Parallel Coordinates

Exploratory Data Analysis with Parallel Coordinates
and the Multi-Dimensional Explorer

Master's Thesis

at

Graz University of Technology

submitted by

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Advisor: Ao.Univ.-Prof. Dr. Keith Andrews

Parallelkoordinaten

Empirische Datenanalyse mit Parallelkoordinaten
und dem Multi-Dimensional Explorer

Masterarbeit

an der

Technischen Universität Graz

vorgelegt von

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Diese Arbeit ist in englischer Sprache verfasst.

Begutachter: Ao.Univ.-Prof. Dr. Keith Andrews

Abstract

Parallel coordinates are an analysis technique in which multi-dimensional data is visualised by arranging axes in parallel to each other on a plane. Each dimension is represented by one axis. Each data record is represented by a polyline connecting to one point on every axis.

The corresponding research field of information visualisation is first presented and numerous techniques are discussed. Parallel coordinates are then discussed in detail, including issues of scalability and performance. Previously developed software tools featuring parallel coordinates are reviewed and their strengths and weaknesses analysed. The interactive features necessary to perform exploratory data analysis with parallel coordinates are illustrated.

A new, general-purpose information visualisation tool, the Multi-Dimensional Explorer (MDE), was developed in C++ and OpenGL. It facilitates exploratory data analysis with high performance and a variety of user interaction features. The thesis documents the modular software architecture of MDE. User and developer guides for MDE are included as appendices.

Kurzfassung

Parallelkoordinaten sind ein Analyseverfahren, bei dem mehrdimensionale Daten visualisiert werden, indem Achsen parallel zueinander auf einer Ebene angeordnet werden. Jede Achse steht für eine Dimension, und jeder Datensatz wird mit einer Polylinie dargestellt, die durch je einen Punkt auf jeder Achse läuft.

Erst werden der dazugehörige Forschungsbereich der Informationsvisualisierung vorgestellt und verschiedene andere Techniken besprochen, dann werden Parallelkoordinaten im Detail erörtert, samt Betrachtungen zu Skalierbarkeit und Performance. Bisher entwickelte Parallelkoordinaten-Software wird besprochen und deren Stärken und Schwächen werden untersucht. Ebenfalls erläutert werden die für die empirische Datenanalyse mit Parallelkoordinaten nötigen Interaktionsmöglichkeiten.

Eine neue, universell verwendbare Informationsvisualisierungs-Software namens Multi-Dimensional Explorer (MDE) wurde mit C++ und OpenGL entwickelt. Sie erleichtert die empirische Datenanalyse durch hohe Performance und eine Reihe von Interaktionsmöglichkeiten. Die Arbeit dokumentiert die modulare Softwarearchitektur von MDE. Der Anhang enthält Anleitungen zum Gebrauch von MDE und zu seiner künftigen Weiterentwicklung.

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 marked all material which has been quoted either literally or by content from the used sources.

Place	Date	Signature

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Ort	Datum	Unterschrift

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As far as programming skills are concerned, I also owe a lot to the regulars of the Usenet newsgroup comp.lang.c++. I gained many insights by just silently following their often heated discussions about the C++ programming language. I'm very grateful also for Alfred Inselberg allowing me to evaluate his Parallax software for free, Ross Shannon and Tom Holland for providing me with a copy of their Paired PCV tool, Daniel Keim for the source code of VisDB, the folks in de.comp.text.tex for help on LaTeX issues, and Anita for her moral support.

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Finally, I wish to thank the people from all over Europe whom I met during my unforgettable times in Milan and as a result of my studies abroad, because it was ultimately their friendship which gave me the strength to believe in my ability to accomplish this project and to complete my studies in Graz the way I had always hoped I would. The encouragement they gave me might have come from distant places, but I felt it all the more close to me.

Thank you, Chiara and Jennifer, for the conversations and e-mail correspondence we had when I was unsure about whether to start this project or not. You helped me make the right decision. I wonder if this thesis would exist if it was not for you. Thank you, Mathilde, Alessandro and Fabio, for believing in me right from the beginning! Thanks to each and every one of you who helped me in the project's intense final phase by expressing emotional support in one way or the other! Giuseppe, Mattia, Andrea, Katrin, Ismael, Paula, Pietro, Despina, Wojtek, Marina, Rafal, Ottavio, Anneke, Abel, Leticia, Alice – I think the list of names could go on forever. A person sometimes just needs to hear or read a few encouraging words to carry on the struggle, and this is exactly what you've given me.

"Ce la farai!" – "You'll make it!" I heard that sentence very often, and my ultimate determination to finally complete my thesis and to really give my best came also from the wish not to disappoint you.

Christian Hackl
Graz, Austria, March 2011

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, 2008b].
- Alfred Inselberg provided a copy of his commercial Parallax software for free [Inselberg, 2010a].
- Ross Shannon and Tom Holland sent me a copy of their Paired Parallel Coordinates View (PPCV) tool [Shannon et al., 2008].
- Daniel Keim gave me access to the source code of VisDB so that I could compile, run and review the program [Keim et al., 2002].
- The screenshot of the FilmFinder in Figure 2.6 was used with the kind permission of the University of Maryland, see copyright notice below.

University of Maryland Copyright Notice

Chapter 1

Introduction

"From the fiery mirror of truth
She smiles upon the researcher,
Towards virtue's steep hill
She guides the endurer's path."

[Friedrich Schiller, Ode to Joy, 1786[1]]

This Master's thesis is about exploratory data analysis using the parallel coordinates technique for information visualisation. The history and general definition of "information visualisation" are discussed in Chapter 2. Information visualisation might sound like a very general term but has a precise scientific meaning which must be established before discussing any material in detail. In particular, geographical maps do not usually belong to that area. The chapter then discusses the importance of user interaction in today's visualisation software and aspects of multi-dimensional information visualisation; scatter plots, star plots, histograms and VisIslands are introduced.

Chapter 3 explains the mathematical background of parallel coordinates. The basic idea is to arrange axes parallel to each other on a plane, rather than aligning them in an orthogonal way. The individual data points are then connected by polylines across all axes. This way, more than three dimensions can be displayed at the same time. However, this visualisation scheme can also be problematic when large data sets must be visualised, because the display soon becomes cluttered by many lines. The thesis discusses the many techniques proposed to handle this problem by means of clustering. It explains also a select number of experimental approaches to extend the original parallel coordinates idea, such as 3D visualisations or replacing polylines with curves. The chapter is concluded with an explanation of how a user interacts with parallel coordinates to analyse data. A large number of software applications implementing parallel coordinates are reviewed, and their individual strengths and weaknesses are outlined.

In most cases, low performance and limited user interaction are problems in parallel coordinates software. Based on this finding, a new software application called "Multi-Dimensional Explorer" (MDE) was developed for this thesis. Chapter 4 discusses it in detail. MDE is a general-purpose information visualisation software application, although special attention has been given to its parallel coordinates component. It was designed and implemented from ground up with high performance and high usability in mind. The software architecture of MDE is discussed and its highly modular architecture is explained. This allows developers to extend the tool in many different aspects, for example by adding new visualisation techniques or by adding new ways of reading data for input.

[1]German Original: "Aus der Wahrheit Feuerspiegel lächelt sie den Forscher an. Zu der Tugend steilem Hügel leitet sie des Dulders Bahn." (English translation by Wikisource [2011].)

Chapter 5 of the thesis discusses selected details of MDE's implementation which are particularly complex. The first of these selected details is MDE's caching mechanism, which divides the process of building a visualisation into different steps and maintains caches of the OpenGL pixel output. The second is the solution MDE employs for embedding text in OpenGL visualisations. This is non-trivial, as OpenGL itself does not support text; additional libraries have to be used for it. Mapping from a font name to a font file's path is a very complex task as well. The thesis explains how these problems were solved.

The conclusion of the thesis in Chapter 6 is about the future of parallel coordinates and how the development of MDE might continue. Parallel coordinates are evolving in many different directions, and the problem of too many lines cluttering the display has not been completely solved yet. Both the theory of parallel coordinates and their practical implementation are still works in progress. More work by software engineers and usability engineers are needed to support their use in actual data analysis.

Appendix A is MDE's user manual and explains the features of MDE with practical examples and many supporting screenshots. Appendix B, on the other hand, is a detailed guide for developers adding new visualisations to MDE.

Chapter 2

Information Visualisation

"When I tell you: 'Observe, please!', then you should, according to your typical language use, ask me: 'Fine, but what? What is it that you want me to observe?' In other words: you will ask me to specify a problem which can be solved by your observation."

[Sir Karl Popper, Alles Leben ist Problemlösen, 1996, pp.19-20[1]]

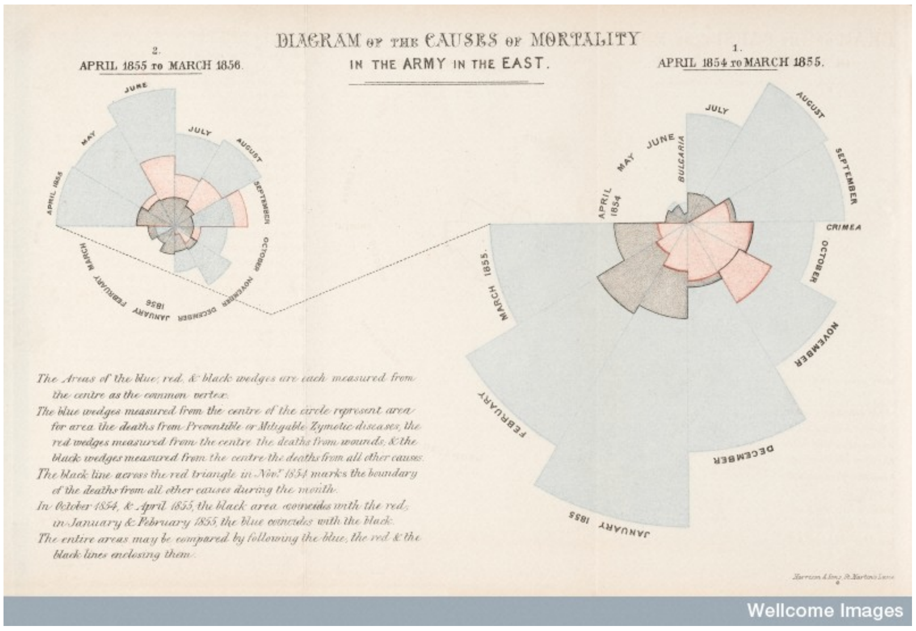
Information visualisation is defined by Andrews [2010] as "the visual presentation of abstract information spaces and structures to facilitate their rapid assimilation and understanding". In other words, the goal of information visualisation is to provide insights into data sets using graphical representations of the data which would be difficult to extract otherwise. Lex [2008] notes that a distinction must be made between *information* visualisation, which deals with abstract information, and *scientific* visualisation, which deals with information bearing intrinsic visual properties. Google Body [Google, 2010] is an example of a visualisation tool not meeting the criteria of information visualisation, because the three-dimensional graphics it produces do not visualise abstract information but are instead just a rendering of the real structure of the human body. A better example of information visualisation would be tag clouds as discussed by Halvey and Keane [2007], because the graphical attributes of that visualisation scheme, such as position, colour and size of words, are derived from non-visual abstract information about the relationship between elements of the cloud.

Modern computer applications excel in the field of information visualisation due to their sheer calculation power in creation of graphics. Nevertheless, information visualisation existed long before computers were invented, as is explained in Section 2.1. Section 2.2 talks about interactivity playing a major role in modern-age information visualisation. Section 2.3 discusses some popular techniques for multi-dimensional data visualisation. Chapter 3 then discusses *parallel coordinates*, the information visualisation technique this thesis focuses on.

2.1 History

Information visualisation might appear a field originating in computer science, but in truth dates back to earlier centuries and is a concept much older than computer science itself. In the second half of the 18th and the first half of the 19th century, British statistician William Playfair published diagrams based on statistical data about England's trade relations [Playfair, 2005]. According to FitzPatrick [1960], he is considered one of the pioneers of information visualisation.

