

RespVis:

A Low-Level Component-Based

Framework for Creating

Responsive SVG Charts

Peter Oberrauner

RespVis:

A Low-Level Component-Based Framework for Creating Responsive SVG Charts

Peter Oberrauner B.Sc.

Master's Thesis

to achieve the university degree of

Diplom-Ingenieur

Master's Degree Programme: Software Engineering and Management

submitted to

Graz University of Technology

Supervisor

Ao.Univ.-Prof. Dr. Keith Andrews
Institute of Interactive Systems and Data Science (ISDS)

Graz, 03 Jan 2022

© Copyright 2022 by Peter Oberrauner, except as otherwise noted.

This work is placed under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

RespVis:

Ein Low-Level Komponenten-Basiertes Framework zum Erstellen von Responsiven SVG Diagrammen

Peter Oberrauner B.Sc.

Masterarbeit

für den akademischen Grad

Diplom-Ingenieur

Masterstudium: Software Engineering and Management

an der

Technischen Universität Graz

Begutachter

Ao.Univ.-Prof. Dr. Keith Andrews
Institute of Interactive Systems and Data Science (ISDS)

Graz, 03 Jan 2022

Diese Arbeit ist in englischer Sprache verfasst.

© Copyright 2022 von Peter Oberrauner, sofern nicht anders gekennzeichnet.

Diese Arbeit steht unter der Creative Commons Attribution 4.0 International (CC BY 4.0) Lizenz.

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The document uploaded to TUGRAZonline is identical to the present thesis.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe. Das in TUGRAZonline hochgeladene Dokument ist mit der vorliegenden Arbeit identisch.

Date/Datum

Signature/Unterschrift

Abstract

[TODO: Write Abstract]

keywords:

- responsive, visualisation, component-based, low-level, framework
- bar chart, line chart, scatterplot, ... [parcoord]
- JavaScript, TypeScript, D3
- SVG, Canvas, WebGL
- Node, gulp, rollup

Kurzfassung

[TODO: Translate abstract into german]

Contents

Contents	iii
List of Figures	vi
List of Tables	vii
List of Listings	ix
Acknowledgements	xi
Credits	xiii
1 Introduction	1
2 Web Technologies	3
2.1 HyperText Markup Language (HTML)	3
2.2 Cascading Style Sheets (CSS)	3
2.2.1 CSS Box Model	5
2.2.2 CSS Flexbox Layout	5
2.2.3 CSS Grid Layout	6
2.3 JavaScript (JS)	7
2.4 TypeScript (TS)	9
2.5 Web Graphics	9
2.5.1 Raster Images	10
2.5.2 Scalable Vector Graphics (SVG)	10
2.5.3 Canvas (2D)	11
2.5.4 Canvas (WebGL)	12
2.6 Layout Engines	14
2.6.1 Browser Engines	14
2.6.2 Yoga	14
2.6.3 FaberJS	14
2.7 Responsive Web Design	15

3	Information Visualization	17
3.1	History of Information Visualization	19
3.2	Information Visualization Libraries for the Web	23
3.2.1	Data-Driven Documents (D3)	23
3.2.2	Vega and Vega-Lite	25
3.2.3	Template-Based Visualization Libraries	28
4	Responsive Information Visualization	33
4.1	Responsive Visualization Patterns	33
4.2	Responsive Visualization Examples	35
4.2.1	Bar Charts	35
4.2.2	Line Charts	36
4.2.3	Scatterplots	36
4.2.4	Parallel Coordinates	37
5	The RespVis Library	39
5.1	Design	39
5.2	Naming Conventions	42
5.3	Project Setup	42
5.3.1	Directory Structure	43
5.3.2	NodeJS	45
5.3.3	Rollup	45
5.3.4	Gulp	48
6	Modules	51
6.1	Core Module	52
6.1.1	Utilities	52
6.1.2	Layouter	56
6.1.3	Axes	59
6.1.4	Chart	61
6.1.5	Chart Window	62
6.2	Legend Module	65
6.3	Tooltip Module	67
6.4	Bar Module	69
6.4.1	Basic Bars	69
6.4.2	Grouped Bars	71
6.4.3	Stacked Bars	73
6.5	Point Module	77

7 Examples	79
7.1 Bar Chart	79
7.2 Grouped Bar Chart	79
7.3 Stacked Bar Chart	79
7.4 Scatterplot	79
8 Selected Details of the Implementation	81
8.1 D3 Select Function Data Modification	81
8.2 Save as SVG	81
9 Outlook and Future Work	83
9.1 Outlook	83
9.2 Ideas for Future Work	83
9.2.1 Post-Processing SVG String Before Download.	83
9.2.2 Relative Positioning of Series Items	83
9.2.3 Container Queries	83
10 Concluding Remarks	85
A User Guide	87
B Developer Guide	89
Bibliography	91

List of Figures

2.1	CSS Box Model	5
2.2	Flexbox <code>justify-content</code> Property	6
2.3	Grid Layout Property Comparision	7
2.4	Desktop Browser Market Share	8
2.5	Raster Image Scaling	10
2.6	SVG Scaling	11
2.7	Canvas With Responsive Circles	13
3.1	Anscombe's Quartet	18
3.2	Chart of Planetary Movements from the 10 th Century	20
3.3	Chart of Changes in Sunspots from 1626	20
3.4	Chart of Longitudinal Distance Determinations Between Toledo and Rome From 1644	20
3.5	Line Chart by William Playfair from 1786	21
3.6	Bar Chart by William Playfair from 1786	21
3.7	Area Chart by William Playfair from 1786	21
3.8	Polar-Area Chart by Florence Nightingale from 1859	22
3.9	High-D	22
4.1	Responsive Bar Chart Example	36
4.2	Responsive Line Chart Example	37
4.3	Responsive Scatterplot Example	37
4.4	Responsive Parallel Coordinates Chart Example	38
5.1	Component Layers of RespVis	41
5.2	RespVis Directory Structure	43
6.1	Modules of RespVis	52
6.2	Layout Process of the Layouter	57
6.3	Render Process When Using the Layouter	60
6.4	RespVis Axis Components	60
6.5	Chart Example	61
6.6	Chart Window Example	63
6.7	Legend Example	65

6.8	Tooltip Example	68
6.9	Bar Chart Window Example	72
6.10	Grouped Bar Chart Window Example	74
6.11	Stacked Bar Chart Window Example	76
6.12	Point Chart Window Example.	77

List of Tables

2.1	CSS Selector Syntax	4
2.2	TypeScript Type System Design Properties	9
3.1	Anscombe's Quartet in Tabular Form	18
3.2	Categories of Interaction Based on User Intent.	19
4.1	Targets of Responsive Visualization Patterns	34
4.2	Actions of Responsive Visualization Patterns	35

List of Listings

2.1	SVG Document Containing a Circle	11
2.2	Canvas With Responsive Circles	12
3.1	D3 Method Chaining	24
3.2	D3 General Update Pattern	25
3.3	Static Bar Chart in Vega	27
3.4	Bar Chart with Tooltip in Vega	28
3.5	Bar Chart with Tooltip in Vega-Lite	29
3.6	Bar Chart in Highcharts	30
3.7	Bar Chart in D3FC	31
3.8	Responsive Rules in Highcharts	32
5.1	RespVis' package.json File	46
5.2	IIFE Module Format	47
5.3	Gulp Task that Bundles the Library Code	49
5.4	Tasks Defined in <code>gulpfile.js</code>	50
6.1	Replicated Layout Structure of an SVG Document	58
6.2	CSS Rules to Style SVG	58
6.3	Source Code of Legend Example	66
6.4	Bar Chart Window Example	71
6.5	Grouped Bar Chart Window Example	73
6.6	Stacked Bar Chart Window Example	75
6.7	Point Chart Window Example	77

Acknowledgements

[TODO: Write acknowledgement]

Peter Oberrauner
Graz, Austria, 03 Jan 2022

Credits

I would like to thank the following individuals and organisations for permission to use their material:

- The thesis was written using Keith Andrews' skeleton thesis [Andrews 2019].

[TODO: Add further credits?]

Chapter 1

Introduction

This thesis introduces RespVis, a component-based framework for creating responsive SVG charts which is built on standard browser technologies like HTML, SVG and JavaScript.

[TODO: Outline the various chapters]

Chapter 2

Web Technologies

RespVis is a web-based framework. As such, it builds on a stack of technologies which are native to the web. The first sections in this chapter introduce the web's core technologies: HTML for content, CSS for presentation, and JavaScript (JS) for behavior. Next, TypeScript is introduced, and the different technologies to embed graphics in web pages are discussed. Due to the importance of layouting in this work, three different forms of layout engines are compared. Finally, the concept of responsive web design is summarized. Since there are many things to examine, none of the following sections goes into great detail, the aim is to give a summary of the concepts that are introduced. For more in-depth information, works referenced in the sections below should be consulted.

2.1 HyperText Markup Language (HTML)

HTML is a document markup language for documents which are to be displayed in web browsers. The original proposal and implementation in 1989 came from Tim Berners-Lee who was a contractor at CERN at the time [Berners-Lee 1989]. Over the years, the standard was further developed by a range of different entities like the CERN and the Internet Engineering Task Force (IETF). Nowadays, HTML exists as a continuously evolving living standard without specific version releases, which is maintained by the Web Hypertext Application Technology Working Group (WHATWG) and the World Wide Web Consortium (W3C) [Hickson et al. 2021].

The primary purpose of HTML is to define the content and structure of web pages. This is achieved with the help of HTML elements, such as `<section>`, `<h1>`, `<p>`, and ``, which are composed into a hierarchical tree structure of modular content, and which is then interpreted by web browsers. A strong pillar of HTML's design is extensibility. There are multiple mechanisms in place to ensure its applicability to a vast range of use cases, including:

- Specifying classes of elements using the `class` attribute. This effectively creates custom elements based on the closest standard elements.
- Using `data-*` attributes to decorate elements with additional data which can be used by scripts. The HTML standard guarantees that these attributes are ignored by browsers.
- Embedding custom data using `<script type="">` elements, which can be accessed by scripts.

2.2 Cascading Style Sheets (CSS)

Cascading Style Sheets (CSS) apply styling to HTML elements, effectively separating presentation from content. In earlier versions of HTML [Raggett 1997], elements like `` and `` muddied the boundary between presentation and content.

Pattern	Matches
*	Any element.
E	Elements of type E.
E F	Any element of type F which is a descendant of elements of type E.
E > F	Any element of type F which is a direct descendant of elements of type E.
E + F	Any element of type F which is a directly preceded by a sibling element of type E.
E:P	Elements of type E which also have the pseudo class P.
.C	Elements which have the class C.
#I	Elements which have the ID I.
[A]	Elements which have an attribute A.
[A=V]	Elements which have an attribute A with a value of V.
S1, S2	Elements which match either the selector S1 or the selector S2.

Table 2.1: A summary of the CSS 2.1 selector syntax. [Table created by the author of this thesis with data from [Çelik et al. 2018].]

A CSS style sheet can either be embedded directly in HTML documents using a `<style>` element or can be defined externally and linked to using a `<link>` element. This characteristic of being able to externally describe the presentation of documents brings great flexibility. Multiple documents with different content can reuse the same presentation by linking to the same CSS file. Conversely, alternative style sheets can be applied to the same HTML content to achieve a different styling.

CSS was initially proposed by Lie [1994] and standardized into CSS1 by the W3C in 1996 [Lie and Bos 1996]. Throughout its history, the adoption of CSS by browser vendors was fraught with complications and even though most major browsers soon supported almost the full CSS standard, their implementations sometimes behaved differently. This meant that authors of web pages often had to resort to workarounds, including providing different style sheets for different browsers. In recent years, CSS specifications have become much more detailed [Bos et al. 2011] and browser implementations have become more stable with fewer inconsistencies. It has therefore become much rarer that browser-specific workarounds need to be applied, dramatically improving the developer experience. CSS 2.1 [Bos et al. 2011] was the last CSS standard published as a single, monolithic specification. Since then, the specification has been modularized into different documents [Jr. et al. 2020], each describing a specific module of the overall CSS specification.

A CSS style sheet contains a collection of rules. Each rule consists of a selector and a block of style declarations. Selectors are defined in a custom syntax and are used to match HTML elements. All elements which are matched by the selector of a rule will have the rule's style declarations applied to them. The selector syntax is fairly straightforward when selecting elements of a certain type, but also has more sophisticated mechanisms for selecting elements based on their contexts or attributes. Table 2.1 summarizes the selector syntax of CSS Selectors Level 3 [Çelik et al. 2018].

Another important characteristic of CSS is the cascading of styles. The exact rules for calculating the final style to be applied to an element are quite involved, and Etemad and Atkins [2021] should be consulted for a detailed description. The most important aspect in the context of this work is that styles can be overwritten. When multiple rules match an element and define different values for the same property, the values of the rule with higher specificity will be applied. If multiple rules have the same specificity, the one defined last in the document tree will overwrite all previous ones.



Figure 2.1: The CSS box model defines the properties of boxes which wrap around HTML elements.
[Image drawn by the author of this thesis.]

2.2.1 CSS Box Model

All elements in an HTML document are laid out as boxes. The CSS box model specifies how every element is wrapped in a rectangular box and every box is described by its content and optional surrounding margin, border, and padding areas. Margins are used to specify invisible spacing between boxes. The border provides a visible frame around the content of a box. The padding provides invisible spacing between the content and the border. A visual representation of these properties can be seen in Figure 2.1.

In early versions of CSS, before the introduction of the Flexible Box (Flexbox) layout module [Deakin et al. 2009], the box model was the only way to lay out elements. Style sheet authors had to meticulously define margins of elements and their relative (or absolute) positions in the document tree. The responsive capabilities of this kind of layouting were very limited, because different configurations for varying screen sizes had to be specified manually using media queries. More complex features, like the filling of available space, required manual implementation via scripting.

2.2.2 CSS Flexbox Layout

CSS Flexible Box layout (Flexbox) [Atkins et al. 2018] is a mechanism for one-dimensional layout of elements in either rows or columns. This one-dimensionality is what separates it from grid-based layout, which is inherently two-dimensional. Even though the first draft of the Flexbox layout module was already published in 2009 [Deakin et al. 2009], implementations by browser vendors have been a slow and bug-ridden process [Deveria 2021a], which held back adoption by users for several years after its inception. More recently though, partly through the deprecation of Internet Explorer [Microsoft 2020], all major browsers have mature implementations of current Flexbox standards [Atkins et al. 2018], and, in most cases, fallback styling is no longer necessary.

Flexbox layouting is enabled for child elements by setting the `display:flex` property on a container element. The direction of the layout can then be specified using the `flex-direction` property which can be set to either `row` or `column`. The items inside a Flexbox container can have either a fixed or a relative size. When items should be sized relative to the size of their containers, the proportions of how the available space should be divided can be controlled using ratios. These ratios can be set on item elements via the `flex` property.

Another important feature of Flexbox layout is the controllable spacing of items, which can be specified separately for both the main axis and the cross axis of the layout. Spacing along the main axis can be configured with the `justify-content` property, which can take a number of different values and is



Figure 2.2: The `justify-content` property is used to distribute items along the main axis of a Flexbox container. [Image created by the author of this thesis.]

illustrated in Figure 2.2. Alignment of items on the cross axis is achieved either by the `align-items` property on the container element or the `align-self` property on the items themselves.

This section only grazed the surface of what is possible with the Flexbox layout module. There are many more useful properties like `flex-grow`, `flex-shrink`, and `flex-wrap`. For a more detailed look at this topic it is recommended to review the specification [Atkins et al. 2018] and read the excellent tutorial by Chris Coyier [Coyier 2021].

2.2.3 CSS Grid Layout

The CSS Grid Layout Module [Atkins et al. 2020] defines the layout of elements in a two-dimensional grid. The initial proposal of the CSS Grid layout module was published in 2011 [Mogilevsky et al. 2011] and has been further refined over the years. At the time of writing, even though it still exists as merely a candidate recommendation for standardization [Atkins et al. 2020], many browsers have already adopted it. Similar to the adoption of Flexbox, the history of browser adoption of CSS Grid was initially strewn with inconsistencies and bugs. However, in 2017 the major browsers Chrome, Firefox, Safari, and Edge removed the need for vendor prefixes and implementations are now considered stable [Deveria 2021b].

Grid layout of elements is enabled by setting the `display:grid` property on their container. The grid in which items shall be laid out is then defined using the `grid-template-rows` and `grid-template-columns` properties. In addition, the `grid-template` property can be used as a shorthand to simultaneously specify both the rows and columns of a grid. Item elements need to specify the cell of the grid into which they shall be positioned. This is done with the `grid-row` and `grid-column` properties, which take the corresponding row and column indices as values. Items can also be configured to span multiple cells by specifying index ranges as the values of those properties.

Every cell in a grid can also be assigned a specific name via the `grid-template-areas` property on the grid container element. The items within the grid can then position themselves in specifically named grid cells using the `grid-area` property instead of directly setting the row and column indices. The benefit of positioning items this way is that the structure of the grid can be freely changed without having to respecify the cells in which items belong. As long as the new layout still specifies the same names of cells somewhere in the grid, the items will be automatically placed at their new positions.

There are also properties which control the layout of items within grid cells and the layout of grid cells themselves. Similar to Flexbox, this can be configured with the `align-items` and `justify-items` properties for laying out within grid cells, and the `align-content` and `justify-content` properties for laying out the grid cells themselves. The latter `*-content` properties only make sense when the cells



Figure 2.3: The `*-items` properties are used to lay out items within their grid cells, whereas the `*-content` properties are used to lay out the grid cells themselves. [Image created by the author of this thesis.]

do not cover the full area of the grid. For a visual comparison between the `*-items` and `*-content` properties, see Figure 2.3.

There is some apparent overlap between the CSS Grid and Flexbox layout modules. At first sight, it seems like Grid layout supersedes Flexbox layout, because everything which can be done using Flexbox layout can also be done with Grid layout. While that is true, the inherent difference in dimensionality and the resulting syntactic characteristics lead to better suitability of one technology over the other, depending on the context of use. As a general rule [Rendle 2017], top-level layouts which require two-dimensional positioning of elements are usually best implemented using a Grid layout, whereas low-level layouts which merely need laying out on a one-dimensional axis are better implemented using a Flexbox layout.

For more details, the CSS Grid specification [Atkins et al. 2020] and other sources like Meyer [2016] and House [2021] are recommended.

2.3 JavaScript (JS)

JavaScript was originally developed as a client-side scripting language run by an interpreter (engine) inside the web browser. Nowadays, there are also standalone JavaScript engines and environments like NodeJS [OpenJS 2021]. JavaScript is a multi-paradigm language which supports event-driven, as well as functional and imperative programming. Driven by the popularity of the web, JavaScript is currently the most used programming language worldwide [Liu 2021].

JavaScript was initially created by Netscape in 1995 [Netscape 1995]. Before that, websites were only able to display static content, which drastically limited the usefulness of the web. Microsoft seemingly saw JavaScript as a potentially revolutionary development, because they reverse-engineered the Netscape's implementation and published their own version of the language for Internet Explorer in 1996 [Microsoft 1996]. The two implementations were noticeably different from one another and



Figure 2.4: Since their release, Firefox and Chrome have contested the monopoly of the Internet Explorer and continuously gained more market share. Recently, Chrome seems to be gaining an increasingly strong position within the market. [Image taken from StatCounter [2021]]

the uncontested monopoly of the Internet Explorer [Routley 2020] held back standardization efforts undertaken by Netscape [ECMA 1997]. When Firefox was released in 2004 [Mozilla 2004] and Chrome in 2008 [Google 2008], they quickly gained a considerable share of the market [StatCounter 2021], as shown in Figure 2.4. Galvanized by this new market reality, all major browser vendors collaborated on the standardization of JavaScript as ECMAScript 5 in 2009 [ECMA 2009]. Since then, JavaScript has been continuously developed and its latest, widely supported version, ECMAScript 6, was released in 2015 [ECMA 2015].

RespVis is a browser-based library which is designed to run within the JavaScript engine of a browser. It builds heavily on widely supported Web APIs, which are JavaScript modules specifically meant for development of web pages. These Web APIs are standardized by the W3C and each browser has to individually implement them in their JavaScript engine.

The most popular Web API, which every web developer is familiar with, is the Document Object Model (DOM). The DOM is the programming interface and data representation of a web page or document. Internally, a document is modeled as a tree of objects, where each object corresponds to a specific HTML or SVG element in the document hierarchy and its associated data and functions. In addition to the querying of elements, the DOM also defines functionality to mutate them and their attributes, as well as functionality for handling and dispatching events. It also exposes the mechanism of `MutationObservers`, which are used to observe changes of attributes and children in the document tree. The initial specification of the DOM was published in 1997 [Wood et al. 1997]. It is currently maintained as a living standard by the WHATWG [Kesteren et al. 2021].

Another important Web API in the context of this work is the `ResizeObserver` API. It provides the ability to observe an element's size and respond to changes, which increases the responsive capabilities of websites. Previously, scripts could only respond to changes in the overall viewport size via the `resize` event on the `window` object, but this meant that changes of an individual element's size through attribute changes could not be detected. This limitation is fixed with the `ResizeObserver` API, which is already fully supported by all modern browsers, even though it has so far only been published as an editor's draft [Totic and Whitworth 2020].

Design Property	Description
Full erasure	Types are completely removed by the compiler, there is no type checking at runtime.
Type inference	Many types can be inferred from usage, minimizing the number of types which have to be explicitly stated.
Gradual typing	Type checking can be selectively prevented using the dynamic type any.
Structural types	Types are defined via their structure as opposed to via their names. This better fits JavaScript, where objects are usually custom-built and used based on their shapes.
Unified object types	A type can simultaneously describe objects, functions, and arrays. These constructs are common in JavaScript and thus TypeScript needs to support their typing.

Table 2.2: A summary of the major design properties on which TypeScript’s type system is built.
 [Table created by the author of this thesis with data from Bierman et al. [2014].]

2.4 TypeScript (TS)

TypeScript (TS) is a strongly-typed programming language which is designed as an extension of JavaScript. Syntactically, it is a superset of JavaScript which enables the annotation of properties, variables, parameters, and return values with types. It requires a transpiler (compiler) to convert the TypeScript code into valid JavaScript code for a specific ECMAScript version.

Initially, TypeScript was released by Microsoft in 2012 [Hoban 2012] to extend JavaScript with features which were already present in more mature languages, and whose absence in JavaScript caused difficulties when working on larger codebases. At the time of TypeScript’s initial development, it provided features which would later be offered by ECMAScript 6, including a module system to be able to split source code into reusable chunks and a class system to aid object-oriented development. TypeScript code using these features could then be transpiled into standard-conformant JavaScript code, which could be interpreted by JavaScript engines of the time. At the time of writing, ECMAScript 6 is widely supported by all modern browsers and therefore the main benefit of TypeScript over JavaScript lies in its provision of a static type system.

The extension of JavaScript with a static type system brings many benefits, including the improved tooling which comes with type-annotated code. Tools such as linters are able to point out errors early in development and assist developers with automated fixes, improved code completion, and code navigation. Additionally, studies like Gao et al. [2017] looked at software bugs in publicly available codebases and found that 15% of them could have been prevented with static type checking.

The TypeScript type system was designed to support JavaScript constructs as completely as possible, via structural types and unified object types. Another goal was to make the type annotation of JavaScript code as effortless as possible to improve adoption by existing projects. This was done by consciously allowing the type system to be statically unsound via gradual typing and also by employing type inference to reduce the number of necessary annotations. The major properties of TypeScript’s type system design are summarized in Table 2.2.

2.5 Web Graphics

Graphics are used as a medium for visual expression to enhance the representation of information on the web. There are many fields of application like the integration of maps, photographs, or charts in a web



Figure 2.5: A raster image of a circle. Pixelation artifacts become very apparent when a raster image is scaled to a different size. [Image created by the author of this thesis.]

page. Multiple complementary technologies exist for web graphics, each with particular strengths and weaknesses depending on the use case. These technologies include pixel-based raster images, Scalable Vector Graphics (SVG), and 2d and 3d graphics through the `<canvas>` element.

2.5.1 Raster Images

A raster image represents a graphic as a rectangular, two-dimensional grid of pixels with a fixed size (resolution) in each dimension. Whenever a raster image is scaled up or down to a different size, visual artifacts become very apparent, as can be seen in Figure 2.5. Raster images are either created by image capturing devices or special editing software and saved as binary files in varying formats. The most widely used formats for raster images are JPEG [JPEG 1994] and PNG (Portable Network Graphics) [Boutell 2003]. JPEG has lossy compression, which achieves low file sizes whilst retaining reasonable image quality, and is typically used for photographs. PNG has lossless compression, which compresses well whilst preserving every original pixel as is, and also supports transparency. Both formats support progressive rendering as an image is loaded.

Raster images are embedded into documents in binary format. This means that the contents of the graphic are not accessible in a non-visual representation. To make the information accessible to visually impaired people, an additional textual description of the graphic's content must be provided via the `alt` and `longdesc` attributes.

2.5.2 Scalable Vector Graphics (SVG)

Vector graphics describe an image in terms of objects and shapes, such as lines, circles, polygons, and text. They can be scaled freely without loss of quality. Scalable Vector Graphics (SVG) is an XML-based format for vector graphics. It was initially published by the W3C in 1999 [Ferraiolo 1999] and the most recent version SVG 1.1 was released in 2011 [Dahlström et al. 2011]. Graphics in an SVG file can be specified in a normalised coordinate space (inside a `viewBox`), enabling them to be freely scaled. Since SVG files are XML, they can be created with any text editor, but numerous tools and editors exist which create or export SVG. A simple example of an SVG document containing a single circle can be seen in Listing 2.1, with its visualization shown in Figure 2.6.

The encoding in XML leads to SVG being the best format to represent graphics in terms of accessibility. Graphics are directly saved in a hierarchical and textual form which describes their shapes and how they are composed. In addition to the shapes being inherently accessible, the various elements of an SVG document can be annotated with further information to aid comprehension when consumed in a non-visual way.

```

1 <svg viewBox="0, 0, 64, 64" xmlns="http://www.w3.org/2000/svg">
2   <circle cx="32" cy="32" r="30" fill="#7c66ff" />
3 </svg>

```

Listing 2.1: A simple SVG document containing a circle element. The visual representation of this document in different sizes is shown in Figure 2.6.

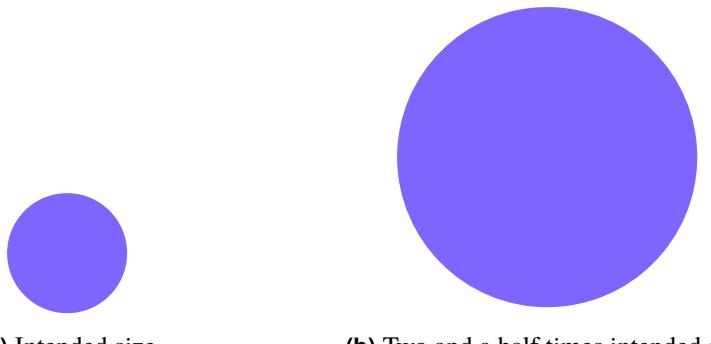


Figure 2.6: SVG documents can be scaled freely without pixelation artifacts. Here, the SVG document from Listing 2.1 is shown. [Image created by the author of this thesis.]

SVG files are XML documents whose meta format is described in a special SVG namespace. Web browsers support mixing of HTML and SVG elements in a web page, and the SVG elements can be accessed by scripts via the DOM Web API just like HTML elements.

The most widely supported way of styling SVG elements is via attributes, which is supported by every software dealing with SVG files. However, the specification aims for maximum compatibility with HTML, and therefore it is also possible to use CSS to style and animate SVG elements when they are rendered in a browser. Using CSS to separate presentation from content has many benefits, which were already described in Section 2.2. Unfortunately, it is not possible to style every SVG attribute with CSS, only so-called presentation attributes like `fill` and `stroke-width` are available through CSS. These presentation attributes are listed in the SVG specification [Dahlström et al. 2011] and will be extended by additional attributes like `x`, `y`, `width` and `height` in upcoming releases [Bellamy-Royds et al. 2018].

2.5.3 Canvas (2D)

[TODO: Link to the correct specification introducing canvas (<https://www.w3.org/standards/history/2dcontext>)]

The `canvas` element was introduced in HTML5 [Hickson et al. 2021] and is used to define a two-dimensional, rectangular region in a document which can be drawn into by scripts. Even though rendering of dynamic graphics as `canvas` elements is often faster than representing them as SVG documents, their use is explicitly discouraged by the WHATWG when another suitable representation is possible. The reasons for this are that `canvas` elements are not compatible with other web technologies like CSS or the DOM Web API and because the resulting rendering provides only very limited possibilities for accessibility.

The graphics are drawn via a low-level API provided by the rendering context of a particular `canvas`. The two most significant rendering contexts are `2d` and `webgl`.

```

1 <!DOCTYPE html>
2 <html xmlns="http://www.w3.org/1999/xhtml" lang="en" xml:lang="en">
3 <body>
4   <canvas width="64" height="64"></canvas>
5   <canvas width="640" height="640"></canvas>
6   <script>
7     const canvases = Array.from(document.getElementsByTagName('canvas'));
8     canvases.forEach((canvas) => {
9       const width = canvas.clientWidth;
10      const height = canvas.clientHeight;
11      const context = canvas.getContext('2d');
12      context.fillStyle = '#7c66ff';
13      context.beginPath();
14      context.arc(width / 2, height / 2, width / 2, 0, Math.PI * 2);
15      context.fill();
16      context.closePath();
17    });
18  </script>
19 </body>
20 </html>

```

Listing 2.2: A basic HTML document containing two canvases of different sizes which render circles relative to the canvas size. The visual representation of this document is shown in Figure 2.7.

The 2d rendering context enables platform-independent 2d rendering via a software renderer, whose API is standardized directly in the canvas specification [WHATWG 2021]. An example of an HTML document containing two differently sized canvases into which responsive circles are drawn using a 2d rendering context can be seen in Listing 2.2 with the corresponding visual output in Figure 2.7.

[TODO: Change size of circle canvases]

2.5.4 Canvas (WebGL)

The webgl rendering context enables 3d drawing through the WebGL version 1 API [Jackson and Gilbert 2014]. The webgl2 rendering context enables 3d drawing through the WebGL version 2 API [Jackson and Gilbert 2017]. Three-dimensional rendering through WebGL hardware-accelerated and is often much faster than rendering via Canvas 2d or SVG.

