examples how these functions can be applied on coordinated interactions:

A user clicks on a bar in a bar chart and this feature then changes its background colour. To coordinate the highlighting, the bar chart visualization replaces the *Highlight* function. The function now returns the id of the entity of the feature with the new background colour.

When a region in a geographical map is clicked, the new *Focus* function will return the id of the clicked entity. A coordinated tree map next to the geographical map now shows a subtree with the focused entity as root node.

If many attributes are chosen from a dropdown menu and some thresholds are specified with a slider, both the *FilterAttributes* and the *FilterByValues* functions are changed. The *FilterAttributes* will return the ordered list of chosen attributes of the dropdown menu. The updated *FilterByValues* function will now expect a new argument list, based on *FilterAttributes*. It then yields either true or false based on the values of these attributes.

6.3.3 Communication pattern

In Section 6.3.2 we discussed how we can describe the types of the interaction. The interaction type determines the signature of the function and describes the interaction itself. However a type does not define how interactions are *coordinated* among views. E.g. what action in one view should lead to what kind of changes in what other views? What is the communication pattern or what is the protocol how messages are exchanged in the framework?

We define a message M as:

$$M(AC, T, F) \tag{5}$$

With AC as an application context, an interaction type T and a function F. The interaction type is one out of the names in Section 6.3.2 and defines the function signature. F is the actual definition of the function, i.e. a call of this function with the provided parameters defined by T returns an expected value.

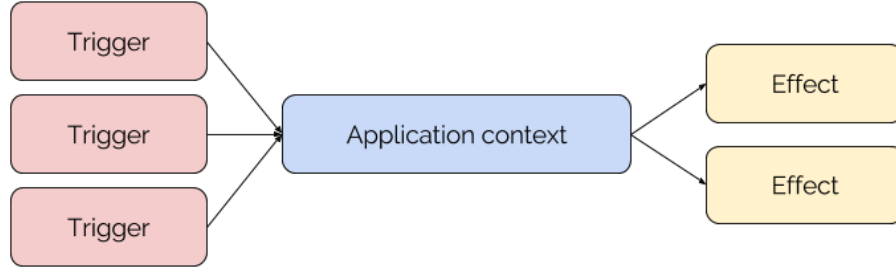Figure 30 gives an overview on the message flow in the communication pattern.

Figure 30: The message flow of the communication pattern: Every view can decide for itself whether to trigger an interaction or respond to an interaction with a visual effect. This is done by a user-defined application context.

Sometimes a visualization may not be able to interpret an interaction. E.g. a bar chart can re-arrange the bars along the x-axis in case of a *Reconfigure* interaction. But a scatter plot constrains x- and y-coordinates of an entity on a certain data attribute. Therefore, not only the *trigger* and *effect* is implementation specific, but also the handling of the interaction itself.

Every visualization decides on its own, how to react to a certain interaction. That leads us to distinguishable, named interactions. Every view can subscribe to certain interactions and receive messages in form of changed interaction types. In order trigger an interaction, the visualization simply publishes to the named interaction.

This pattern is known as the *Publish-subscribe pattern* and widely used in message queues. The term *interaction* in our case is equivalent to the term *channel* or *topic* commonly used in message queues.

7 Implementation

This section describes the implementation details for the described concepts. We start with a list of to be implemented features. Next, we describe the architecture of the software and why we chose this architecture. What requirements and considerations lead to this particular architecture.

7.1 Implemented interactions

In the course of this thesis we want to implement the following interactions:

- *Select*: The user clicks on a building or region in a geographical map and all affected properties in the 2.5D tree map will be highlighted.

- *Explore*: The user clicks on a block in the 2.5D tree map and the viewpoint in the geographical map will be centered on relevant area.

- *Abstract/Elaborate*: The user selects a different granularity in the geographical map (e.g. postal code regions instead of federal states) and the change is reflected in the 2.5D tree map.

- *Filter*: The user double-clicks on a region in a geographical map and the 2.5D tree map will be based on data of only that region.

7.2 Observer pattern

Explain observer pattern

Figure 31 shows how coordinated multiple views can be automatically updated even if the environment lacks a native update-mechanism. We use the observer pattern: The root of our views is an observable implementation of the common interface described in section6. If one of the views updates the view state, it will send the necessary information to the observable. The observable will then broadcast the change to all it's observers.