[1]German Original: "Wenn ich Sie auffordere: 'Bitte, beobachten Sie!', so sollten Sie mich, dem Sprachgebrauch gemäß, fragen: 'Ja, aber was? *Was* soll ich beobachten?' Mit anderen Worten, Sie bitten mich, Ihnen ein *Problem* anzugeben, das durch Ihre Beobachtung gelöst werden kann." (English translation by the author of this thesis.)



The Areas of the blue, red, & black wedges are each measured from the centre as the common vertex.
The blue wedges measured from the centre of the circle represent area for area the deaths from Preventible or Mitigable Zymotic diseases, the red wedges measured from the centre the deaths from wounds, & the black wedges measured from the centre the deaths from all other causes.
The black line across the red triangle in Novr. 1854 marks the boundary of the deaths from all other causes during the month.
In October 1854, & April 1855, the black area coincides with the red; in January & February 1855, the blue coincides with the black.
The entire areas may be compared by following the blue, the red & the black lines enclosing them.

Figure 2.1: Florence Nightingale's wedge diagram from 1857 is a historical example of information visualisation long before computers came into existence. The visualisation shows the majority of soldiers in the Crimean Wars died because of poor sanitary conditions, rather than being killed by the enemy in combat. Image copyright of the Wellcome Library [2011a]

The wedge diagram by famous British nurse Florence Nightingale, shown in Figure 2.1, can be cited as another historical example of creating abstract graphical representations of information long before computers came into existence. In 1857, Nightingale created a chart representation of statistical numbers of deaths during the Crimean Wars, proving that more soldiers fell victim to poor sanitary conditions in the armies rather than being killed by the enemy [Wielemaker, 2010]. Today, Nightingale's chart is often referred to as a "Coxcomb Chart", although according to Small [1998], she never used that name herself.

Ancient maps are often cited as historical examples for information visualisation. Applying the definition from this chapter's introductory paragraph, however, they usually cannot be considered as such, because the data visualised by them is not abstract; they are just visualisations of the real physical positions of cities, countries or other places. Therefore, in such cases it is more correct to talk about *geographical visualisation*.

Andrews [2010] names John Snow's historical cholera map from 1854, shown in Figure 2.2, as a famous example of geographical visualisation *not* to be considered information visualisation, because it is primarily based on topographical data. The map visualised deaths caused by cholera in different parts of London, illustrating Snow's theory of the outbreak of the epidemic in the city to be caused by a specific water pump. However, contrary to popular belief, it is not true that Snow came up with his theory as a result of analysing the map; he drew the map as an illustration afterwards [Brody et al., 2000].

Friendly and Denis [2001] cite many other historical examples of maps, diagrams, and information visualisation, dating the beginning of the modern age of information visualisation to the beginning of the second half of the 20th century.

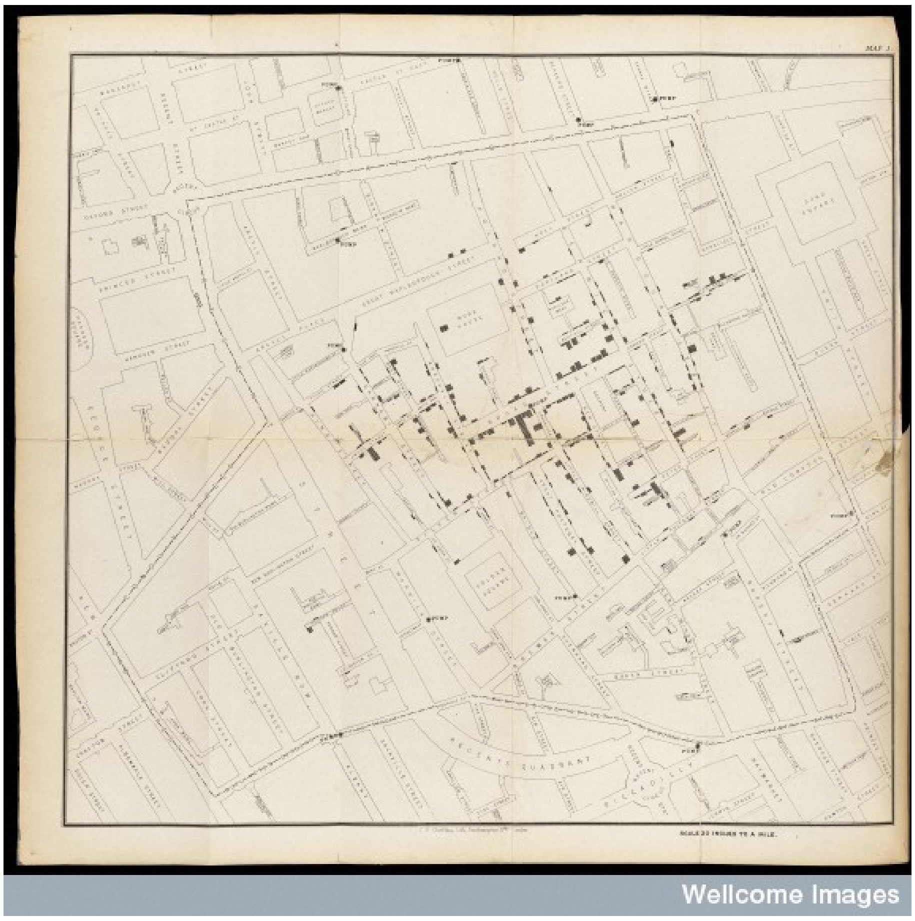


Figure 2.2: John Snow's cholera map from 1854 is sometimes misunderstood as an important contribution to the field of information visualisation when it is actually an example of geographical visualisation. The map visualised deaths caused by cholera in different parts of London, illustrating the theory that a particular water pump in the city had caused the outbreak of the epidemic. Popular belief has it that Snow came up with his theory through analysis of the map, but in truth the map only illustrated his previously established theory. Image copyright of the [Wellcome Library, 2011b]

2.2 Interaction

Rather than just being capable of quickly generating visual *output*, computers also have the ability to accept *input* from their users. This makes visualisations *interactive*, because parameters of the visualisation can be immediately updated. Shneiderman [1996] famously describes the principle of good interactive visualisation as "overview first, zoom and filter, then details-on-demand". A user looking at the visualisation of a large data set should first obtain an idea of the entirety of the data available (overview), then a closer view of the data points in a particular area of interest (zoom), then be able to remove from the view those data points which are not relevant to the task at hand (filter), and finally be shown all information available for particular data points by explicit request (details-on-demand).

With information visualisation becoming ever more complex and more interactive, usability becomes a greater concern, too. Andrews [2006, 2008a] discusses how traditional usability evaluation methods are inappropriate for testing new visualisation techniques. Cawthon and Moere [2007] describe a case study exploring the relationship between visually pleasing data representation and the perceived usability of a visualisation.

Keeping a software application responsive during user interaction contributes greatly to usability as well. Piringer et al. [2009] discuss the use of multi-threading to improve information visualisation software in this regard. They observe the problem of reduced responsiveness when software performance suffers from the amount of data to be visualised. The crux of the matter is that the time needed to perform a particular rendering step may exceed the time span between two consecutive user decisions, meaning that the software will not respond in time before the second action (a mouse click, for example). To mitigate these problems, a generic software architecture for implementation of information visualisation techniques is proposed. In that architecture, the main thread delegates each instance of a visualisation to a dedicated visualisation thread.

Wide-spread use of multi-threading in visualisation applications is hindered by the fact that concurrency itself is always very complex to handle in software engineering. Thread-safety is particularly hard to achieve when underlying software modules do not provide sufficient thread-safety guarantees. For example, the popular OpenGL graphics rendering library [Shreiner, 2009; Khronos Group, 2011a], which is often used to implement high-performance information visualisation software, requires developers to take a number of precautions to ensure the robustness of software when multi-threading is present [Apple, 2010].

2.3 Multi-Dimensional Data Visualisation

Input data to be visualised comes in different forms and variations. One of them is multi-dimensional data, as explained by Andrews [2010]. Such data consists of n records and m dimensions. Therefore, the data can be seen as a matrix, an item d of the matrix indexed by n and m, as shown in Figure 2.3. A concrete example would be a matrix for cities, each city record having the dimensions "Name", "Area", "Elevation" and "Population", as shown in Figure 2.4.

Multi-dimensional data is not just a synonym for vector space data. The most important difference is defined by Mader [2007] as the number of dimensions, which is typically significantly higher in vector space data. For example, Widdows et al. [2006] describe a linguistic vector space data set with 1000 dimensions. In contrast, multi-dimensional data visualisation is more limited with regards to the number of dimensions, as explained by Yang et al. [2007]: *"However, most traditional multidimensional visualization techniques suffer from visual clutter and only scale up to tens of dimensions. Up to now, few multidimensional visualization systems have claimed to be scalable to data sets with hundreds of dimensions."*

$$\begin{pmatrix} d(0,0) & \cdots & d(i,0) & \cdots & d(m,0) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d(0,i) & \cdots & d(i,i) & \cdots & d(m,i) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d(0,n) & \cdots & d(i,n) & \cdots & d(m,n) \end{pmatrix}$$

Figure 2.3: A matrix of multi-dimensional data with n records and m dimensions. This is an abstraction of input for information visualisation software tools capable of dealing with multi-dimensional data.

$$\begin{pmatrix} \textbf{Name} & \textbf{Area (km}^{\textbf{2}}\textbf{)} & \textbf{Elevation (m)} & \textbf{Population} \\ Graz & 127.56 & 353 & 255354 \\ Milan & 183.77 & 120 & 1306637 \\ London & 1706.8 & 24 & 7556900 \end{pmatrix}$$

Figure 2.4: An example of concrete multi-dimensional data for a list of cities with three records and four dimensions: “Name”, “Area”, “Elevation” and “Population”. This could be actual input for an information visualisation software tool.

There is also a subtle semantic difference, in that in multi-dimensional data the meaning of the dimensions themselves is equally important. Mader [2007] explains that, for example, with multi-dimensional data it makes sense to filter rows of a matrix by some condition defined on one of the columns, whereas in vector space one works with reference vectors.

Many techniques exist for visualising multi-dimensional data. One of them is parallel coordinates. They are the major topic of this thesis and are discussed in detail in Chapter 3. Parallel coordinates do not have any theoretical limit in the number of dimensions they can display at the same time; they are only limited by very practical boundaries like screen space. Other visualisation techniques discussed in the following subsections are also conceptually more limited with regards to the possibility of displaying an arbitrary number of dimensions all at once.

Note that the usefulness of visualisation techniques can be increased by viewing the same data set with different but synchronised methods on the same screen, combining their distinct advantages [Bertini et al., 2005; Shannon et al., 2008]. This consideration has become an important aspect of information visualisation, and in 2003, a dedicated annual conference has been launched, the “International Conference on Coordinated & Multiple Views in Exploratory Visualization” (CMV) [Roberts, 2007]. Nevertheless, as far as usability is concerned, multiple views have also certain costs associated with them, because there is less screen space available for individual visualisations and because the multitude of visualisation techniques results in increased complexity for the end user. Baldonado et al. [2000] give guidelines a software designer should take into account when deciding on whether or not to show different visualisations of the same data set on the same screen.

2.3.1 Scatter Plots

A scatter plot is a two-dimensional visualisation of multi-dimensional information, each axis of the display corresponding to one of the dimensions in the data set. Data points are entered on the two-dimensional area according to their values in both dimensions. The points themselves can be made to convey information about additional dimensions, as shown by Cleveland and McGill [1984]. Examples of such additional information channels include:

- **Point Size.** For example, in a data set of cities, larger points may indicate cities with greater population.

- **Point Colour.** For example, the blue tone of a point's colour may correspond to the city's total area.
- **Point Form.** For example, dots may indicate cities in Europe, rectangles cities in America.

A different approach to overcome the two-dimension limit of scatter plots is to create a set of each x/y combination and display the resulting plots next to each other in a matrix. This technique is called "scatter plot matrix" [Elmqvist et al., 2008].

Figure 2.5 shows the visualisation of a data set about prices and earnings in different cities around the globe [UBS, 2009] using a basic scatter plot display implemented in MD^{2}VS, a software tool developed by Mader [2007], which is discussed in detail in Chapter 3. Ahlberg and Shneiderman [1994] provide an example of the scatter plot technique applied to the task of finding movies in software called FilmFinder, which is shown in Figure 2.6. The horizontal and vertical axes of the plot displayed by the software correspond to popularity and age, while the colour of the plotted points is used as an additional channel conveying information about a film's category.