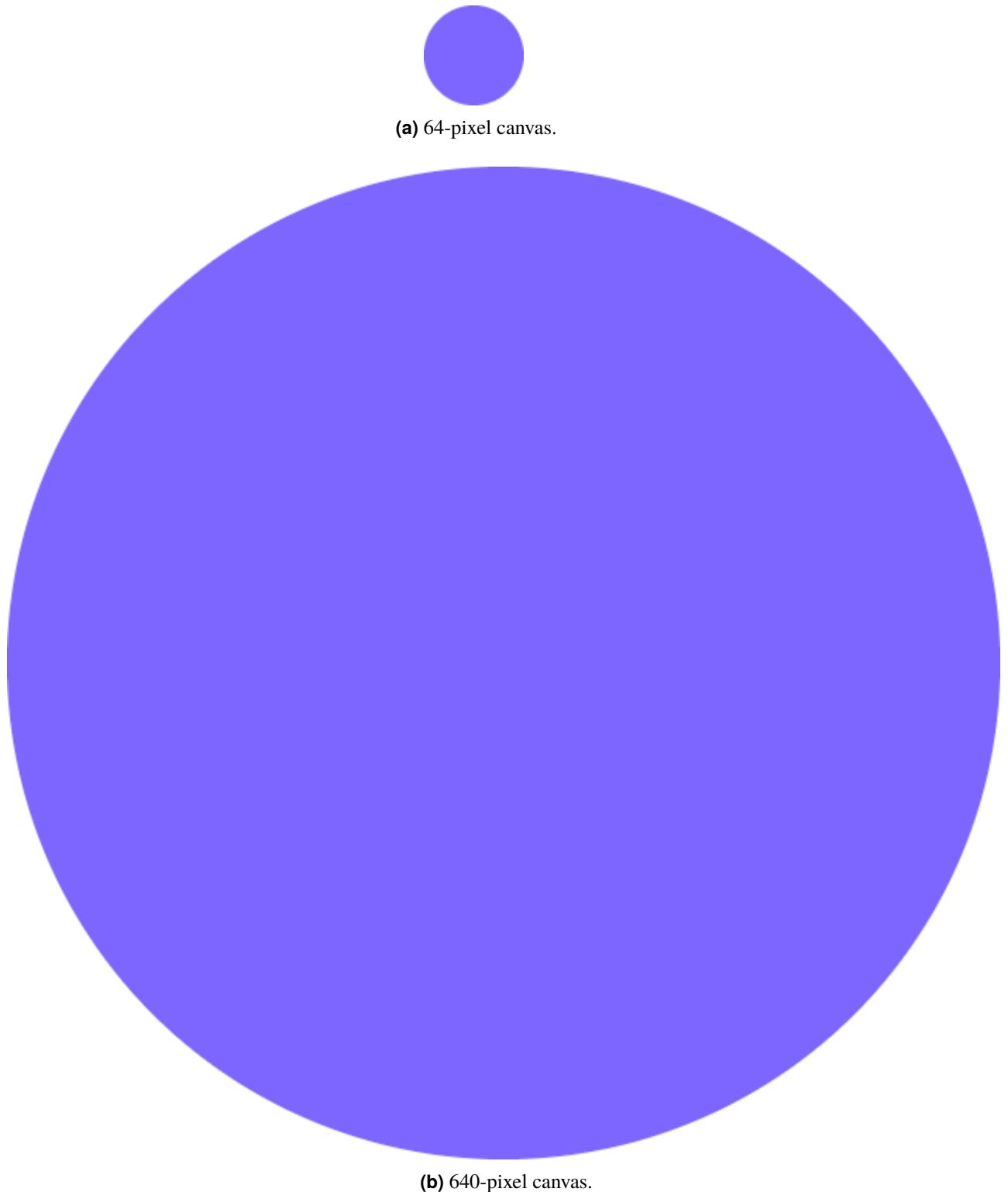


Figure 2.7: Responsive rendering of graphics inside canvas elements has to be implemented manually by calculating everything relative to the canvas' dimensions. This figure shows the visual output of the canvas example in Listing 2.2. [Image created by the author of this thesis.]

2.6 Layout Engines

A layout engine is used to calculate the boundary coordinates of visual components based on input components annotated with layout constraints. These layout constraints describe the size and position of components and their relationships between each other in a syntax understood by the layout engine. For browser-based layout engines, the input components are normally declared as HTML documents which are constrained using CSS. More low-level layout engines require custom formats, which usually involve a hierarchy of objects constrained using specific properties. The most relevant layout engines in the context of this work are summarized in the following sections.

2.6.1 Browser Engines

The purpose of a browser engine is to transform document and any additional resources, like CSS, into a visual representation. A browser engine is a core component of every web browser, and it is responsible for laying out elements and rendering them. The terminology of browser engines is ill-defined, with them sometimes also being referred to as layout or render engines. Theoretically, the layout and render processes could be separated into different components, but in practice they are tightly-coupled into a combined component, which will be referred to as a browser engine in this work. Some notable browser engines are WebKit [Apple 2021], Blink [Chromium 2021], and Gecko [Sikorski and Peters 1999].

In a browser engine, the layout of elements is constrained with CSS, which yields great flexibility as already described in Section 2.2. A range of mechanisms is available to precisely control the layout of elements, like the Flexible Box and Grid Layout modules, which can also be used in combination.

The layout module of a browser engine can only be invoked directly by browsers to position HTML elements in actively rendered documents. To use it for calculating layouts of non-HTML constructs, they must be replicated in active documents, so they can be parsed, laid out and rendered by the browser engine. These replicated constructs do not necessarily have to be visible, and they could also be removed from the document after the layout has been acquired, meaning they do not need to be noticeable at all. A strong limitation of using browser engines to calculate layouts is that it requires a browser runtime to work and, even though there are solutions like Electron available, which enable development of desktop applications using web technologies, this limitation forces applications into a very specific stack of technologies.

2.6.2 Yoga

Yoga [Facebook 2021d] is a layout engine which enables the computation of layouts constrained using the grammar defined in the CSS Flexible Box layout module (see Section 2.2.2). It has been maintained by Facebook as an open-source project since 2016 [Sjölander 2016], with the goal of providing a small and high-performance library which can be used across all platforms. Yoga is implemented in C/C++, which works on a myriad of devices, with bindings available for other platforms like JavaScript, Android, and iOS. Yoga has been widely adopted and is used to perform layouting in major frameworks such as React Native [Facebook 2021c], Litho [Facebook 2021b], and ComponentKit [Facebook 2021a].

2.6.3 FaberJS

FaberJS [FusionCharts 2021] is a layout engine very similar to the Yoga layout engine in that it enables the computation of layouts for constructs other than HTML documents, using a layout grammar originally created for CSS. In contrast to Yoga, which is used to create one-dimensional layouts using the Flexbox layout grammar, FaberJS implements a two-dimensional layout algorithm built on the grammar of the CSS Grid layout module (see Section 2.2.3). This inherently two-dimensional approach to layouting is more suited to information visualization than a one-dimensional approach. FaberJS is an open-source JavaScript project developed since 2019 by Idera. Even though the layouts it computes are constrained with the Grid Layout grammar, it only supports a subset the functionality defined in the original CSS

module. Some examples of missing functionality include missing support for margins, gaps, and the `*-content` and `grid-auto-*` properties. Working around the limitations caused by these missing features is non-trivial, and it seems unlikely that support for them will be added by the FaberJS maintainers in the near future because, at the time of writing, the project has not been updated in nearly two years.

2.7 Responsive Web Design

[TODO: Also mention Marcotte's book and not only the article here.]

Influenced by the increasing use of mobile devices and their vastly varying screen sizes, responsive web design has established itself as the predominant way of designing web pages. The core idea of responsive web design is that instead of designing pages for different types of devices, website authors create a single design for a page, which adapts to the characteristics of the consuming device. The term “Responsive Web Design” was defined by Marcotte [2010], where the author differentiates between flexible and responsive web designs. A flexible web design, which merely fluidly scales blocks of content to make them fit into the width of a browser window, is not enough to provide a good experience for users. Such designs will work well enough for similarly sized viewports to the one they were created for, but they will lead to noticeable artifacts on lower resolutions.

These problems can be avoided by positioning the individual components of a page in a manner which provides them with enough space to render correctly. This can be achieved by using CSS media queries to adapt the overall layout of a page to the dimensions of the consuming device. Another crucial part of responsive web design is to support the different modes of interaction inherent to the various types of devices used to access the web. Desktop users might access a website using a mouse, mobile device users typically interact via a touchscreen, and yet others might consume a page in a purely textual form with a screen reader and interact via a keyboard. It is one of the mantras of responsive web design to provide smooth and complete access to information to all users, regardless of the device they are using.

Chapter 3

Information Visualization

Information visualization seeks to use interactive graphics to assist in the analysis and presentation of abstract information. Information visualization builds on capabilities of human visual perception, including the rapid scanning, recognition, and recall of visual information, as well as the automatic detection of visual patterns. In contrast to textual representations of data, the processing of well-designed visualizations requires less cognitive effort, because it leverages features of the human visual processing system. One of these features is *preattentive processing*, whereby certain visual attributes can be processed very quickly and without conscious effort [Treisman 1985].

In addition to visuals being easier to assimilate by humans, a purely textual and statistical view of data can also lead to erroneous assumptions. This is demonstrated in Anscombe's famous example of four completely different datasets (variables in x and y) having identical summary statistics (mean and standard deviation), called Anscombe's Quartet [Anscombe 1973], shown in Table 3.1. An observer trying to understand these datasets from their summary statistics alone might mistakenly deem them to be identical. Their inequality only becomes obvious after carefully examining and comparing the individual entries in the datasets themselves. However, the differences in the four datasets are immediately obvious when plotted graphically, as can be seen in Figure 3.1. Even though Anscombe's Quartet is likely the most famous example demonstrating this characteristic, it is certainly not the only example, as has been shown by Chatterjee and Firat [2007].

This thesis adheres to the characterization of the field of visualization as having three main subfields, as defined by Andrews [2021]:

1. *Information Visualization (InfoVis)*: Deals with abstract data, which has no inherent geometry or visual form and for which a suitable type of visualization has to be chosen.
2. *Geographic Visualization (GeoVis)*: Deals with map-based data which has inherent 2d or 3d spatial geometry.
3. *Scientific Visualization (SciVis)*: Deals with real-world objects having inherent 2d or 3d geometry, which is used as the basis for visualization.

The often-used term “data visualization” (*DataVis*) is defined as the combination (union) of information visualization and geographic visualization.

Visualizations presented in an interactive medium do not merely consist of visual representations. It is equally important to provide means for interacting with these representations to analyze more complex datasets. Without interactions, a visualization is just a static image and has only very limited use when dealing with large and multidimensional datasets. Even though the majority of attention in the field of information visualization has been directed towards the presentational aspect of visualizations, research has also been done on their interactive aspects. Numerous taxonomies have been formulated with the goal

	v₁		v₂		v₃		v₄	
	<i>x₁</i>	<i>y₁</i>	<i>x₂</i>	<i>y₂</i>	<i>x₃</i>	<i>y₃</i>	<i>x₄</i>	<i>y₄</i>
	10.00	8.04	10.00	9.14	10.00	7.46	8.00	6.58
	8.00	6.95	8.00	8.14	8.00	6.77	8.00	5.76
	13.00	7.58	13.00	8.74	13.00	12.74	8.00	7.71
	9.00	8.81	9.00	8.77	9.00	7.11	8.00	8.84
	11.00	8.33	11.00	9.26	11.00	7.81	8.00	8.47
	14.00	9.96	14.00	8.10	14.00	8.84	8.00	7.04
	6.00	7.24	6.00	6.13	6.00	6.08	8.00	5.25
	4.00	4.26	4.00	3.10	4.00	5.39	19.00	12.50
	12.00	10.84	12.00	9.13	12.00	8.15	8.00	5.56
	7.00	4.82	7.00	7.26	7.00	6.42	8.00	7.91
	5.00	5.68	5.00	4.74	5.00	5.73	8.00	6.89
mean	9.00	7.50	9.00	7.50	9.00	7.50	9.00	7.50
sd	3.3166	2.0316	3.3166	2.0317	3.3166	2.0304	3.3166	2.0306

Table 3.1: The four datasets (variables) in Anscombe's Quartet look identical if only standard summary statistics like mean and standard deviation are considered. The difference between the datasets is only apparent after careful examination of the numbers.



Figure 3.1: When plotted graphically, it is immediately apparent that the four datasets in Anscombe's Quartet are very different. [Image extracted from Andrews [2021]. Used with kind permission by Keith Andrews.]

Category	Description	Examples
Select	Mark something as interesting.	Highlighted selections, placemarks, assigning classes.
Explore	Show me something else.	Different subset of data, panning, direct-walk.
Reconfigure	Show me a different arrangement.	Sorting, rearranging columns, plotting different dimensions, using an alternative projection.
Encode	Show me a different representation.	Changing visual encoding (color, size, shape), or even chart type.
Abstract / Elaborate	Show me more or less detail.	Details-on-demand, drill-down and roll-up, tooltips, zooming in and out.
Filter	Show me something conditionally.	Dynamic queries, range sliders, toggle buttons, query by example.
Connect	Show me related items.	Brushing across views, highlighting connected items on mouseover.

Table 3.2: Categories of interaction with visualizations based on what a user wants to achieve (user intent). [From Yi et al. [2007]]

of defining the design space of interactions to support analytic reasoning, but they vary greatly depending on the concepts they are focusing on. Some taxonomies have been defined on the concept of low-level interaction techniques [Shneiderman 1996; Wilkinson 2005], providing a very system-centric view on interaction. Other taxonomies focus on user tasks [Amar et al. 2005], which are not necessarily strongly related to interacting with visualizations. Yi et al. [2007] aims to provide a view in between the purely system-centric and purely user-centric extremes by defining a taxonomy based on what a user wants to achieve, also known as *user intent*. The categories of this taxonomy are shown in Table 3.2. They provide a good framework for the discussion of interactivity in the context of information visualization.

3.1 History of Information Visualization

The history of information visualization goes back a long time. One of its earliest examples dates back to the 10th Century, when an unknown astronomer created the chart about the movement of prominent planets [Macrobius 1175] shown in Figure 3.2. Other noteworthy early visualizations include the first occurrence of the principle which Tufte [1983] later called “small multiples” in the 1626 chart by Scheiner [1630] demonstrating sunspot changes shown in Figure 3.3, and the 1644 chart displaying longitudinal distance determinations between Toledo and Rome by Florent [1644] shown in Figure 3.4.

William Playfair (1759–1823) is considered by many to be one of the forefathers of modern information visualization. His published works contain the first occurrences of many graphical forms still widely used today. In one of his earlier works [Playfair 1786], he introduced the concepts of line charts (Figure 3.5), bar charts (Figure 3.6), and area charts (Figure 3.7) to communicate economic factors of England during the eighteenth century. In a related later work [Playfair 1801], he used the first ever published pie and circle charts to show and compare the resources of states and kingdoms in Europe. The charts he created are very similar to modern ones, containing familiar concepts such as labeled axes, grids, titles, and color-coding.

It would be amiss not to mention Florence Nightingale (1820–1910) [Cohen 1984] when talking about the history of information visualization. She was a British statistician, social reformer, and the founder of modern nursing and might be the first person who used visualizations to persuade others of a need for change. During her service as a superintendent of nurses in the Crimean War, she realized that a large number of deaths in hospitals resulted from preventable diseases which originated in poor sanitary conditions. One of her contributions to the field of information visualization was the creation of a new



Figure 3.2: A line chart created by an unknown astronomer in the 10th Century, depicting the movements of seven prominent planets. [Image extracted from Friendly [2008]. Original appearance in Macrobius [1175].]



Figure 3.3: The observed changes in sunspots based on recordings of two months of data from 1611. It is the first occurrence of the principle later called “small multiples” by Tufte [1983]. [Image extracted from Friendly [2008]. Original appearance in Scheiner [1630].]

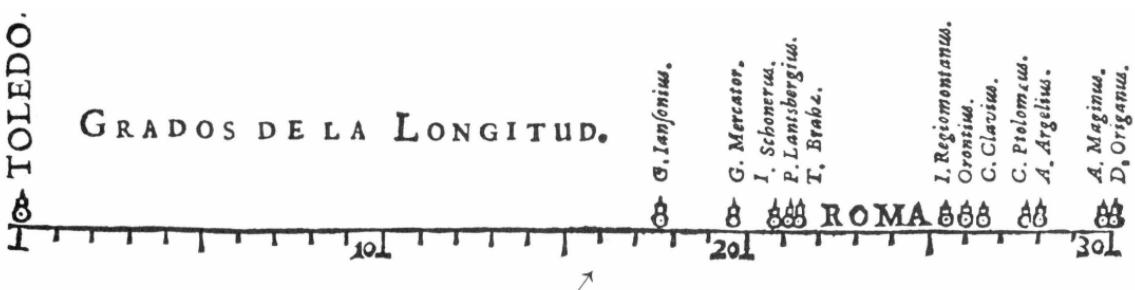


Figure 3.4: A comparison of the twelve known estimates in longitudinal distance between Rome and Toledo by various astronomers. The correct distance is marked by the arrow beneath. It is considered by Tufte [1997, page 15] to be the first visual representation of statistical data. [Image extracted from Friendly [2008]. Original appearance in Florent [1644].]

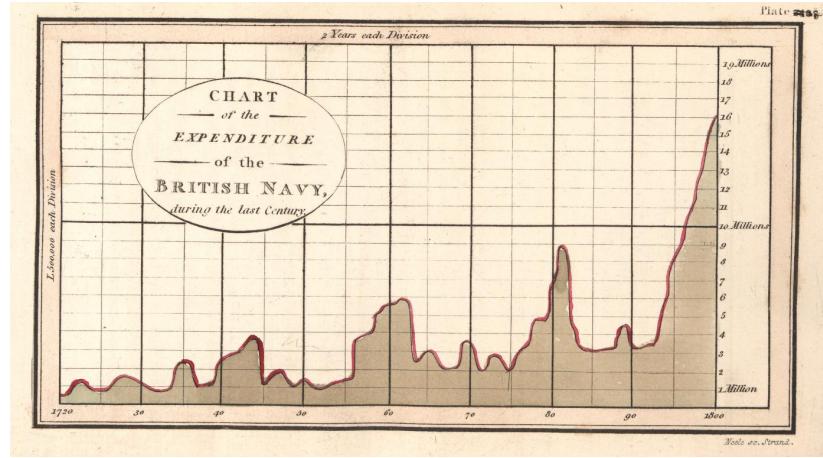


Figure 3.5: Line chart of the expenditure of the British Navy during the 18th Century. It was published in 1786 and is considered to be one of the first occurrences of a line chart containing components found in modern visualizations. [Image extracted from Schoenberg Center for Electronic Text and Image (SCETI). Used under the terms of Creative Commons CC BY 2.5.]



Figure 3.6: Bar chart of England's exports and imports to and from Scotland in 1781. Published in 1786, it is considered to be one of the first occurrences of a bar chart containing most components found in modern visualizations. [Image extracted from Schoenberg Center for Electronic Text and Image (SCETI). Used under the terms of Creative Commons CC BY 2.5.]



Figure 3.7: Area chart of annual revenues of England and France between 1550 and 1800. Published in 1786, it is considered to be one of the first occurrences of an area chart containing most components found in modern visualizations. [Image extracted from Schoenberg Center for Electronic Text and Image (SCETI). Used under the terms of Creative Commons CC BY 2.5.]

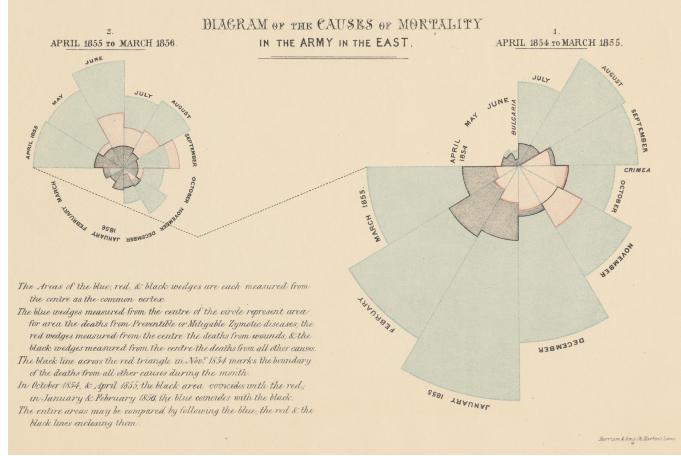


Figure 3.8: One of the polar-area charts created by Florence Nightingale in 1859 to convince people of a need for more sanitary conditions in hospitals. It visualizes the causes of mortality for soldiers during the Crimean War and demonstrates that a large percentage of patients died from preventable diseases linked to unsanitary environments. [Image extracted from Harvard Library. Used under the terms of Creative Commons Attribution 4.0.]



Figure 3.9: High-D by Macrofocus is a visual analytics tool specialized in analyzing multidimensional data. [Screenshot of High-D [Macrofocus 2021] taken by the author of this work.]

type of diagram, called a rose diagram or polar-area chart, shown in Figure 3.8. She used these charts to communicate data she collected on the mortality of soldiers during the war and to grab the attention of politicians and the public.

Modern visualizations benefit from the interactive nature of the devices used to consume them. They can be more complex than static visualizations, because various interaction techniques enable users to navigate large amounts of data and make sense of it. High-D by Macrofocus [Macrofocus 2021] is a representative example of a modern interactive visual analytics tool, and is shown in Figure 3.9.

It is out of the scope of this work to provide a full account of the long and eventful history of information visualization. This section only provides a brief and very selective view of the topic. More comprehensive works for further reading include Friendly [2008], Meirelles [2013], Rendgen [2019], and Friendly and Wainer [2021].

3.2 Information Visualization Libraries for the Web

There are many web-based libraries which simplify the rendering of interactive visualizations. The approaches used to create and update a visualization differ widely between libraries. D3 is a low-level library which enables data-driven transformations of documents. Vega and Vega-Lite provide a declarative grammar to express the visual and interactive characteristics of a visualization. Template-based visualization libraries provide a higher-level template-based interface which can easily be configured.

3.2.1 Data-Driven Documents (D3)

D3 [Bostock et al. 2011] is a free, open-source document manipulation library built in JavaScript by Mike Bostock and actively maintained by him and a community on GitHub [Bostock 2021]. Mike Bostock is also the creator of Observable [Observable 2021] and was one of the authors of the now deprecated Protovis visualization library [Bostock and Heer 2009]. Wattenberger [2019] is a great introduction to D3.

D3 enables data-driven document transformations allowing developers to describe documents as functions of data. As an example, developers can define transformations which take a dataset and transform it into a basic HTML table or into a more sophisticated visualization as an SVG chart. This focus on explicitly defining transformations is well suited to dynamic visualizations, because developers have complete control over the creation, modification, and removal of elements. It also sets D3 apart from other visualization libraries, where developers define the desired state of a representation using a declarative domain-specific language.

In contrast to other visualization libraries, D3 contains no proprietary visual primitives and relies on well established web standards like HTML, SVG, and CSS to implement its visual representations. This yields great flexibility, because developers work directly with web standards implemented in browsers and do not need to wait for D3 to support new features as standards evolve. If developers chose to switch to a different library, the knowledge of web standards gained during their work with D3 might be applicable to their future work. The reliance on web standards also makes it possible to use the native debugging tools available in web browsers.

Other important aspects of D3's design include immediate evaluation of functions, the principle of parsimony, and support for method chaining. Immediate evaluate of functions means that operations, such as modifying attributes, are applied instantaneously at the time of calling the respective functions. This reduces internal complexity by handing control flow decisions over to invoking code. It also avoids errors related to missing state changes when state is modified multiple times between rendering, which commonly occur in libraries which use delayed evaluation of functions.

The principle of parsimony, also referred to as Occam's razor, is a problem-solving principle which stems from the field of philosophy [Sober 1979]. It is frequently paraphrased as "entities should not be multiplied beyond necessity", and when applied to API design it means that superfluous functions in an API should be avoided. As an example, the background color of a circle element can already be set with the generic `Selection.attr` method to set the `background-color` attribute of all elements in a Selection. Adding an additional `backgroundColor` method would violate the principle of parsimony because it would introduce a special method to achieve something that was already achievable.

Method chaining is a popular syntax which allows functions to be chained after one another. The use of method chaining avoids having to store intermediate method results in variables which would not otherwise be needed. It is implemented in D3 by returning the Selection on which a modifying method is called as a result of that method. Methods which insert new elements into the DOM, such as `Selection.append` and `Selection.insert`, return a Selection of the newly added elements to enable the creation of nested structures. This method chaining syntax is further aided by the `Selection.call` method, which invokes a callback receiving the current Selection as a parameter and returns the original

```

1 d3.select('body')
2   .call(s => s.append('h1').text('Method Chaining in D3'))
3   .call(s => s.append('p').text('This is a demonstration of method chaining'));

```

Listing 3.1: A simple example of method chaining in D3. A h1 element and a p element are created inside an existing body element.

Selection to chain further methods on it after the callback has been executed. The `Selection.call` method enables the creation of complex method chaining structures and is widely used by developers. A simple example of method chaining in D3 with the `Selection.call` method can be seen in Listing 3.1.

Selections are the atomic building blocks of D3 and are used to access almost any functionality. Selections are created using the `d3.select` or `d3.selectAll` methods. These methods are built on the `querySelector` and `querySelectorAll` methods of the DOM Selectors API, which allow the selection of elements via CSS selectors (see Section 2.2). The `d3.select` and `d3.selectAll` methods create a Selection containing either a single element matching the provided selector, or multiple elements matching it, respectively. A Selection acts as a wrapper container around selected elements to perform frequently performed DOM operations on them. Among others, the element operations provided by a Selection include the setting and getting of: attributes using the `Selection.attr` method, styles using the `Selection.style` method, properties using the `Selection.property` method, text or HTML content using the `Selection.text` or `Selection.html` methods, and event listeners using the `Selection.on` method. Selections also provide wrapper methods to insert additional elements using the `Selection.append` or `Selection.insert` methods, as well as to remove them using the `Selection.remove` method. Accessing the DOM via this wrapper is less tedious than accessing it directly, because the native DOM API is very verbose, and also because the method chaining API provided by D3 does not require the storage of unnecessary intermediate variables.

An additional feature of D3 is the ability to bind data to elements using the `Selection.data` and `Selection.datum` methods. The `Selection.datum` method binds a single provided data record to all elements in the Selection, whereas the `Selection.data` method receives an array of data records and binds each individual data record to exactly one element. The `Selection.data` method performs a join operation between data and elements to ensure that exactly one element per data record exists. This data join results in three separate Selections: the enter Selection, containing the elements which were newly created, the update Selection, containing the elements which merely receive new data, and the exit Selection, containing the elements which are being removed. Each of these Selections can be individually transformed using the `Selection.join` method, which can receive three callbacks for the enter, update, and exit Selections of the data join, respectively. This ability to individually control changes to entering, updating, and exiting elements is referred to in D3 as the *general update pattern*. A simple demonstration of how it is used can be seen in Listing 3.2. All the previously mentioned DOM wrapper methods can receive either constant values or dynamic values defined as functions. These functions receive the bound element data, the element's index in the group of nodes represented by the Selection, and the group of nodes themselves as input and then calculate a dynamic value based on these parameters, which is forwarded to the corresponding DOM method.

D3 also offers a convenient, optional API to perform JavaScript-based animations via Transitions, which wrap a Selection and allow the animation of various element characteristics. Transitions are created using the `Selection.transition` method which creates a Transition wrapping the Selection on which it has been called. The duration of a Transition is defined using the `Transition.duration` method and its easing can be configured using the `Transition.ease` method. It is also possible to interrupt and

```

1 function renderCircles(container, positions) {
2   container.selectAll('circle').data(positions).join(
3     (enter) => enter.append('circle')
4       .attr('r', '50')
5       .attr('fill', 'lightgray')
6       .attr('stroke', 'darkgray')
7       .attr('cx', d => d.x)
8       .attr('cy', d => d.y),
9     (update) => update.attr('cx', d => d.x).attr('cy', d => d.y),
10    (exit) => exit.remove()
11  );
12 }

```

Listing 3.2: A simple demonstration of D3's general update pattern being used to specify different transformations for entering, updating, and exiting elements. The full utility of this pattern is only apparent in more complex scenarios involving transitions.

chain transitions. Transitions provide an almost identical API to Selections. The major change is that the wrapping methods interpolate towards their target values using the given easing function over the given duration instead of setting the target value directly. Using D3 Transitions is completely optional and developers can choose instead to use other animation technologies, like CSS transitions and animations.

At its core, D3 is simply a low-level library to perform data-driven document transformations. Even though this generic core technology is applicable to a wide range of use cases, D3 was created with a focus on creating visualizations. There are many additional modules which simplify the higher-level tasks necessary for creating and rendering visualizations. All D3 modules follow the same inherent patterns, like method chaining and configurable functions. Therefore, despite this higher-level functionality being split over multiple modules, a consistent experience is provided to developers. Listing all available modules here would be out of the scope of this work, but some noteworthy modules include: `d3-shape` to create visual primitives like lines and areas, `d3-scale` to encode abstract data dimensions, `d3-axis` to render scales as human-readable axes, and many more such as `d3-array`, `d3-layout` and `d3-zoom`.

3.2.2 Vega and Vega-Lite

Vega [IDL 2021] is a library consisting of a grammar to describe interactive graphics and a parser which translates specifications written in this grammar into static images or web-based views built on SVG documents or the Canvas Web API. An interactive visualization in Vega is fully described by a specification written in Vega's grammar. This grammar is essentially a domain-specific language designed for the declarative specification of interactive graphics. Its syntax is based on the easy-to-read JavaScript Object Notation (JSON), which is among the most frequently used textual serialization formats. Vega builds on previous research in the field of declarative visualization design [Wilkinson 2005]. In contrast to previous work, it contains powerful capabilities to declaratively describe interactions [Satyanarayanan et al. 2015] in addition to describing visual appearance.

The visual aspects of a visualization are described in a grammar similar to the Grammar of Graphics defined by Wilkinson [2005]. At its top level, a Vega specification contains properties to configure sizing and padding of the container of a visualization. Every specification also contains a data section, which either defines data or specifies where to load it from. The Vega grammar also supports various forms of data transformation which can successively be applied to a dataset to perform various transformations like filtering, deriving additional fields, or deriving additional datasets. In a majority of cases, the defined

data will consist of abstract information which is then mapped to visual properties. This mapping is configured and performed using scales. Vega already contains a variety of scales to help with mapping abstract values to visual properties. They can broadly be categorized into quantitative scales which map quantitative inputs to quantitative outputs, discrete scales which map discrete inputs to discrete outputs, and discretizing scales which map quantitative inputs to discrete outputs. For spatially encoded dimensions, scales can be visualized as axes, whereas non-spatial encodings such as encodings as colors, sizes, or shapes can be visualized as legends.

At the core of every visualization lies the encoding of data as visual primitives, which is achieved in Vega via marks. Marks use scales to encode data fields as properties of their shapes. Based on the general update pattern of the underlying D3 library, the encoding of marks can be separately controlled for newly created (entering) marks, existing and not exiting (updating) marks, and to-be-removed (exiting) marks. In addition to these basic visualization components, the Vega grammar contains further capabilities to describe interactions (via signals, triggers, and event streams), cartographic projections, sequential or layered views (via mark groups), layouts, and color schemes. To demonstrate how the various aspects of a Vega specification are defined, an example of a static bar chart can be seen in Listing 3.3.

In template-based visualization libraries, interactions are typically defined by configuring premade interaction templates, which is easy but limiting, or by manually modifying the visualization in various callbacks, which is flexible but tedious and not serializable. The ability to describe custom interactions using a serializable, data-driven grammar is what sets Vega apart from other declarative visualization libraries [Satyanarayan et al. 2015]. This approach offers the flexibility of callback-driven interactions, while still remaining fully serializable and declarative. The grammar to define interactions is based on the syntax of event-driven functional reactive programming [Wan et al. 2001], a high-level grammar which resembles mathematical equations to describe reactive systems. In Vega, the primitives to express interactions are called *signals*. Signals can be seen as dynamic variables which change their values based on input events or other signals. These signals and the way their values change are defined declaratively, and they can be used as dynamic variables in most places in a Vega specification to change various characteristics of a visualization dynamically. Listing 3.4 shows an example of how the previously shown static bar chart specification can be extended with signals to display a tooltip when hovering over bars.