Publisher subscriber In our particular case we apply a special form of the observer pattern, the so called "Publish-subscribe" pattern[10]. Publish-subsribe is a messaging pattern which is widely used in message queues. In this scenario, senders of messages simply categorize their messages which will be consumed by subscribers of the category. The scenario has very low coupling, publishers do not even need to know the existence of subscribers.

How can multiview subscribe to the multiview controller

7.3 Component pattern

State-of-the-art javascript frameworks like ReactJS and EmberJS follow the component pattern for the architecture of a single page web application. The
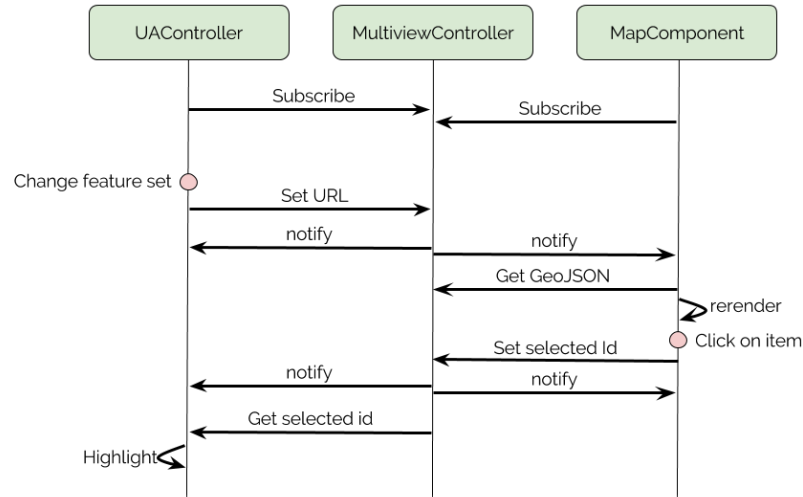
Figure 31: The sequence diagram shows the notification of different components. The user first chooses a feature set and hovers over a polygon in the geographical map.

component pattern imposes a hierarchical structure on a website. Each component is responsible for a task and may contain other components. The components are joined at the root node of the page.

This pattern is very applicable to coordinated multiple views. The different views of coordinated multiple views share state, i.e. the feature, that is currently highlighted or the applied filter on the data. So the views are components and their closest common ancestor is the coordinated multiple view itself, controlling state and passing user interaction down to it's children.

Actions up — Data down Version 2.0 of Ember introduced a common phrase how to use this pattern effectively: "Data down, actions up"[33] In the domain of coordinated multiple views actions would mean user interactions, e.g. a click on a feature. The action will notify the controlling coordinated multiple view component. Actions may change data, and the changes will be passed to to all dependen views. These views are then rerendered.

Examples for the kind of data that might trigger a rerendering of a view:

- The selected feature or a list of selected features

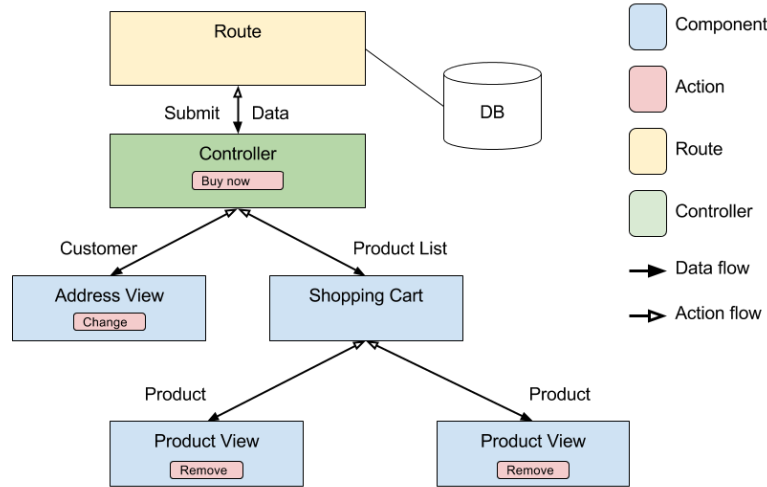- A list of thresholds for certain features as a filter

41

Figure 32: Implementation of the component pattern in EmberJS. The example shows a page of a webshop. The customer is about to order the items in the shopping cart.

7.4 Web components W3C specification

Web components is a recent standard of the W3C[34] to bring component-based software engineering to the world wide web. They look perfectly suited to be used in coordinated multiple views. However the attributes of web components are string based. If arbitrary javascript objects need to be passed into the web component it is suggested to use one of the common javascript frameworks that allow for data binding.