2.3.2 Histograms

Histograms are a common information visualisation technique invented by Pearson [1895]. In their most basic form, they map one-dimensional data on a two-dimensional visualisation. The *distribution* of data points on the horizontal axis is projected on the vertical axis, or vice versa, as shown in Figure 2.7. In order to do so, the range of the first axis is divided into subranges of equal length, so-called "bins". The size of the bins in the other dimension is determined by the number of data points belonging to the corresponding subrange. Wand [1997] explains mathematical approaches to determine appropriate bin width, or number of bins.

2.3.3 Star Plots

Star plots [Chambers et al., 1983] are a technique for visualisation of multi-dimensional data. Friendly [1991] describes star plots as a series of depictions for each record in a data set. Each of those smaller depictions resembles a star (hence the name), the rays of each star corresponding to dimensions, so that there are n rays for n dimensions. The length of a ray depends on the value of the data point in the corresponding dimension relative to all other data points' values in the same dimension. The end points of a ray are connected to those of the two neighbouring rays. Figure 2.8 shows the XmdvTool [2010] software displaying a star plot visualisation of the cereals data set provided by Velleman [1996].

Fanea et al. [2005] discuss an extension of star plots named "parallel glyphs", in which star plots are merged with parallel coordinates (see Chapter 3).

2.3.4 VisIslands

Andrews et al. [2001] discuss an information visualisation technique they call VisIslands. The goal of this technique is to reflect similarity between data vectors and display them such that a user can immediately spot similarities. The dynamic creation of such a visualisation is an iterative process. It involves a hierarchical clustering technique and clustering vectors in the data set around the centroids in terms of similarity. The clustered vectors are then placed on a two-dimensional rectangular area, peaks displayed in red with circles in other colours around them. The resulting graphics bear a certain resemblance to a map of islands in the sea; this is where the name comes from.

Figure 2.9 shows a VisIslands visualisation of the data set about prices and earnings in different cities around the globe [UBS, 2009] introduced in Section 2.3.1, again using the MD^{2}VS software application developed by Mader [2007], showing similar cities corresponding to the peak of an "island".

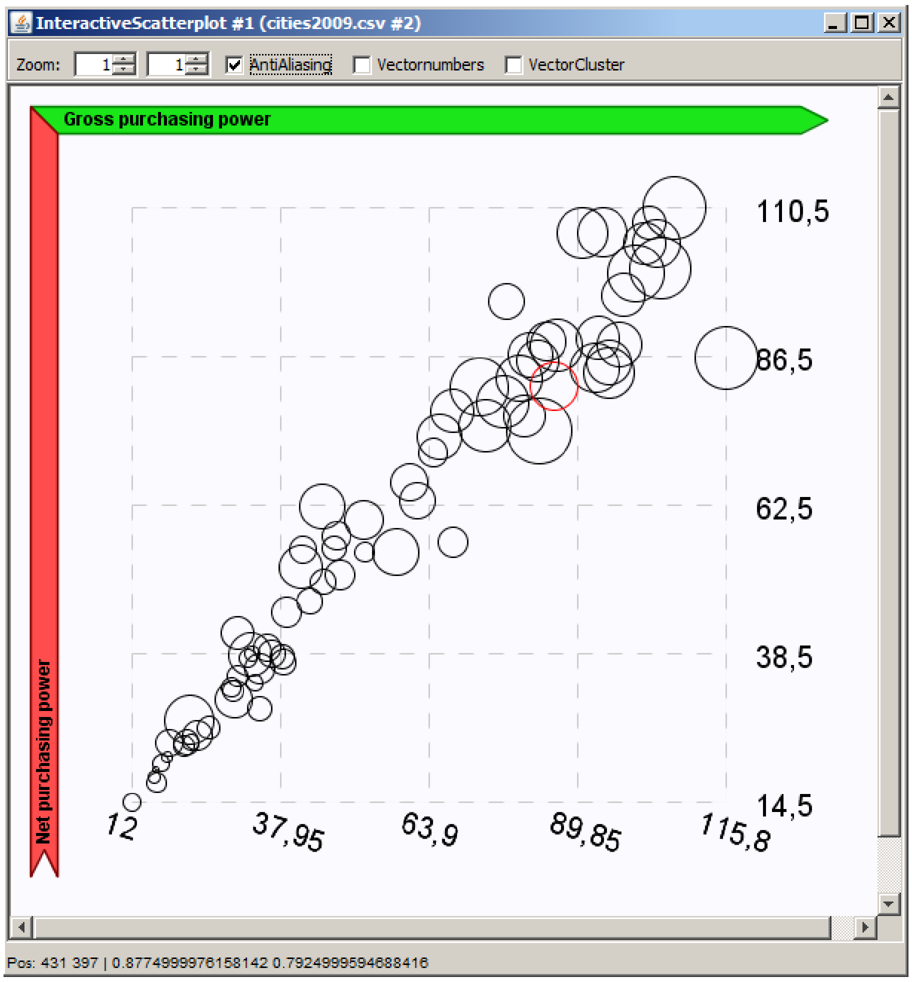


Figure 2.5: MD^{2}VS scatter plot developed by Mader [2007], visualising a data set about prices and earnings in different cities around the globe, provided by UBS [2009]. The data set was turned into a comma-separated value file suitable for opening in MD^{2}VS with the InfoScope tool made by Brodbeck and Girardin [2003]. The horizontal axis of the plot corresponds to dimension “Gross purchasing power”, the vertical axis to “Net purchasing power”. The dots represent data points; in this case, individual cities. Their position on the plot therefore depend on their values in the two dimensions corresponding to the axes. Dot size is a third information channel; the greater the radius of a dot, the greater the data point’s value, in this case in the dimension “Prices (excluding rent)”.

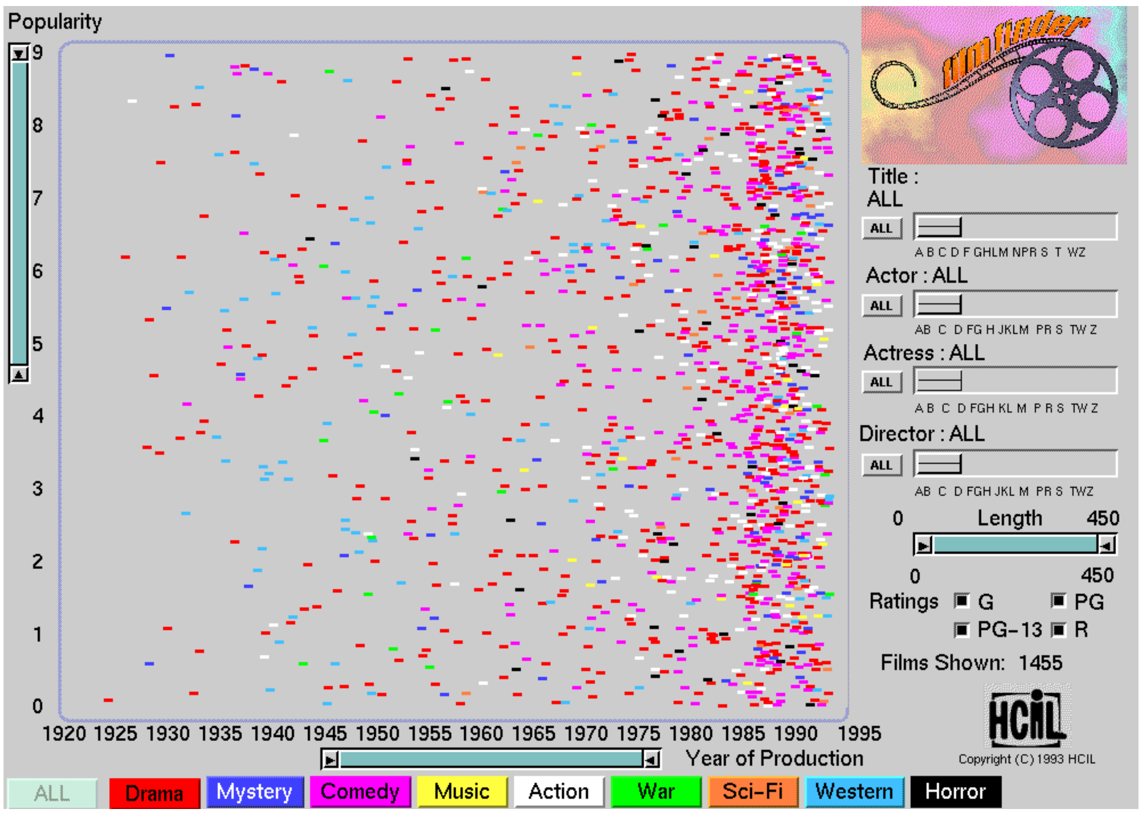


Figure 2.6: The FilmFinder is a software application developed in the nineties of the 20th century using the scatter plot technique to visualise a data set about films [Ahlberg and Shneiderman, 1994]. The horizontal and vertical axes correspond to the films' popularity and age, while the colour of the plotted points conveys information about film categories. For example, the red point in the bottom left corner shown here denotes a rather unpopular drama film from around 1925. Image copyright of the HCIL [2006]

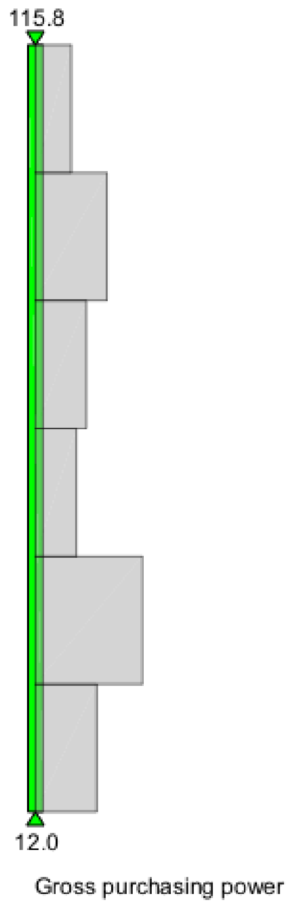
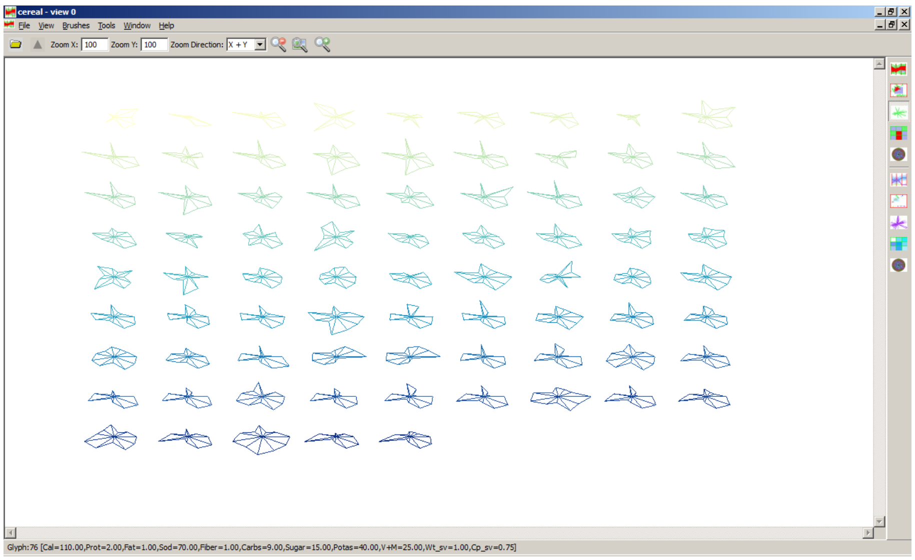


Figure 2.7: Vertical histogram feature of Multi-Dimensional Explorer (MDE), the tool developed for this thesis, applied to the data set of prices and earnings in different cities around the globe provided by UBS [2009] and turned into a comma-separated value file suitable for opening in MDE with InfoScope [Brodbeck and Girardin, 2003]. The 6-bin histogram shows distribution of records in the "Gross purchasing power" dimension. Each bin represents a subrange of the dimension's entire range, which spans from 12.0 to 115.8. The wider a bin, the more records belong to the corresponding subrange.


cereal - view 0
File View Brushes Tools Window Help
Zoom X: 100 Zoom Y: 100 Zoom Direction: X + Y

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Glyph:76 [Cal=110.00,Prot=2.00,Fat=1.00,Sod=70.00,Fiber=1.00,Carbs=9.00,Sugar=15.00,Potas=40.00,V+M=25.00,Wt_sv=1.00,Cp_sv=0.75]
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Figure 2.8: Star plot visualisation of the cereals data set provided by Velleman [1996] in XmdvTool [2010]. Each record in the data set is visualised by one of the stars, each ray of a star corresponding to one of the dimensions and each ray's length to the value of the record in that dimension, relative to other records. In this example, the stars are sorted by the "Sugar" dimension, so it is easy to see how the "Sugar" ray, the 8th in clockwise direction here, becomes longer as the "Sugar" value becomes greater.