Visualizations created with Vega closely follow their specifications and minimal assumptions are made in the compilation process. This results in very verbose specifications, because all configurations for all parts of the visualization need to be explicitly defined in them. It also means that specification authors have full control over the resulting graphics, making Vega a good base on which to build further libraries and tools. Many tools have already been built on top of Vega [Wongsuphasawat et al. 2015; Satyanarayan and Heer 2014; Wongsuphasawat et al. 2016]. Most noteworthy is Vega-Lite [Satyanarayan et al. 2016]. Vega-Lite is described as a “high-level grammar of interactive graphics”, which summarizes its difference to Vega fairly well. Vega-Lite is a higher-level grammar than Vega, allowing authors to write specifications for common visualizations in a much more concise form. Specifications written in Vega-Lite are then compiled into Vega specifications. During compilation, the compiler automatically derives default configurations for axes, legends, and scales by following a set of carefully designed rules. This makes Vega-Lite more convenient for quick authoring of visualizations, since many of the details which need to be explicitly stated in a Vega specification can be omitted. In those cases where the derived default configurations are not suitable, Vega-Lite also offers the possibility to override them. Since Vega-Lite specifications are simply compiled into Vega ones, it is a sensible choice to use Vega-Lite as a primary tool to describe visualizations, and switch to Vega for more exotic cases which are not easily achievable in Vega-Lite. To illustrate the difference between a Vega and a Vega-Lite specification, Listing 3.5 shows a Vega-Lite version of the Vega bar chart specification from Listings 3.3 and 3.4 combined.

```

1 {
2   "$schema": "https://vega.github.io/schema/vega/v5.json",
3   "width": 600,
4   "height": 300,
5   "data": [
6     {"name": "data",
7      "values": [
8        { "category": "A", "value": 16 },
9        { "category": "B", "value": 23 },
10       { "category": "C", "value": 32 }
11     ]
12   }],
13   "scales": [
14     {
15       "name": "x",
16       "type": "band",
17       "domain": { "data": "data", "field": "category" },
18       "range": "width",
19       "padding": 0.05
20     },
21     {
22       "name": "y",
23       "domain": { "data": "data", "field": "value" },
24       "range": "height"
25     }
26   ],
27   "axes": [
28     { "orient": "bottom", "scale": "x" },
29     { "orient": "left", "scale": "y" }
30   ],
31   "marks": [
32     {
33       "type": "rect",
34       "from": { "data": "data" },
35       "encode": {
36         "enter": {
37           "x": { "scale": "x", "field": "category" },
38           "width": { "scale": "x", "band": 1 },
39           "y": { "scale": "y", "field": "value" },
40           "y2": { "scale": "y", "value": 0 }
41         },
42         "update": { "fill": { "value": "green" } }
43       }
44     }
45   ]
46 }
```

Listing 3.3: The Vega specification of a static bar chart. It demonstrates the use of data, scales, axes, and marks to construct the bar chart.

```

1  {
2    "...": "...",
3    "signals": [
4      "name": "tooltip",
5      "value": {},
6      "on": [
7        { "events": "rect:mouseover", "update": "datum" },
8        { "events": "rect:mouseout", "update": "{}" }
9      ]
10    ],
11    "marks": [
12      { "...": "...", },
13      {
14        "type": "text",
15        "encode": {
16          "enter": {
17            "align": { "value": "center" },
18            "baseline": { "value": "bottom" }
19          },
20          "update": {
21            "x": { "scale": "x", "signal": "tooltip.category", "band": 0.5 },
22            "y": { "scale": "y", "signal": "tooltip.value", "offset": -5 },
23            "text": { "signal": "tooltip.value" },
24            "opacity": [{ "test": "datum === tooltip", "value": 0 }, { "value": 1 }]
25          }
26        }
27      }
28    ]
29 }

```

Listing 3.4: The necessary additions to the static bar chart specification in Listing 3.3 to display a tooltip when hovering over bars. It demonstrates the basic functionality of signals in Vega. When the mouse hovers over a rect mark, the tooltip signal will receive the value of the rect's bound data record. The tooltip signal will be reset to an empty object when the mouse leaves the rect mark. It is then used in the newly added text mark section of the specification to define the position, text, and visibility of the tooltip whenever an update occurs.

3.2.3 Template-Based Visualization Libraries

Template-based visualization libraries work by providing templates for possible types of visualizations and allowing users to customize them. These types of visualization libraries are easier to use than D3 or Vega because they offer a concise form of configuration which does not require users to have detailed knowledge over the underlying rendering technology or complex, non-standardized domain specific languages. Even though these types of libraries are usually flexible enough to create a huge range of visualizations, at some point users may run into limitations. Some of these limitations can only be worked around by writing custom source code, which requires a deep understanding of the underlying library. This effectively eliminates the ease-of-use benefit of these types of libraries for users who run into these limitations.

For this thesis, a total of 20 template-based JavaScript visualization libraries were examined and compared according to factors such as their rendering technology, usage popularity (number of downloads), open-source popularity, license, and recent development activity. In terms of rendering technology, most libraries render visualizations as either SVG documents or canvas elements, although some implement a hybrid renderer which can be configured to render as either one of them. Usage popularity was measured

```

1 {
2   "$schema": "https://vega.github.io/schema/vega-lite/v5.json",
3   "width": 600,
4   "height": 300,
5   "data": {
6     "values": [
7       { "category": "A", "value": 16 },
8       { "category": "B", "value": 23 },
9       { "category": "C", "value": 32 }
10    ],
11  },
12  "mark": "bar",
13  "encoding": {
14    "x": { "field": "category", "type": "ordinal" },
15    "y": { "field": "value", "type": "quantitative" },
16    "tooltip": [{ "field": "value" }]
17  }
18 }
```

Listing 3.5: A Vega-Lite specification of the Vega bar chart shown in Listings 3.3 and 3.4 combined.

by the cumulative package downloads from the npm package manager over the previous twelve months. This was deemed one of the most relevant metrics for the comparison, because it reflects actual user behavior and gives an indication on how widespread a library is used in practice. The 20 libraries found in the initial collection phase were filtered by their usage popularity and recent development activity to remove those which were not sufficiently used or no longer maintained. This filtering step yielded the following ten libraries: (1) ChartJS [Chart.js 2021], (2) Highcharts [Highsoft 2021], (3) ECharts [Li et al. 2018], (4) ApexCharts [Chhipa and Lagunas 2021], (5) PlotlyJS [Plotly 2021], (6) C3JS [Tanaka 2020], (7) Chartist [Kunz 2021], (8) amCharts [amCharts 2021], (9) billboardJS [NAVER 2021], and (10) D3FC [Scott Logic 2021]. These ten libraries were selected for further consideration.

Eight of the ten libraries are completely free to use without restrictions, amCharts has a free license for users who are comfortable with an attribution logo on their visualizations, and Highcharts offers a free license option for non-profit, educational and personal applications. Nine of the libraries implement an SVG-based renderer, two of which (ECharts and D3FC) also offer alternative rendering to Canvas elements for high-performance scenarios, and only ChartJS solely targets canvas-based rendering. Eight libraries are very actively maintained with most of them showing development activity within the last month. C3JS and Chartist seem to be no longer actively maintained, but were included nonetheless in the deeper evaluation, due to their historic and thematic relevance and because they are still widely used.

Template-based visualization libraries have a strong inclination towards designing their APIs according to principles of declarative programming. APIs following these principles allow users to describe a desired state they want the underlying system to be in. This is in strong contrast to the typical imperative way of designing APIs in which users are instead given a set of tools to query and modify a system's state. The difference can be summarized in simple terms as follows: With declarative APIs, users specify what state shall be achieved, whereas with imperative APIs, users specify how a certain state is achieved. Declarative APIs are typically built on top of lower-level imperative APIs and can therefore be seen as a higher level of abstraction over them. They are popular among developers because they are expressive, easy to use and effectively encapsulate complexity which would otherwise have to be handled by users. An often overlooked disadvantage of declarative APIs is that they frequently only provide high-level access to a system and that more specific use cases might not be achievable if they can not be expressed

```

1 Highcharts.chart('container', {
2   chart: { type: 'column' },
3   title: { text: 'Highcharts API Demonstration' },
4   xAxis: { categories: ['A', 'B', 'C', 'D', 'E'], title: { text: 'Categories' } },
5   yAxis: { type: 'linear', title: { text: 'Values' } },
6   series: [
7     {
8       name: 'data',
9       data: [107, 31, 635, 203, 50],
10      color: 'green',
11      borderColor: 'black',
12    }],
13 });

```

Listing 3.6: A basic column (vertical bar) chart defined using Highcharts' generic chart creation API. A high-level, declarative configuration object is passed to the creation function.

in the domain-specific language defined by the API. In many cases, it makes sense to provide additional imperative APIs for users which require a lower level of access to the system to implement functionality not achievable via the declarative parts of the interface.

All of the evaluated libraries, except D3FC, expose declarative interfaces in the form of nested configuration objects which are used to specify the characteristics of individual visualizations. Apart from Chartist, all those libraries feature generic high-level creation functions. These functions create charts from declarative configuration objects, which allow the specification of different forms of visualization for different data dimensions. This type of interface is demonstrated by the Highcharts code in Listing 3.6. Generic chart creation functions seem to correlate with the ability to dynamically change the type of visualization. Chartist, on the other hand, provides separate chart creation functions for each type of chart, and it is not possible to alter the type of chart after it has been created. Another limitation which may originate from partitioning the API by chart type is that mixed charts which combine multiple forms of visualization in one composite visualization cannot be expressed.

The only library in the deeper evaluation which does not provide a high-level declarative configuration API is D3FC. The design philosophy of D3FC is based on the idea of “unboxing” D3. Even though many visualization libraries are implemented on top of D3, it is usually hidden behind public APIs which are easier to work with but do not provide the full flexibility of D3. D3FC exposes a component-based interface which closely follows design patterns frequently encountered when working with D3. These components form higher-level building blocks upon which advanced visualizations can be built. They are also highly configurable and in those cases where the options for configuration are not sufficient, a decorator pattern allows users to hook into the underlying D3 functionality and inject custom code into the various stages of the general update pattern at the core of D3. Code demonstrating the usage of D3FC can be seen in Listing 3.7.

amCharts is the only evaluated library, which exposes a hybrid API with the possibility of configuring visualizations using both declarative configuration objects and manually composing higher-level visualizations from lower-level components, such as axes and series. Its component-based interface is still rather declarative, with most options being configurable by modifying specific properties on the components. However, modifying only the properties which require changing instead of processing a full configuration object and figuring out the necessary changes from it, is less costly in terms of performance. In addition to these performance benefits, the components provide additional functions to perform operations which would not be available using a purely declarative API.

```

1 const data = [
2   { category: 'A', value: 107 },
3   { category: 'B', value: 31 },
4   { category: 'C', value: 635 }
5 ];
6
7 const bar = fc
8   .autoBandwidth(fc.seriesSvgBar())
9   .crossValue((d) => d.category)
10  .mainValue((d) => d.value)
11  .align('left')
12  .decorate((selection) => {
13    selection.attr('fill', 'green');
14  });
15
16 const chart = fc
17   .chartCartesian(d3.scaleBand(), d3.scaleLinear())
18   .chartLabel('D3FC API Demonstration')
19   .xDomain(data.map((d) => d.category))
20   .yDomain([0, Math.max(...data.map((d) => d.value))])
21   .xPadding(0.1)
22   .xLabel('Categories')
23   .yLabel('Values')
24   .yOrient('left')
25   .yNice()
26   .svgPlotArea(bar);
27
28 d3.select('#container').datum(data).call(chart);

```

Listing 3.7: A basic bar chart defined using D3FC's component-based API.

When comparing the evaluated libraries in terms of their responsive configurability, most libraries offer similar capabilities albeit in slightly different ways. Six of the ten libraries (Highcharts, C3JS, Chartist, amCharts, billboardJS, and D3FC) support the styling of elements in their created visualizations with CSS, which requires rendering as SVG documents, since only document-based visualizations can be affected by CSS. The styling of visualizations with CSS is powerful, because it leads to a separation of concerns and designers can make use of CSS-inherent mechanisms to configure responsive styles. Unfortunately, CSS-based styling is only of limited applicability because not all CSS properties affect SVG elements, as described in Section 2.5.2.

To responsively configure other visualization characteristics, such as their type, data, and layout, designers have to resort to configuration mechanisms offered by the libraries. Four libraries (Highcharts, ApexCharts, Chartist, and amCharts) provide the possibility to specify rule-based responsive configurations as part of their declarative interfaces, illustrated in the Highcharts example in Listing 3.8. These declarative rules consist of a condition part which specifies when to apply the rule, and a configuration part which specifies the configuration options which should be set when applying the rule. Even though this is a convenient form of responsive configuration, if the desired conditions can not be expressed via the provided declarative properties, designers have to fall back to more generic mechanisms which are also applicable to other libraries. The mechanisms for responsive configuration in the other libraries are more generic, because they do not offer these configurations as part of their declarative interfaces. This means that developers need to trigger responsive configurations themselves by manually reconfiguring visualizations via their APIs in custom resize or media query event listeners. Nearly all libraries provide

```
1 Highcharts.chart('container', {
2   ...
3   responsive: {
4     rules: [{
5       condition: { maxWidth: 500 },
6       chartOptions: {
7         chart: { type: 'bar' },
8         yAxis: { title: { text: null } },
9         xAxis: { title: { text: null } },
10      },
11    }],
12  },
13});
```

Listing 3.8: The declaration of responsive rules in Highcharts. In this example, the x-axis and y-axis titles are removed if the chart is narrower than 500 pixels.

a means to dynamically resize visualizations and update their data, type, and options. The exceptions are C3JS, which only supports dynamic changes of some options, and Chartist, which does not support changing a visualization's type at all.

Chapter 4

Responsive Information Visualization

A *responsive* visualization is a visualization which adapts itself to the available display space and properties of the device used to access it. Analogous to responsive web design, the need for responsive visualizations arises from the growing variety of devices used to consume content and the physical differences between them. Visualizations and charts often form significant blocks of content embedded inside web pages. For a web page to be responsive, any embedded content such as visualizations and charts must also be responsive.

Visual elements require proper sizing and spacing to be of value. Merely scaling visualizations to fit into their allocated space is insufficient to provide a seamless experience to users, as has already been discussed in Section 2.7. Another factor which is often ignored is the different methods of interaction inherent to specific types of devices, such as touch and keyboard interaction. For example, to ensure that data points remain selectable on less precise input devices such as touchscreens, a visualisation might adapt by reducing the data density and increasing the size of individual elements. The goal of responsive visualizations is that they should adapt themselves to the characteristics of the consuming device and context so as to remain as effective and usable as possible [Kim et al. 2021a].

The topic of responsive visualization only gained prominence in recent years, as responsive web design became mainstream. Hinderman [2015] used the term responsive visualization, but only described how to implement scalable visualizations. Körner [2016] covered scalable visualizations, but also considered interactive selection and touch events. Andrews [2018] was possibly the first academic work to address design patterns for responsive visualization. More recently, [Hoffswell et al. 2020] surveyed the design space of responsive visualizations, created a taxonomy of currently used techniques and recurring patterns, and presented a tool to help design responsive visualisations side-by-side. In addition to surveying design patterns, Kim et al. [2021a] also consider issues around different forms of “message loss” when reducing chart complexity.

4.1 Responsive Visualization Patterns

Patterns are templates for solving recurring problems. Hoffswell et al. [2020] created a comprehensive taxonomy of responsive techniques, as well as a tool to help design responsive visualisations side-by-side. They proposed describing responsive techniques according to five *actions*, which are applied to different components. These actions are: (1) resize, (2) reposition, (3) add, (4) modify and (5) remove. A sixth action refers to leaving a component unchanged, but this is deemed a non-technique and therefore left out here. They also described a non-exhaustive set of eleven *components*, upon which these actions can be performed: (1) axis, (2) axis labels, (3) axis ticks, (4) gridlines, (5) legend, (6) data, (7) marks, (8) labels, (9) title, (10) view, and (11) interaction. It should be noted that some combinations of actions and components do not make sense and therefore do not occur in practice. It is, for example, not possible

Category	Description
Data	Data is the information which is encoded in a visualization. This category includes targets such as data records, data fields, or levels of hierarchy in the data.
Encoding	Encodings are the visual forms in which data is represented.
Interaction	Interactions define how users can engage with visualizations. This category includes targets such as interaction triggers, interaction feedback and interaction features.
Narrative	This category groups targets based on the story a visualization should convey. It contains targets such as the presented sequence of information (views and states) and the information itself in the form of annotations, emphases, and texts.
References/Layout	References represent additional information which makes visualizations easier to understand, and a layout describes how the individual visual components are placed.

Table 4.1: The targets of responsive visualization patterns identified by Kim et al. [2021a]. [Table adapted from Kim et al. [2021a].]

to resize interactions or reposition data. Hoffswell et al. [2020] performed their research following a desktop-first approach of responsive design, because the interviews they conducted with visualization authors revealed a strong inclination towards this approach. They found that when adapting desktop visualizations for narrow screens, it was much more common to remove elements (37.7%) than to add them (11.3%). Another interesting finding was that most visualizations (88.7%) implemented no change at all for their interactions, while some (10%) even removed interactive capabilities completely. Only very few visualizations (5.6%) improved the experience of mobile users by adapting interactions accordingly.

The most detailed research on patterns in responsive visualization design was performed by Kim et al. [2021a]. Following Hoffswell et al. [2020], they characterised the responsive visualization strategies according to (the same) two dimensions: *targets*, representing what entity is changed, and *actions*, representing how entities are changed. However, the targets and actions are more finely grained, having a number of sub-categories. Targets are grouped into five distinct categories (Data, Encoding, Interaction, Narrative, and References/Layout), with four of the five categories further divided into sub-categories, as shown in Table 4.1. Actions are also grouped into five distinct categories (Recompose, Rescale, Transpose, Reposition, and Compensate), with four of the five top-level categories again having sub-categories, as shown in Table 4.2. The actions are defined as operations with distinct input and output states to ensure they can be inverted, and thus can be applied to either desktop-first or mobile-first design approaches. Categorizing techniques using these dimensions, the authors identified a total of 76 viable strategies, whereby some of them are not used in the visualizations they studied. However, their explorable online gallery [Kim et al. 2021b] contains examples demonstrating all these patterns.

Category	Description
Recompose	Actions which affect the existence of targets. Includes remove, add, replace and aggregate actions.
Rescale	Actions which affect the size of targets. Includes reduce width, simplify labels and elaborate labels actions.
Transpose	Actions which affect the orientation of targets. Includes serialize, parallelize and axis-transpose actions.
Reposition	Actions which affect the position of targets. Includes externalize, internalize, fix, fluid and relocate actions.
Compensate	Actions which compensate for loss of information. Includes toggle and number actions.

Table 4.2: The actions of responsive visualization patterns identified by Kim et al. [2021a]. [Table adapted from Kim et al. [2021a].]

4.2 Responsive Visualization Examples

The goal of this section is to provide the reader with some demonstrative examples of responsive visualizations. The figures in this section were taken from external scientific sources which put most of their effort into demonstrating responsive visualization patterns rather than communicating messages in the data they used. Owing to this, some figures below are lacking essential features, such as titles and axes descriptions, which would usually be present in practice.

The examples in this section are organized by chart type. It would be an immense endeavor to bring examples for every pattern used for all types of charts, so only a subset which demonstrates some of the most frequently encountered patterns for frequently used types of charts is summarized here.

4.2.1 Bar Charts

Bar charts are very widespread, accounting for 135 (= 36%) of the 378 responsive charts in the corpus collected by Kim et al. [2021a]. Bar charts are usually used to visualize two-dimensional data, with one categorical dimension and one quantitative dimension. Two variants of bar charts support the visualization of categorical datasets having subdimensions: grouped bar charts [Ferdio 2021a] compare subdimensions with each other, and stacked bar charts [Ferdio 2021b] compare part-to-whole relationships of the subdimensions. Even though responsive design of visualizations is slowly becoming more common, most charts found in today's web articles are still created as static images [NYT 2018a; NYT 2020b; Bui 2019; NYT 2020a].

A good example of a responsive bar chart can be seen in Figure 4.1 [Andrews 2018]. Bar charts are freely scalable by adjusting the width of individual bars [Barnett et al. 2016; Francis 2017; Minczeski et al. 2017], so they all can fit into their allocated space. When reducing the width of any type of chart past a certain point, the tick labels of the horizontal axis may start to overlap. This is why the reducing width pattern usually occurs together with the recompose axis ticks and simplify/elaborate axis labels patterns [Minczeski et al. 2017; Francis 2017; WSJ 2017]. Another effective pattern for avoiding overlapping tick labels is to rotate the labels by up to 90 degrees so they take up less horizontal space [Andrews 2018]. If there is too much data to fit into the available width, the chart can be transposed and grown to as much height as is required necessary [Andrews 2018]. Doing this is more advisable than simply extending the width of the chart past the viewport, since vertical scrolling is easier than horizontal scrolling. When reducing the width of charts containing annotations, a number of patterns can be applied to avoid annotations overlapping. For example, annotations can be removed [Bui 2021; Aisch et al. 2017], simplified, or relocated [WSJ 2017].

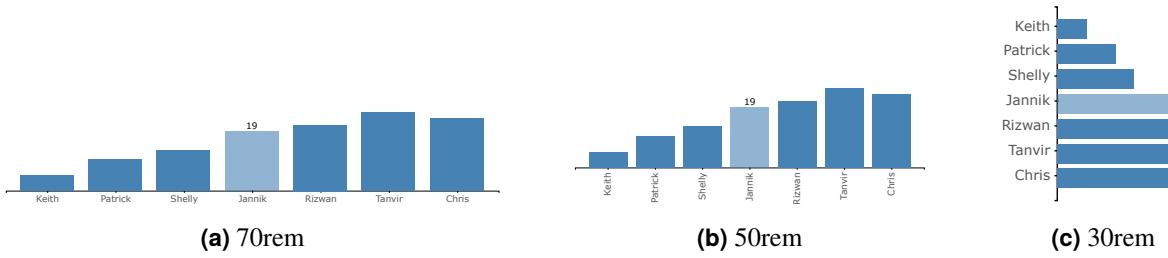


Figure 4.1: An example of a responsive bar chart at different display widths. (a) At 70rem, axis tick labels are aligned horizontally. (b) At 50rem, axis tick labels are aligned vertically. (c) At 30rem, the chart is transposed. [Screenshots of Andrews [2018] created by the author of this thesis. Used with kind permission by Keith Andrews.]

4.2.2 Line Charts

The second most frequent type of responsive charts according to the responsive visualization gallery [Kim et al. 2021a] are line charts, which number 98 (= 26%) out of the 378 responsive visualizations in the gallery. Line charts are used to show trends in two-dimensional datasets by plotting them as points connected by lines (a polyline). They can be extended to compare trends in an additional categorical dimension by drawing additional polylines for each category. Many line charts on the web are published in non-responsive forms [NYT 2019b; NYT 2019a], although some authors take the extra effort to make their charts responsive. The minimum which can be done to make a line chart responsive is to reduce their width [Barton and Recht 2018] on narrower screens by shrinking the horizontal distance between neighboring points. This usually occurs together with the recomposition and simplification of horizontal ticks. If the chart contains annotations, it may also be necessary to recompose, relocate, and simplify them as well [Fessenden and Park 2016; Katz and Sanger-Katz 2021; Francis 2017; Aisch et al. 2017].

A good demonstration of which responsive patterns can be applied to make a line chart responsive is shown in the responsive line chart created by Andrews [2018] which can be seen in Figure 4.2. In addition to the recomposition of ticks, tick labels are rotated to reduce their required horizontal space. For exceptionally limited space, it can make sense to remove the axes of a line chart entirely and turn it into a sparkline. However, it should be noted that by doing this, the consumer of the visualization loses information about the type and scale of the chart’s dimensions. This technique should therefore only be applied in cases where no other pattern is applicable or if the trend in the data is the most important message to convey. It is rare to encounter transposed versions of line charts, although transposition could sometimes benefit heavily annotated line charts [Munroe 2021]. Applying a transpose pattern would allow the chart to take up as much vertical space as necessary to neatly accommodate annotations without requiring the consumer to scroll horizontally.

4.2.3 Scatterplots

Scatterplots are also quite frequently encountered among responsive charts, numbering 26 (= 7%) of the 378 responsive charts contained in the gallery by Kim et al. [2021a]. A scatterplot represents two-dimensional data as points in a 2d Cartesian coordinate system. There are many examples of scatterplots published as static images [NYT 2018b; NYT 2018c], with responsive versions starting to emerge.

The first step to making scatterplots responsive is to reduce their width to fit them into the space available. As for other types of chart, care must be taken to avoid overlapping of labels and annotations by applying recomposition, relocation and simplification patterns [Canipe and Yeip 2017; Shifflett 2016]. To counteract the increased density of points when reducing the size of their container, various interaction features are usually implemented in scatterplots which help consumers in making sense of the represented data. The most useful interaction features in these charts are elaborative zooming interactions and the



Figure 4.2: An example of a responsive line chart at different display widths. (a) At 65rem, the x axis labels are horizontal. (b) At 40rem, the x axis ticks have been thinned out and the labels fully rotated by 90°. (c) At 20rem, both axes have been removed, and the chart has become a sparkline. [Screenshots of Andrews [2018] created by the author of this thesis. Used with kind permission by Keith Andrews.]

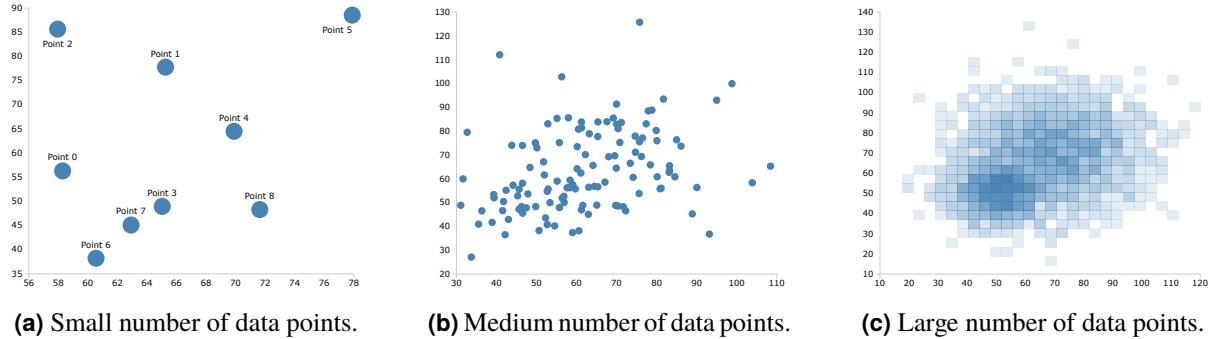


Figure 4.3: An example of a responsive scatterplot based on data density (data points per pixel). (a) With a small number of data points, all points and their corresponding labels are shown. (b) At a certain density, labels are only shown for selected points. (c) At very large densities, the scatterplot is replaced by a heatmap to more efficiently display the large amount of data. [Screenshots created by the author of this thesis. Visualization created by Rabinowitz [2014].]

explorative panning interactions. In addition to zooming and panning, Andrews [2018] employs additional methods to ameliorate the overlapping of individual points, including fisheye distortion, Cartesian distortion, and temporary displacements of points.

An interesting technique for responsive scatterplots based on the visualization's density (data points per pixel) rather than its width was introduced by Rabinowitz [2014]. The benefit of this approach is that charts adapt to changing amounts of data and reconfigure their appearance accordingly. The patterns applied in the responsive scatterplot shown in Figure 4.3 are the recomposition of annotations to only show annotations for selected data records, and the switching of the encoding from a scatterplot to a heatmap for high point densities. Other techniques, such as the recomposition of data records, would also be applicable to responsive scatterplots, but no examples for such patterns could be found. If the data to be encoded is inherently cyclic, a radial scatterplot, using polar coordinates, can be used to better reflect the cyclic nature of the data [Barton and Recht 2018].

4.2.4 Parallel Coordinates

Even though parallel coordinates charts are rarely encountered in non-technical contexts, they are very popular when it comes to visualizing multidimensional data in visual analytics systems [Macrofocus 2021]. In these kinds of charts, multiple dimensions are rendered as parallel axes, upon which points are connected via paths (polylines). Each polyline represents a data record and its values at the corresponding dimensions. The axes of a parallel coordinates chart are typically laid out horizontally, meaning that the



Figure 4.4: A responsive parallel coordinates chart at different display widths. (a) At larger widths, all dimensions are shown. (b) Dimensions are removed based on their priority, dimension labels are rotated by 45 degrees, and a dimensions toggle is shown which enables the configuration of dimensions. (c) Further dimensions are removed. (d) Further dimensions are removed, and dimension labels are rotated by 90 degrees. (e) The dimension configuration panel has been opened, and the user has taken control over which dimensions to show. [Screenshots of Andrews [2018] created by the author of this thesis. Used with kind permission by Keith Andrews.]

chart can be made narrower by reducing the distance between individual axes. Previously mentioned axis-related responsive patterns, such as rotating labels and recomposing ticks, can also be applied.

Another technique is to temporarily hide some dimensions, based on some criteria. When automatically hiding dimensions, it is necessary to apply compensation patterns, giving the user additional controls to configure which dimensions are displayed and override the system's hiding behavior. An example of a responsive parallel coordinate chart incorporating some of these patterns can be seen in Figure 4.4. If reducing the chart's complexity is not appropriate, an alternative is to transpose the chart, so its dimensions are laid out vertically and vertical scrolling can be used to explore the full chart.

Chapter 5

The RespVis Library

RespVis is an open-source D3 library for creating responsive SVG charts. It enables the use of CSS, which is a core pillar of designing responsive HTML documents, for the design of visualizations. Since CSS can only be applied to documents, RespVis focuses on rendering visualizations as pure and complete SVG documents, meaning that the whole visualization is contained in one SVG document that includes no elements of other XML namespaces. RespVis is designed as an extension library of D3. Unlike most other visualization libraries that are built on top of D3, RespVis does not hide it behind a custom API. Rather than that, users invoke RespVis functionalities by binding specially structured data on D3 Selections, in which visual components are then rendered using render functions that transform the bound data into some form of visual representation. This strong separation between data and code and the application of strongly-typed TypeScript are the main principles guiding the software design of RespVis.

5.1 Design

The design of the RespVis library is guided by six main concepts, which are further discussed in the later paragraphs of this section:

1. CSS should be used as much as possible for describing the style and layout of visualizations.
2. Visualizations should be rendered as pure and complete SVG documents.
3. RespVis is an extension of D3 rather than a wrapper around it.
4. Data and code are treated as separate entities.
5. Everything should be as strongly-typed as possible.
6. Components are structured in layers with different levels of abstraction.

Firstly, every part of the presentation that can be configured with CSS should be configured with CSS. The visual appearance of HTML elements and their layout can already be controlled by CSS. Unfortunately, SVG elements are not affected by CSS-based layouting, which seriously limits responsive possibilities of styling SVG charts with CSS. Without powerful CSS layout technologies like Flexbox or Grid, all the individual components of an SVG chart have to be positioned manually via JavaScript. A Layouter component has been developed that calculates bounding boxes of SVG elements from their CSS configuration to enable laying them out via CSS. Using this Layouter offers visualization authors comparable configurability to what they are used to when styling HTML documents for styling SVG charts. Positioning elements with CSS does not require visualization authors to understand any library-specific APIs because they can apply the knowledge of CSS-based layouting they most likely already possess. Since CSS can only be applied to documents, RespVis does not support rendering to HTML

canvas elements because graphics rendered there are not exposed as document elements and therefore can not be affected by CSS.

Secondly, every rendered visualization should be a pure and complete SVG document. An SVG document is considered pure if it contains only elements defined in the SVG namespace. This means that it must not contain any `<foreignObject>` elements that nest elements of an XML namespace other than SVG. When an SVG document represents a visualization, it is considered complete if it contains all visualization components within it. Splitting components into multiple SVG documents is considered bad practice because these components conceptually belong together and should therefore be represented as a whole. Having a full visualization enclosed in a complete SVG document allows whole visualizations to be exported and stored as standard-compliant SVG files that can be further processed using the wide range of tools supporting them.

Thirdly, RespVis has been designed as a library that extends D3. Compared to other visualization libraries that are built on top of D3, RespVis does not represent a wrapping layer around it. It does not provide an entirely new interface to library users but uses D3 Selections as the core interface with which to interact. The typical workflow of invoking RespVis functionality is to bind data objects of a specific structure onto the elements of a Selection and visualize this data by calling a render function that transforms it into visual marks. If D3 was hidden behind a custom API, its powerful capabilities for the rendering of documents would not be accessible to users of the library and would need to be exposed manually through special mechanisms. By designing RespVis as an extension of D3, users can continue to leverage its expressive and concise API and author their documents using data joins and the general update pattern.