7.5 Frontend framework comparison

We evaluated three javascript frontend frameworks for our application: *GlimmerJS*, *Google Polymer* and *ReactJS*. Figure 33 shows the pros and cons of each framework for our use case.

GlimmerJS is the rendering enginge of EmberJS[36]. In 2017 it was released as a standalone framework. Applications written in GlimmerJS can be exported as web components. These web components can be included in any website, which makes GlimmerJS a reasonable choice to build high-quality widgets for user interfaces. GlimmerJS also uses handlebars[21], a user-friendly templating

language. The downside of GlimmerJS is the current lack of documentation and immaturity due to the recent first release this year.

Another popular framework to build web components is Google's Polymer library[19]. With 18,469 stars on Github it is the most popular framework for web components at the time of writing. Polymer has a large community and comprehensive documentation and therefore more suitable than GlimmerJS for our task.

Unfortunately, the web component standard does not specify how arbitrary Javascript objects can be passed to web components. This raises some problems in legacy apps: Usually, legacy apps are written in plain javascript without the use of a component-based frontend framework. Any part of the code may call any other part of the code, leading to the dreaded "spaghetti code". Refactoring the existing app requires the framework to have a reliable way of communication with the legacy parts. E.g. parts of the legacy code call the backend in order to load data. This data needs to be passed to the compponents of the user interface. Web components do not have a designated interface Because of that, libraries like Polymer come back on proprietary solutions. But those proprietary solutions defeat the main advantageof developing against a standard, as it is unclear how components may interact with each other.

Lifting the constraint to implement against web components, we finally decided to go for ReactJS[18]. ReactJS does not have the ability to export web components. It has, in return, an ascertained way of integrating the framework into a legacy app built with jQuery. Along with its major advantage of easy integration, it has a striving community, heaps of documentation and tutorials and is well tested.

All of these reasons make us choose ReactJS for the task of coordinating multiple views in our existing VISUAL ANALYTICS PLATFORM.

Pros/cons of GlimmerJS, Polymer, React

7.6 Observer pattern and component pattern in coordinated multiple views

Figure 34 shows the final result. We try to put as much code as possible under the root node of ReactJS. By that we eliminate the amount of custom updating implementation. The root node of the DOM-tree of our react application is connected with the existing app through the common interface. Both urban analytics controller and the multiview map component will observe changes to the common interface. Also sub-components may communicate with the common interface.

7.7 GeoJSON

An example of aggregated user data merged with geometry data can be seen in listing 1.

```
1   {
```