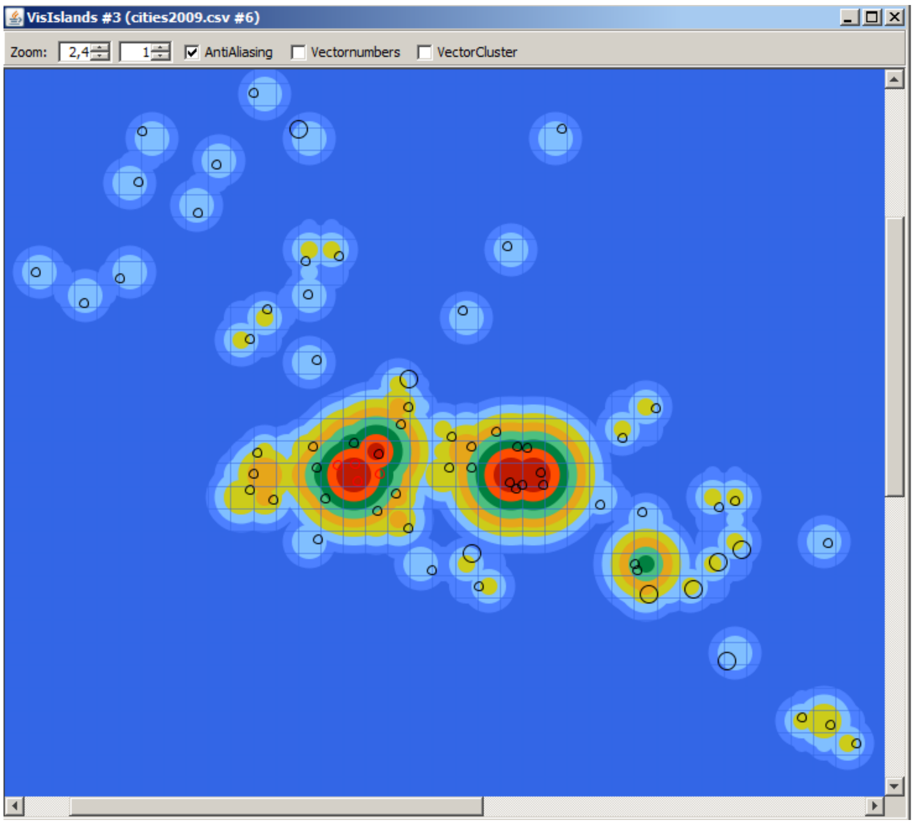


Figure 2.9: VisIslands display of MD^{2}VS, a tool developed by Mader [2007], visualising a data set about prices and earnings in different cities around the globe, provided by UBS [2009]. The data set was turned into a comma-separated value file suitable for opening in MD^{2}VS with the "InfoScope" tool made by Brodbeck and Girardin [2003]. Data points clustered in the centre of the left "island", displayed as red circles, are Bratislava, Copenhagen, Prague, Vilnius and Warsaw, indicating that these cities are similar in terms of prices and earnings.

Chapter 3

Parallel Coordinates

“Take that, you lousy dimension!”

[Chief Wiggum in “The Simpsons”, Episode 3F04, 1995]

Parallel coordinates are a way to visualise multi-dimensional data by displaying axes in parallel, rather than orthogonal, to each other. Parallel coordinates belong to the computer science field of multi-dimensional data visualisation, which was introduced and discussed in Chapter 2.

Section 3.1 explains the theory of parallel coordinates and their roots in mathematics. Section 3.2 discusses problems of parallel coordinates handling large data sets and possible solutions thereof. Section 3.3 introduces some variations on the general idea of parallel coordinates proposed by the scientific community. Section 3.4 explains the operations provided by interactive parallel coordinates visualisation for data analysis in high-dimensional space. Finally, Section 3.5 gives an overview of existing software solutions in the field.

Chapter 4 discusses the original software developed for this thesis, based on the experience gained from using the other software tools.

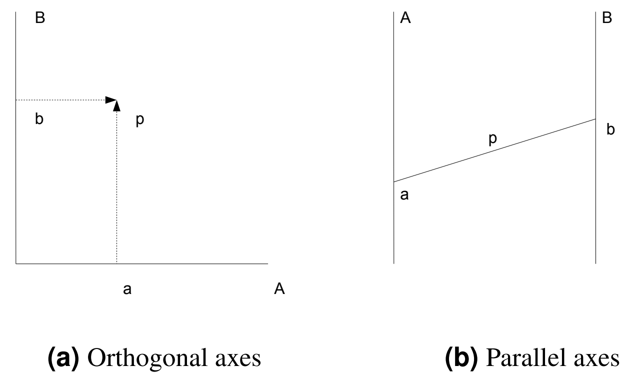
3.1 Background

Parallel coordinates did not originate in the field of information visualisation. They were invented as a purely mathematical concept, the transformation of orthogonal axes into parallel ones, and can be traced back to 1885, when Maurice d’Ocagne, a French mathematician, published his book *Coordonnées parallèles et axiales. Méthode de transformation géométrique et procédé nouveau de calcul graphique déduits de la considération des coordonnées parallèlles* (“Parallel and axial coordinates. A geometric transformation method and a new graphical calculation procedure derived from the consideration of parallel coordinates”) [d’Ocagne, 1885].

d’Ocagne applied parallel coordinates to numerical problems. It was not until 1959 that Alfred Inselberg rediscovered them independently and applied them to information visualisation [Inselberg, 2010b]. Quoting Inselberg himself in [Inselberg, 2007, p.645]:

“I wondered why geometry was being tackled without using (the fun and benefits of) pictures? (...) What is ‘sacred’ about orthogonal axes, which quickly ‘use up’ the plane associated with them?”

Inselberg’s publications [Inselberg, 1985; Inselberg and Dimsdale, 1990] would later help spread the concept of parallel coordinates in the field of information visualisation. Inselberg [2009] explains exactly



(a) Orthogonal axes **(b)** Parallel axes

Figure 3.1: In (a), point *p* lies at coordinates *a* and *b*, corresponding to axes *A* and *B*. The axes are orthogonal to each other. In (b), *p* is still at coordinates *a* and *b* on axes *A* and *B*, but the axes are now *parallel* to each other. Consequently, *p* is no longer represented by a point, but by the *line* drawn from *a* to *b*.

how parallel coordinates can be used to extract information from data sets. He also discusses some of the difficulties in applying parallel coordinates to very large data sets, where the visualisation technique may not scale very well. Those problems are discussed in detail in Section 3.2 of this thesis.

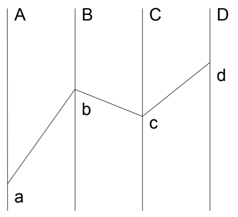
As far as usability issues are concerned, Siirtola et al. [2009] performed eye-tracking studies on parallel coordinates visualisations, finding that even inexperienced users quickly learn to use the technique effectively, despite initial scepticism or uneasiness with the visualisation.

Following the teachings of d'Ocagne, the theory of parallel coordinates begins with the basic idea of *duality* between lines and points. Any two-dimensional point defined by orthogonal axes can also be visualised as a two-dimensional line. Expanding on this concept, any *n*-dimensional point can be visualised as a polyline consisting of *n-1* elements.

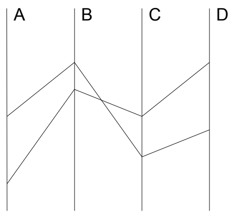
Imagine a two-dimensional point *p* on a plane. It has two coordinates, one for each axis. Let the axes be denoted *A* and *B*; the coordinates shall be denoted *a* and *b*. The axes are orthogonal but may also be viewed in *parallel* to each other, as shown in Figure 3.1. The coordinates *a* and *b* of *p* remain the same; their positions on the corresponding axes are connected by a line. A parallel coordinates visualisation has been created. The line connecting the axes represents *p* in the same way as a two-dimensional point represents *p* using orthogonal axes.

Once the duality between lines and points has been established, the concept can be extended. *p* can have many more dimensions and still be displayed by parallel coordinates, as long as there is enough horizontal space. There is no geometrical limit to how many axes one can display in *parallel* to each other. This is not true for orthogonal axes, which can display only up to three dimensions, because of human perception.

Figure 3.2 shows an example of a 4D point *p* visualised with parallel coordinates, *p* being represented now by the polyline connecting the axes. This way, any number of points (or records) can be visualised at the same time. As one can see, there are no theoretical limitations on the number of dimensions or records displayed at the same time. Limits arise in the practical use of parallel coordinates due to limited screen space and because of overlapping lines, as discussed in Section 3.2. Figure 3.3 shows what the visualisation of a data set consisting of 73 records and 24 dimensions looks like with parallel coordinates.