Fourthly, data and code are decoupled from each other. Everything in RespVis is built from functions and objects without using any classes. Classes have been avoided because they are not common when working with D3 and also because they lead to a tight coupling between data and functionality, which has been deemed undesirable. The decoupling of data and code results in various benefits compared to the prevalent object-oriented way of building software. Among these benefits are easier reuse and testing of functions and a software system that requires less cognitive effort to understand it. Functions are easier to reuse because they only require certain-shaped input data to perform their task, and no mechanisms like inheritance or composition, which tend to increase the complexity of a system, are necessary. Compared to class-based code, where an object needs to be instantiated before testing its methods, it is easier to test functions in isolation when they are not coupled to their data. The reason for this is that the instantiation of an object might be a complex operation that depends on other methods and could affect the results of a test case. Possibly the main benefit of decoupling data and code lies in the reduced complexity of the resulting system. A software system that treats data and code as different entities might be composed of more entities than a system that does not, but individual entities have fewer dependencies between one another. This reduced number of dependencies between entities in such a system comes from separating entities into a data entities group and a function entities group, with no relationships between them. The research related to software complexity is hard to convey in simple terms, but one rule that is related to this concept of data and code separation is well summarized by Sharvit [2022] as “A system made of disjoint simple parts is less complex than a system made of a single complex part.” Of course, there are also various drawbacks when designing a system adhering to this concept, but they are not too severe and are therefore not listed here. For further research on this topic, readers are advised to review Sharvit [2022] and Moseley and Marks [2006].

Fifthly, the library is written in TypeScript, with everything being as strongly-typed as possible. For the most part, interfaces are used to describe the structure of data objects, and function parameters are annotated with types. Whenever working with D3 Selections, their contents are typed as strongly as possible using the generic type variables available on Selections. Most of the time, it is sufficient to specify only the type of elements contained in a Selection and the structure of the data bound on them. If the element and data types of a Selection are declared, the various functions can assume that parameters

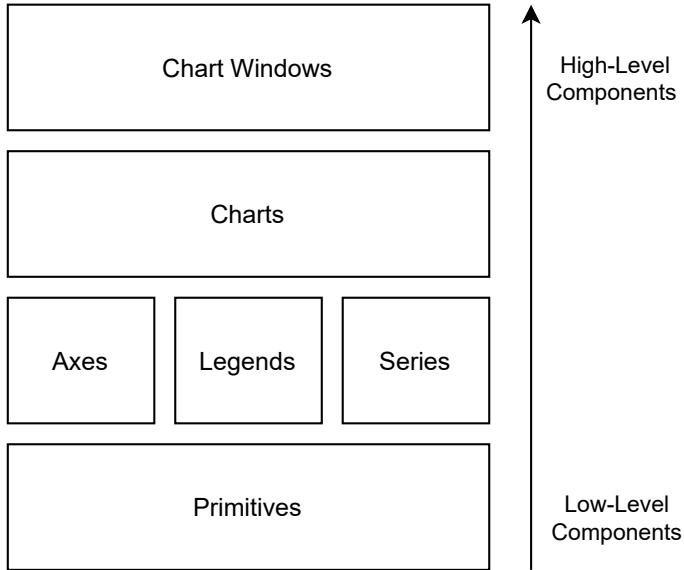


Figure 5.1: This diagram shows the different layers of components of the RespVis library. Layers that are higher in the hierarchy contain increasingly higher-level components that make more assumptions than components in lower layers. The lowest level of components are primitives that are merely SVG elements such as `<rect>`, `<circle>`, and `<text>` elements. Axes, legends and series are composite components that only contain primitives. Charts are composite components that are composed of lower-level primitives or other composite components to form a complete visualization. Chart Windows are wrapper components around Charts, manage their rendering process and provide a toolbar for them. [Image created by the author of this thesis.]

passed to them have specific types, and they do not have to worry about dynamic type checking. Applying a strongly-typed type system has many advantages like better development tooling and the compile-time identification of type-related bugs. These advantages have already been described in Section 2.4.

Sixthly, components in RespVis are structured in layers with different levels of abstraction. Components in higher layers need to make more assumptions about their content than components in lower layers. The bottom-most layer with the lowest level of abstraction consists of visual primitives that are represented by basic SVG elements like `<rect>`, `<circle>`, and `<text>` elements. These primitives do not require any data to be bound on them and are simply rendered by setting their attributes to the desired values. The layer above primitive elements is formed by composite components, which are usually rendered as `<svg>` or `<g>` elements that only contain primitive elements. The components in this layer include axes, legends, and series and are the lowest-level components that are configured using structured data bound on their elements. Series components are composite elements that render a collection of underlying elements using a data join and the general update pattern. The next higher layer consists of chart components. Charts are composite components that can also include other composite components. They are the visual entities that represent complete visualizations and are usually composed of axes, series, and legend components. In many other visualization libraries, charts are the highest-level components users can work with, but RespVis contains an additional layer above them, formed by Chart Window Components. Chart Windows are also composite components, but unlike all previously discussed layers, they are not rendered as SVG elements but as HTML `<div>` elements. Their purpose is to nest Charts into a Layouter Component, render them in a three-phased rendering process, and provide a toolbar for them. Toolbars are customizable and will hold different tools for different types of charts. The hierarchy of component layers in RespVis can be seen in Figure 5.1.

5.2 Naming Conventions

The naming of entities in RespVis follows the same naming conventions used in D3 modules. In D3-related modules, names of entities usually start with the name of the group to which an entity belongs and are then further narrowed down by successively adding more words until the exact entity is accurately described. This convention is not explicitly named, but it is referred to as “top-down naming” in this work. An example of the top-down naming convention can be seen in the `d3-scale` [Bostock 2022b] and `d3-axis` [Bostock 2022a] modules, in which entities are called things like `scaleLinear`, `scaleOrdinal`, `axisBottom`, and `axisLeft` rather than `linearScale`, `ordinalScale`, `bottomAxis`, and `leftAxis`. Since this is the exact opposite of how these entities would be called in the natural English language, using such names can feel odd for the uninitiated. However, the experience of working with APIs following such a naming convention is superior to when they do not. The reason for this is that users of such APIs can easily discover specialized entities by inputting the general entity type and browsing through code completion suggestions provided by their development tools. Due to this superiority and to stay consistent with other D3 modules, the decision has been made that entity names in RespVis should also follow this convention.

RespVis’ public interface is mostly made up of types and functions. Types are usually written as interfaces and represent the shape of an object. Their names are written in `PascalCase` and adhere to the top-down naming convention. They always start with the group a type belongs to, and more words are successively added to distinguish between gradually more specialized types. The naming of types can best be demonstrated by the different names given to interfaces describing data objects that configure different kinds of Bar Charts. Data objects for the configuration of Basic Bar Charts are described by the `ChartBar` interface, those of Grouped Bar Charts are described by the `ChartBarGrouped` interface, and those of Stacked Bar Charts are described by the `ChartBarStacked` interface.

The API of RespVis is mainly composed of functions. Function names are always written in `camelCase` and also follow the top-down naming convention. They always start with the type of object on which they operate, followed by the operation they perform. A component in RespVis always consists of a data object that describes it, an element to which the data object is bound, and a render function that transforms the bound data into some form of visual representation. The names of functions that create data objects for the configuration of components are always in the form of `componentNameData`, such as `chartBarData` or `chartBarGroupedData`. Functions that transform bound data into the visual representation of a component are always named in the form of `componentNameRender`, such as `chartBarRender` or `chartBarGroupedRender`.

5.3 Project Setup

RespVis is set up as a NodeJS [OpenJS 2021] project that is hosted as an open-source project on GitHub [Oberrauner 2022]. The implementation is written in TypeScript and grouped into different modules by thematic affinity. These TypeScript source files must be compiled to JavaScript and bundled into one combined package so that users can import the library into their projects. The Rollup module bundler [Rollup 2022] is used to perform this compilation and bundling. In addition to the bundled JavaScript library, users are required to import an accompanying CSS file containing default styling for the generated visualizations. The project also contains examples to demonstrate usage of the library by creating various charts. These examples are HTML files that import required files and contain JavaScript that invokes RespVis functionality to create and update visualizations. The build process of the library contains multiple steps and includes the preparation of the output directory, the bundling of library code, and the copying of various files to the correct locations in the output directory. It would be tedious to manually perform all these steps every time the library needs to be rebuilt, and therefore this process is automated using the Gulp [Gulp 2022] task runner, a task-based workflow automation tool. The following sections will briefly introduce the setup of RespVis and the tools used in the development process.



Figure 5.2: The directory structure of RespVis project. Only important files are shown here for readability reasons. [Figure created by the author of this thesis.]

5.3.1 Directory Structure

This section aims to give an overview of the directory structure of the RespVis project. Roughly summarized, the project contains configuration files for various tools, a `src/` directory containing the source code for the whole library and accompanying examples, a `node_modules` directory containing the project's cached NodeJS dependencies, and a `dist/` directory containing built versions of the library and examples ready for distribution. The configuration files are only discussed broadly here, as later sections go into more details about the setup of the various tools. A tree visualization of the whole directory structure, including all important files and directories but excluding individual source files, can be seen in Figure 5.2.

At the root directory of the RespVis project reside the necessary project configuration files for NodeJS, TypeScript, and Gulp. The NodeJS configuration file, `package.json`, describes the meta-data of the NodeJS project. It is used to specify the project's dependencies to other packages and is required for every NodeJS project so that it can be uploaded to the npm package registry [npm 2022]. The TypeScript configuration file, `tsconfig.json`, specifies the configuration the TypeScript compiler uses to compile

the libraries' TypeScript source files into their JavaScript counterparts. The Gulp configuration file, `gulpfile.js`, is used to describe atomic, recurring tasks and compositions of them. These tasks can then be invoked via the Gulp command-line tool to automate otherwise tedious workflow processes.

The `src/` directory at the root of the project contains all the implementation files of the library in the `src/lib/` directory and examples in the `src/examples/` directory. The `src/lib/` directory contains all TypeScript source files of the library. They have been partitioned into modules formed around the thematic affinity of the various components. The `core` module contains the core functionality of the library and is a prerequisite for all the other modules. It includes the Layouter, Chart base functionality, Chart Window base functionality, and various utility functions that simplify diverse tasks when creating visualizations. The `legend` module contains a Legend Component, which renders a Legend consisting of a title and configurable labeled symbols. The `tooltip` module contains functions to show and hide tooltips, modify their contents, and position them. It also contains helper functions for Series Components to prevent the replication of tooltip-related code in their data creation and rendering functions. The `bars` and `points` modules contain the necessary Series, Chart, and Chart Window Components to render bar, grouped bar, stacked bar, and point visualizations. At the moment, all these modules are being built into a combined package, but there are plans to distribute them separately to allow users of the library to only import those packages they need to not unnecessarily increase their bundle sizes with code they do not require.

Beside the `src/lib/` directory, the `src/` directory also contains the `src/examples/` directory, which holds the source files of the developed examples. These examples are distributed alongside the library files, so they are copied to the `dist/examples/` directory upon building the project. Every example consists of an HTML file that imports all the requirements such as `respvis.js` and `respvis.css` as well as external dependencies such as D3. It then invokes the necessary RespVis functionality within a `<script>` tag, which is embedded in the body of the document. In addition to the individual example files, the `examples` directory also contains a `vendor` directory, which contains third-party dependencies, and a `data` directory containing data, which is imported by individual examples to make it reusable.

In addition to configuration files and the `src/` directory, the root directory also contains two directories that are automatically generated during the build process. These are the `node_modules/` and `dist/` directories. The `node_modules/` directory is a directory that exists in every NodeJS project. It is created when installing the dependencies of a NodeJS project and contains a cached copy of every direct and indirect dependency. The `dist/` directory is generated by the Gulp build tasks and contains all the files necessary to distribute a built version of the library.

The code of RespVis is distributed as JavaScript bundles of different formats that can be used depending on the situation. These formats are based on both Immediately Invoked Function Expressions (IIFE) and the more modern ES modules format, both of which are explained in more detail in Section 5.3.3. Bundles containing the `.js` extension in their file name contain IIFE source code, whereas bundles containing the `.mjs` extension contain ES module source code. These bundles are also distributed in gradually more minimized versions. The `dist/respvis.[m]js` file contains the unmodified JavaScript bundle that can be used by library consumers who require readable code, `dist/respvis.min.[m]js` contains the minimized JavaScript bundle, and `dist/respvis.min.[m]js.gz` contains the minimized JavaScript bundle that has additionally been compressed in the GZIP format [Deutsch 1996]. Beside these code bundles, the Rollup module bundler has been configured to create source maps for the `dist/respvis.[m]js` and `dist/respvis.min.[m]js` bundles: `dist/respvis.[m]js.map` and `dist/respvis.min.[m]js.map`. These source maps are interpreted by developer tools in browsers to map from certain instructions in the bundled JavaScript code to the exact instruction in the original TypeScript code. Source maps are an immense help when developing the library because, without them, debugging in browsers would be virtually impossible. Since RespVis aims to perform all possible styling in CSS, the distribution also contains a `dist/respvis.css` file that contains all the default styles of visualizations created with RespVis. Currently, this file is written manually as a whole in the `src/` directory and merely copied to the

`dist/` directory during the build process. In the future, this process should be improved by employing a CSS preprocessing tool such as SASS [O'Donnell 2019] so that the styles can be split into multiple files during development. Besides the bundled library source code and stylesheets, the `dist/` directory also contains usage examples of the library within the `dist/examples/` directory. This directory is identical to the one under `src/examples/` because it is merely copied to the `dist/` folder during the build process.

5.3.2 NodeJS

NodeJS is a standalone JavaScript runtime built on top of the V8 JavaScript engine [Google 2022], which is an open-source and multi-platform runtime that enables the execution of JavaScript code outside of web browsers. NodeJS is heavily used for server-side development to unify the technology stack of web developers and allow them to use JavaScript for both client-side and server-side development. However, with the appropriate project setup, NodeJS can be used for any kind of development, and it can even be set up as a very powerful framework to develop client-side applications as done in this project. One of the most important tools in the NodeJS environment is the npm package manager [*npm* 2022], which exists to simplify the sharing of source code modules and the dependency management of a module. The npm package registry hosts a huge number of open-source modules for NodeJS projects, which can easily be imported and used to create new ones.

RespVis is developed as an npm package. Every npm package is configured via a `package.json` file. This file contains all the necessary meta-data of a package to make it identifiable and provide enough information about what the package contains. The `package.json` file also lists all the dependencies of a package, so they can easily be updated and downloaded during its installation process. A package can include normal dependencies and development dependencies. The difference between those two types of dependencies is that normal dependencies of a package are required for it to work and need to be installed alongside it, whereas development dependencies are only required for a package's development process and are only installed when installing a local package. The `package.json` file that is located in the root directory of the RespVis package can be seen in Listing 5.1.

5.3.3 Rollup

The Rollup module bundler is used to bundle the source code of the RespVis library in bundles of different module formats. Bundling combines code written as multiple smaller modules into one combined one to make it easier to distribute. Developers do not have to worry about the details of how their code will be packaged, as Rollup takes care of all the necessary transformations. In addition to bundling source code, Rollup also performs tree shaking on the bundled code, which eliminates unused code from the resulting bundle by statically analyzing dependencies between modules.

Rollup supports creating bundles in most common module formats like CommonJS, Asynchronous Module Definition (AMD), Universal Module Definition (UMD), Immediately Invoked Function Expressions (IIFE), and ES. RespVis is distributed as both IIFE and ES modules. IIFEs have already existed for a long time, as they were used to support modular software designs in JavaScript before more elaborate module formats were defined. They are anonymous functions that are executed directly after declaring them. These functions contain the full logic of the module and return an object representing its publicly accessible interface. This object is usually stored in a variable to allow interactions with the module after its creation. IIFE modules are plain JavaScript and do not require any modern features to be supported by browsers. They are simply loaded in web documents like any other JavaScript resource via a `<script>` element. The example in Listing 5.2 was created to demonstrate the IIFE module format.

ES modules are a more recent addition to JavaScript, as they have only been introduced in ECMAScript 6 [ECMA 2015]. They are a native module system that is built on the `import` and `export` statements, which are widely supported by modern browsers. Given that the individual modules of the RespVis library are built as ES modules, Rollup mostly only has to merge them to create a valid, combined ES module.

```

1  {
2    "name": "respvis",
3    "version": "0.2.0",
4    "description": "A library to build responsive SVG-based visualizations.",
5    "main": "index.js",
6    "scripts": {
7      "build": "npx gulp build",
8      "start": "npx gulp"
9    },
10   "repository": {
11     "type": "git",
12     "url": "git+https://github.com/AlmostBearded/respvis.git"
13   },
14   "keywords": [
15     ...
16   ],
17   "author": "Peter Oberrauner",
18   "license": "MIT",
19   "bugs": {
20     "url": "https://github.com/AlmostBearded/respvis/issues"
21   },
22   "homepage": "https://github.com/AlmostBearded/respvis#readme",
23   "devDependencies": {
24     "rollup": "^2.45.2",
25     "rollup-plugin-gzip": "^2.5.0",
26     "rollup-plugin-terser": "^7.0.2",
27     "@rollup/plugin-commonjs": "^18.0.0",
28     "@rollup/plugin-node-resolve": "^11.2.1",
29     "@rollup/plugin-typescript": "^8.2.1",
30     "@types/...": "...",
31     "browser-sync": "^2.26.14",
32     "del": "^6.0.0",
33     "gulp": "^4.0.2",
34     "gulp-cli": "^2.3.0",
35     "gulp-rename": "^2.0.0",
36     "tslib": "^2.2.0",
37     "typescript": "^4.2.4"
38   },
39   "dependencies": {
40     "d3": "^7.2.1",
41     "debounce": "^1.2.1",
42     "to-px": "^1.1.0",
43     "uuid": "^8.3.2"
44   }
45 }
```

Listing 5.1: The package.json file of the RespVis library. This file contains all the meta-data to describe the package and it's dependencies. Keywords and type dependencies have been omitted for readability reasons.

```
1 // do-something.js
2 export function doSomething() {
3   console.log('something incredible was done!');
4 }
5
6
7 // module.js
8 var someModule = (function () {
9   function doSomething() {
10     console.log('something incredible was done!');
11   }
12   return { doSomething };
13 })();
14
15
16 // application.js
17 someModule.doSomething();
```

Listing 5.2: Immediately Invoked Function Expression (IIFE) modules wrap the module code into a function that gets executed immediately after declaring it and returns the public interface of the module. Comments were added to show in which files the individual pieces of code reside. `do-something.js` contains the original code that should be wrapped into an IIFE module, `module.js` contains the code of the IIFE module, and `application.js` demonstrates usage of the module.

Since ES modules are natively supported in browsers, they can be loaded directly in a web document using a `<script>` element. However, it is necessary to mark them as modules via the `type="module"` attribute on the loading `<script>` element so that browsers can interpret them accordingly.

The core package of Rollup is only able to create mostly unmodified bundles from JavaScript source files. Various plugins exist that add frequently-required additional functionality. There are two kinds of Rollup plugins: bundle plugins, which affect the bundling process, and output plugins, which transform the already bundled code.

The bundle plugins that are used for the bundling of RespVis are the `@rollup/plugin-node-resolve`, `@rollup/plugin-commonjs`, and `@rollup/plugin-typescript` plugins. The `@rollup/plugin-node-resolve` plugin is used to resolve imports from other NodeJS packages that reside in the `node_modules` directory. Since many NodeJS packages are still implemented as CommonJS modules, which are not natively supported by Rollup, the `@rollup/plugin-commonjs` plugin has been added to interpret them. Lastly, the `@rollup/plugin-typescript` plugin is used to compile TypeScript source files to JavaScript before bundling them. The configuration with which the TypeScript compiler is invoked is taken from the `tsconfig.json` file at the root directory of the project.

The output plugins used during the bundling process are the `rollup-plugin-terser` and `rollup-plugin-gzip` plugins. These plugins do not affect every created bundle but are used to selectively transform the contents of specific bundles. The `rollup-plugin-terser` plugin is used to minify the code of created bundles containing the `.min` extension in their file names. Logically, they are equivalent to non-minified bundles, but they are compressed as much as possible to reduce their file size while still containing valid, although unreadable, JavaScript code. Another output plugin used for even stronger minification is the `rollup-plugin-gzip` plugin. This plugin has been applied to all bundles containing the `.gz` extension in their file names. It performs another step of compression on bundles that have already been minified using the `rollup-plugin-terser` plugin, by packing them in the GZIP compression format [Deutsch 1996].

Another noteworthy thing is that D3 is not included in any of the generated bundles. The reason for this is that RespVis is designed to be an extension of D3 and, most of the time, an application that wishes to use RespVis will already be relying on it. If D3 were to be included in the bundle of RespVis, it would unnecessarily be loaded a second time. This redundancy would cause a needless increase in the bundle size and loading time of the library. To prevent D3 from being included in the created bundles, all dependencies from D3-related packages are marked as external.

The actual bundling is performed via the JavaScript API of Rollup in the private `bundleJS` Gulp task. This task is executed in various automation processes set up with Gulp, which are explained in more detail in Section 5.3.4. The code of the `bundleJS` task can be seen in Listing 5.3. As can be observed in the code, the Rollup API allows the library to be bundled once via the `Rollup.rollup` function that returns the created bundle. This bundle can then be written to the target destination via the `Bundle.write` method, which allows the specification of the target bundle format and the plugins used to transform the code before writing it.

5.3.4 Gulp

Gulp is a task runner that automates workflow processes via a set of named tasks. It is used to automate processes like building the library and serving examples on a development server. Tasks perform a certain operation that needs to be carried out recurring. They can perform an atomic operation or represent a composition of other tasks. These composite tasks can execute tasks contained in them in a serial or parallel order. Individual tasks are implemented as JavaScript functions in the Gulp configuration file, `gulpfile.js`, which can be found in the root directory of the project. This approach of favoring code over declarative configuration files means that the person setting up process automation needs to be familiar with JavaScript. In return, the possibilities of configuration are endless.

Tasks in the `gulpfile.js` file have been separated into private and public tasks. Private tasks are simply asynchronous functions that perform a certain action that does not necessarily have to be executed by external entities. The private Gulp tasks set up in the RespVis project are the `bundleJS`, `bundleCSS`, `copyExamples`, `cleanDist`, `cleanNodeModules`, and `reloadBrowser` tasks. Public tasks are also asynchronous functions, but they are exported and are therefore available to be executed via the Gulp command-line interface. Most public tasks set up in this project are compositions of other tasks. The public tasks that are available are the `clean`, `cleanAll`, `build`, and `serve` tasks. The default task that is being executed when no other task is specified via the command-line interface is the `serve` task. A hierarchical representation of all the tasks in the `gulpfile.js` file can be seen in Listing 5.4.

Bundling of the library's source code is implemented in the private `bundleJS` task. It uses the JavaScript API of Rollup to bundle all TypeScript files into IIFE and ES modules of varying levels of minification. This task has already been described in detail in Section 5.3.3, so it won't be discussed further here. It is executed during the public `build` and `serve` tasks.

The `bundleCSS` task is used to copy the `src/respvis.css` file to the `dist/` directory. Since one of the design pillars of RespVis is to style everything possible with CSS, this file contains all the default styles for visualizations created with RespVis. Currently, this file is written as a whole in the `src/` directory and merely copied to the `dist/` directory, but there are plans to build this file from different modules using a CSS preprocessor in the future, which will require an additional bundling step. This task is executed as part of the public `build` and `serve` tasks.

The private `copyExamples` task copies all the files from the `src/examples/` directory to the `dist/` directory. This task is required because the examples are being developed inside the `src/` directory, and they need to be made available as library distributables. Another reason for the copying is that the `BrowserSync` development server is initialized with the `dist/` directory as its root, and every file that should be viewable on this server must reside somewhere in there. The `copyExamples` task is executed during the public `build` and `serve` tasks.

```

1  async function bundleJS() {
2    const bundle = await rollup.rollup({
3      input: 'src/lib/index.ts',
4      external: [
5        'd3-selection',
6        'd3-array',
7        'd3-axis',
8        'd3-brush',
9        'd3-scale',
10       'd3-transition',
11       'd3-zoom',
12     ],
13     plugins: [
14       rollupNodeResolve({ browser: true }),
15       rollupCommonJs(),
16       rollupTypeScript()
17     ],
18   });
19
20  const minPlugins = [rollupTerser()];
21  const gzPlugins = [rollupTerser(), rollupGzip()];
22  const writeConfigurations = [
23    { ext: 'js', format: 'iife', plugins: [] },
24    { ext: 'min.js', format: 'iife', plugins: minPlugins },
25    { ext: 'min.js', format: 'iife', plugins: gzPlugins }, // .gz added by plugin
26    { ext: 'mjs', format: 'es', plugins: [] },
27    { ext: 'min.mjs', format: 'es', plugins: minPlugins },
28    { ext: 'min.mjs', format: 'es', plugins: gzPlugins }, // .gz added by plugin
29  ];
30
31  return Promise.all(
32    writeConfigurations.map((c) =>
33      bundle.write({
34        file: `dist/respvis.${c.ext}`,
35        format: c.format,
36        name: 'respVis',
37        globals: {
38          'd3-selection': 'd3',
39          'd3-array': 'd3',
40          'd3-axis': 'd3',
41          'd3-brush': 'd3',
42          'd3-scale': 'd3',
43          'd3-transition': 'd3',
44          'd3-zoom': 'd3',
45        },
46        plugins: c.plugins,
47        sourcemap: true,
48      })
49    )
50  );
51}

```

Listing 5.3: The private Gulp task that bundles the code of the RespVis library. Bundling is performed once using the Rollup.rollup function. After the library has been bundled, it is written multiple times with different configurations using the `Bundle.write` method.

```

1 Tasks for gulpfile.js
2 |-- clean
3 |-- cleanAll
4 | |-- <series>
5 |   |-- cleanDist
6 |   |-- cleanNodeModules
7 |-- build
8 | |-- <series>
9 |   |-- cleanDist
10 |   |-- <parallel>
11 |     |-- bundleJS
12 |     |-- bundleCSS
13 |     |-- copyExamples
14 |-- serve
15 |-- default

```

Listing 5.4: A hierarichal representation of the tasks defined in the `gulpfile.js` file. This presentation has been created with the `gulp --tasks` command.

The private `cleanDist` and `cleanNodeModules` tasks are used to respectively delete the `dist/` and `node_modules/` directories. The `cleanDist` task is exported under a different name as the public `clean` task. This task is necessary because without cleaning the `dist/` directory before every rebuild, files from previous builds that might have disappeared in the meantime would cause littering and confusion. Therefore, this task is being executed as the first step of the `build` task. The public `cleanAll` task is composed of the private `cleanDist` and `cleanNodeModules` tasks. It is only manually executed when developers want to delete the currently cached dependencies of the project to reinstall them from scratch.

The public `build` task is responsible for building all parts of the project. It is a composite task that executes the `clean`, `bundleJS`, `bundleCSS`, and `copyExamples` tasks. The `clean` task is invoked before all of the other tasks, which are then executed in parallel. After this task finishes, the `dist/` directory will contain all distributable JavaScript and CSS files of the library, as well as the distributable `examples/` directory.

To simplify the development of RespVis, a Browsersync [Browsersync 2022] development server is used to host the built distributables. Browsersync is a useful tool for synchronized browser testing. It has many features like simulated network throttling, interaction synchronization, and file synchronization that enable simultaneous testing in multiple environments. In the setup of RespVis, it is only used for its ability to synchronize and hot-reload files on the fly. The public `serve` task, which is also exported as the default task, initializes a Browsersync development server that serves files from the `dist/` directory. Automatic reloading of the development server is implemented manually via the Gulp `.watch` function. This function enables a task to be executed whenever a change to a file matched by the supplied glob pattern is detected. The `serve` task implements three different cases that cause the development server to reload. Firstly, every time one of the TypeScript files in the `src/lib/` directory changes, the `bundleJS` task is executed, and the browser is reloaded. Secondly, every time the `src/respvis.css` file changes, the `bundleCSS` task is executed, and the browser is reloaded. Thirdly, whenever a file in the `src/examples/` directory is changed, the `copyExamples` task is executed, and the browser is reloaded.

Chapter 6

Modules

The source code of RespVis is structured into modules written in the ES module format. Currently, all these modules are combined into a single, monolithic library bundle during the build process. In the future, each module will be released on its own to allow users to import only the ones they need. The reason for this is that most users will likely only require a subset of all the features included in the library, and it would unnecessarily increase the size of their bundles to import all of them. A good example of this is D3, which also separates its considerable amount of features into different modules that can be successively added to a project when the need arises.

At the time of writing, the RespVis library contains five different modules: the Core, Legend, Tooltip, Bar, and Point Modules. Each of these modules contains submodules that have been grouped by thematic similarity. The Core Module holds the core functionality of the library that all other modules depend on and includes the Layouter and Axis Components, Chart and Chart Window base functionality, and various utility functions and types. The Legend Module contains the implementation of a Legend Component that is mostly meant to describe discrete data by rendering distinct values as labeled symbols. The Tooltip Module holds functions to control the showing, placement, and content of Tooltips, as well as utility functions that simplify the configuration and initialization of Tooltips on Series Components. The Bar Module distinguishes between Single-Series, Grouped, and Stacked Bars and includes various low-level and high-level components to render each of those types. Similarly, the Point Module contains low-level and high-level components to visualize Point Charts. All of the different modules and the dependencies between them are shown in Figure 6.1.

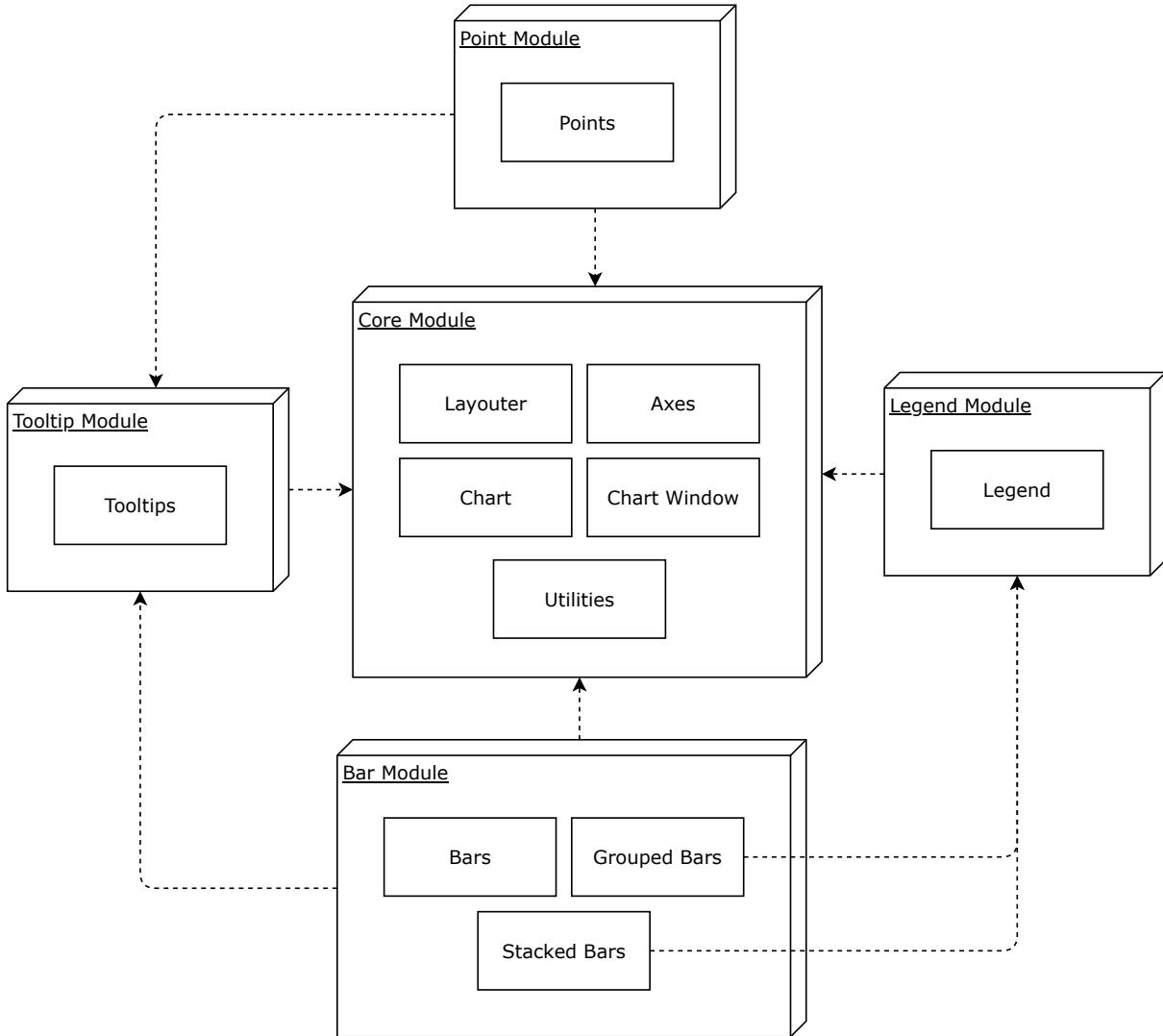


Figure 6.1: This diagram shows the different modules of the RespVis library. It also shows the most important submodules contained in the individual modules. The directional arrows connecting modules indicate dependencies between them. [Image created by the author of this thesis using diagrams.net.]