Glimmer

+	-
familiar	mature
	documentation
	community

Polymer

+	-
mature	
documentation	
community	

React

+	-
mature	standard
documentation	
community	
declarative	
size	
integration	

Webcomponents

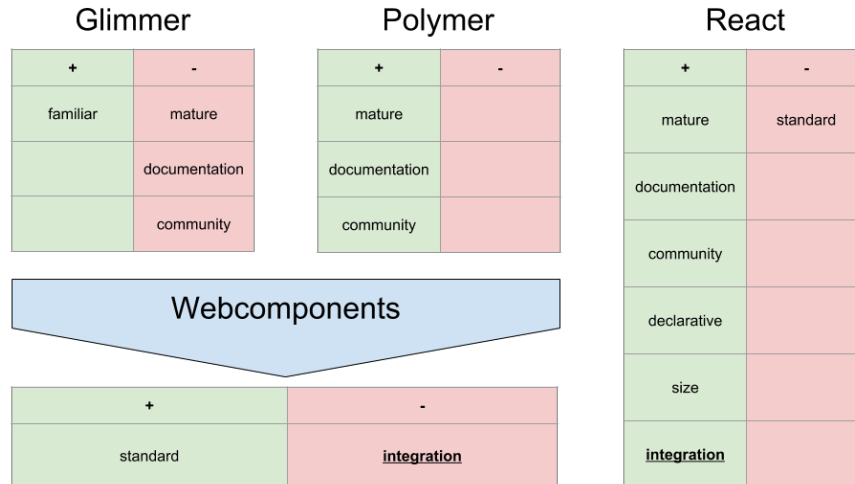| +	-
standard	**integration**

Figure 33: Comparison of frontend frameworks

```
 2    "type": "FeatureCollection",
 3    "features": [
 4      {
 5        "type": "Feature",
 6        "geometry": {
 7          "type": "MultiPolygon",
 8          "coordinates": []
 9        },
10        "properties": {
11          "NAME_1": "Baden-Württemberg",
12          "state_code": "BW",
13          "user_count_total": "34",
14          "user_count_normalized": "0.10149253731343283"
15        },
16        "id": 0
17      },
18      {
19        "type": "Feature",
20        "geometry": {
21          "type": "Polygon",
22          "coordinates": []
23        },
24        "properties": {
25          "NAME_1": "Bayern",
26          "state_code": "BY",
27          "user_count_total": "36",
```
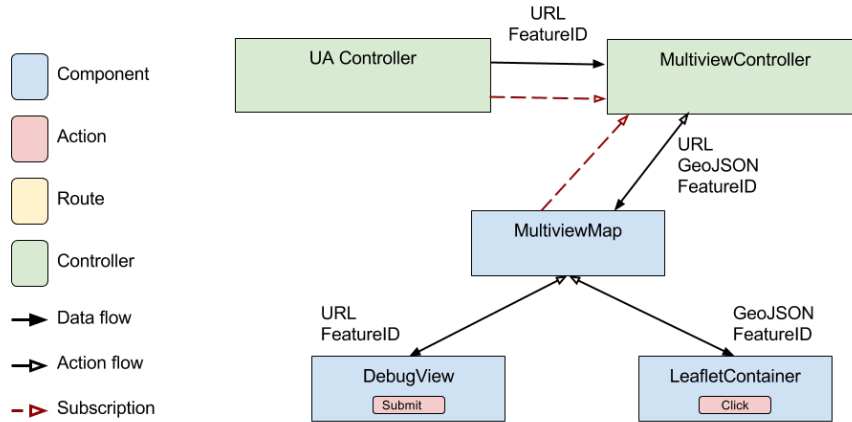
Figure 34: Both observer pattern and component pattern applied in the field of coordinated multiple views

```
28          "user_count_normalized": "0.10746268656716418"
29        },
30        "id": 1
31      }
32    ]
33 }
```

Listing 1: Geojson example

We can use this data as input for our common VISUAL ANALYTICS PLATFORM, e.g. figure 35 shows the user distribution of RUNDFUNK MITBESTIMMEN.
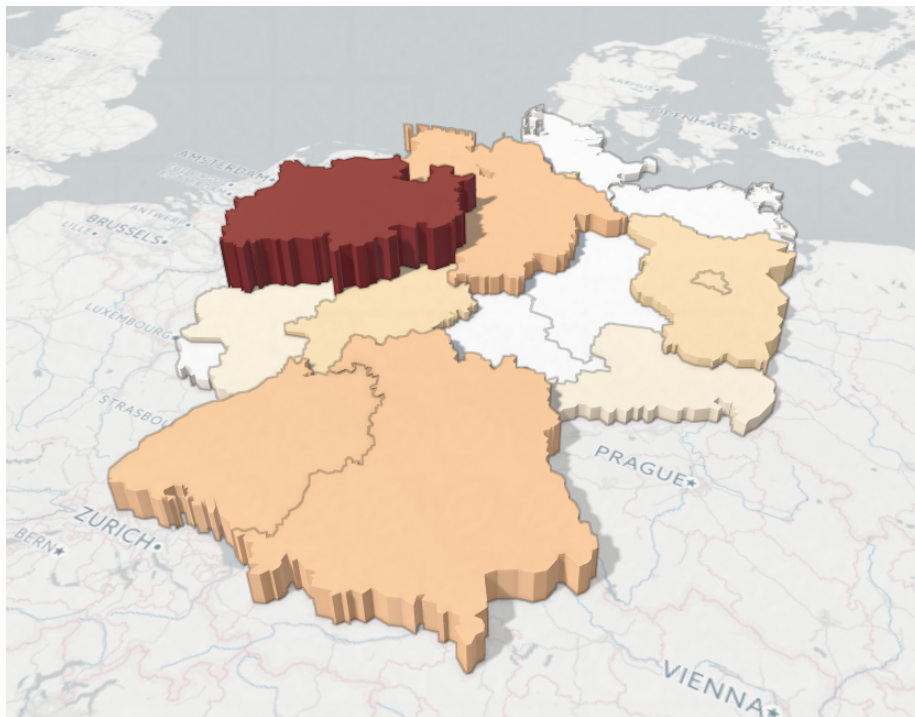
Figure 35: User distribution of RUNDFUNK MITBESTIMMEN across German federal states

8 Evaluation

How and what can we evaluate?

The performance?

The flexibility?

9 Conclusion

Did we achieve our goals?

Is the concept sane in regarding the implementation?

10 Future Work

List stuff which was not accomplished in this master thesis

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