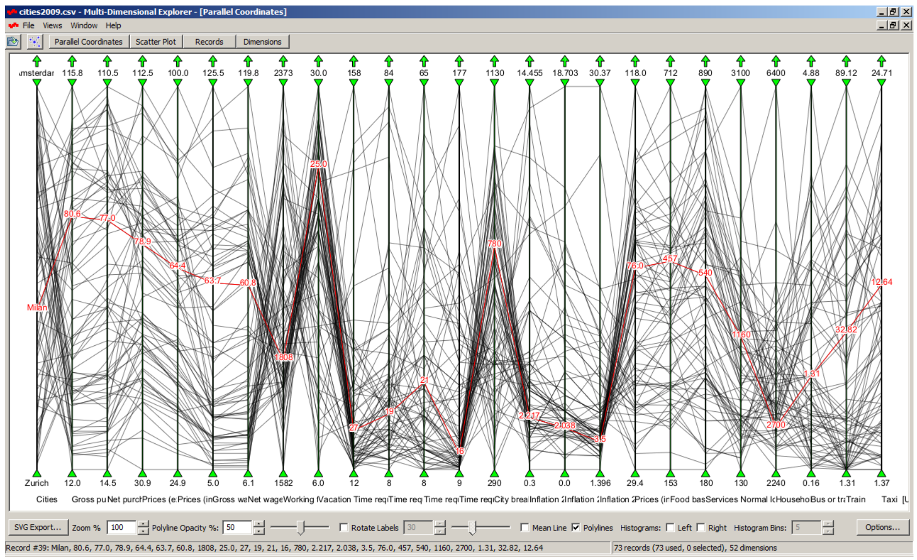


(a) One 4D point on parallel axes



(b) Two 4D points on parallel axes

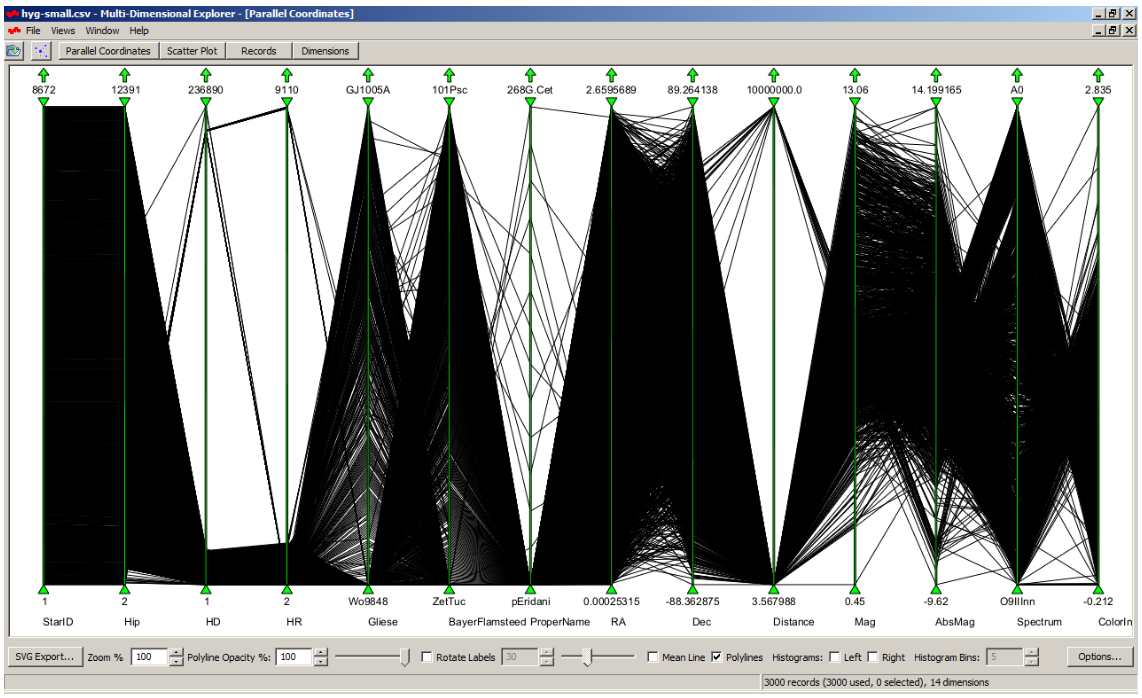
Figure 3.2: (a) shows a 4-dimensional point *p* represented by a vector of three connected lines at coordinates *a*, *b*, *c* and *d* on axes *A*, *B*, *C* and *D*, respectively. This example demonstrates how parallel coordinates can be used to display records with any number of dimensions as long as there is enough horizontal space, while orthogonal axes are restricted to 3D because of human visual perception. In (b), two 4D points are displayed using parallel coordinates. Each of them is represented by a vector of three connected lines.



Record #39: Milan, 80.6, 77.0, 78.9, 64.4, 63.7, 60.8, 1808, 25.0, 27, 19, 21, 16, 780, 2.217, 2.038, 3.5, 76.0, 457, 540, 1160, 2700, 1.31, 32.82, 12.64

73 records (73 used, 0 selected), 52 dimensions

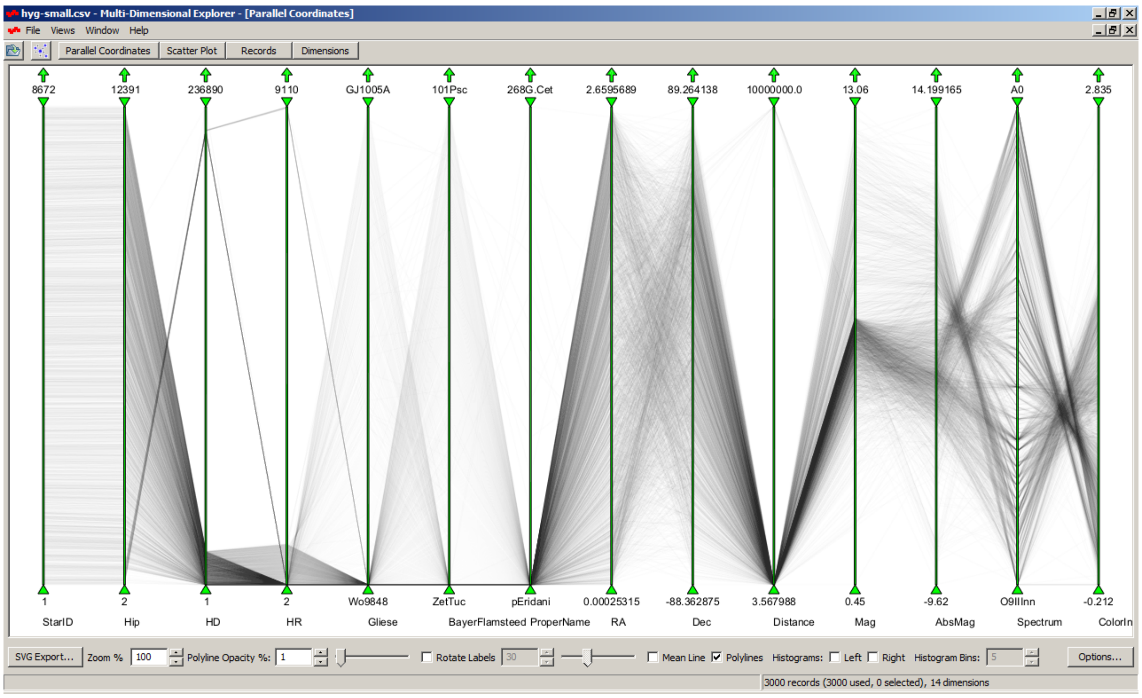
Figure 3.3: Parallel coordinates visualisation with Multi-Dimensional Explorer (MDE), the software developed for this thesis. In this example, the application visualises the data set about prices and earnings in different cities around the globe [UBS, 2009] (turned into a comma-separated value file suitable for opening in MDE with the InfoScope tool made by Brodbeck and Girardin [2003]). 73 records and 24 dimensions are shown at the same time. Every polyline corresponds to one record. The record for the city of Milan and all its data points have been highlighted in red.



Zoom % 100 Polyline Opacity %: 100 Rotate Labels 30 Mean Line Polylines Histograms: Left Right Histogram Bins: 5

3000 records (3000 used, 0 selected), 14 dimensions

Figure 3.4: Too many polylines can easily clutter a parallel coordinates visualisation. This example in Multi-Dimensional Explorer (MDE) shows the result of rendering 3000 polylines from a data set of 3000 records and 14 dimensions, a subset of a data set about stars [Nash, 2006]. The massive number of lines clutter the display and make the visualisation unusable; various techniques to reduce clutter have been proposed.



Zoom % 100 Polyline Opacity %: 1 Rotate Labels 30 Mean Line Polylines Histograms: Left Right Histogram Bins: 5

3000 records (3000 used, 0 selected), 14 dimensions

Figure 3.5: When the sheer number of polylines clutter the display of a parallel coordinates visualisation, reduced opacity can mitigate the problem. This is another example of Multi-Dimensional Explorer (MDE), showing the same data set as Figure 3.4. The opacity of each polyline, however, has been reduced to 1%, so the user can once again recognise certain patterns in the data.

3.2 Handling Large Data Sets

Figure 3.4 shows what happens when the data set to be visualised by parallel coordinates is very large: the display becomes cluttered with polylines up to a point where the entire visualisation becomes unusable, because lines overlap and no more patterns can be seen [Artero et al., 2004; Wegman and Luo, 1996]. The problem can be mitigated somewhat by reducing the polylines' opacity, as shown in Figure 3.5. When each polyline is rendered with reduced transparency, patterns previously hidden to the eye can once again be recognised, because areas of many overlapping lines will appear darker than areas with fewer lines [Holten and van Wijk, 2010].

Reducing polyline opacity is a simple way to mitigate the problem of cluttered parallel coordinates displays, but may not always be sufficient. Fua et al. [1999] argue that the root of all such problems is the idea of mapping every record of the data set to one particular graphical element, and that visualisation techniques based on such direct mapping will always scale badly in face of large input data. Novotný [2004] refers also to performance problems with software applications having to render overly complex graphics. Therefore, clustering may be needed for many large data sets. Novotný and Hauser [2006] name "a few thousand" as the number of records visually comprehensible with parallel coordinates, whereas "hundreds of thousands" of records are an indication that problems will arise. An exact measure obviously cannot be given, as the critical number of records will always depend to a certain degree on the data set. The following techniques are specifically tailored towards reducing clutter in parallel coordinates:

- Fua et al. [1999] discuss clustering of records under the name of "hierarchical parallel coordinates". The clustered display is achieved by creating an internal tree structure from the data set. Each node in the tree corresponds to a certain number of data points and their mean value. The level of clustering, that is, how many lines are displayed in the parallel coordinates view, depend on a parameter which can be imagined to horizontally split the tree structure (the word "cut" is used for this in the paper). By changing that parameter, the user of a visualisation can dynamically change the degree by which records are joined to clustered polylines. Figure 3.6 shows the technique implemented in XmdvTool [2010].

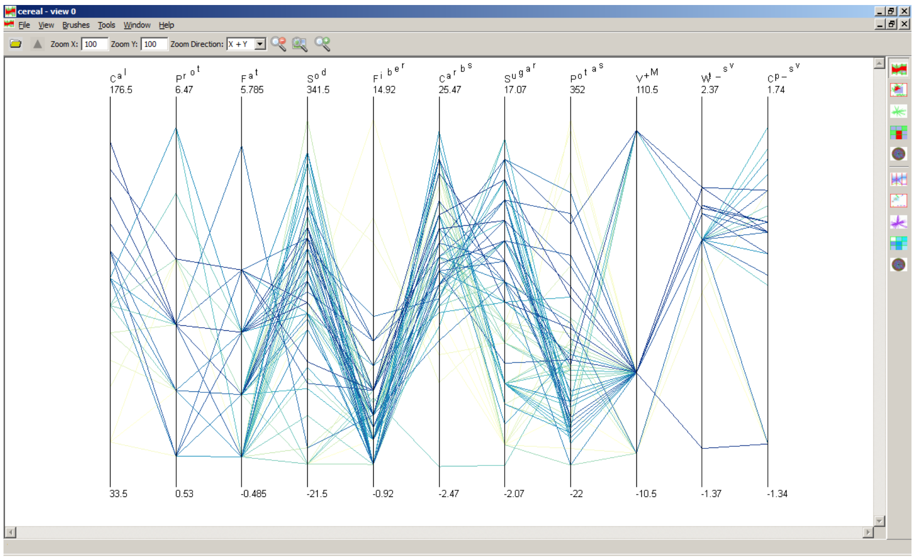
- Zhou et al. [2008] take a different approach. Instead of basing any clustering on calculation in the data set itself, they base their technique directly on the *geometry* of polylines which would result otherwise from a normal parallel coordinates visualisation. Lines are denoted as belonging to the same cluster according to their parallelism and their position. Actual visual clustering is achieved by turning straight lines into curves, leaving the colour aspect of the visualisation free to carry other information.

  The use of curves instead of lines for parallel coordinates is addressed in a different context by Graham and Kennedy [2003], see Section 3.3.3.

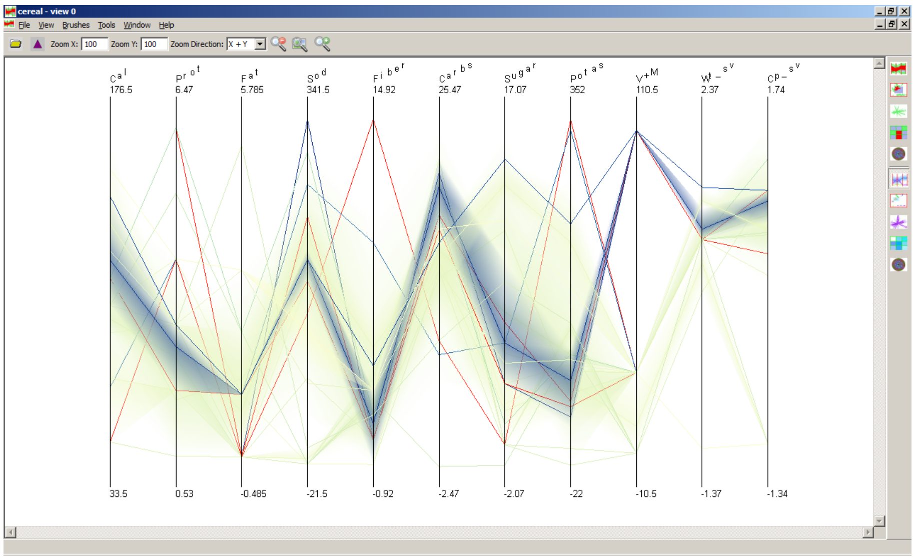
- *Randomness* can be exploited for reducing clutter, too. Dix and Ellis [2002] introduce the idea of visualising random samples of the input data set and apply the idea to parallel coordinates in [Ellis and Dix, 2006]. Ease of use is stated as a distinct advantage of such techniques. Doubts about the validity of random sampling in data analysis are met with references to other areas in computer science where randomness plays an important role, such as keys in cryptography or neuronal networks.