6.1 Core Module

The Core Module contains the necessary core functionality of the library. It is the base module that all other modules depend on and includes various utility functions, the Layouter, Axes, Chart base functionality, and Chart Window base functionality. RespVis heavily relies on utility functions to reuse and structure recurring operations. The Core Module contains utilities to deal with arrays, elements, Selections, and texts, as well as geometric utilities that simplify the handling of positions, sizes, rectangles, circles, and paths. The Layouter is a custom component that enables controlling the layout of SVG elements with CSS. Axis Components have been included in the Core Module because they are important components that occur in nearly every visualization. Lastly, the Core Module offers Chart and Chart Window base functionalities that simplify the creation of more specialized Charts and Chart Windows. The implementation of the Core Module is located in the `src/lib/core/` directory of the project.

6.1.1 Utilities

The utilities provided by RespVis are split into multiple modules that are placed in the `utilities/` directory of the core module. These modules include types and functions that perform array, element,

Selection, and text operations, as well as modules that simplify geometric operations with positions, sizes, rectangles, circles, and paths. Utility functions are grouped into modules by the type of entity on which they operate. This grouping is also reflected in the names of functions because they all begin with the type of entity with which a function is associated.

Array utilities can be found in the `utilities/array.ts` module. The `Array` class in the JavaScript base implementation already offers a wide variety of convenient methods to work with arrays. These methods form a solid foundation to handle a broad range of situations, but not everything is covered, and some things require manual implementations, which is why the `RespVis` library offers additional functions that simplify commonly encountered tasks. The `arrayEquals` function is used to verify the equality of two arrays and also works if they contain nested arrays within them. Type guard functions are used to determine the type of a variable at runtime. For this purpose, two different array type guard functions are provided in the array utility module: `arrayIs`, which evaluates to true if the passed parameter is an array, and `arrayIs2D`, which evaluates to true if the handed parameter is a two-dimensional array. The `arrayIs` function is merely a wrapper around the `Array.isArray` method. Theoretically, the `Array.isArray` method could be used directly instead of the `arrayIs` function, but because the `arrayIs2D` function is required, the `arrayIs` function has also been added for consistency reasons. The last function in the array utility module is the `arrayPartition` function. This function receives an array and a partition size as parameters and returns a partitioned version of the input array with each chunk containing the number of items specified by the partition size parameter.

The Element Utility Module located at `utilities/elements.ts` in the Core Module contains functions and constants related to elements in a document. The `elementRelativeBounds` function is used to calculate the bounding box of an element relative to the bounding box of its parent in viewport coordinates. Internally, it uses the `getBoundingClientRect` function, which returns the actual bounding box of an element in viewport coordinates and, as opposed to other ways of accessing an element's position, it also takes transformations into account. Every element has a set of CSS styles applied to them, and the `Window.getComputedStyle` method can be used to access the active style of an element. The style declaration object returned by this method contains all possible CSS properties and their values, regardless of whether or not they are set to default values. Sometimes this behavior may be desired, but in this library, the computed style is used to prepare a downloadable SVG document to transform styling information set in CSS to attributes on the individual elements. If every possible CSS property on every element would be mapped to an attribute, the resulting SVG document would be unnecessarily bloated because only those properties that are not set to their default values actually have an effect. For this reason, the `elementComputedStyleWithoutDefaults` function has been implemented to calculate the computed style of an element and remove all properties that are at default values from the returned style declaration object. This is implemented by adding a `<style-dummy>` element as a sibling of the element of interest, getting the computed styles of both elements, and calculating the difference between them. To accelerate these calculations, the `elementComputedStyleWithoutDefaults` function accepts an array of property names as its second parameter and will only consider the properties listed in this array. The constant `elementSVGPresentationAttrs` array contains all names of the presentation attributes listed in the SVG 1.1 specification [Dahlström et al. 2011]. Since only these SVG attributes can be styled via CSS, only these properties must be considered when preparing downloadable SVG documents.

Selection utilities are implemented in the `utilities/selection.ts` module. They include typing improvements for the D3 Selection, Transition, and SelectionOrTransition interfaces and type guards to distinguish between Selections and Transitions. The Selection, Transition, and SelectionOrTransition interfaces allow the specification of four type variables: the type of elements contained in the Selection or Transition, the type of data bound to those elements, the type of the parents of those elements, and the type of data bound to those parents. In most cases, the type variables related to parent elements do not influence the logic of code using these interfaces and could be omitted to keep it more concise. For this reason, these interfaces have been reexported with default types set on all of the type variables, which means that whenever type variables need to be manually specified, only those

that need to be set to specific types need to be explicitly stated. Further typing improvements have been made to the `attr` and `dispatch` methods of the `Selection` interface. The D3 type declarations of the `Selection.attr` method do not include `null` as a possible return value, which is wrong because this method will result in a `null` value when reading an attribute that does not exist. To fix this inconsistency and catch potential bugs related to it during compilation, the type declaration of the `Selection.attr` method has been overwritten in the Selection Utility Module to include `null` as a possible return value. A less important but convenient improvement has been made to the type declaration of the `Selection.dispatch` method. This method allows the dispatching of custom events with certain parameters that control different aspects of how this event is dispatched and the data bound to it. In practice, not all parameters need to be specified at every invocation because the implementation of the `Selection.dispatch` method will provide default values for all of them, but this is not reflected in the type declaration of the function, which requires every parameter to be set every time the function is called. To fix this, the Selection Utility Module provides a type declaration overwrite for the `Selection.dispatch` function that wraps the type of the `parameters` parameter into the `Partial` utility type. Apart from these typing improvements, this module also provides the `isSelection` and `isTransition` type guard functions that are used to distinguish between Selections and Transitions.

Utilities for dealing with `<text>` elements can be found in the `utilities/text.ts` module. It contains rather basic functionalities that simply set specific `data-*` attributes to specific values on `<text>` elements. The Text Utility Module holds functions that set `data-*` attributes controlling the horizontal and vertical alignment of `<text>` elements, as well as their orientation. Horizontal and vertical alignment is configured using the `textAlignHorizontal` and `textAlignVertical` functions. These functions respectively set the `data-align-h` and `data-align-v` attribute on a Selection or Transition to the value passed into either function as a string enum parameter of type `HorizontalAlignment` or `VerticalAlignment`. The `HorizontalAlignment` enum represents the string values "left", "center" and "right", while the `VerticalAlignment` enum represents the values "top", "center" and "bottom". The distinct `data-align-h` and `data-align-v` attribute values are then used in the Selectors of CSS rules to declare different `text-anchor` and `dominant-baseline` property values. Text orientation is set using the `textOrientation` function, which sets the `data-orientation` attribute on a Selection or Transition to the value specified via the string enum parameter of type `Orientation`. The `Orientation` enum represents the values "horizontal" and "vertical". These `data-orientation` attribute values are then used in CSS to set the `text-anchor`, `dominant-baseline`, and `transform` properties of a `<text>` element, in order to rotate it accordingly and position it correctly inside the bounding box calculated by the layouter.

The Core Module also contains utilities that simplify geometric operations. One of these utilities is the Position Utility Module located in the `utilities/position.ts` file. This module contains the `Position` interface and various functions to perform operations related to it. The `Position` interface consists of the `x` and `y` number properties. Rounding these properties is necessary to be able to correctly compare the equality of two `Position` objects and to not render unnecessarily long strings when transforming them into string representations. This rounding is performed with the `positionRound` function, which allows the specification of the number of decimals the properties should be rounded on. Equality comparison between two `Position` objects can be done with the `positionEquals` function, which evaluates to `true` if both `Position` objects are equal and `false` if not. To transform a `Position` object into its string representation of the form "`x, y`", the `positionToString` function can be used. Its counterpart, the `positionFromString` function, can be used to transform a string of the correct format into a `Position`. A large part of `RespVis` consists of modifying the attributes of elements. Therefore, the `positionToAttrs` function can be used to set the `x` and `y` attributes of a `SelectionOrTransition` to the values of the `x` and `y` members of a `Position`. Similarly, the `positionToTransformAttr` function can be used to set the `transform` attribute of a `SelectionOrTransition` to a translation representing a `Position`. The Position Utility Module also contains the `positionFromAttrs` function, which can be used to create a `Position` object from the `x` and `y` attributes of a `SelectionOrTransition`.

The Size Utility Module located in the `utilities/size.ts` file in the Core Module is very similar

to the Position Utility Module. It contains the `Size` interface, which consists of the `width` and `height` number properties. The `sizeRound` function is used to round the properties of a `Size` object to a certain number of decimals. To compare two `Size` objects for equality, the `sizeEquals` function can be used. Similar to the equivalent functions in the position utility module, the `sizeToString` and `sizeFromString` functions can be used to convert between `Size` objects and their string representations. Moreover, the `sizeToAttrs` function can be used to set the `width` and `height` attributes of a `SelectionOrTransition` to the property values of a `Position` object and the `sizeFromAttrs` function can be used to create a new `Position` object from the values of these attributes.

Utilities for dealing with rectangles can be found in the Rectangle Utility Module, which is located in the `utilities/rect.ts` file of the Core Module. This module contains the `Rect` interface, which is the union of the `Position` and `Size` interfaces and therefore describes an object with the number properties `x`, `y`, `width`, and `height`. Similar to the `Position` and `Size` Utility Modules, this module contains the `rectRound` function to round `Rect` objects, the `rectEquals` function to compare two of them for equality, the `rectToString` and `rectFromString` functions to convert between `Rect` objects and their string representations, and the `rectToAttrs` and `rectFromAttrs` functions to convert between objects and `x`, `y`, `width`, and `height` attributes. Since the `Rect` interface is a combination of the `Position` and `Size` interfaces, most of the functions in this module internally use the functions provided by the `Position` and `Size` Utility Modules. The `rectMinimized` function is used in transitions that grow or shrink a `<rect>` element from or to their center. It creates a minimized version of the passed `Rect`, which is infinitely small and positioned at the original `Rect` object's center. When declaring a stroke for SVG elements, it is drawn exactly on the outline of an element's silhouette, which means that a stroke will extend outside the original bounds of an element by half the stroke width. This can lead to unwanted artifacts like the stroke of bars in a bar chart overlapping over the chart's axes. To counteract this, the `rectFitStroke` function is provided to adjust the properties of `Rect` objects to account for a specific stroke width around them. Lastly, the Rectangle Utility Module provides functions to calculate specific positions inside rectangles. The most generic of these functions is the `rectPosition` function, which enables the calculation of a position inside a rectangle via a two-dimensional parameter that expresses a position as the percental width and height distance from a rectangle's top-left corner. All other position-calculating rectangle utility functions are simply shorthand functions that internally call the `rectPosition` function. The `rectCenter` function returns a `Position` object representing the center position of a `Rect` object. The `rectLeft`, `rectRight`, `rectTop`, and `rectBottom` functions return `Position` objects that represent the middle position of the corresponding edge of a `Rect` object. Similarly, The `rectTopLeft`, `rectTopRight`, `rectBottomRight`, `rectBottomLeft` functions can be used to calculate the corner positions of a rectangle.

The last geometric primitive whose handling is simplified by a `RespVis` utility module is a circle. The Circle Utility Module can be found in the `utilities/circle.ts` file in the Core Module. It contains the `Circle` interface, which describes a circle object as a `center` property of type `Position` and a `radius` number property. This module also contains equivalent functions to those found in previously mentioned utility modules: `circleRound`, `circleEquals`, `circleToString`, `circleFromString`, `circleToAttrs`, `circleFromAttrs`, `circleMinimized`, and `circleFitStroke`. Furthermore, the `circlePosition` function can be used to calculate positions using an angle that defines the direction and an optional parameter that specifies the distance from a circle's center as a percentage of a circle's radius. The Circle Utility Module also contains functions to create circles from rectangles, which are the `circleInsideRect` function to calculate the largest circle that can fit inside of a rectangle and the `circleOutsideRect` function to calculate the smallest circle that encloses a rectangle.

The purpose of the Path Utility Module is to provide functions that simplify the creation of path definitions that can be set on `<path>` elements. It is located in the `utilities/path.ts` file in the Core Module and only contains a small number of functions. The `pathRect` function creates a rectangle path definition that can be set on `<path>` elements instead of using `<rect>` elements. Similarly, the `pathCircle` function creates a circle path definition that can be set on a `<path>` element instead of using a `<circle>` element. The reason for using `<path>` elements rather than more descriptive shape elements is that their

shape can be changed dynamically. Since only the `d` attribute of a path needs to change when a `<path>` element's shape is changed, it is also possible to smoothly transition between shapes by interpolating the path definition strings.

6.1.2 Layouter

The Layouter is the most novel contribution of this work. It is a component wrapped around an SVG document and allows configuration of the layout of elements in this document with CSS. Instead of implementing a custom layout algorithm, the Layouter builds on layout engines integrated into browsers, which have already been summarized in Section 2.6.1. Earlier proof of concept implementations used the FaberJS [FusionCharts 2021] and Yoga [Facebook 2021d] layout engines to calculate layouts, but these implementations were not further pursued because they limited layouting to either Grid or Flexbox-based constraints. Furthermore, the use of already existing browser functionality in the current implementation leads to a reduced bundle size and to visualization authors being able to use all the layouting capabilities natively offered by browsers.

CSS has always been the foundation of responsive web design for HTML-based websites because of its ability to adapt an element's presentation and the possibility of defining different presentations for different contexts via media queries. A large part of the responsive power that CSS offers comes from its ability to change the positioning and layout of elements. As already mentioned in previous chapters, CSS can style certain aspects of SVG documents, but it is not possible to use CSS layouting techniques to position SVG elements. Even though there are already other visualization libraries such as Chartist [Kunz 2021] and Highcharts [Highsoft 2021] that allow the use of CSS to style visualizations, none of them offer the possibility to modify the layout of visualizations via CSS. This means that visualization authors have to learn and use custom APIs to position elements, limiting the range of possible layouts to those supported by the individual libraries.

The Layouter distinguishes between laid-out and non-laid-out elements because not every visualization element profits from being laid out by it. The positions and sizes of laid-out elements are being calculated by the Layouter, whereas non-laid-out elements are ignored during the layout process. Theoretically, the Layouter could position all visualization elements since it is only necessary to determine a good mapping for each element that maps a rectangular bounding box to the desired SVG shape. However, the positioning of elements in a visualization is constrained more strictly than element positioning in typical HTML documents. The content of a visualization is communicated through visual features such as position, size, and shape of elements rather than simply through text which can be positioned much more freely. For this reason, many elements of a visualization must be positioned at specific locations with specific dimensions, which means there is very little profit in laying them out with an elaborate layout algorithm. These exactly-positioned elements like the `<rect>` elements of Bar Series and the `<circle>` elements of Point Series are usually positioned directly via their SVG attributes. Positioning them via the Layouter would be pointless and only cause unnecessary overhead.

The layout process can be seen in Figure 6.2 and consists of three phases that have been implemented in the `layouterCompute` function:

1. Replication: The structure of the SVG document that shall be laid out must be replicated with HTML `<div>` elements, which are referred to as “layout elements”. These layout elements have the same classes and `data-*` attributes as the original SVG elements they are replicating. This replication of the SVG document with HTML documents is necessary because CSS-based positioning can only affect HTML elements.
2. Layout: The replicated layout elements are affected by CSS rules that configure their positioning and are automatically laid out by browsers. If the Selectors of CSS rules used to style SVG elements only select them using classes and `data-*` attributes, their layout can be directly configured in these rules because they will also be applied to the corresponding layout elements.

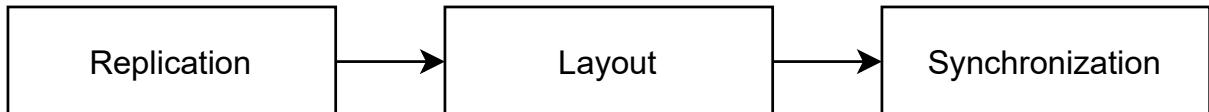


Figure 6.2: This diagram shows the three phases of the layout process of the RespVis Layouter. During the replication phase, the SVG document that shall be laid out is replicated with HTML `<div>` elements. Afterward, these HTML elements are laid out by the browser in the layout phase, and the positions of the laid-out HTML elements are applied to their respective SVG elements during the synchronization phase. [Image created by the author of this thesis using diagrams.net.]

3. Synchronization: The positions of the layout elements are synchronized with their respective SVG elements. The calculated bounding boxes of layout elements are set as `bounds` attributes on SVG elements to make the boundary information available in subsequent renderings. In addition to that, the Layouter sets different default attributes on different types of SVG elements that aim to represent the boundaries of individual elements.

During the replication process, the structure of an SVG document is replicated with HTML `<div>` elements. Replication is implemented using a hierarchical D3 data join in which the original SVG elements are bound as data objects to layout elements. The hierarchical data join results in a counterpart in the hierarchy of layout elements for each SVG element that should be affected by the layouter. Since not every SVG element should be positioned via the Layouter, the Layouter must know which to ignore. For this, the `data-ignore-layout` and `data-ignore-layout-children` attributes have been introduced. Elements that have the `data-ignore-layout` attribute or are children of elements that have the `data-ignore-layout-children` attribute will not be replicated.

To configure the layout of layout elements in CSS, it must be possible to select them uniquely with a CSS Selector. This Selector should be as similar as possible to the Selector of the original SVG element to make it as easy as possible to configure the CSS properties of layout elements. For this purpose, the `class` attributes and all `data-*` attributes of SVG elements are copied to their corresponding layout elements. In addition to the classes of the replicated SVG element, the `layout` class is set on all layout elements. By doing this, it is possible to specifically select the layout element of an SVG element via the same Selector by adding the `layout` class to it. If CSS rules of SVG elements use only classes and `data-*` attributes in their Selectors, the properties of corresponding layout elements can directly be configured in the same rules. An example of how the replicated layout element tree of an SVG document looks can be seen in Listing 6.1. Furthermore, an example of CSS rules that set various properties of SVG elements and their layout elements can be seen in Listing 6.2.

The size of dynamically-sized elements depends on the size of their content. Since layout elements exist separately from their SVG elements and can not access their content, a manual solution had to be implemented that sets the size of layout elements to the content size of their SVG elements when required. An example of dynamically-sized elements is `<text>` elements because their size is rarely declared in absolute units and usually depends on the size of their text contents. The custom `--fit-width` and `--fit-height` CSS properties were introduced to activate the manual copying of dimensions from SVG elements to their layout elements. These boolean properties can be set in CSS rules and are being checked during the replication phase via the `window.getComputedStyle` method. If at least one of these properties is set to true, the dimensions of the SVG element are calculated with the `Element.getBoundingClientRect` method and respectively set as `width` or `height` properties of the `style` attribute on the corresponding layout element. By doing this, layout elements will have the same sizes as their SVG elements and can be properly used in the calculation of the overall layout.

Layout elements are automatically laid out by the browser during the layout phase of the layout process. Since layout elements are simply `<div>` elements that have been styled via CSS rules, the browser can position them automatically via its integrated layout engine. This positioning by the browser happens as soon as the layout elements have been rendered. After this, the final bounding boxes of layout elements

```

1 <div class="layouter">
2   <svg class="chart">
3     <rect class="box" data-index="0" />
4     <rect class="box" data-index="1" />
5     <rect class="box" data-index="2" />
6   </svg>
7   <div class="layout chart">
8     <div class="layout box" data-index="0" />
9     <div class="layout box" data-index="1" />
10    <div class="layout box" data-index="2" />
11  </div>
12</div>

```

Listing 6.1: The replicated layout element structure of an SVG document. Every SVG element has a corresponding layout element that has the same classes and `data-*` attributes. In addition to the classes of the original SVG element, every layout element also has the `layout` class to allow specific targeting of layout elements via CSS Selectors.

```

1 .chart {
2   display: grid;
3   grid-template: 25rem 15rem / 50% 50%;
4   grid-template-areas:
5     'a b'
6     'c c';
7 }
8
9 .box[data-index=0] {
10   grid-area: a;
11   fill: red;
12 }
13
14 .box[data-index=1] {
15   grid-area: b;
16   fill: green;
17 }
18
19 .box[data-index=2] {
20   grid-area: c;
21   fill: blue;
22 }

```

Listing 6.2: These CSS rules are used to configure the layout and style of an SVG document that is being laid out by the Layouter. Since the Selectors of these CSS rules only use `class` and `data-*` attributes to match elements, the same rule can be used to configure the properties of an SVG element and its corresponding layout element. The structure of the SVG document and its replicated layout elements can be seen in Listing 6.1.

can be calculated and used for further operations.

In the synchronization phase of the layout process, the Layouter iterates over all the layout elements, calculates their bounding boxes, and set this boundary information as attributes on the corresponding SVG elements. Bounding boxes of layout elements are calculated relative to their parent elements using the `elementRelativeBounds` utility function. This bounding box is then converted to its string representation via the `rectToString` utility function and set as the `bounds` attribute on the corresponding SVG elements. The `bounds` attribute can then be deserialized to a `Rect` object whenever the bounding box of an SVG element is needed in subsequent renderings. In addition to setting the `bounds` attribute of SVG elements, the Layouter also sets specific attributes on different types of SVG elements that make them fit into their calculated bounding boxes. These attributes can be overwritten in later renderings, but they represent sensible defaults that express the boundaries of laid-out elements. If the Layouter would not set these default attributes, they would have to be set manually on every laid-out element during the rendering process, which would be less convenient and lead to duplicated code in various places. For SVG elements that can be mapped directly to rectangular areas, such as `<svg>` and `<rect>` elements, the Layouter sets the `x`, `y`, `width`, and `height` attributes to the values of their bounding boxes. SVG shape elements that have explicit sizes and positions but are not rectangular, such as `<circle>` and `<line>` elements, also receive attributes that make them fit into their boundaries. Other SVG elements that are not explicitly sized, such as `<g>` and `<text>` elements, are merely moved to the correct position by setting their `transform` attribute to a translation so that their top-left corners aligns with the top-left corners of their bounding boxes. The Layouter does not automatically reposition exactly-positioned elements based on the changed boundary of the composite `<svg>` or `<g>` element containing them, so this has to be implemented manually in the render functions of various components.

Using the Layouter requires a more complex rendering process than would be needed if the boundaries of elements would already be known before rendering them. The way the Layouter works, some elements need to be rendered before calculating the layout, and afterward, when the positions and sizes of all elements are known, the visualization needs to be rendered in its final form. This rendering process of a visualization when using the Layouter consists of three phases and is shown in Figure 6.3. The three phases of the render process are the first rendering phase to render elements affecting the layout, the layouting phase, and the second rendering phase to render elements affected by the layout. In the first rendering phase, all elements and attributes that affect the layout of a visualization need to be rendered. This mostly includes laid-out container `<svg>` and `<g>` elements that contain exactly-positioned child elements, but it also means that the contents of dynamically-sized elements, such as `<text>` elements and axes, need to be fully rendered in this phase too. The layouting phase is where all the operations of the already-described layout process are being performed. During this phase, the bounding boxes of laid-out elements are calculated and persisted as attributes that can be accessed during the second rendering phase. In the second rendering phase, the previously calculated bounding boxes of every element can be used to perform a second rendering of the complete visualization. Here, every element affected by the layout, which actually encompasses every element, is rendered at its final position with its final dimensions. In theory, the first and second rendering phases of components could be implemented in separate functions, but it is more convenient to invoke the same render function twice and perform some operations only if the appropriate `bounds` attribute has already been set.

6.1.3 Axes

Axes are used to visualize scales representing the mapping of abstract values to spatial dimensions. The implementation of all available Axis Components can be found in the `axis.ts` file in the Core Module. Currently, only cartesian Axes are provided by the RespVis library because only cartesian charts have been implemented so far. These cartesian Axis Components are distinguished by their position relative to a visualization's draw area. At the current time, only Left and Bottom Axis Components have been implemented in the RespVis library because they are the most commonly encountered positions of



Figure 6.3: This diagram shows the three phases of the render process when using the RespVis Layouter. During the first render phase, every element that affects the layout needs to be rendered. The layout phase of the render process is equivalent to the layout process described in Figure 6.2. In this phase, the Layouter calculates the final positions and sizes of laid-out elements and stores them as attributes on the SVG elements. During the second render phase, all elements of the visualization are rendered at their final positions with their final dimensions by using the boundary information calculated in the layout phase. [Image created by the author of this thesis using diagrams.net.]

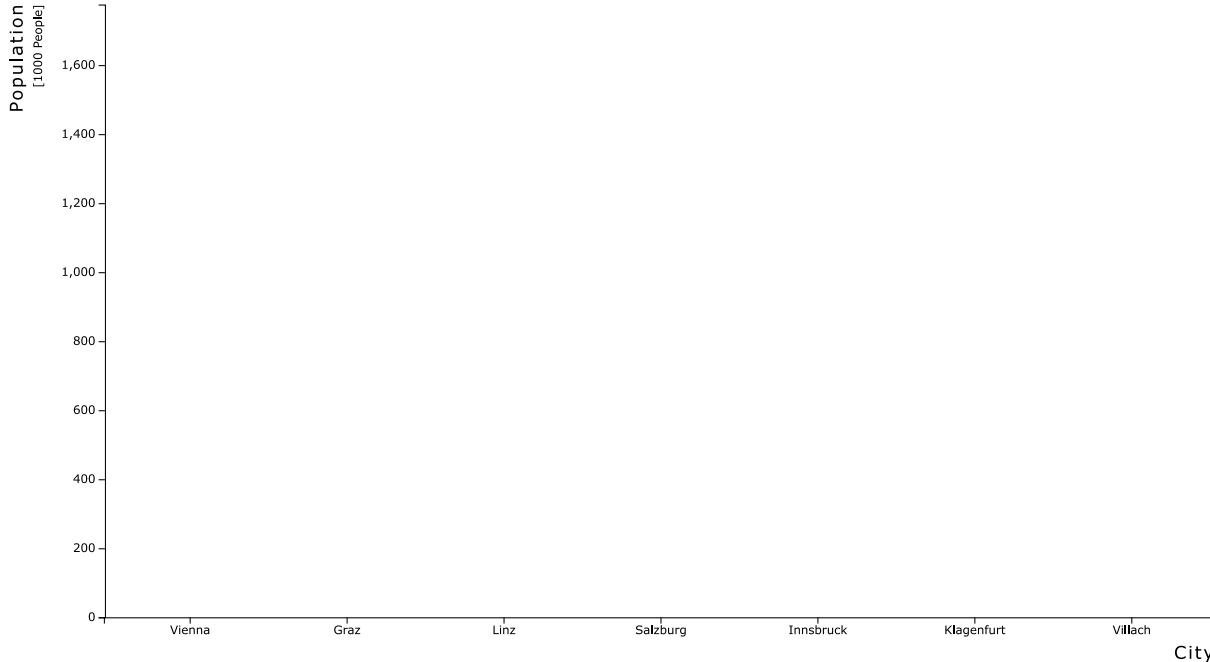


Figure 6.4: This figure shows how a rendered Left and Bottom Axis may look like. The Left Axis consists of a title, subtitle, and ticks, whereas the Bottom Axis only consists of ticks and a title. [Image created by the author of this thesis using RespVis and Inkscape.]

cartesian Axes and cover most use cases. An Axis consists of ticks, an optional title, and an optional subtitle. The ticks of an Axis are the actual visualization of the Axis' scale, and the title and subtitle can be specified to additionally describe it. An example of what a rendered Left and Bottom Axis might look like can be seen in Figure 6.4.

The Axis interface describes the shape of a data object with which an Axis can be configured. It includes a `scale` property, which represents the scale that has to be visualized, the `title` and `subtitle` string properties, and the `configureAxis` function property, which can be used to configure the underlying D3 axis before rendering it. Like most other components, axis components consist of two main functions: a data creation function and a render function. The `axisData` function is used to create an `Axis` data object from a `Partial<Axis>` object parameter where all non-set but required properties are filled with default values. The `axisBottomRender` and `axisLeftRender` functions are used to render a Left and Bottom Axis in a composite element on which an `Axis` data object has been bound. An Axis' root element is a CSS Grid container and defines the layout of the title, subtitle, and ticks elements. The default configuration of a Left Axis positions these elements in a three-column layout in which the title, subtitle, and ticks elements are placed in this order from left to right. For a Bottom Axis, the default configuration positions the same elements in a three-row layout in which the ticks, title, and subtitle elements are placed in this order from top to bottom. Furthermore, the title and subtitle elements of a Left Axis are vertically oriented to save

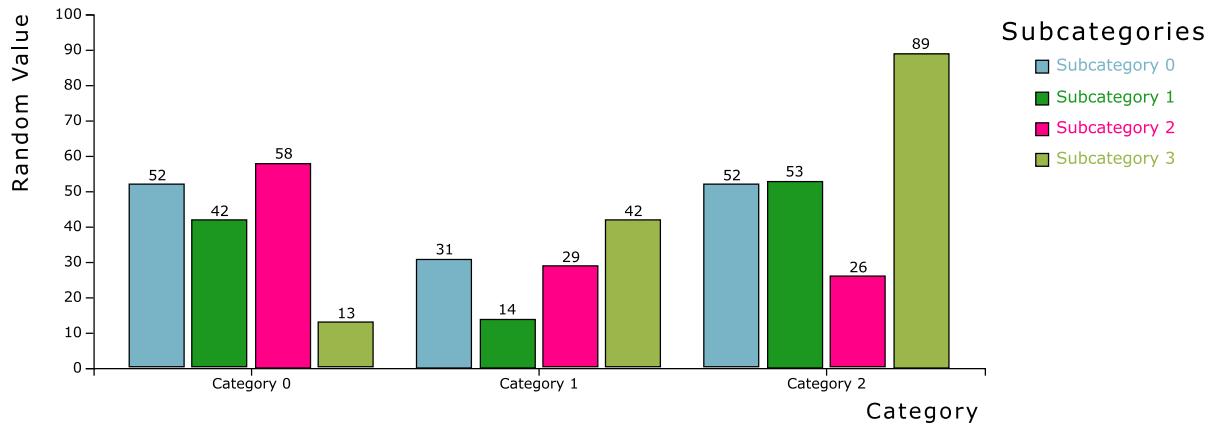


Figure 6.5: An example of a Chart that contains two Axes, a Grouped Bar Series, a Label Series and a Legend. [Image created by the author of this thesis.]

horizontal space using the `textOrientation` utility function. The RespVis Axis Components internally use the `axisBottom` and `axisLeft` functions from the D3 Axis Module [Bostock 2022a] to render the ticks of an Axis. Since these D3 functions use attributes to position and style elements, as many of these attributes as possible must be removed directly after the ticks have been rendered to allow configuration via CSS.

6.1.4 Chart

Charts are high-level components that represent a complete visualization with Axes, Legends, and Series. An example of a rendered RespVis Chart that includes two Axes, a Grouped Bar Series, a Label Series, and a Legend can be seen in Figure 6.5. A Chart is typically rendered in the root `<svg>` element of an SVG document that has at least the `chart` class set in its `class` attribute and the appropriate SVG namespace set in its `xmlns` attribute. These attributes can be set in more specific Chart Components either manually or via the `chartRender` function from the `chart.ts` file in the Core Module, which only sets these attributes.

As already mentioned, the RespVis library currently contains only the implementations of Cartesian Charts, which visualize data in a Cartesian coordinate system. The implementation of the base functionality of Cartesian charts is located in the `chart-cartesian.ts` file in the Core Module. The `ChartCartesian` interface describes a data object for the configuration of Cartesian Charts. These data objects contain the `xAxis` and `yAxis` Axis properties which describe the X and Y Axes of the Chart respectively. Transposing Axes is a useful pattern to improve the responsiveness of visualizations and is configured using the `flipped` boolean properties. If the `flipped` property is set to `false`, the `xAxis` object is used to configure the Bottom Axis and the `yAxis` object is used to configure the Left Axis. If it is set to `true`, it is the other way around.

The `chartCartesianData` function is used to create a `ChartCartesian` data object. This function gets a partial data object with only those properties set that are of interest to the calling code, and all non-set properties are filled with default values. The default values of the `xAxis` and `yAxis` properties are set by the `axisData` function from the Axis Module and the `flipped` property is initialized to `false`.

The rendering of Cartesian Charts is split into two functions that have to be called separately because not all parts of a Cartesian Chart can be rendered simultaneously. The general structure of a Chart must be rendered before anything else can be rendered, as this includes the draw area container element into which individual Series Components are rendered. A Chart's Axes need fully initialized scales to be rendered correctly. However, the range of a scale, i.e. the range of values into which abstract values are mapped, depends on the size of the draw area and is only set during the `render` function of the individual

Series Components. Therefore, Axes must be rendered after Series Components to ensure fully initialized scales.

The structure of a Cartesian Chart is rendered with the `chartCartesianRender` function, which sets the necessary attributes and classes on the root element and attaches the draw area `<svg>` element to it. The draw area is the container element into which the Series Components of a Chart are rendered. An `<svg>` element without actual content is not able to catch input events, which means that it would, for example, not be possible to capture scroll events to control a zoom interaction when the cursor is over the empty area of the draw area. To counteract this, a transparent `<rect>` background element that fills the whole draw area is added, which allows capturing input events in empty areas.

The `chartCartesianAxesRender` function is used to render the Axes of a Cartesian Chart. This function may only be called on elements with a bound `ChartCartesian` data object and after the scales that are to be visualized by the axes have been fully initialized. Charts must first render the Chart's structure using the `chartCartesianRender` function, followed by the desired Series Components, and only after those the Chart's Axes can be rendered using the `chartCartesianAxesRender` function. The `chartCartesianAxesRender` function creates two `<g>` elements and renders a Left and a Bottom Axis on them. Depending on whether the `flipped` property in the bound data object is set to `true` or `false`, the `xAxis` data object is used to configure the Bottom or Left Axis and the `yAxis` data object is used to configure the other one. After the Axes are rendered, the `x-axis` class is set on the one the `x-axis` data object is bound to, and the `y-axis` class is set on the other one.

The elements of a Cartesian Chart are positioned using a CSS Grid layout. By default a grid is created which defines the `axis-left`, `axis-bottom`, `draw-area`, and `legend` areas. Most rows and columns of this grid are sized to fit their content, with the only exception being the row and column containing the draw area, which is set to fill all the remaining space. The default configuration of the `chart-cartesian` class positions an eventual legend to the right of the draw area. The position of the legend can be changed by either adjusting the grid directly via CSS or activating one of the preconfigured positions via the `data-legend-position` attribute. To simplify setting the `data-legend-position` attribute, the `chartLegendPosition` function can be used, which sets this attribute to the value of a passed `LegendPosition` enum parameter.

6.1.5 Chart Window

chart windows sind wrapper komponenten um charts die einen chart innerhalb eines Layouter container elementes rendern und mit einer toolbar dekorieren. ein beispiel eines chart windows mit einem ausgeklappten tool menu in welchem sich zwei nominale filtering tools und ein svg download tool befinden kann in Figure 6.6 gesehen werden. die implementierung der chart window komponente befindet sich in der `chart-window.ts` datei im core module. diese komponenten stellen einen noch higher-level layer als charts dar und werden verwendet um den render prozess und die konfiguration von charts zu managen. in den meisten anderen visualization libraries werden charts als der hoechste level an komponenten die konfiguriert werden koennen zur verfuegung gestellt. typischerweise bedeutet das, dass zusaetzliche HTML elemente fuer die runtime configuration von charts von der einbettenden website selbst erzeugt und gemanaged werden muessen. ein chart window wird ausserhalb des SVG dokumentes eines charts auf einem HTML `<div>` element mit der `chartWindowRender` funktion gerendert. ihre struktur besteht aus einem `<div>` element in welches die toolbar mit der `toolbarRender` funktion gerendert wird und aus einem weiteren `<div>` element auf welchem ein Layouter mit der `layouterRender` funktion initialisiert wird. das SVG dokument eines charts wird dann an das `<div>` element des Layouters als child angehaengt.

zum aktuellen zeitpunkt befindet sich in der toolbar nur das tool menu als einziges element. das tool menu ist ein dropdown menu in welchem die einzelnen tools als menueintraege oder als untermenues zu finden sind. ein dropdown menu wird ueber die `menuDropdownRender` funktion auf den elementen der mitgegebenen Selection gerendert. diese funktion setzt die `menu` klasse auf den root elementen auf

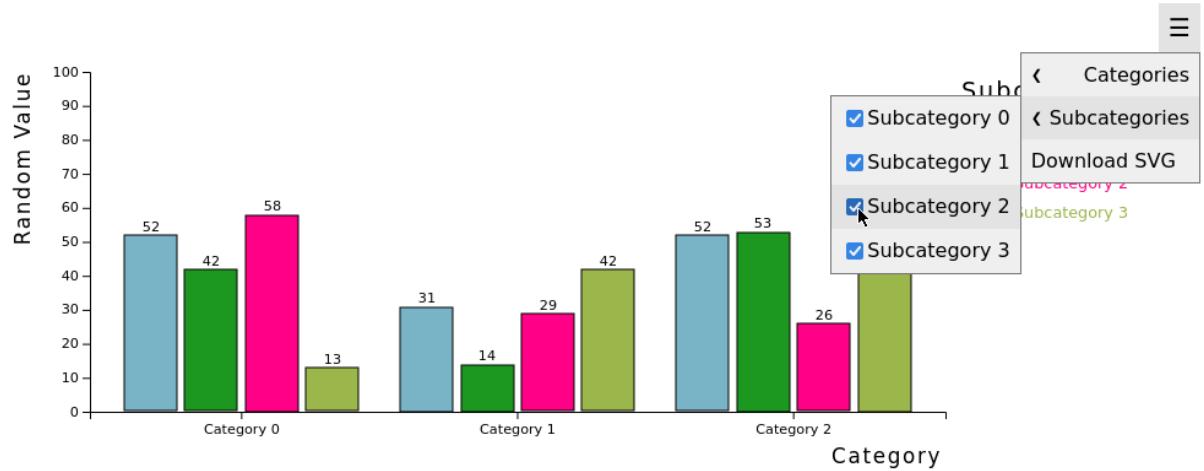


Figure 6.6: An example of a chart that is wrapped in a chart window. The tool menu has been expanded by hovering over it and the menu entries of two nominal filtering tools and the download SVG tool can be seen inside. [Image created by the author of this thesis.]

welchen das dropdown menue gerendert wird. ein dropdown menue besteht aus einem `` element mit der `chevron` klasse dessen `text content` ein nach links zeigendes Unicode chevron symbol ist, einem zweiten `` element mit der `text` klasse dessen `text` der titel des dropdown menues ist, und einem `` element mit der `items` klasse dass die unterelemente des dropdown menues beinhaltet. die unterelemente eines dropdown menues werden ueber CSS absolut positioniert und angezeigt sowie highlighted solange eine hover interaktion auf dem menue stattfindet. das tool menue wird ueber die `menuToolsRender` funktion erzeugt welche intern die `menuDropdownRender` funktion verwendet um das tool menue als dropdown menue zu initialisieren. das root dropdown menue des tool menues wird ohne chevron symbol gerendert und enhaelt ein Unicode symbol in seinem `` element mit der `text` klasse. das symbol dass fuer das tool menue verwendet wurde ist das “trigram for heaven” Unicode symbol mit dem code U+2630 welches haeufig fuer burger menues verwendet wird.

[TODO: Rename nominal filtering tool to categorical filtering tool] das core module stellt tools zur verfuegung die zu den tool menues von spezifischeren chart windows hizugefuegt werden koennen. eines dieser tools ist das nominale filtering tool welches sich in der `tools/tool-filter-nominal.ts` datei im core module befindet. dieses tool wird verwendet um eine nominale datendimension eines visualisierten datasets ueber ein dropdown menue dass eine checkbox series beinhaltet zu filtern. nominale daten sind im gegensatz zu ordinalen daten nur gelabelte oder kategorische daten deren werten kein quantitativer wert zugewiesen ist und welche daher keine reihenfolge besitzen und auch nicht sortiert werden koennen. das data object fuer die konfiguration eines nominalen filter tools wird durch das `ToolFilterNominal` interface beschrieben. dieses interface enthaelt ein `text` string property welches den titel des dropdown menues definiert, ein `options` string array property welches die einzelnen optionen die gefiltert werden koennen definiert, und ein `keys` string array property welches die keys der einzelnen optionen definiert. die `toolFilterNominalData` funktion wird verwendet um ein data objekt vom typ `ToolFilterNominal` von einem partiellen input objekt zu erzeugen bei welchem die nicht definierten properties mit standardwerten befuellt werden. das tool kann dann ueber die `toolFilterNominalRender` funktion auf einem element mit einem gebundenen `ToolFilterNominal` data objekt gerendert werden. diese funktion verwendet intern die `menuDropdownRender` funktion um das tool als dropdown menue zu initialisieren. die items des nominalen filter tool dropdown menues werden als eine checkbox series gerendert.

die implementierung einer checkbox series befindet sich in der `series-checkbox.ts` datei im core module. eine checkbox series wird ueber ein data objekt in der form des `SeriesCheckbox` interfaces konfiguriert. dieses interface beschreibt eine checkbox series ueber ein `container` string property mit welchem der element typ von checkbox container elementen gewaehlt werden kann, ein `labels` string

array property mit welchem die labels der individuellen checkboxes konfiguriert werden koennen, und ein keys string array property mit welchem die keys der individuellen checkboxes definiert werden koennen. ein data objekt von diesem typ kann mit der seriesCheckboxData funktion erzeugt werden, welche ein gueltiges objekt ausgehend von einem partiellen input objekt erstellt. eine checkbox series wird ueber die seriesCheckboxRender funktion gerendert. diese funktion setzt die series-checkbox klasse auf den Selection elementen, fuegt einen custom click listener hinzu welcher das toggling von checkboxes durch klicks irgendwo in ihrem container element ermoeglicht, und rendert die eigentlichen checkbox elemente durch einen D3 data join. um den data join durchzufuehren wird ein data object pro zu rendernder checkbox benoetigt. dies wird durch eine transformation des SeriesCheckbox data objektes in ein array von Checkbox data objekten erreicht. jedes dieser Checkbox data objekte beinhaltet ein container property mit welchem der tag des container elementes definiert wird, ein label property und ein key property. alle dieser properties werden von den container, labels, und keys properties des SeriesCheckbox data objektes abgeleitet. die seriesCheckboxJoin funktion wird mit der Selection, welche aus dem data join mit den Checkbox data objekten entsteht, aufgerufen. diese funktion rendert die einzelnen checkboxes welche aus einem container element, einem <input> checkbox element, und aus einem <label> element bestehen. die tags der container elemente haengen von dem werten der container properties in den gebundenen data objekten ab. jedes container element erhaelt außerdem die checkbox klasse und ein data-key attribut welches auf den wert des key property des data objektes gesetzt wird. das checkbox <input> element und das <label> element werden als kinder des container elementes angehaengt. um das <label> element dem <input> element semantisch zuzuweisen muss das for attribut am <label> element auf die id des <input> elementes gesetzt werden. hierfuer muss jedoch zuerst jedem <input> element eine einzigartige id zugewiesen werden. diese id wird beim erstmaligen erzeugen der checkbox ueber die die uuid funktion generiert und am <input> element als id attribut sowie auf dem <label> element als for attribut gesetzt. die uuid funktion ist ein alias fuer die v4 funktion aus dem uuid npm package [uuid 2022]. sie wird verwendet um UUIDs (Universally Unique IDentifiers) [Leach et al. 2005] der vierten version zu erzeugen welche mit enormer wahrscheinlichkeit eindeutig sind und welche daher bedenkenlos als werte fuer id attribute verwendet werden koennen.

ein weiteres tool welches vom core module zur verfuegung gestellt wird und welches von jedem chart window eingebunden wird ist das SVG download tool. ein SVG dokument welches in ein HTML dokument einbettet ist kann nicht einfach wie ein eingebettetes bild durch einen rechtsklick von benutzern heruntergeladen werden. um ein SVG dokument zu downloaden muss dieses zuerst als string in einen Blob enkodiert werden welcher dann als object URL im href attribut auf einem <a> element gesetzt wird. da die praesentation von RespVis visualisierungen allerdings hauptsaechlich ueber CSS konfiguriert wird, muessen die aktiven CSS properties zu attributen konvertiert werden bevor das SVG dokument gedownloaded werden kann. um dies zu tun wird zuerst das ganze SVG dokument geklont um attribute auf den geklonten elementen setzen zu koennen ohne die gerenderte visualisierung zu beinflussen. nachdem das dokument geklont wurde werden auf jedem geklonten element die notwendigen attribute gesetzt die den aktiven CSS properties des originalem objektes entsprechen. die aktiven CSS properties des originalem objektes werden ueber die elementComputedStyleWithoutDefaults utility funktion berechnet. nachdem alle notwendigen attribute auf den geklonten elementen gesetzt worden sind wird die string representation des gesamten geklonten dokumentes ueber das Element.innerHTML property berechnet und in einem Blob objekt mit dem typ image/svg+xml enkodiert. zum aktuellen zeitpunkt wird die string representation des SVG dokumentes nicht weiter nachbearbeitet oder formatiert was zu einer recht schwer lesbaren SVG datei fuehrt und was in der zukunft verbessert werden soll. das Blob objekt wird dann ueber die URL.createObjectURL methode in eine URL konvertiert die ein downloadable Blob objekt representiert und im href attribut eines neu erzeugten <a> elementes gesetzt. dieses neu erzeuge <a> element wird dann kurzzeitig an das <body> element des aktiven dokumentes angehaengt und ueber die Element.click methode geklickt was den dowload des fertig praeparierten SVG dokumentes initiiert. die implementierung des SVG download tools befindet sich in der tools/tool-download-svg.ts datei im core module. um dieses tool als menueintrag des tool menues zu rendern wird die toolDownloadSVGRender funktion verwendet. diese funktion initialisiert den menueintrag mit der tool-download-svg klasse und einem



Figure 6.7: This is an example of three different legends that have been created from the source code in Listing 6.3. One legend has been configured to have rectangles as symbols, one has been configured to have circles as symbols, and the last one has been configured with rectangle symbols but with horizontally laid out legend items. [Image created by the author of this thesis.]

angemessenen text content. außerdem setzt die `toolDownloadSVGRender` funktion einen click event listener auf dem menueintrag welcher bei interaktion des benutzers den download des gerenderten SVG dokumentes ueber die `chartDownload` funktion initiiert. die `chartDownload` funktion fuehrt dann alle bereits beschriebenen operationen aus die fuer die praeparation und den download des gerenderten SVG dokumentes notwendig sind.

6.2 Legend Module

das legend module besteht nur aus der `legend.ts` datei welche die implementierung einer legende beinhaltet. eine legende wird verwendet um scales zu visualisieren deren werte nicht auf raeumliche werte in einem koordinatensystem gemappt werden. stattdessen werden in den scales die durch eine legende visualisiert werden abstrakte werte auf visuelle eigenschaften wie zum beispiel farbe, form oder groesse abgebildet. die legende die in diesem modul implementiert wurde visualisiert dieses mapping durch gelabelte konfigurierbare symbole. ein beispiel welches die verwendung des legend modules demonstriert befindet sich in der `legend.html` datei im `src/examples/` ordner. ein auszug dieses beispiels kann in Listing 6.3 und dessen rendering in Figure 6.7 gesehen werden.

ein data object mit welchem das rendering einer legende konfiguriert werden kann wird durch das Legend interface beschrieben. dieses interface beinhaltet ein `title` string property, ein `labels` string array property, ein `symbols` function oder function array property, ein `styleClasses` string oder string array property, und ein `keys` string array property. der titel einer legende kann optional ueber das `title` property gesetzt werden. das `labels` string array property definiert die labels neben den symbolen der einzelnen legend items. die symbole der legend items werden ueber das `symbols` property bestimmt. da die symbole einer legende komplett konfigurierbar sein sollen wird nicht einfach ein `<rect>` oder `<circle>` element als symbol gerendert sondern ein `<path>` element. die verwendung eines `<path>` elementes ermoeglicht es beliebige symbole in der legende zu visualisieren. der nachteil hiervon ist dass die konfiguration von `<path>` elementen aufwaendiger ist als die konfiguration von eingeschraenkteren SVG elementen. das rendern eines symbols als `<path>` wird ueber eine funktion erledigt welche als input das jeweilige `<path>` element und die vom Layouter berechneten boundaries erhaelt. in dem `symbols` property des Legend data objektes kann entweder eine einzelne solche funktion oder ein array von solchen funktionen gesetzt sein. ist eine einzelne funktion gesetzt, erhaelt jedes symbol die selbe path konfiguration. sollte hier ein array an funktionen gesetzt sein, dann wird jedes symbol durch eine eigene path konfiguration visualisiert. das `styleClasses` property erlaubt die konfiguration der style klassen von legend items. eine style klasse wird in dem `data-style` attribut eines elementes gesetzt und dient der konfiguration von visuellen eigenschaften ueber CSS. ein beispiel fuer verfuegbare style klassen sind die `categorical-0` bis `categorical-9` style klassen. das setzen einer dieser klassen im `data-style` attribut eines elementes fuehrt dazu dass das CSS `fill` property auf die jeweilige kategorische farbe gesetzt wird.

```

1 <html>
2 <head>
3   <style>
4     /* ... */
5     .horizontal-legend .items {
6       flex-direction: row;
7     }
8   </style>
9 </head>
10 <body>
11   <div id="chart"></div>
12   <script type="module">
13     // imports, init chart window, init chart, ...
14
15     const labels = [0, 1, 2, 3].map((n) => 'Label ${n}');
16
17     // legend with rectangle symbols
18     const rectLegendData = legendData({
19       title: 'Legend',
20       labels,
21       symbols: (p, s) => pathRect(p, rectFromSize(s)),
22     });
23
24     // legend with circle symbols
25     const circleLegendData = legendData({
26       title: 'Legend',
27       labels,
28       symbols: (p, s) => pathCircle(p, circleInsideRect(rectFromSize(s))),
29     });
30
31     // horizontal legend with rectangle symbols
32     const horizontalLegendData = rectLegendData;
33
34     // handle render process, resize, ...
35   </script>
36 </body>
37 </html>

```

Listing 6.3: The source code of the example website implemented in the `legend.html` file of the `src/examples/` directory that renders the three different legends seen in Figure 6.7. Non-essential parts of the source code have been removed to focus on the configuration of the individual legends. The horizontal legend has the same configuration in their data object as the rectangle symbol legend. The only difference between those two legends is that the items of the horizontal legend have been laid out horizontally via the `flex-direction: row` CSS property.

wird in dem `styleClasses` property eine einzelne style klasse deklariert, dann wird diese style klasse auf allen legend items gesetzt. alternativ dazu akzeptiert dieses property auch ein array an style klassen, was dazu fuehrt das jedes legend item eine eigene style klasse gesetzt bekommt. das `keys` property eines Legend data objektes bestimmt die werte der `data-key` attribute der einzelnen legend items. ein data objekt das der form des Legend interface entspricht kann mit der `legendData` funktion erzeugt werden. diese funktion erhaelt ein input objekt von dem selben typ wie jener den sie erzeugt bei welchem die werte die fuer den aufrufenden code nicht von interesse sind nicht gesetzt sein muessen und mit standardwerten befuellt werden.

eine legende wird mit der `legendRender` funktion auf elementen gerendert auf denen ein Legend data objekt gebunden ist. diese funktion setzt die legend klasse auf den elementen der uebergebenen Selection. innerhalb des root elementes der legende befindet sich ein `<text>` element mit der `text` klasse welches den titel der legende representiert, und ein `<g>` element mit der `items` klasse in welches die einzelnen legend items ueber einen data join gerendert werden. um den legend item data join durchzufuehren benoetigt man ein data objekt pro legend item das gerendert werden soll. dieses array an `LegendItem` data objekten, welche aus den `label`, `styleClass`, `symbol`, und `key` eigenschaften bestehen, wird durch transformation des Legend data objektes erzeugt. ueber einen data join mit diesem array an data objekten wird fuer jedes legend item ein `<g>` element mit der `legend-item` klasse erzeugt. an jedes dieser `<g>` elemente werden dann ein `<path>` element mit der `symbol` klasse und ein `<text>` element mit der `label` klassen angehaengt. das `label` property des gebundenen `LegendItem` data objektes wird dann als textinhalt des `<text>` elementes gesetzt und das `symbol` property wird verwendet um die form des `<path>` objektes zu bestimmen. ausserdem werden die `data-style` und `data-key` attribute auf dem `<g>` legend item element auf die werte der `styleClass` und `key` eigenschaften des data objektes gesetzt. im kern kann eine legende auch als legend item series angesehen werden und wie auch alle anderen series components kann auch in den data join der legende direkt ueber die `enter`, `update`, und `exit` events, welche auf dem root element der legende gesendet werden, eingegriffen werden. die event objekte dieser events beinhalten im `detail.selection` property jeweils die `enter`, `update`, und `exit` Selections des darunterliegenden data joins. ueber diese properties koennen beliebige operationen in den verschiedenen phasen des data joins ausgefuehrt werden.

[TODO: Capitalize "Core Module", "Bar Module", "Chart", "Chart Component", "Axis", "Axis Component" according to Keith]

6.3 Tooltip Module

[TODO: Capitalize "Tooltip", "Tooltip Module", ...]

tooltips werden verwendet um zusaetzliche informationen eines elementes anzuzeigen die zu umfangreich sind um sie permanent anzuzeigen. eine visualisierung die zu viele informationen zur selben zeit darstellt verliert an effektivitaet da ein groesserer kognitiver aufwand aufgebracht werden muss um sie zu interpretieren. durch die verwendung von tooltips kann dieses problem dadurch geloest werden dass zu detaillierte informationen erst durch interaktion der benutzer mit einem element in dessen kontext die information steht angezeigt werden. ausserdem ist es fuer tooltips ok andere wichtige teile einer visualisierung zu ueberdecken da sie nicht permanent sichtbar sind. ein beispiel eines bar charts in welchem zusaetzliche informationen ueber einen tooltip angezeigt werden kann in Figure 6.8 gesehen werden.

das tooltip module befindet sich im `src/lib/tooltip/` odner des projektes. die hauptdatei welche die implementierung der tooltip funktionalitaet beinhaltet ist die `tooltip.ts` datei. so wie tooltips hier implementiert wurden, wird die gleichzeitige anzeigen mehrerer tooltips unterstuetzt. um dies zu erreichen, erwarten alle funktionen die tooltip operationen ausfuehren, dass das tooltip element auf welchem die operation ausgefuehrt werden soll als erster parameter an die funktion uebergeben wird. diese funktionen erlauben es allerdings auch ein `null` objekt in diesem parameter zu uebergeben, was zur verwendung eines standard tooltip elementes, welches an das `<body>` element des aktiven dokumentes angehaengt

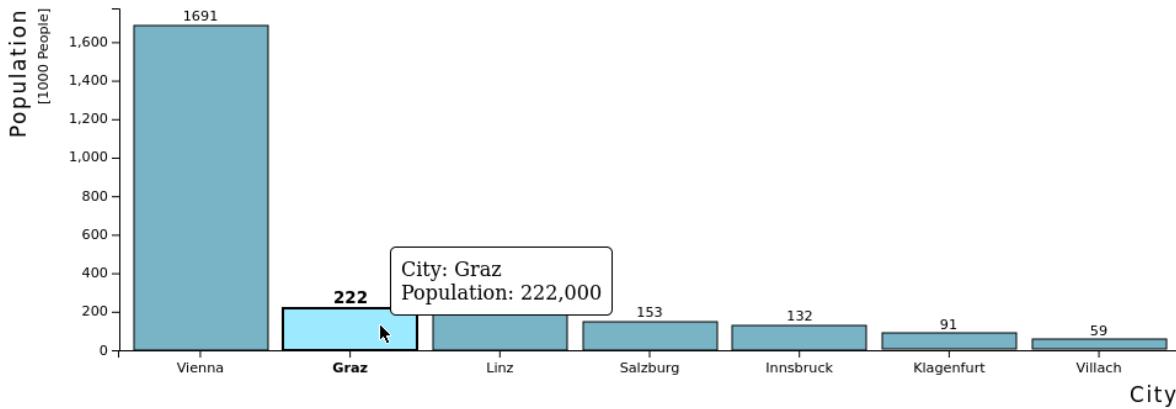


Figure 6.8: A bar chart with a tooltip showing additional information of the data record associated with an individual bar. Since the tooltip is only visible while the user interacts with the context element, it is ok that the tooltip covers other important parts of the visualization. [Image created by the author of this thesis.]

wird, fuehrt. tooltups sind HTML <div> elemente mit der tooltip klasse und werden ueber CSS gestyled. der inhalt eines tooltups wird mit der tooltipContent funktion gesetzt. diese funktion erlaubt es den inhalt eines tooltups als string zu definieren welcher als HTML inhalt des tooltip elementes gesetzt wird. die position eines tooltups wird ueber die tooltipPosition funktion gesetzt. diese funktion erhaelt ein objekt als parameter mit welchem die position in viewport koordinaten und ein optionaler offset von dieser position bestimmt werden. wird kein expliziter offset gefordert berechnet die tooltipPosition funktion einen welcher den tooltip so postioniert dass er immer in dem sichtbaren bereich des browsers positioniert wird. tooltups werden ueber viewport koordinaten positioniert und die endgueltige position eines tooltups wird ueber die CSS top, bottom, left, und right eigenschaften gesetzt. welche dieser eigenschaften verwendet wird haengt von der offset richtung des tooltups ab. tooltups werden mit der tooltipShow funktion angezeigt und mit der tooltipHide funktion versteckt. diese funktionen setzen und entfernen jeweils die show klasse von dem tooltip element wodurch die CSS opacity eigenschaft des elementes beinflusst wird.

neben der tooltip.ts datei beinhaltet das tooltip modul noch die series-config-tooltips.ts datei. in dieser datei befindet sich keine eigene komponente sondern utility funktionen um die konfiguration und das handling von tooltups auf series komponenten zu vereinfachen. die datenobjekt interfaces von series komponenten mit welchen tooltups konfiguriert werden sollen koennen von dem SeriesConfigTooltips interface erben. dieses interface beinhaltet die tooltipsEnabled, tooltips, und tooltipPositions eigenschaften. die tooltipsEnabled boolean eigenschaft ermoeglicht das aktivieren und deaktivieren von tooltups. der inhalt der tooltups von individuellen series item elements wird ueber die tooltips eigenschaft konfiguriert. in dieser eigenschaft wird eine funktion gesetzt die mit dem series item element aufgerufen wird fuer welches ein tooltip angezeigt werden soll und welche den tooltipinhalt als string zurueckliefert. die positionen der einzelnen tooltups werden ueber die tooltipPositions eigenschaft gesetzt. der wert dieser eigenschaft ist ebenfalls eine funktion welche mit dem kontext series item element und der aktuellen mausposition in viewport koordinaten als parameter aufgerufen wird. die gewuenschte position des tooltups kann dann ueber diese parameter berechnet werden. zusaetzlich zu dem SeriesConfigTooltips interface kann die seriesConfigTooltipsHandleEvents funktion in der series-config-tooltips.ts datei gefunden werden. diese funktion kann in series komponenten verwendet werden um mouseover, mousemove, und mouseout event listener an die root elemente einer series anzuhangen die fuer das management von tooltups zustaendig sind. diese event listener verwenden die SeriesConfigTooltips eigenschaften der an den series elementen gebundenen datenobjekte um die sichtbarkeit, den inhalt, und die position von tooltups zu modifizieren. die verwendung dieser utility typen und funktionen ist optional. es steht series komponenten frei eigene eigenschaften fuer die konfiguration

von tooltips zur verfuegung zu stellen und das handling von tooltips selbst zu implementieren. allerdings ist es aus konsistenzgruenden besser wenn sich die art der konfiguration von tooltips nicht zu sehr zwischen unterschiedlichen series komponenten unterscheidet.

6.4 Bar Module

das bar modul befindet sich in dem `src/lib/bars/` ordner des projektes und beinhaltet komponenten um unterschiedliche arten von bar charts zu rendern. bar charts werden zur visualisierung von kategorischen datensaetzen durch rectangles eingesetzt wobei die laenge der rectangles proportional zu den werten einer quantitativen datendimension ist. in einem kategorischen datensatz ist eine kategorie eindeutig anderen dimensionen der einzelnen dateneintraege zuordenbar. ein beispiel hierfuer waere ein datensatz in welchem unterschiedliche charakteristiken einzelner laender aufgelistet sind. bar charts gehoeren zu den aeltesten arten von charts mit einem der ersten aufkommen in Playfair [1786] und gehoeren auch heute noch zu den am haeufigsten vorgefundenen visualisierungen (36% der 378 studied charts by Kim et al. [2021b]) im modernen web. die bars einens bar charts koennen entweder horizontal oder vertikal ausgerichtet sein. bei einem horizontalen bar chart, manchmal auch row chart genannt, wird die quantitative dimension ueber die X achse ausgedrueckt. diese variante von bar charts eignet sich besser fuer die darstellung in layouts mit eingeschraenker breite, da die labels der kategorischen achse leichter ohne zu ueberlappen positioniert werden koennen und da ein horizontaler bar chart vertikal gescrollt werden kann was horizontalem scrollen zu bevorzugen ist. im gegensatz zu horizontalen bar charts wird bei vertikalen bar charts, manchmal auch column charts genannt, die quantitative dimension ueber die Y achse ausgedrueckt. das bar modul beinhaltet komponenten fuer das rendering von basic, grouped, und stacked bar charts welche in unterschiedlichen visualisierungsszenarien eingesetzt werden koennen. fuer jede art von bar chart wird eine Series Component, eine Chart Component und eine Chart Window Component zur verfuegung gestellt. die implementierung der unterschiedlichen arten von bar charts und wann welche art am besten zur anwendung kommt wird in den folgenden sections beschrieben.

6.4.1 Basic Bars

[TODO: Is "Basic Bars" a good name? Maybe "Single Bars" or "Bars" or something else?]