- Johansson et al. [2004] approach the problem with *neural networks* and propose a solution involving the classification of records using the Self-Organising Map (SOM) algorithm [Kohonen, 1997]. The clusters displayed are then based on that classification.

- "Splatting" of parallel coordinates polylines is discussed by Zhou et al. [2009]. The idea here is to exploit time to visualise the process of clustering step by step as each line is added separately to



(a) Parallel Coordinates with no Clustering



(b) Parallel Coordinates with Clustering

Figure 3.6: "Hierarchical parallel coordinates" display in XmdvTool [2010], building on the idea of Fua et al. [1999]. (a) is a normal parallel coordinates visualisation of the cereals data set provided by Velleman [1996]. (b) shows the results of applying a clustering method to the data set.

the display. Whenever one line is added, opacity of neighbouring lines is increased while opacity of all lines is reduced. Allowing users to pause the resulting animation allows them to select their desired level of detail.

Animation is noted as an important visualisation technique also by Ellis and Dix [2007], who give an overview of different approaches to mitigate the problem of cluttered displays in information visualisation and conclude that better results are achieved by a combination of different methods, such as animating the clustering process. Johansson et al. [2005b] use animation as an information channel of its own, using motion in a clustered parallel coordinates visualisation to express additional information about a cluster of records.

A high number of dimensions, rather than just records, may cause similar problems, but can be approached in different ways. Jing et al. [2003] discuss ways of clustering dimensions to reduce visual overload. They apply their technique not only to parallel coordinates, but also to other visualisation methods.

3.3 Variations

The basic idea of parallel coordinates is to draw polylines corresponding to records in a data set on a 2D display. Building on this basic idea, other, similar visualisation techniques have been devised. The following subsections give an overview of variations on the original parallel coordinates theme.

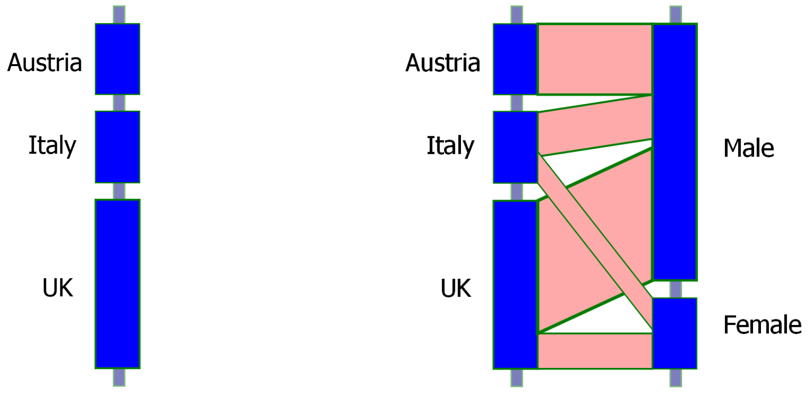
3.3.1 Parallel Sets

Parallel sets [Bendix et al., 2005] adapt parallel coordinates for enumerated dimensions. Parallel coordinates usually deal with continuous numeric data types, having an obvious order defined for them and no fixed number of allowed values. In contrast, enumerated dimensions such as “Gender” or “Country” usually have no natural ordering relationship (is “Austria” less than “Italy”?) and define a fixed number of values a record in the data set may have. Although enumerated dimensions can be normalised in order to be treated like dimensions of numeric type [Mader, 2007], parallel sets take a different approach altogether.

Just like parallel coordinates, parallel sets display axes arranged parallel to each other. However, parallel sets do not plot points on the axes which are then connected by polylines; instead rectangles of equal width and different height are drawn on an axis. Each rectangle represents an element of an enumeration set such as all countries on earth for a dimension “Country”. Users are also free to group subsets: for example, in a “Country” dimension, elements might be grouped by continent, so that the visualisation effectively has to deal with only six graphical elements. Dimensions of a continuous numerical type may be adapted for use in parallel sets by defining a set of exclusive ranges (for example “less than 50”, “greater or equal than 50”, “greater than 100”).

The height of a rectangle depends on the number of records belonging to the corresponding enumeration value in that dimension. When axes are displayed next to each other, the parallel sets equivalent of parallel coordinates polylines comes into play. From each of an axis’ rectangles a number of polygons extend to the adjacent right axis (always assuming that all axes in a parallel sets display are of an enumerated type). The right edge of each polygon is connected to a rectangle on the right axis such that every polygon between two axes N and M represents one of the possible combination of the axes’ respective dimensions.

With M different enumeration elements in the left axis and N in the right axis, N x M combinations are possible, resulting also in a maximum of $N\ x\ M$ polygons. In other words, each of the polygons represents the existence of at least one record belonging to one particular enumeration element in both dimensions. See Figure 3.7 for an exemplary depiction of parallel sets.



(a) An individual axis in parallel sets.

(b) Two adjacent axes in parallel sets.

Figure 3.7: Parallel sets [Bendix et al., 2005] are a variation of the original parallel coordinates idea suitable for data with enumerated dimensions. While traditional parallel coordinates visualise continuous data such as real numbers, enumerated like "Gender" or "Country" pose different problems. In a parallel sets visualisation, instead of points pertaining to individual records, sets of enumeration values are connected on parallel axes by polygons. (a) shows how an axis is organised in parallel sets by drawing a rectangle for each element in the enumeration, its height depending on the number of records belonging to the element in that dimension. (b) shows how adjacent axes are connected by polygons (in red). In this fictional example, the visualisation shows more records with people from the UK than from Austria or Italy; men are from all three countries, while there is no record for an Austrian woman. The image was adapted from Bendix et al. [2005].

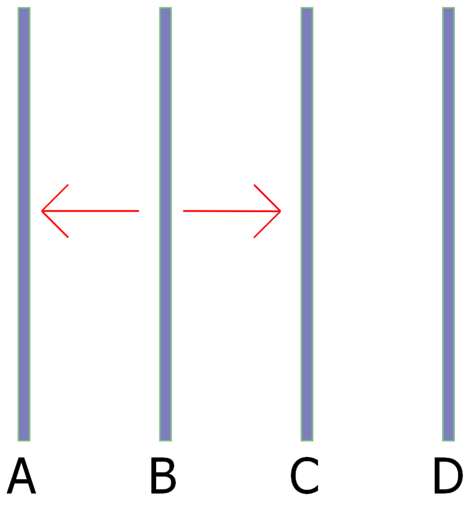
Parallel sets differ from the approach discussed in [Andrienko and Andrienko, 2004], which also discusses subset visualisation in parallel coordinates, though still based on defining subsets by dividing continuous numeric types into ranges.

3.3.2 Three-Dimensional Displays

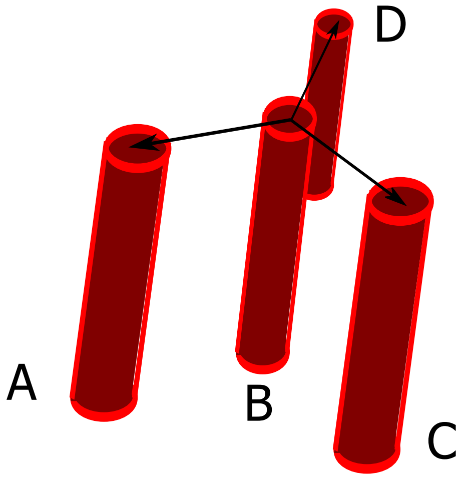
Parallel coordinates have traditionally been visualised on a 2D display. It is, however, possible to extend the idea to projecting multi-dimensional data on 3D space. Johansson et al. [2005a] propose a technique they call "clustered multi-relational parallel coordinates" to implement 3D parallel coordinates.

The idea is to take the axes of traditional 2D parallel coordinates and put them into 3D space such that all of them still point in the same direction, though their position on the plane is changed. One axis is placed in the centre of the display and all other axes are evenly distributed around the centre axis in a circle. Polylines connect the centre axis with the outer axes; there are no connecting polylines between the outer axes themselves. In addition, Johansson et al. [2005a] use clustering just as some traditional 2D visualisations do, though this is not directly related to the 3D concept.

With this approach it is possible to explore relations between dimensions more easily. In 2D parallel coordinates, one instance of the visualisation pertains to only one combination of dimensions; for example, in a data set with four dimensions A, B, C and D, to explore the relationship between A and each of the other dimensions requires at least two visualisations, because the axis corresponding to A may have only two neighbours, not three. With 3D parallel coordinates, there is no such inherent limit; A can be made the centre axis, B, C and D arranged around it in a circle. Figure 3.8 explains the concept.



(a) An axis in traditional 2D parallel coordinates has at most neighbours.



(b) The centre axis in 3D parallel coordinates can have multiple neighbours.

Figure 3.8: 3D parallel coordinates by Johansson et al. [2005a], turning parallel coordinates from plane to space by placing one axis into the centre and arranging the others around it in a circle. (a) shows a disadvantage of 2D parallel coordinates, in that an axis, *B* in this fictional example, can have at most two neighbours, even when the user might want to explore the relationship of one dimension to many others. (b), an adaption of images appearing in Johansson et al. [2005a], shows 3D parallel coordinates overcoming this problem by allowing multiple neighbouring axes. All other axes are now neighbours of the central axis, *B*.

Moving axes along the *Z* dimension is not the only way of turning parallel coordinates into 3D. Wegenkittl et al. [1997] propose instead to turn the two-dimensional axis lines of traditional parallel coordinates into *planes* arranged in 3D space. Parallel axes transformed to parallel planes move quite far away from the original idea of parallel coordinates, whereas the previously discussed approach feels more like a natural evolution of the concept.

3.3.3 Curves

Parallel coordinates traditionally use straight lines to connect axes. This leads to the problem of polylines crossing the same point, making it impossible to tell which lines belong to which polylines. Graham and Kennedy [2003] call this the "cross-over" problem and suggest the use of curves as a solution to overcome it. Using curves, as shown in Figure 3.9, allows users to immediately keep apart entire polylines using natural visual perception even when all polylines cross at the same point on the same axis. The paper argues that except for their end points, the lines in traditional parallel coordinates visualisations carry no information of their own, so other means of connecting points on the axes can be employed without any loss of information. This is in line with Theisel [2000], who notes that the horizontal space between parallel coordinates axes can be leveraged to convey more information.

3.3.4 Continuous Parallel Coordinates

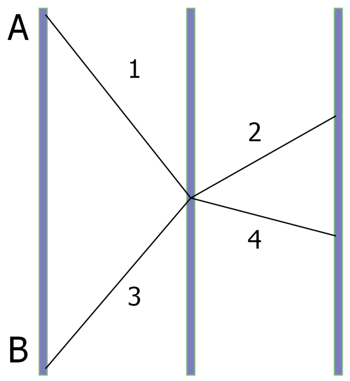
Continuous parallel coordinates were introduced by Heinrich and Weiskopf [2009]. They argue that traditional parallel coordinates techniques miss an important aspect of the input data: the continuous nature of data gathered from scientific observations. Discretisation of such data in visualisations inevitably leads to a loss of information conveyed. Therefore, mathematical techniques to express the continuity of input values in an adapted form of parallel coordinates have been devised.

3.4 Using Parallel Coordinates

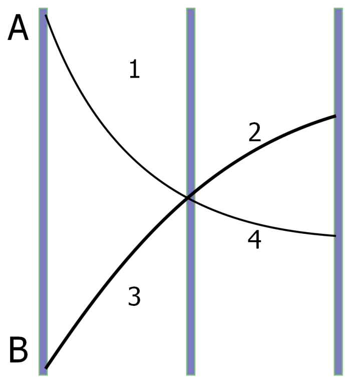
This section discusses commonly used procedures in exploratory analysis with interactive parallel coordinates. The discussion is based on the tutorial of Bauer et al. [2010], created for Keith Andrews' course on information visualisation at Graz University of Technology [Andrews, 2010]. However, the tutorial contained in this thesis uses screenshots from the Multi-Dimensional Explorer (MDE), discussed in Chapter 4, and InfoScope [Brodbeck and Girardin, 2003], discussed in Section 3.5.2. Furthermore, it uses a different data set for its examples. Bauer et al. use data about the correlation between smoking and cancer [Fraumeni, 1968], whereas this thesis uses data about prices and earnings in different cities provided by UBS [2009]. The data set was turned into a comma-separated value file suitable for opening in MDE (and many other software applications) with InfoScope. Table 3.1 shows part of the cities data set.

3.4.1 Removing Axes

Often, not all the dimensions of a multi-dimensional data set are of interest to the task at hand. Therefore, it makes sense to view only the axes for important dimensions and remove the others. Figure 3.10 shows the entire data set with all 52 dimension axes. Figure 3.11 shows the parallel coordinates visualisation after removal of those axes which the user is not interested in. All but 5 of the 52 dimensions in the cities data set have been hidden by the user, leaving: city names, paid vacation days per year, time required for 1 kg of bread, time required for 1 kg of rice and normal local rent medium.



(a) Polylines crossing an axis at the same point.

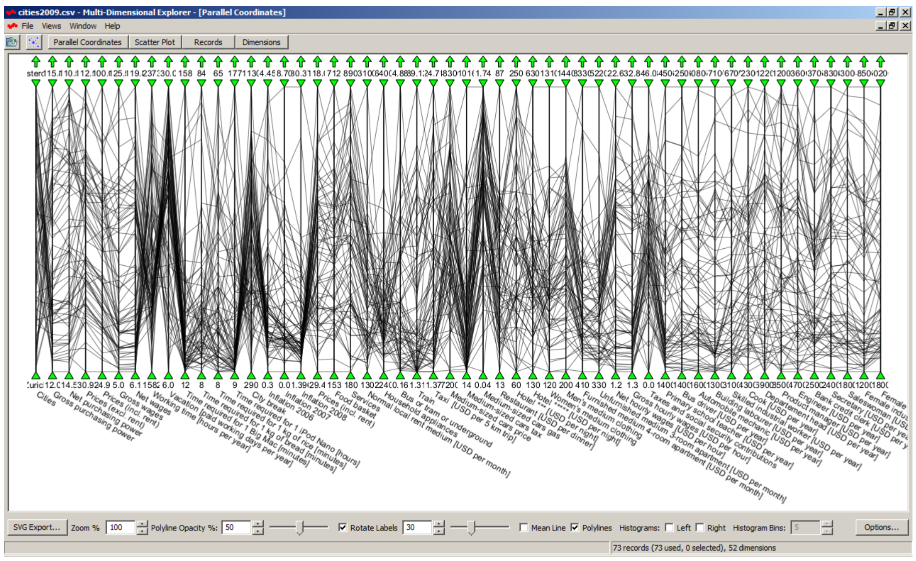


(b) Curves crossing an axis at the same point.

Figure 3.9: Using curves instead of polylines for parallel coordinates, a technique introduced by Graham and Kennedy [2003]. (a) shows a problem with polylines in traditional parallel coordinates visualisations: it is difficult or outright impossible to tell which lines belong to which polylines, because many polylines may cross axes at the same point. For example, does line 2 belong to polyline A or to polyline B? (b) show curves solving the problem intuitively; a user can immediately and visually observe that curve segment 2 belongs to polyline B. The images are adaptions of example diagrams in Graham and Kennedy [2003].

Cities	Gross purchasing power	Net purchasing power	Prices (excl. rent)	...
Amsterdam	95.3	85.5	83.0	...
Athens	61.8	63.3	72.7	...
Auckland	64.8	70.8	62.3	...
Bangkok	18.4	24.1	58.7	...
Barcelona	65.7	73.6	83.5	...
Beijing	21.7	24.1	57.4	...
Berlin	93.5	89.4	81.0	...
Bogotá	32.3	37.9	47.1	...
Bratislava	35.7	39.5	59.4	...
Brussels	97.2	88.5	84.7	...
Budapest	34.2	29.6	54.4	...
Buenos Aires	30.5	34.9	50.4	...
Bucharest	33.5	33.7	46.0	...
Caracas	22.0	27.7	91.0	...
Chicago	97.9	96.3	82.0	...
Delhi	18.2	21.8	37.6	...
Doha	30.3	41.8	67.6	...
Dubai	45.1	62.3	84.9	...
Dublin	90.7	106.4	92.7	...
Frankfurt	92.9	84.6	90.8	...
Geneva	104.4	100.6	106.8	...
Helsinki	86.1	88.1	94.5	...
Hong Kong	41.6	52.3	80.9	...
Istanbul	29.9	31.0	74.2	...
Jakarta	12.0	14.5	47.8	...
Johannesburg	52.8	54.8	48.6	...
Cairo	22.4	24.1	45.3	...
Kiev	21.1	23.7	52.1	...
Copenhagen	115.8	86.2	108.4	...
Kuala Lumpur	33.1	38.4	43.2	...
Lima	29.6	32.5	50.5	...
Lisbon	60.6	66.0	74.0	...
Ljubljana	68.0	56.4	64.3	...
London	81.5	86.7	84.6	...
...	...	...	...	...

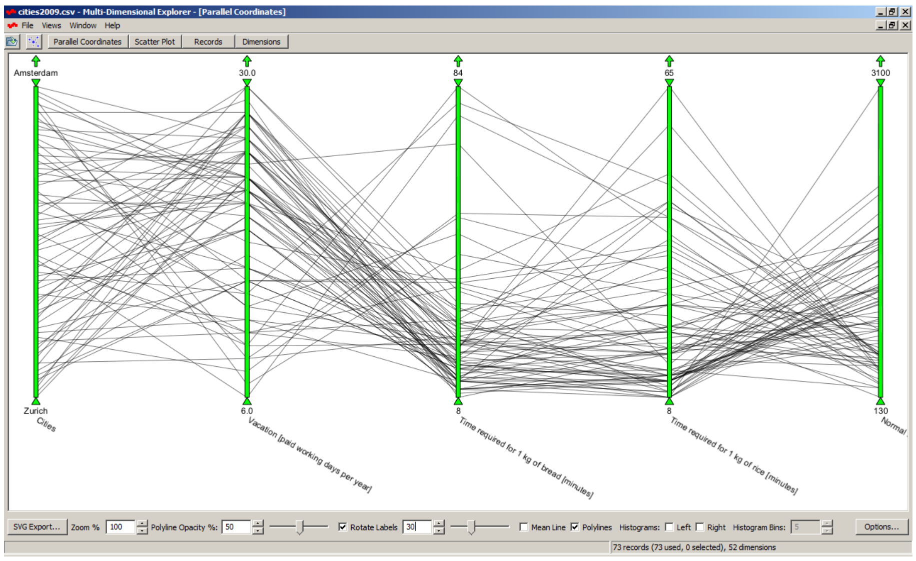
Table 3.1: Part of the cities data set by UBS [2009], containing information about prices and earnings of various cities in different countries. This data set is a popular benchmark for testing information visualisation software. There are 73 records (one for each city) and 52 dimensions, including the name of the city.


cities2009.csv - Multi-Dimensional Explorer - [Parallel Coordinates]
File Views Window Help
Parallel Coordinates
Scatter Plot
Records
Dimensions
Cities
Gross purchasing power
Net purchasing power
Prices (excl. rent)
Prices (incl. rent)
Gross wages
Net wages
Working time [hours per year]
Vacation [paid working days per year]
Time required for 1 Big Mac [minutes]
Time required for 1 kg of bread [minutes]
Time required for 1 kg of rice [minutes]
Time required for 1 iPod Nano [hours]
City break
Inflation 2006
Inflation 2007
Inflation 2008
Prices (incl. rent)
Food basket
Services
Normal local rent medium [USD per month]
Household appliances
Bus or tram or underground
Train
Taxi [USD per 5 km trip]
Medium-sized cars price
Medium-sized cars tax
Medium-sized cars gas
Restaurant [USD per dinner]
Hotel *****[USD per night]
Hotel ***[USD per night]
Women's medium clothing
Men's medium clothing
Furnished medium 4-room apartment [USD per month]
Unfurnished medium 3-room apartment [USD per month]
Net hourly wages [USD per hour]
Gross hourly wages [USD per hour]
Taxes and social security contributions
Primary school teacher [USD per year]
Bus driver [USD per year]
Automobile mechanic [USD per year]
Building labourer [USD per year]
Skilled industrial worker [USD per year]
Cook [USD per year]
Departement head [USD per year]
Product manager [USD per year]
Engineer [USD per year]
Bank credit clerk [USD per year]
Secretary [USD per year]
Saleswoman [USD per year]
Female industrial worker
Female call center worker

SVG Export... Zoom % 100 Polyline Opacity %: 50 ☑ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5 Options...

73 records (73 used, 0 selected), 52 dimensions

Figure 3.10: Initially, a parallel coordinates visualisation usually shows all axes. The cities data Set used here [UBS, 2009] contains 52 dimensions. The user will want to remove some, if not most of them, from the view.


cities2009.csv - Multi-Dimensional Explorer - [Parallel Coordinates]
File Views Window Help
Parallel Coordinates
Scatter Plot
Records
Dimensions
Amsterdam
30.0
84
65
3100
Zurich
6.0
8
8
130
Cities
Vacation [paid working days per year]
Time required for 1 kg of bread [minutes]
Time required for 1 kg of rice [minutes]
Normal

SVG Export... Zoom % 100 Polyline Opacity %: 50 ☑ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5 Options...

73 records (73 used, 0 selected), 52 dimensions

Figure 3.11: In contrast to Figure 3.10, all but 5 of the 52 dimensions in the Cities Data Set have been hidden by the user, leaving: City Names, Paid Vacation Days Per Year, Time Required for 1 kg of Bread, Time Required for 1 kg of Rice, and Normal Local Rent Medium.

3.4.2 Moving Axes

Once the set of dimensions has been reduced to a suitable subset, ordering becomes an issue. Axes in parallel coordinates are restricted to two neighbours (at least in their traditional 2D form, see Section 3.3.2 for a variation of parallel coordinates overcoming this limitation), and correlations between dimensions can be explored, only if the corresponding axes are placed next to each other. This calls for a means to move axes to obtain a desired ordering.

Figure 3.12 shows how axes are moved in parallel coordinates visualisations. Following up on the previous example, users might want to know more about how Medium Rents and Paid Vacation Days Per Year are related, so the axis about rents is moved next to that about paid vacation days.

3.4.3 Looking for Patterns

With dimensions reduced to a suitable subset and arranged in a suitable order, the pattern of lines between the axes can be analysed. Siirtola and Räihä [2006] explain that the crossings of lines should be observed: if many lines cross, and if they become more parallel to each other after having flipped one of the axes upside down, a correlation between the two dimensions can be deduced. Figure 3.13 shows how flipping one of the axes immediately reveals that:

1. Rents and paid vacation days are not much related to each other.
2. People living in cities with low rents tend to work longer to earn enough money to buy 1 kg of bread.

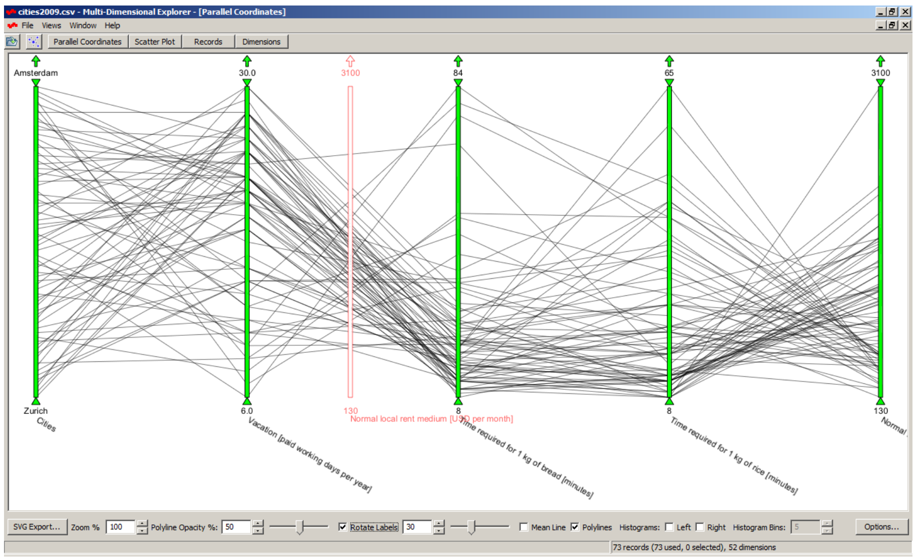
3.4.4 Selecting Records (Brushing)

Selection means choosing a subset of records of particular interest: a selection is usually highlighted by colouring the records differently. Figure 3.14 continues the previous example. It shows how one of the lines stands out between two apparently correlated dimensions. This record has been selected and is highlighted in blue. Its details are shown and reveal the city of Caracas to be an example of a place where rents are much higher compared to other cities in relation to the time required to earn enough money for 1 kg of bread. The selected record is shown in blue so that the user can distinguish between selected and unselected records.