[TODO: Add figure of vertical and horizontal bar charts (subfigures?)]

basic bar charts, manchmal auch single-series bar charts genannt, werden verwendet um unterschiede einer quantitativen dimension verschiedener kategorien eines kategorischen datensatzes zu verdeutlichen. von jedem dateneintrag wird jeweils eine kategoriale und eine quantitative dimension als eine bar visualisiert, wobei die zu visualisierenden kategorien eindeutig auf einen quantitativen wert gemapped werden koennen muessen. die kategorien eines bar charts werden ueber eine band scale auf raeumliche dimensionen gemapped. eine band scale wird verwendet um werte gleichmaessig auf gleich grosse intervale (baender) des verfuegbaren platzes aufzuteilen. der abstand zwischen den einzelnen intervallen ist konfigurierbar. die breite der zu rendernden bars ergibt sich durch die anzahl der kategorien, dem bereich auf welchen sie ueber die band scale aufgeteilt werden sollen, und dem abstand zwischen den bars. die quantitativen werte, welche die laenge der individuellen bars bestimmen, werden ueber eine continuous scale auf raemliche dimensionen gemapped. eine continuous scale bildet abstrakte quantitative werte ueber eine kontinuierliche interpolationsfunktion auf den bereich zwischen zwei extemen ab. in den meisten faellen kommt eine lineare interpolation ueber eine linear scale zur anwendung. es steht dem author einer visualisierung jedoch frei eine andere form der interpolation, wie zum beispiel eine logarithmische funktion ueber eine logarithmic scale, zu waehlen.

die lowest-level komponente die fuer das rendern eines bar charts notwendig ist ist eine bar series. eine bar series ist eine sammlung von `<rect>` elementen welche die bars innerhalb der draw area eines bar charts representieren. die implementierung der bar series komponente befindet sich in der `series-bar.ts`

datei des bar moduls. das datenobjekt fuer die konfiguration einer bar series wird ueber das SeriesBar interface beschrieben. diese interface beschreibt ein objekt mit den categories, values, categoryScale, valueScale, flipped, styleClasses, und keys eigenschaften. zusaetzlich zu diesen eigenschaften wird die konfiguration von tooltips ueber die eigenschaften des SeriesConfigTooltips interface, welches in Section 6.3 beschrieben wird, ermoeglicht. die categories und values eigenschaften sind arrays welche die individuellen kategorien und deren quantitative werte repraesentieren. das mapping der kategorischen und quantitativen werte auf raeumliche dimensionen wird ueber die categoryScale und valueScale eigenschaften bestimmt. ob vertikale oder horizontale bars gerendert werden haengt von dem wert der flipped eigenschaft ab, wobei ein wert von false fuer vertikale bars und ein wert von true fuer horizontale bars steht. die data-style attribute, welche die farbe von bars bestimmen, und die data-key attribute, welche zur identifikation von zusammengehoeerenden elementen verwendet werden, werden ueber die styleClasses und keys eigenschaften bestimmt. ein mit standardwerten initialisiertes SeriesBar datenobjekt kann mit der seriesBarData funktion von einem partiellen input objekt erzeugt werden. diese datenobjekte koennen an <svg> oder <g> elemente gebunden werden in welche dann eine bar series mit der seriesBarRender funktion gerendert werden kann. die individuellen bar elemente werden ueber einen data join mit einem array an Bar datenobjekten erzeugt, welches durch transformation des gebundenen SeriesBar datenobjektes berechnet wird. die position und groesse der bars wird mithilfe der beiden scales berechnet deren output values auf die dimensionen der bounding box des series elementes gemapped werden, welche vom Layouter berechnet und im bounds attribut gespeichert wurden. jede bar hat eine enter und exit transition und ihre position und groesse wird ueber eine update transition zwischen aktuellen und neuen werten interpoliert. diese transitions erleichtern es aenderungen in den visualisierten daten nachzuvollziehen und fuehren zu einer verbessierung der user experience. wie bei alle anderen series komponenten, werden die enter, update, und exit events mit der jeweiligen Selection des bar data joins auf dem root element der series dispatched um das injizieren von eigenem verhalten in die verschiedenen phasen des data joins zu ermoeglichen.

die implementierung von bar charts befindet sich in der chart-bar.ts datei im bar modul. bar charts sind kartesische charts die eine bar series mit optionalen labels in ihrer draw area rendern. das ChartBar interface beschreibt die form von datenobjekten fuer die konfiguration von bar charts. es beinhaltet alle eigenschaften der ChartCartesian und SeriesBar interfaces und fuegt zusaetzliche eigenschaften zur konfiguration von bar labels hinzu. ein mit standardwerten initialisiertes datenobjekt vom typ ChartBar kann mit der chartBarData funktion von einem partiellen input objekt erzeugt werden. nachdem solch ein datenobjekt auf einem <svg> oder <g> element gebunden wurde, kann ein bar chart mit der chartBarRender funktion in dieses element gerendert werden. diese funktion initialisiert einen kartesischen chart, initialisiert und rendert eine bar series und eine optionale label series in der draw area des charts, und rendert die scales mit welchen die bar series gerendert wurde als left und bottom axes des charts. weiters werden mouseover event listener an die bar series angehaengt die fuer das hervorheben von bars und den dazugehoerigen ticks auf der category axis zustaendig sind.

ein bar chart window ist die highest-level komponente die verwendet werden kann um einen bar chart zu rendern der in ein Layouter element eingebettet wird um dessen elemente ueber CSS zu positionieren. ueber die toolbar des bar chart windows koennen die kategorien des bar charts gefiltert und das SVG dokument des bar charts gedownloaded werden. das datenobjekt fuer die konfiguration eines bar chart windows wird durch das ChartWindowBar interface beschrieben. dieses interface erbt vom ChartBar interface und beinhaltet dadurch alle eigenschaften die fuer die konfiguration des darunterliegenden bar charts benoetigt werden. zusaetzlich zu diesen, werden weitere eigenschaften fuer das filtern von kategorien, wie etwa die derzeit aktiven kategorien und das verhalten der value scale, zur verfuegung gestellt. die chartWindowBarData funktion kann verwendet werden um ein datenobjekt fuer die konfiguration eines bar chart windows von einem partiellen input objekt zu erzeugen bei welchem die nicht definierten werte mit standardwerten initialisiert werden. mit der chartWindowBarRender funktion kann ein bar chart window in einem <div> element auf welchem ein angemessenes datenobjekt gebunden is gerendert werden. diese funktion rendert die toolbar mit den kategorie filter und SVG download tools, initialisiert

```

1 select('#chart')
2   .append('div')
3   .datum(
4     chartWindowBarData({
5       categories: ['A', 'B', 'C', 'D', 'E', 'F'],
6       values: [2, 4, 3, 1, 5, 2],
7       xAxis: { title: 'Category' },
8       yAxis: { title: 'Value' },
9     })
10  )
11  .call(chartWindowBarRender)
12  .call(chartWindowBarAutoResize)
13  .call(chartWindowBarAutoFilterCategories);

```

Listing 6.4: The example source code that creates a Bar Chart Window. The Bar Chart Window is configured with the bound data object that is initialized via the `chartWindowBarData` function. After configuration, the Chart Window is rendered by the `chartWindowBarRender` function. Since no special responsive behavior is desired in this example, the default resize and category filter behavior is attached to the Chart Window via the `chartWindowBarAutoResize` and `chartWindowBarAutoFilterCategories` functions.

den eingebetteten chart mit den gefilterten werten des chart window datenobjektes, und rendert den chart, entsprechend des render prozesses definiert in Section 6.1.2, zweimal mit einem layout computation schritt dazwischen. standardmaessig wird das chart window nicht automatisch rerendert wenn sich die groesse des viewports aendert oder wenn die aktiven kategorien gefiltert werden. das rerendern bei viewport groessenaenderungen kann ueber einen `resize` event listener auf dem chart window root element implementiert werden in welchem die chart window render funktion erneut aufgerufen wird nachdem das gebundene datenobjekt angemessen an die neuen dimensionen des viewports angepasst wurde. das bar chart window sendet ein `categoryfilter` event mit den derzeit aktiven kategorien immer wenn kategorien ueber das filter tool aktiviert oder deaktiviert werden. um den bar chart auf die neue filterkonfiguration anzupassen muss ein `categoryfilter` event listener implementiert werden welcher die aktiven kategorien im datenobjekt des chart windows aktualisiert und das chart window rerendert. muessen keine speziellen konfigurationen bei aenderung der viewport groesse oder des kategoriefilters durchgefuehrt werden, koennen die `chartWindowBarAutoResize` und `chartWindowBarAutoFilterCategories` funktionen verwendet werden um `resize` und `categoryfilter` event listener an das chart window anzuhaengen die das standardverhalten implementieren. ein simples beispiel dafuer wie ein skalierendes bar chart window erzeugt werden kann welches das filtern von kategorien erlaubt ist in Listing 6.4 ersichtlich. die resultierende visualisierung dieses codes kann in Figure 6.9 gesehen werden.

6.4.2 Grouped Bars

ein grouped bar chart, manchmal auch clustered oder multi-series bar chart genannt, wird verwendet um mehrere quantitative dimensionen unterschiedlicher kategorien eines kategorischen datensatzes miteinander zu vergleichen. in einem solchen chart wird fuer jede kategorie eine gruppe an bars gerendert deren laengen proportional zu den werten der unterschiedlichen quantitativen dimensionen sind. die verschiedenen zu visualisierenden quantitativen dimensionen muessen miteinander vergleichbar sein und koennen als unterkategorien der einzelnen kategorien betrachtet werden. wie bei basic bar charts werden auch hier die kategorien ueber band scales auf raeumliche dimensionen abgebildet. der unterschied befindet sich darin dass bei grouped bar charts zwei verschiedene band scales zur anwendung kommen. ueber die category scale wird der verfuegbare platz der draw area auf die anzahl der kategorien aufgeteilt und ueber

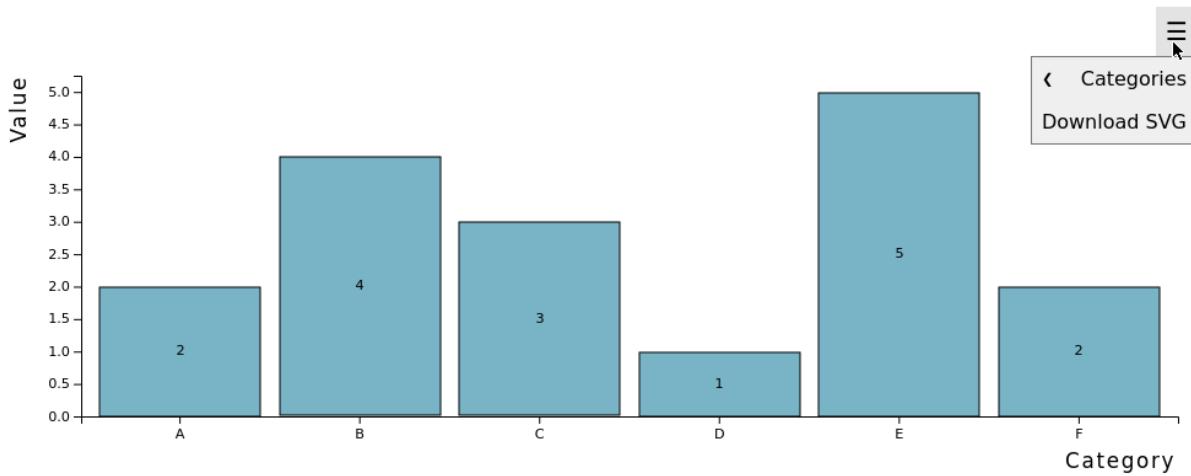


Figure 6.9: The resulting Bar Chart of the example code in Listing 6.4. [Image created by the author of this thesis using RespVis.]

die subcategory scale wird der platz innerhalb der daraus resultierenden gleich grossen intervalle auf die anzahl der unterkategorien aufgeteilt. das abbilden von quantitativen werten auf raeumliche dimensionen wird wieder ueber eine continuous scale durchgefuehrt, wobei die selbe scale fuer jeden wert verwendet werden muss damit die werte miteinander vergleichbar sind.

fuer das rendering von grouped bar charts werden drei verschiedene komponenten zur verfuegung gestellt welche ihren gegenstuecken fuer das rendering von basic bar charts sehr aehnlich sind. die grouped bar series ist die lowest-level komponente die dafuer gedacht ist eine sammlung an <rect> elementen, welche die jeweiligen werte und kategorien eines grouped bar charts representieren, in die draw area eines charts zu rendern. der unterschied einer grouped bar series zu einer basic bar series ist dass zusaetzliche eigenschaften fuer die konfiguration der unterkategorien notwendig sind und dass manche bereits vorhandene eigenschaften hier zwei-dimensionale arrays erfordern um deren werte den hier zwei-dimensional (kategorie/unterkategorie) gruppierten bars zuzuordnen. allen bars die der selben unterkategorie angehoeren werden die selben style klassen zugewiesen um die werte der einzelnen kategorien leichter miteinander vergleichen zu koennen. ein grouped bar chart ist ein kartesischer chart mit einer grouped bar series und optionalen labels in seiner draw area, einer left und bottom axis die die scales der grouped bar series visualisieren, und einer legende die die unterkategorien des charts beschreibt. ein solcher Chart implementiert ausserdem event listener auf unterschiedlichen elementen die das gemeinsame hervorheben von zusammengehoeerenden bars, labels, category axis ticks, und legend items abwickeln. ein Grouped Bar Chart Window ist die highest-order komponente die verwendet werden kann um einen Grouped Bar Chart zu rendern. diese komponente plaziert den Chart innerhalb eines Layouters und managed den render prozess der es erlaubt individuelle elemente ueber CSS zu positionieren. weiters dekoriert ein solches Chart Window den Grouped Bar Chart mit einer toolbar in welcher sich ein SVG download tool und zwei filter tools befinden um die visualisierten kategorien und unterkategorien zu filtern. die konfiguration des eingebetteten Charts mit den gefilterten eigenschaften des am Chart Window gebundenen datenobjektes wird von der render funktion des Grouped Chart Windows durchgefuehrt. immer wenn der user mit den filter tools interagiert und die zusammenstellung der aktiven kategorien und unterkategorien veraendert werden die categoryfilter und subcategoryfilter events mit jeweils den neuen aktiven kategorien und unterkategorien ausgesandt. der author der visualisierung kann entweder spezielles verhalten in eigenen resize und filter event listenern implementieren oder das standardverhalten ueber die zur verfuegung gestellten chartWindowBarGroupedAutoResize, chartWindowBarGroupedAutoFilterCategories, und chartWindowBarGroupedAutoSubcategories funktionen aktivieren. der beispielcode um einen einfachen grouped bar chart zu erzeugen welcher sich an die groesse seines container elementes anpasst und in welchem die kategorien und unterkategorien ueber die toolbar gefiltert werden koennen befindet sich

```

1 select('#chart')
2   .append('div')
3   .datum(
4     chartWindowBarGroupedData({
5       categories: ['A', 'B', 'C'],
6       subcategories: ['X', 'Y', 'Z'],
7       values: [
8         [2, 3, 4],
9         [3, 4, 2],
10        [2, 1, 3],
11      ],
12      xAxis: { title: 'Category' },
13      yAxis: { title: 'Value' },
14      legend: { title: 'Subcategories' },
15    })
16  )
17  .call(chartWindowBarGroupedRender)
18  .call(chartWindowBarGroupedAutoResize)
19  .call(chartWindowBarGroupedAutoFilterCategories)
20  .call(chartWindowBarGroupedAutoFilterSubcategories);

```

Listing 6.5: The example source code that creates a Grouped Bar Chart Window. The Grouped Bar Chart Window is configured with the bound data object that is initialized via the `chartWindowBarGroupedData` function. After configuration, the Chart Window is rendered by the `chartWindowBarGroupedRender` function. Since no special responsive behavior is desired in this example, the default resize, category filter, and subcategory filter behavior is attached to the Chart Window via the `chartWindowBarGroupedAutoResize`, `chartWindowBarGroupedAutoFilterCategories`, and `chartWindowBarGroupedAutoFilterSubcategories` functions.

in Listing 6.5. die resultierende visualisierung dieses beispiels kann in Figure 6.10 gesehen werden.

6.4.3 Stacked Bars

ein stacked bar chart wird verwendet um die relativen beitraege mehrerer quantitativer dimensionen zu einem kombinierten gesamten von unterschiedlichen kategorien eines kategorischen datensatzes miteinander zu vergleichen. die quantitativen dimensionen koennen als unterkategorien der einzelnen kategorien gesehen werden und muessen in einer part-to-whole beziehung zueinander stehen. Stacked Bar Charts existieren in zwei verschiedenen variationen: Basic Stacked Bar Charts und Percent Stacked Bar Charts. bei Basic Stacked Bar Charts werden alle bars einer kategorie einfach uebereinander platziert was bedeutet dass die kombinierten gesamten unterschiedlicher kategorien miteinander verglichen werden koennen. die laengen eines Percent Stacked Bar Charts werden hingegen nur als prozentuelle anteile eines gesamten betrachtet. das kombinierte gesamte jeder kategorie eines solchen Charts betraegt immer genau 100% wodurch zwar die information ueber die summe aller werte einer kategorie verloren geht aber die beitraege der einzelnen werte zu dem gesamten klarer ersichtlich ist. alle bars innerhalb einer kategorie werden uebereinander platziert und die bars die der selben unterkategorie angehoeren haben den selben style. das abbilden von kategorien und quantitativen werten auf raeumliche dimensionen wird so wie bei Basic Bar Charts ueber eine band scale und eine continuous scale erreicht. der unterschied besteht darin, dass der ursprung von bars nicht auf dem unteren extrem der value scale liegt sondern sich aus der summe der laengen der vorhergegangenen bars derselben kategorie ergibt.

die RespVis library stellt drei verschiedene komponenten unterschiedlicher layer fuer das rendern von

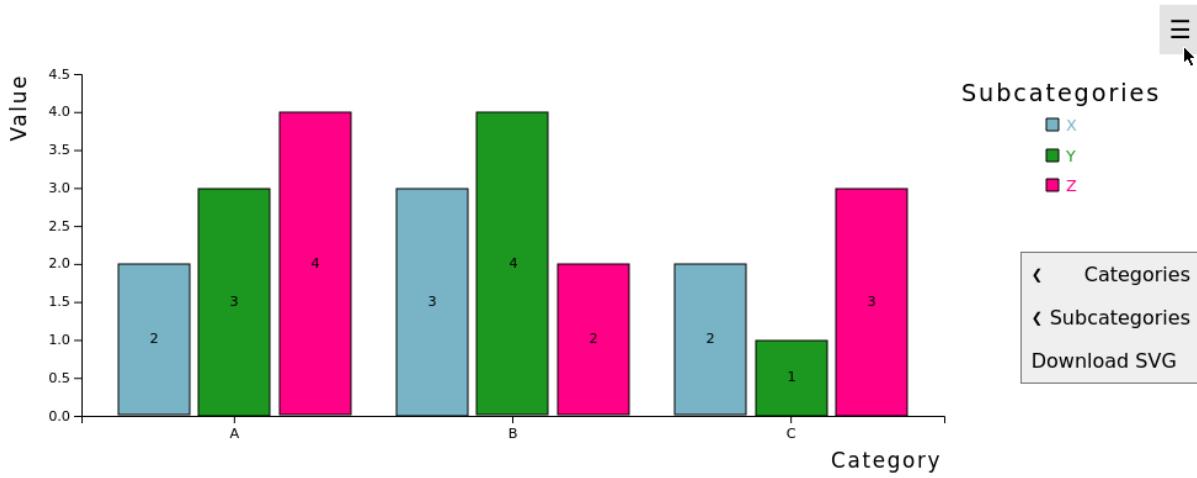


Figure 6.10: The resulting Grouped Bar Chart of the example code in Listing 6.5. The tool menu popup has manually been displaced to not cover the legend. [Image created by the author of this thesis using RespVis.]

Stacked Bar Charts zur verfuegung. die Stacked Bar Series, Stacked Bar Chart und Stacked Bar Chart Window komponenten sind ihren gegenstuecken fuer das rendern von Grouped Bar Charts sehr aehnlich. auch bei diesen komponenten werden bars ueber die zwei-dimensionale (kategorie/unterkategorie) grupierung von quantitativen werten gerendert, wobei eigenschaften welche individuelle bars beeinflussen ebenfalls als ein zwei-dimensionales array konfiguriert werden koennen. der hauptunterschied in der implementierung der Stacked Bar Series von der Grouped Bar Series besteht in der berechnung der positionen und ausmasse von bars. Stacked Bar Charts sind, so wie Grouped Bar Charts, kartesische Charts die aus einer Stacked Bar Series mit optionalen labels, zwei achsen, und einer legende bestehen. Stacked Bar Chart Windows sind ebenfallst äquivalent zu ihren Gegenstuecken von Grouped Bar Charts und rendern einen Stacked Bar Chart innerhalb eines Layouters unter einhaltung des erforderlichen render prozesses waehrend in der toolbar tools fuer das filtern der kategorien und unterkategorien des gerenderten Charts zur verfuegung gestellt werden. um das rendern eines Percent Stacked Bar Charts zu vereinfachen, koennen die quantitativen werte in dem datenobjekt eines Stacked Bar Chart Windows ueber die `valuesAsRatios` boolean eigenschaft als anteile deklariert werden was dazu fuehrt dass werte in prozentuelle anteile ihrer summen innerhalb einer kategorie transformiert werden. in Listing 6.6 ist der notwendige code ersichtlich mit dem ein skalierendes Stacked Bar Chart Window erzeugt werden kann dessen kategorien und unterkategorien ueber die toolbar gefiltert werden koennen. das gerenderte resultat dieses codes kann in Figure 6.11 gesehen werden.

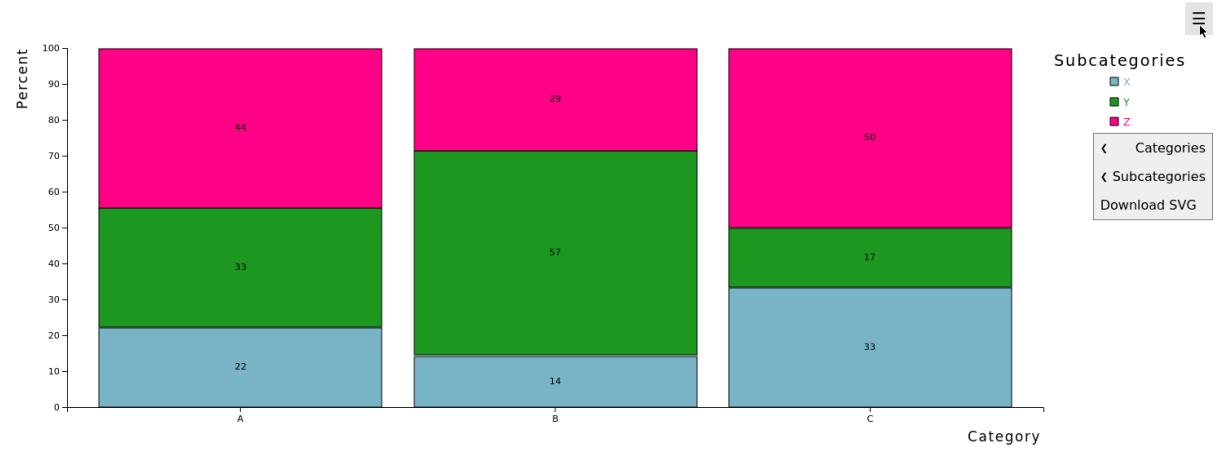
```
1 select('#chart')
2   .append('div')
3   .datum(
4     chartWindowBarStackedData({
5       categories: ['A', 'B', 'C'],
6       subcategories: ['X', 'Y', 'Z'],
7       values: [
8         [2, 3, 4],
9         [1, 4, 2],
10        [2, 1, 3],
11      ],
12    },
13    // to turn into a percent stacked bar chart
14    // valuesAsRatios: true,
15    {
16      xAxis: { title: 'Category' },
17      yAxis: { title: 'Percent' },
18      legend: { title: 'Subcategories' },
19    }
20  )
21  .call(chartWindowBarStackedRender)
22  .call(chartWindowBarStackedAutoResize)
23  .call(chartWindowBarStackedAutoFilterCategories)
24  .call(chartWindowBarStackedAutoFilterSubcategories);
```

Listing 6.6: The example source code that creates a Stacked Bar Chart Window.

The Stacked Bar Chart Window is configured with the bound data object that is initialized via the `chartWindowBarStackedData` function. After configuration, the Chart Window is rendered by the `chartWindowBarStackedRender` function. Since no special responsive behavior is desired in this example, the default resize, category filter, and subcategory filter behavior is attached to the Chart Window via the `chartWindowBarStackedAutoResize`, `chartWindowBarStackedAutoFilterCategories`, and `chartWindowBarStackedAutoFilterSubcategories` functions.



(a) Basic Stacked Bar Chart



(b) Percent Stacked Bar Chart

Figure 6.11: The resulting Stacked Bar Charts of the example code in Listing 6.6. The tool menu popup has manually been displaced to not cover the legend. (a) A Basic Stacked Bar Chart to compare the category totals and subcategory contributions to these totals. (b) A Percent Stacked Bar Chart to better compare the subcategory contributions to category totals. [Image created by the author of this thesis using RespVis.]

```

1 select('#chart')
2   .append('div')
3   .datum(
4     chartWindowPointData({
5       xValues: [10, 50, 20, 15, 35, 15, 35, 25, 45],
6       yValues: [1.5, 4, 3, 3.5, 4.5, 2.5, 4, 4, 4.5],
7       xAxis: { title: 'X Values' },
8       yAxis: { title: 'Y Values' },
9     })
10   )
11   .call(chartWindowPointRender)
12   .call(chartWindowPointAutoResize);

```

Listing 6.7: The example source code that creates a Point Chart Window. The Point Chart Window is configured with a bound data object that is initialized via the `chartWindowPointData` function. After configuration, the Chart Window is rendered by the `chartWindowPointRender` function. Since no special responsive behavior is desired in this example, the default resize behavior is attached to the Chart Window via the `chartWindowPointAutoResize` function.

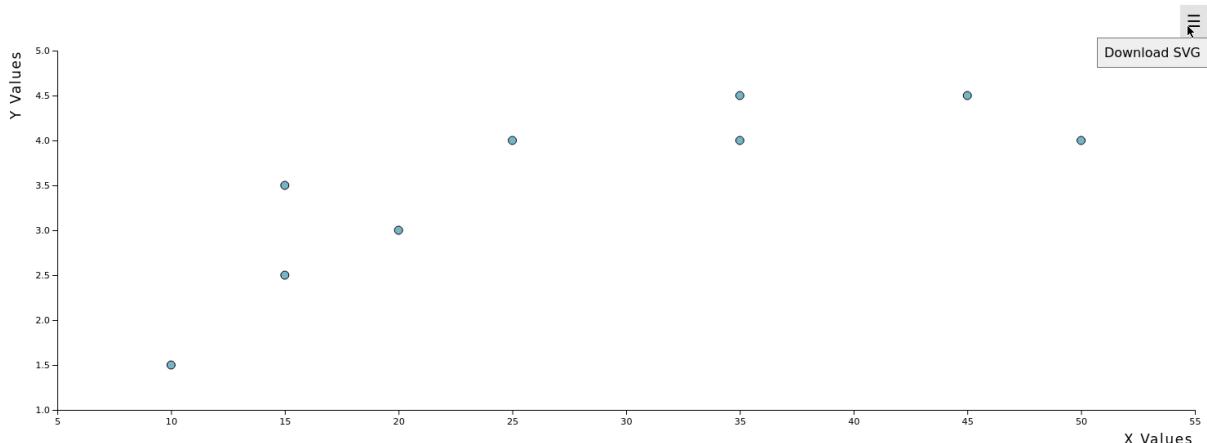


Figure 6.12: The resulting Point Chart of the example code in Listing 6.7. [Image created by the author of this thesis using RespVis.]

6.5 Point Module

Point Charts, manchmal auch scatter charts oder scatter plots genannt, werden verwendet um die beziehung zwischen zwei dimensionen eines datensatzes ueber punkte in einem kartesischen koordinatensystem zu verdeutlichen. ueber eine solche visualisierung koennen potentielle korrelationen und muster zwischen diesen dimensionen identifiziert werden. ueblicherweise werden zwei numerische dimensionen fuer die positionierung der punkte verwendet. die art der zu visualisierenden daten ist jedoch nicht von bedeutung, solange individuelle werte ueber eine scale auf raeumliche dimensionen abgebildet werden koennen. durch zusaetzliche kodierung der punkte mit farben, groessen oder formen koennen mehr als zwei dimensionen in einem Point Chart visualisiert werden. Point Charts in welchen eine dritte dimension ueber die groesse der punkte visualisiert wird, werden auch bubble charts genannt. der source code um einen skalierenden Point Chart mit der RespVis library zu erzeugen befindet sich in Listing 6.7 und die daraus resultierende visualisierung kann in Figure 6.12 gesehen werden.

das Point Module befindet sich im `src/lib/point/` ordner der RespVis library und beinhaltet die implementierung der Point Series, Point Chart, und Point Chart Window komponenten. mit einer Point Series wird eine sammlung an `<circle>` elementen gerendert deren mittelpunkte ueber X und Y werte arrays mit deren dazugehoerigen X und Y scales bestimmt werden und deren styles ueber style klassen gesetzt werden. da die radiuse der einzelnen `<circle>` elemente konfigurierbar sind, kann eine Point Series auch verwendet werden um einen bubble chart zu erzeugen. wie auch bei anderen Series Components, wird auch hier das gebundene datenobjekt in ein array an datenobjekten transformiert welches verwendet wird um die elemente der Series ueber einen data join zu rendern. ein Point Chart ist ein kartesischer Chart mit einer Point Series in seiner draw area und zwei achsen welche die scales visualisieren mit welchen die Point Series gerendert wurde. Point Chart Windows sind wrapper komponenten um Point Charts die diese in einen Layouter einbetten, ihren render prozess abwickeln, und sie mit einer toolbar dekorieren. zum aktuellen zeitpunkt wird nur ein SVG download tool ueber die toolbar eines Point Chart Windows zur verfuegung gestellt da bislang nur eine begrenzte anzahl an tools entwickelt wurden und diese sich nicht fuer die anwendung an Point Charts eignen. werden weitere tools benoetigt muessen diese manuell von visualisierungsauthoren implementiert und hinzugefuegt werden.

Chapter 7

Examples

7.1 Bar Chart

7.2 Grouped Bar Chart

7.3 Stacked Bar Chart

7.4 Scatterplot

[TODO: Write about application example (newspaper article?)]

Chapter 8

Selected Details of the Implementation

8.1 D3 Select Function Data Modification

8.2 Save as SVG

Chapter 9

Outlook and Future Work

9.1 Outlook

9.2 Ideas for Future Work

9.2.1 Post-Processing SVG String Before Download

9.2.2 Relative Positioning of Series Items

[TODO: Write about plans to use relative units (%) to position series items which would most likely get rid of the need to update components on bound changes]

9.2.3 Container Queries

Chapter 10

Concluding Remarks

Appendix A

User Guide

Appendix B

Developer Guide

Bibliography

- Aisch, Gregor, Larry Buchanan, Amanda Cox, and Kevin Quealy [2017]. *Some Colleges Have More Students From the Top 1 Percent Than the Bottom 60. Find Yours.* The New York Times. 18 Jan 2017. <https://nytimes.com/interactive/2017/01/18/upshot/some-colleges-have-more-students-from-the-top-1-percent-than-the-bottom-60.html> (cited on pages 35–36).
- Amar, Robert, James Eagan, and John Stasko [2005]. *Low-level Components of Analytic Activity in Information Visualization.* Proc. of the 2005 IEEE Symposium on Information Visualization (InfoVis 05) (Minneapolis, USA). IEEE, 2005, pages 111–117. doi:10.1109/INFVIS.2005.1532136. <http://citesee rx.ist.psu.edu/viewdoc/download?doi=10.1.1.86.1013&rep=rep1&type=pdf> (cited on page 19).
- amCharts [2021]. *amCharts.* 2021. <https://www.amcharts.com/> (cited on page 29).
- Andrews, Keith [2018]. *Responsive Visualization.* Proc. of the CHI 2018 Workshop on Data Visualization on Mobile Devices (MobileVis 2018) (Montréal, Canada). 21 Apr 2018. https://mobilevis.github.io/assets/mobilevis2018_paper_4.pdf (cited on pages 33, 35–38).
- Andrews, Keith [2019]. *Writing a Thesis: Guidelines for Writing a Master's Thesis in Computer Science.* Graz University of Technology, Austria. 24 Jan 2019. <http://ftp.iicm.edu/pub/keith/thesis/> (cited on page xiii).
- Andrews, Keith [2021]. *Information Visualisation - Course Notes.* Graz University of Technology, Austria. 01 Apr 2021. <https://courses.isds.tugraz.at/ivis/ivis.pdf> (cited on pages 17–18).
- Anscombe, Francis J [1973]. *Graphs in Statistical Analysis.* The American Statistician 27.1 (Feb 1973), pages 17–21. doi:10.1080/00031305.1973.10478966. <https://www.jstor.org/stable/pdf/2682899.pdf> (cited on page 17).
- Apple [2021]. *WebKit - A fast, open-source web browser engine.* 2021. <https://webkit.org/> (cited on page 14).
- Atkins, Tab, Elika J. Etemad, and Rossen Atanassov [2018]. *CSS Flexible Box Layout Module Level 1.* W3C Candidate Recommendation. W3C, 19 Nov 2018. <https://w3.org/TR/css-flexbox-1> (cited on pages 5–6).
- Atkins, Tab, Elika J. Etemad, Rossen Atanassov, and Oriol Brufau [2020]. *CSS Grid Layout Module Level 1.* W3C Candidate Recommendation. W3C, 18 Dec 2020. <https://w3.org/TR/css-grid-1/> (cited on pages 6–7).
- Barnett, Andrew, Jason French, and Robert Wall [2016]. *Comparing the World's Fighter Jets.* The Wall Street Journal. 25 Sep 2016. <https://graphics.wsj.com/how-the-worlds-best-fighter-jets-measure-up> (cited on page 35).
- Barton, Susanne and Hannah Recht [2018]. *The Massive Prize Luring Miners to the Stars.* Bloomberg. 08 Mar 2018. <https://bloomberg.com/graphics/2018-asteroid-mining/> (cited on pages 36–37).

- Bellamy-Royds, Amelia, Bogdan Brinza, Chris Lilley, Dirk Schulze, David Storey, and Eric Willigers [2018]. *Scalable Vector Graphics (SVG) 2*. W3C Candidate Recommendation. W3C, 04 Oct 2018. <https://w3.org/TR/SVG2/> (cited on page 11).
- Berners-Lee, Tim [1989]. *Information management: A Proposal*. 1989. <http://w3.org/History/1989/proposal.html> (cited on page 3).
- Bierman, Gavin, Martín Abadi, and Mads Torgersen [2014]. *Understanding TypeScript*. Proc. of the 28th European Conference on Object-Oriented Programming (Uppsala, Sweden). Springer, Aug 2014, pages 257–281. doi:10.1007/978-3-662-44202-9_11. <https://users.soe.ucsc.edu/~abadi/Papers/FTS-submitted.pdf> (cited on page 9).
- Bos, Bert, Tanek Çelik, Ian Hickson, and Håkon Wium Lie [2011]. *Cascading Style Sheets Level 2 Revision 1 (CSS 2.1) Specification*. W3C Recommendation. W3C, 07 Jun 2011. <https://w3.org/TR/CSS2> (cited on page 4).
- Bostock, Michael [2022a]. *d3-axis*. GitHub. 06 Jan 2022. <https://github.com/d3/d3-axis> (cited on pages 42, 61).
- Bostock, Michael [2022b]. *d3-scale*. GitHub. 06 Jan 2022. <https://github.com/d3/d3-scale> (cited on page 42).
- Bostock, Michael and Jeffrey Heer [2009]. *Protovis: A Graphical Toolkit for Visualization*. IEEE Transactions on Visualization and Computer Graphics 15.6 (23 Oct 2009), pages 1121–1128. doi:10.1109/TVCG.2009.174. <https://idl.cs.washington.edu/files/2009-Protovis-InfoVis.pdf> (cited on page 23).
- Bostock, Michael, Vadim Ogievetsky, and Jeffrey Heer [2011]. *D³ Data-Driven Documents*. IEEE Transactions on Visualization and Computer Graphics 17.12 (03 Nov 2011), pages 2301–2309. doi:10.1109/TVCG.2011.185. <https://idl.cs.washington.edu/files/2011-D3-InfoVis.pdf> (cited on page 23).
- Bostock, Mike [2021]. *D3.js – Data-Driven Documents*. 2021. <https://d3js.org/> (cited on page 23).
- Boutell, Thomas [2003]. *Portable Network Graphics (PNG) Specification (Second Edition)*. W3C Recommendation. W3C, 10 Nov 2003. <https://w3.org/TR/PNG/> (cited on page 10).
- Browsersync* [2022]. GitHub. 04 Jan 2022. <https://browsersync.io/> (cited on page 50).
- Bui, Quoctrung [2019]. *Three Months’ Salary for an Engagement Ring? For Most People, It’s More Like Two Weeks*. The New York Times. 13 Feb 2019. <https://nytimes.com/interactive/2019/02/13/upshot/engagement-rings-cost-two-weeks-pay.html> (cited on page 35).
- Bui, Quoctrung [2021]. *Delta Variant Hasn’t Yet Changed Many Return-to-Office Plans*. The New York Times. 23 Aug 2021. <https://nytimes.com/2021/08/12/upshot/covid-return-to-office.html> (cited on page 35).
- Canipe, Chris and Randy Yeip [2017]. *Health-Care Holdouts in the House*. The Wall Street Journal. 02 May 2017. <https://wsj.com/graphics/house-health-care-holdouts-round-two/> (cited on page 36).
- Çelik, Tanek, Elika J. Etemad, Daniel Glazman, Ian Hickson, Peter Linss, and John Williams [2018]. *Selectors Level 3*. W3C Recommendation. W3C, 06 Nov 2018. <https://w3.org/TR/selectors-3/> (cited on page 4).
- Chart.js* [2021]. GitHub. 2021. <https://github.com/chartjs/Chart.js> (cited on page 29).
- Chatterjee, Sangit and Aykut Firat [2007]. *Generating Data with Identical Statistics but Dissimilar Graphics: A Follow up to the Anscombe Dataset*. The American Statistician 61.3 (Aug 2007), pages 248–254. doi:10.1198/000313007X220057. <https://www.jstor.org/stable/pdf/27643902.pdf> (cited on page 17).
- Chhipa, Juned and Brian Lagunas [2021]. *ApexCharts*. 2021. <https://apexcharts.com/> (cited on page 29).

- Chromium [2021]. *Blink - Rendering Engine*. 2021. <https://chromium.org/blink/> (cited on page 14).
- Cohen, I. Bernard [1984]. *Florence Nightingale*. Scientific American 250.3 (Mar 1984), pages 128–137. doi:10.1038/scientificamerican0384-128. <https://accounts.smccd.edu/case/biol675/docs/nightingale.pdf> (cited on page 19).
- Coyer, Chris [2021]. *A Complete Guide to Flexbox*. 10 Sep 2021. <https://css-tricks.com/snippets/css/a-guide-to-flexbox/> (cited on page 6).
- Dahlström, Erik, Patrick Dengler, Anthony Grasso, Chris Lilley, Cameron McCormack, Doug Schepers, and Jonathan Watt [2011]. *Scalable Vector Graphics (SVG) 1.1 (Second Edition)*. W3C Recommendation. W3C, 16 Aug 2011. <https://w3.org/TR/SVG11/> (cited on pages 10–11, 53).
- Deakin, Neil, Ian Hickson, and David Hyatt [2009]. *CSS Flexible Box Layout Module*. W3C Working Draft. W3C, 23 Jul 2009. <http://w3.org/TR/2009/WD-css3-flexbox-20090723/> (cited on page 5).
- Deutsch, Peter [1996]. *RFC1952: GZIP File Format Specification Version 4.3*. RFC. IETF, May 1996. <https://datatracker.ietf.org/doc/html/rfc1952> (cited on pages 44, 47).
- Deveria, Alexis [2021a]. *Can I use CSS Flexible Box Layout Module*. 13 Aug 2021. <https://caniuse.com/flexbox> (cited on page 5).
- Deveria, Alexis [2021b]. *Can I use CSS Grid Layout*. 19 Aug 2021. <https://caniuse.com/css-grid> (cited on page 6).
- ECMA [1997]. *ECMAScript: A general purpose, cross-platform programming language*. ECMA-262. Ecma International, Jun 1997. https://ecma-international.org/wp-content/uploads/ECMA-262_1st_edition_june_1997.pdf (cited on page 8).
- ECMA [2009]. *ECMAScript 5th Edition Language Specification*. ECMA-262. Ecma International, Dec 2009. https://ecma-international.org/wp-content/uploads/ECMA-262_5th_edition_december_2009.pdf (cited on page 8).
- ECMA [2015]. *ECMAScript 6th Edition Language Specification*. ECMA-262. Ecma International, Jun 2015. <https://262.ecma-international.org/6.0/> (cited on pages 8, 45).
- Etemad, Elika J. and Tab Atkins [2021]. *CSS Cascading and Inheritance Level 3*. W3C Recommendation. W3C, 11 Feb 2021. <https://w3.org/TR/css-cascade-3/> (cited on page 4).
- Facebook [2021a]. *ComponentKit: A declarative UI framework for iOS*. Facebook Open Source. 2021. <https://componentkit.org/> (cited on page 14).
- Facebook [2021b]. *Litho: A declarative UI framework for Android*. Facebook Open Source. 2021. <https://fb.litho.com> (cited on page 14).
- Facebook [2021c]. *React Native*. Facebook Open Source. 2021. <https://reactnative.dev> (cited on page 14).
- Facebook [2021d]. *Yoga Layout*. Facebook Open Source. 2021. <https://yogalayout.com> (cited on pages 14, 56).
- Ferdio [2021a]. *Grouped Bar Chart*. Data Viz Project. 22 Oct 2021. <https://datavizproject.com/data-type/grouped-bar-chart/> (cited on page 35).
- Ferdio [2021b]. *Stacked Bar Chart*. Data Viz Project. 22 Oct 2021. <https://datavizproject.com/data-type/stacked-bar-chart/> (cited on page 35).
- Ferraiolo, Jon [1999]. *Scalable Vector Graphics (SVG) Specification*. W3C Working Draft. W3C, 11 Feb 1999. <https://w3.org/TR/1999/WD-SVG-19990211/> (cited on page 10).

- Fessenden, Ford and Haeyoun Park [2016]. *Chicago's Murder Problem*. The New York Times. 27 May 2016. <https://nytimes.com/interactive/2016/05/18/us/chicago-murder-problem.html> (cited on page 36).
- Florent, Michael Florent van [1644]. *La Verdadera Longitud por Mar y Tierra*. 1644 (cited on pages 19–20).
- Francis, Theo [2017]. *Why You Probably Work for a Giant Company, in 20 Charts*. The Wall Street Journal. 06 Apr 2017. <https://wsj.com/graphics/big-companies-get-bigger/> (cited on pages 35–36).
- Friendly, Michael [2008]. *A Brief History of Data Visualization*. In: *Handbook of Data Visualization*. Springer, 2008, pages 15–56. ISBN 3540330364. doi:10.1007/978-3-540-33037-0_2 (cited on pages 20, 22).
- Friendly, Michael and Howard Wainer [2021]. *A History of Data Visualization and Graphic Communication*. Harvard University Press, 08 Jun 2021. 320 pages. ISBN 0674975235 (cited on page 22).
- FusionCharts [2021]. *FaberJS*. GitHub. 21 Oct 2021. <https://github.com/fusioncharts/faberjs> (cited on pages 14, 56).
- Gao, Zheng, Christian Bird, and Earl T. Barr [2017]. *To Type or Not to Type: Quantifying Detectable Bugs in JavaScript*. Proc. of the 39th International Conference on Software Engineering (Buenos Aires, Argentina). Institute of Electrical and Electronics Engineers, May 2017, pages 758–769. doi:10.1109/ICSE.2017.75. <https://earlbarr.com/publications/typestudy.pdf> (cited on page 9).
- Google [2008]. *A fresh take on the browser*. 01 Sep 2008. <https://googleblog.blogspot.com/2008/09/fresh-take-on-browser.html> (cited on page 8).
- Google [2022]. *V8 JavaScript Engine*. 06 Jan 2022. <https://v8.dev/> (cited on page 45).
- Gulp [2022]. 06 Jan 2022. <https://gulpjs.com/> (cited on page 42).
- Hickson, Ian, Simon Pieters, Anne van Kesteren, Philip Jägenstedt, and Domenic Denicola [2021]. *HTML Standard*. Living Standard. WHATWG, 11 Aug 2021. <https://html.spec.whatwg.org> (cited on pages 3, 11).
- Highsoft [2021]. *Highcharts*. 2021. <https://www.highcharts.com/> (cited on pages 29, 56).
- Hinderman, Bill [2015]. *Building Responsive Data Visualization for the Web*. Wiley, 02 Nov 2015. ISBN 1119067146 (cited on page 33).
- Hoban, Luke [2012]. *Announcing TypeScript 0.8.1*. 15 Nov 2012. <https://devblogs.microsoft.com/typescript/announcing-typescript-0-8-1/> (cited on page 9).
- Hoffswell, Jane, Wilmot Li, and Zhicheng Liu [2020]. *Techniques for Flexible Responsive Visualization Design*. Proc. of the Conference on Human Factors in Computing Systems (CHI 2020) (Online). ACM, 25 Apr 2020, pages 1–13. doi:10.1145/3313831.3376777. <https://idl.cs.washington.edu/files/2020-ResponsiveVis-CHI.pdf> (cited on pages 33–34).
- House, Chris [2021]. *A Complete Guide to Grid*. 09 Nov 2021. <https://css-tricks.com/snippets/css/complete-guide-grid/> (cited on page 7).
- IDL [2021]. *Vega – A Visualization Grammar*. UW Interactive Data Lab. 2021. <https://vega.github.io/vega> (cited on page 25).
- Jackson, Dean and Jeff Gilbert [2014]. *WebGL Specification*. Technical report. Version 1.0.3. Khronos Group, 27 Oct 2014. <https://khronos.org/registry/webgl/specs/1.0/> (cited on page 12).
- Jackson, Dean and Jeff Gilbert [2017]. *WebGL 2 Specification*. Technical report. Version 2.0.0. Khronos Group, 11 Apr 2017. <https://khronos.org/registry/webgl/specs/2.0/> (cited on page 12).

- JPEG [1994]. *Overview of JPEG 1*. ISO/IEC 10918. Joint Photographic Experts Group, Feb 1994. <https://jpeg.org/jpeg/> (cited on page 10).
- Jr., Tab Atkins, Elika J. Etemad, and Florian Rivoal [2020]. *CSS Snapshot 2020*. W3C Working Group Note. W3C, 22 Dec 2020. <https://w3.org/TR/css-2020/> (cited on page 4).
- Katz, Josh and Margot Sanger-Katz [2021]. ‘It’s Huge, It’s Historic, It’s Unheard-of’: Drug Overdose Deaths Spike. The New York Times. 14 Jul 2021. <https://nytimes.com/interactive/2021/07/14/upshot/drug-overdose-deaths.html> (cited on page 36).
- Kesteren, Anne van, Aryeh Gregor, and Ms2ger [2021]. *DOM Standard*. Living Standard. WHATWG, 02 Aug 2021. <https://dom.spec.whatwg.org/> (cited on page 8).
- Kim, Hyeok, Dominik Moritz, and Jessica Hullman [2021a]. *Design Patterns and Trade-Offs in Responsive Visualization for Communication*. Computer Graphics Forum 40.3 (Jun 2021), pages 459–470. doi:10.1111/cgf.14321. <https://arxiv.org/pdf/2104.07724.pdf> (cited on pages 33–36).
- Kim, Hyeok, Dominik Moritz, and Jessica Hullman [2021b]. *Responsive Visualization Gallery*. 2021. <https://mucollective.github.io/responsive-vis-gallery/> (cited on pages 34, 69).
- Körner, Christoph [2016]. *Learning Responsive Data Visualization*. Packt Publishing, 23 Mar 2016. ISBN 178588378X (cited on page 33).
- Kunz, Gion [2021]. *Chartist.js*. 2021. <http://gionkunz.github.io/chartist-js/> (cited on pages 29, 56).
- Leach, P., M. Mealling, and R. Salz [2005]. *RFC4122: A Universally Unique Identifier (UUID) URN Namespace*. RFC. IETF, Jul 2005. <https://www.ietf.org/rfc/rfc4122.txt> (cited on page 64).
- Li, Deqing, Honghui Mei, Yi Shen, Shuang Su, Wenli Zhang, Junting Wang, Ming Zu, and Wei Chen [2018]. *ECharts: A declarative framework for rapid construction of web-based visualization*. Visual Informatics 2.2 (17 May 2018), pages 136–146. doi:10.1016/j.visinf.2018.04.011. <http://chinavis.org/2018/echarts.pdf> (cited on page 29).
- Lie, Håkon Wium [1994]. *Cacading HTML Style Sheets: A Proposal*. 1994. <https://w3.org/People/home/p/cascade.html> (cited on page 4).
- Lie, Håkon Wium and Bert Bos [1996]. *Cascading Style Sheets Level 1 (CSS 1) Specification*. W3C Recommendation. W3C, 17 Dec 1996. <https://w3.org/TR/CSS1/> (cited on page 4).
- Liu, Shanhong [2021]. *Most used programming languages among developers worldwide*. 05 Aug 2021. <https://statista.com/statistics/793628/worldwide-developer-survey-most-used-languages/> (cited on page 7).
- Macrobius, Ambrosius Theodosius [1175]. *Commentarii in somnium Scipionis*. De Gruyter, 1175. ISBN 3598715269. doi:10.1515/9783110951899 (cited on pages 19–20).
- Macrofocus [2021]. *High-D: High Dimensionality Analytics Using Parallel Coordinates*. 2021. <https://www.high-d.com/> (cited on pages 22, 37).
- Marcotte, Ethan [2010]. *Responsive Web Design*. A List Apart. 25 May 2010. <https://alistapart.com/article/responsive-web-design> (cited on page 15).
- Meirelles, Isabel [2013]. *Design for Information: An Introduction to the Histories, Theories, and Best Practices Behind Effective Information Visualizations*. Rockport, 01 Oct 2013. 224 pages. ISBN 1592538061 (cited on page 22).
- Meyer, Eric A. [2016]. *Grid Layout in CSS: Interface Layout for the Web*. O’Reilly Media, 18 Apr 2016. ISBN 1491930217 (cited on page 7).

- Microsoft [1996]. *Microsoft Internet Explorer 3.0 Beta Now Available*. 29 May 1996. <https://news.microsoft.com/1996/05/29/microsoft-internet-explorer-3-0-beta-now-available/> (cited on page 7).
- Microsoft [2020]. *Microsoft 365 apps say farewell to Internet Explorer 11 and Windows 10 sunsets Microsoft Edge Legacy*. 17 Aug 2020. <https://techcommunity.microsoft.com/t5/microsoft-365-blog/microsoft-365-apps-say-farewell-to-internet-explorer-11-and/ba-p/1591666> (cited on page 5).
- Minczeski, Pat, Donato Paolo Mancini, Colleen McEnaney, and Jason French [2017]. *France's New Political Class*. The Wall Street Journal. 03 Jul 2017. <https://wsj.com/graphics/french-assembly-2017/> (cited on page 35).
- Mogilevsky, Alex, Phil Cupp, Markus Mielke, and Daniel Glazman [2011]. *Grid Layout*. W3C Working Draft. W3C, 07 Apr 2011. <https://w3.org/TR/2011/WD-css3-grid-layout-20110407/> (cited on page 6).
- Moseley, Ben and Peter Marks [2006]. *Out of the Tar Pit* (06 Feb 2006). <https://github.com/papers-we-love/papers-we-love/blob/master/design/out-of-the-tar-pit.pdf> (cited on page 40).
- Mozilla [2004]. *Firefox 1.0 Release Notes*. 09 Nov 2004. https://website-archive.mozilla.org/www.mozilla.org/firefox_releasenotes/en-us/firefox/releases/1.0 (cited on page 8).
- Munroe, Randall [2021]. *Earth Temperature Timeline*. xkcd. 21 Oct 2021. <https://xkcd.com/1732/> (cited on page 36).
- NAVER [2021]. *billboard.js*. 2021. <https://naver.github.io/billboard.js/> (cited on page 29).
- Netscape [1995]. *Netscape and Sun Announce JavaScript, the Open, Cross-Platform Object Scripting Language for Enterprise Networks and the Internet*. Netscape Communications Corporation. 04 Dec 1995. <https://web.archive.org/web/20070916144913/http://wp.netscape.com/newsref/pr/newsrelease67.html> (cited on page 7).
- npm [2022]. 06 Jan 2022. <https://npmjs.com/> (cited on pages 43, 45).
- NYT [2018a]. *What's Going On in This Graph? Dec. 5, 2018*. The New York Times. 06 Dec 2018. <https://nytimes.com/2018/11/29/learning/whats-going-on-in-this-graph-dec-5-2018.html> (cited on page 35).
- NYT [2018b]. *What's Going On in This Graph? March 13, 2018*. The New York Times. 15 Mar 2018. <https://nytimes.com/2018/03/08/learning/whats-going-on-in-this-graph-march-13-2018.html> (cited on page 36).
- NYT [2018c]. *What's Going On in This Graph? Oct. 17, 2018*. The New York Times. 18 Oct 2018. <https://nytimes.com/2018/10/16/learning/whats-going-on-in-this-graph-oct-17-2018.html> (cited on page 36).
- NYT [2019a]. *What's Going On in This Graph? March 6, 2019*. The New York Times. 09 Mar 2019. <https://nytimes.com/2019/09/12/learning/whats-going-on-in-this-graph-sept-18-2019.html> (cited on page 36).
- NYT [2019b]. *What's Going On in This Graph? Sept. 18, 2019*. The New York Times. 19 Sep 2019. <https://nytimes.com/2019/09/12/learning/whats-going-on-in-this-graph-sept-18-2019.html> (cited on page 36).
- NYT [2020a]. *What's Going On in This Graph? North American Bird Populations*. The New York Times. 28 Feb 2020. <https://nytimes.com/2020/01/09/learning/whats-going-on-in-this-graph-north-american-bird-populations.html> (cited on page 35).
- NYT [2020b]. *What's Going On in This Graph? Voters by Age Group*. The New York Times. 05 Mar 2020. <https://nytimes.com/2020/02/27/learning/whats-going-on-in-this-graph-voters-by-age-group.html> (cited on page 35).

- O'Donnell, Jane [2019]. *SASS (Syntactically Awesome Style Sheets)*. Journal of Computing Sciences in Colleges 34.4 (Apr 2019), pages 101–102 (cited on page 45).
- Oberrauner, Peter [2022]. *RespVis*. GitHub. 06 Jan 2022. <https://github.com/almostbearded/respvis> (cited on page 42).
- Observable [2021]. *Observable: Explore, analyze, and explain data. As a team.* 2021. <https://observablehq.com/> (cited on page 23).
- OpenJS [2021]. *Node.js*. OpenJS Foundation. 2021. <https://nodejs.org> (cited on pages 7, 42).
- Playfair, William [1786]. *Commercial and Political Atlas: Representing, by Copper-Plate Charts, the Progress of the Commerce, Revenues, Expenditure, and Debts of England, during the Whole of the Eighteenth Century*. Cambridge University Press, 1786. ISBN 0521855543 (cited on pages 19, 69).
- Playfair, William [1801]. *Statistical Breviary; Shewing, on a Principle Entirely New, the Resources of Every State and Kingdom in Europe*. Cambridge University Press, 1801. ISBN 0521855543 (cited on page 19).
- Plotly [2021]. *Plotly JavaScript Open Source Graphing Library*. 2021. <https://plotly.com/javascript> (cited on page 29).
- Rabinowitz, Nick [2014]. *Responsive Data Visualization*. GitHub. 25 Sep 2014. <https://nrabinowitz.github.io/rdv/> (cited on page 37).
- Raggett, Dave [1997]. *HTML 3.2 Reference Specification*. W3C Recommendation. W3C, 14 Jan 1997. <https://w3.org/TR/2018/SPSD-html32-20180315> (cited on page 3).
- Rendgen, Sandra [2019]. *History of Information Graphics*. Taschen, 26 Jun 2019. 462 pages. ISBN 3836567679 (cited on page 22).
- Rendle, Robin [2017]. *Does CSS Grid Replace Flexbox?* 31 Mar 2017. <https://css-tricks.com/css-grid-replace-flexbox/> (cited on page 7).
- Rollup [2022]. 06 Jan 2022. <https://rollupjs.org> (cited on page 42).
- Routley, Nick [2020]. *Internet Browser Market Share (1996–2019)*. 20 Jan 2020. <https://visualcapitalist.com/internet-browser-market-share/> (cited on page 8).
- Satyanarayan, Arvind and Jeffrey Heer [2014]. *Lyra: An Interactive Visualization Design Environment*. Computer Graphics Forum 33.3 (12 Jul 2014), pages 351–360. doi:10.1111/cgf.12391 (cited on page 26).
- Satyanarayan, Arvind, Dominik Moritz, Kanit Wongsuphasawat, and Jeffrey Heer [2016]. *Vega-Lite: A Grammar of Interactive Graphics*. IEEE Transactions on Visualization and Computer Graphics 23.1 (10 Aug 2016), pages 341–350. doi:10.1109/TVCG.2016.2599030. <https://files.osf.io/v1/resources/mqzyx/providers/osfstorage/5be5e643d354e900197998bd?version=1&direct&format=pdf> (cited on page 26).
- Satyanarayan, Arvind, Ryan Russell, Jane Hoffswell, and Jeffrey Heer [2015]. *Reactive Vega: A Streaming Dataflow Architecture for Declarative Interactive Visualization*. IEEE Transactions on Visualization and Computer Graphics 22.1 (12 Aug 2015), pages 659–668. doi:10.1109/TVCG.2015.2467091. <http://dl.cs.washington.edu/files/2015-ReactiveVega-InfoVis.pdf> (cited on pages 25–26).
- Scheiner, Christoph [1630]. *Rosa Ursina sive Sol ex Admirando Facularum & Macularum Suarum Phoenomeno Varius*. 1630 (cited on pages 19–20).
- Scott Logic [2021]. *D3FC*. 2021. <https://d3fc.io/> (cited on page 29).
- Sharvit, Yehonathan [2022]. *Data-Oriented Principle #1: Separate Code from Data*. 15 Jan 2022. <https://blog.klipse.tech/databook/2020/10/02/separate-code-data.html> (cited on page 40).

- Shifflett, Shane [2016]. *A Divided America*. The Wall Street Journal. 09 Nov 2016. <https://wsj.comgraphics/elections/2016/divided-america/> (cited on page 36).
- Shneiderman, Ben [1996]. *The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations*. Proc. of the 1996 IEEE Symposium on Visual Languages (Boulder, USA). 1996, pages 336–336. doi:10.1109/vl.1996.545307. <https://citeserx.ist.psu.edu/viewdoc/download?doi=10.1.1.445.8909&rep=rep1&type=pdf> (cited on page 19).
- Sikorski, Robert and Richard Peters [1999]. *Netscape's Gecko and You*. Science 283.5409 (19 Mar 1999), pages 1871–1872. doi:10.1126/science.283.5409.1871b. <https://www.science.org/doi/full/10.1126/science.283.5409.1871b> (cited on page 14).
- Sjölander, Emil [2016]. *Yoga: A cross-platform layout engine*. Facebook Engineering. 07 Dec 2016. <https://engineering.fb.com/2016/12/07/android/yoga-a-cross-platform-layout-engine> (cited on page 14).
- Sober, Elliott [1979]. *The Principle of Parsimony*. The British Journal for the Philosophy of Science 32.2 (10 Dec 1979), pages 145–156. doi:10.1093/bjps/32.2.145 (cited on page 23).
- StatCounter [2021]. *Desktop Browser Market Share Worldwide*. 2021. <https://gs.statcounter.com/browser-market-share/desktop/worldwide/#yearly-2009-2021> (cited on page 8).
- Tanaka, Masayuki [2020]. *C3.js*. 08 Aug 2020. <https://c3js.org/> (cited on page 29).
- Totic, Aleks and Greg Whitworth [2020]. *Resize Observer*. W3C Working Draft. W3C, 11 Feb 2020. <https://w3.org/TR/2020/WD-resize-observer-1-20200211/> (cited on page 8).
- Treisman, Anne [1985]. *Preattentive Processing in Vision*. Computer Vision, Graphics, and Image Processing 31.2 (Aug 1985), pages 156–177. doi:10.1016/S0734-189X(85)80004-9 (cited on page 17).
- Tufte, Edward Rolf [1983]. *The Visual Display of Quantitative Information*. 1st Edition. Graphics Press, 1983. ISBN 1930824130 (cited on pages 19–20).
- Tufte, Edward Rolf [1997]. *Visual Explanations*. Graphics Press, 14 Jan 1997. ISBN 1930824157 (cited on page 20).
- uuid* [2022]. 06 Jan 2022. <https://github.com/uuidjs/uuid> (cited on page 64).
- Wan, Zhanyong, Walid Taha, and Paul Hudak [2001]. *Event-Driven FRP*. Proc. of the 4th International Symposium on Practical Aspects of Declarative Languages (Las Vegas, USA). Springer, 20 Dec 2001, pages 155–172. ISBN 354043092X. doi:10.1007/3-540-45587-6_11 (cited on page 26).
- Wattenberger, Amelia [2019]. *Fullstack D3 and Data Visualization*. Fullstack.io, 29 Jul 2019. ISBN 0991344650. <https://newline.co/fullstack-d3> (cited on page 23).
- WHATWG [2021]. *HTML Living Standard. The canvas element*. Technical report. Web Hypertext Application Technology Working Group (WHATWG), 08 Dec 2021. <https://html.spec.whatwg.org/#the-canvas-element> (cited on page 12).
- Wilkinson, Leland [2005]. *The Grammar of Graphics*. 2nd Edition. Springer, 15 Jul 2005. ISBN 0387245448. doi:10.1007/0-387-28695-0 (cited on pages 19, 25).
- Wongsuphasawat, Kanit, Dominik Moritz, Anushka Anand, Jock Mackinlay, Bill Howe, and Jeffrey Heer [2015]. *Voyager: Exploratory Analysis via Faceted Browsing of Visualization Recommendations*. IEEE Transactions on Visualization and Computer Graphics 22.1 (12 Aug 2015), pages 649–658. doi:10.1109/TVCG.2015.2467191. <https://www.domoritz.de/papers/2015-Voyager-InfoVis.pdf> (cited on page 26).
- Wongsuphasawat, Kanit, Dominik Moritz, Anushka Anand, Jock Mackinlay, Bill Howe, and Jeffrey Heer [2016]. *Towards a general-purpose query language for visualization recommendation*. Proc. of the

2016 Workshop on Human-In-the-Loop Data Analytics (San Francisco, USA). ACM Digital Library, 26 Jun 2016, pages 1–6. doi:10.1145/2939502.2939506. <http://idl.cs.washington.edu/files/2016-CompassSQL-HILDA.pdf> (cited on page 26).

Wood, Lauren, Arnaud Le Hors, Andrew Watson, Bill Smith, Chris Lovett, David Singer, Gavin Nicol, James Clark, Jared Sorensen, Mike Champion, Paul Grosso, Peter Sharpe, Phil Karlton, Rick Gessner, Robert Sutor, Scott Isaacs, Sharon Adler, Steve Byrne, Tim Bray, and Vidur Apparao [1997]. *Document Object Model Specification*. W3C Working Draft. W3C, 09 Oct 1997. <https://w3.org/TR/WD-DOM-971009/> (cited on page 8).

WSJ [2017]. *October's Not as Bleak as Its Reputation for Stock Markets*. The Wall Street Journal. 07 Oct 2017. <https://wsj.com/articles/octobers-not-as-bleak-as-its-reputation-for-stock-markets-1507384342> (cited on page 35).

Yi, Ji Soo, Youn ah Kang, John Stasko, and Julie A Jacko [2007]. *Toward a Deeper Understanding of the Role of Interaction in Information Visualization*. IEEE Transactions on Visualization and Computer Graphics 13.6 (05 Nov 2007), pages 1224–1231. doi:10.1109/TVCG.2007.70515. <https://innovis.psc.ucalgary.ca/innovis/uploads/Courses/InformationVisualizationDetails2009/Yi.pdf> (cited on page 19).