The terminology is sometimes inconsistent in the literature. Inselberg [2009] calls the operation "querying" and gives it a more general meaning. He defines a query as any command the user can issue to parallel coordinates software to change the display such that desired information can be gained visually, which may or may not involve a change in the appearance of individual records. Note that the word is not to be understood in the classical computer science sense; it has nothing to do with query languages such as Structured Query Language (SQL) or even with retrieving records from a database. Instead, the word denotes visual interaction mechanisms provided by the user interface.

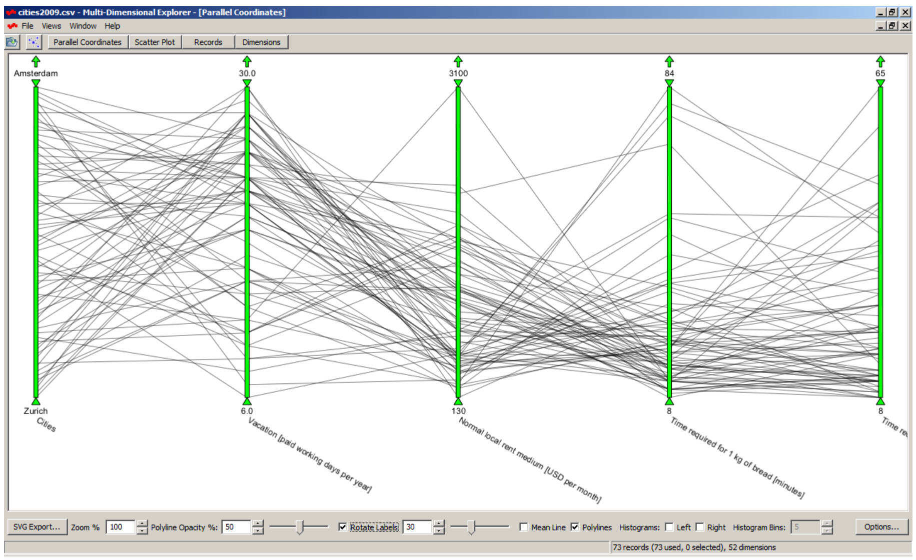
Other sources call the operation "brushing" [Ward, 1994]. For reasons of consistency, the term "selection" will be used throughout this thesis.

Selection or brushing is preferably achieved by dragging the mouse to enclose desired line segments within a box. The enclosed records are highlighted as selected. For the aggregation of different selections, it makes sense to use additional keyboard actions as well; for example, when the shift key is pressed while a selection rectangle is being drawn with the mouse, the enclosed records might be added to the previous set of selected records, rather than *replacing* it. This is an established user interface paradigm;



73 records (73 used, 0 selected), 52 dimensions

(a) A parallel coordinates axis is being moved (shown in red here during movement).



73 records (73 used, 0 selected), 52 dimensions

(b) After moving, dimensions about vacation and rent are located next to each other.

Figure 3.12: In parallel coordinates, users sometimes want to move axes, so that dimensions whose correlations they wish to explore are placed next to each other. For example, the user might want to study the correlation between Medium Rents and Paid Vacation Days Per Year. (a) shows the axis about medium rents being moved by dragging it with the mouse; (b) shows the result of the operation, the two axes are located next to each other.

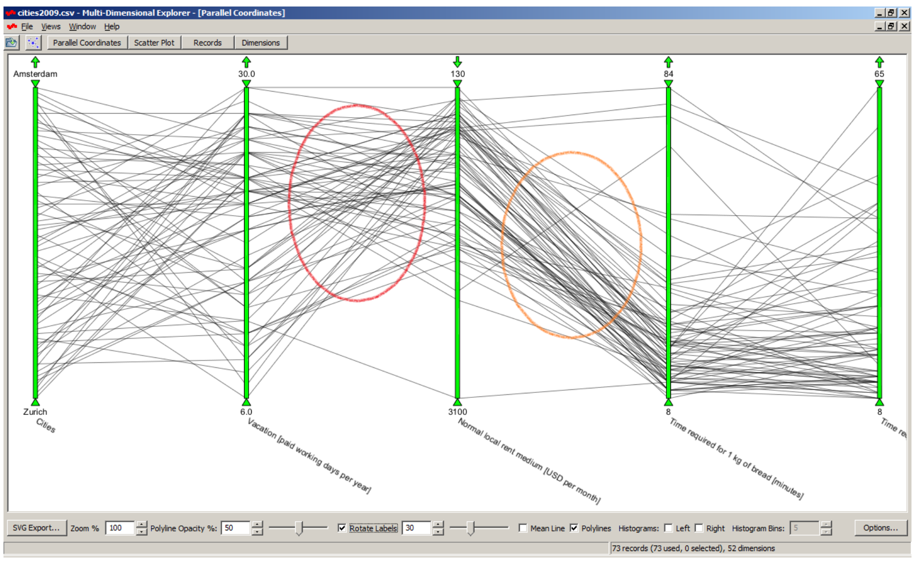
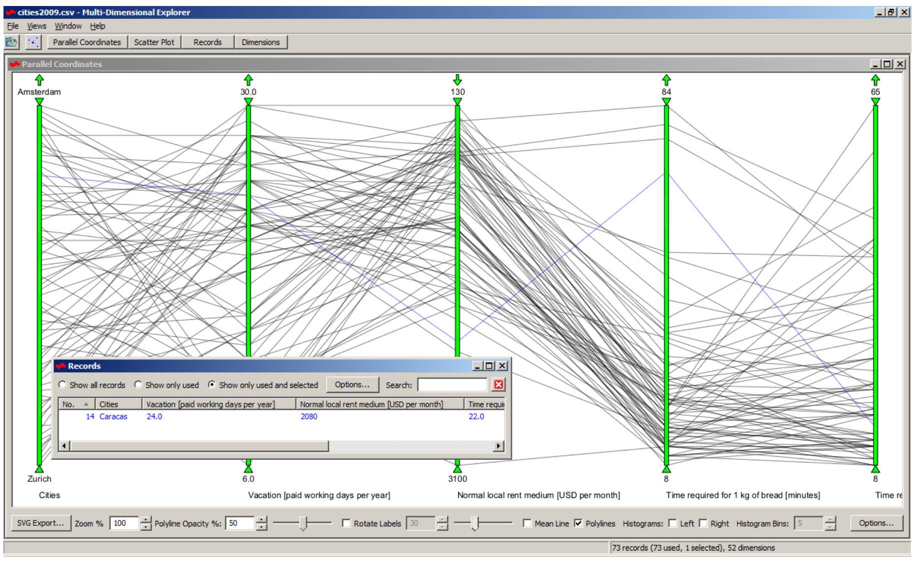


Figure 3.13: In parallel coordinates visualisations, if many lines cross in the interval between two axes, and if the crossings give way to more parallel lines upon flipping either of the axes, a correlation between the two dimensions can be deduced. In this example, which continues the scenario from Figure 3.12, the axis about medium rents has been flipped. The left interval, marked with a red ellipse, still shows many crossed lines, so it can be assumed that rents are not much related to the left-hand dimension ("vacation [paid working days per year]"). The right interval, however, marked with an orange ellipse, now shows many, more parallel, lines. This indicates a correlation between medium rents and the right-hand dimension ("time required for 1 kg of bread [minutes]"). In other words: people living in cities with low rents tend to work longer to earn enough money to buy 1 kg of bread.



No.	Cities	Vacation [paid working days per year]	Normal local rent medium [USD per month]	Time requi
14	Caracas	24.0	2080	22.0

Figure 3.14: One of the records in a parallel coordinates visualisation is selected. In this example, building on the example in Figure 3.13. one record stood out between the two apparently correlating dimensions "Normal Local Rent Medium" and "Time Required for 1 kg of bread [minutes]" due to the direction of its line. It has been selected here (highlighted in blue) and revealed to be that of Caracas. Therefore, Caracas is an example of a place where rents are much higher compared to other cities in relation to the time required to earn enough money for 1 kg of bread. The selected record is shown in blue so that the user can distinguish between selected and unselected records.

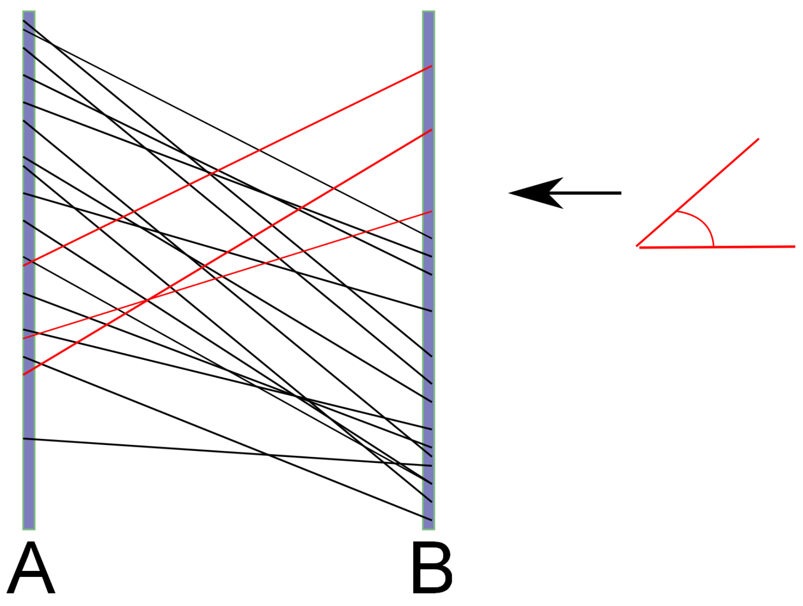


Figure 3.15: Angular brushing is used to select records in parallel coordinates by defining an angle interval between two axes. On the right, there is an illustration of interval definition; the upper red line has an angle of 45 degrees from the axis lines, the bottom red line an angle of 90 degrees. Applied between axes A and B, shown on the left side, the angle between every polyline segment and the axis lines is considered; the red segments match the filter because for them the angle is between 45 and 90 degrees, so they are considered selected. The other, black ones, are not selected. The idea for this concept and the source of this adapted image are from Hauser et al. [2002].

it works similar to how items are selected in everyday file managers like Windows Explorer [Microsoft, 2011] or the Finder in Mac OS X [Shadovitz, 2007].

Furthermore, if additional visualisations of the same data set are present (see Section 2.3), selections should be synchronised in both directions. Records selected in a parallel coordinates visualisation should be highlighted as selected in any other views, while records selected in the other views should likewise be highlighted as selected in the parallel coordinates view. For example, if a user selects dots corresponding to records in a synchronised scatter plot window (which may also be achieved by enclosing them with a box), the polylines corresponding to the same records should be highlighted in the application's parallel coordinates window.

“Angular brushing”, discussed by Hauser et al. [2002], is the name of a special parallel coordinates record-selection technique which considers the angle of lines between two axes. The degree of the angle of a line reaching from one axis to the next is in the range *(0,180)*. The brushing angle can likewise be defined as an interval of degrees. This is especially useful for discerning records whose values go against the general trend between two axes. Figure 3.15 shows an example of the concept.

3.4.5 Colour Shading

Colour shading is an operation in which one dimension is selected by the user and every polyline is then assigned a colour within a colour range according to the record's data value in that dimension. Figure 3.16 is an example of colour shading; the operation is applied to the first dimension, colours ranging from black over red to white. The higher a record's data value in the first dimension, the darker its polyline. This aids in detecting correlations to other dimensions. One can, for instance, immediately observe that the order of the records in the dimensions on the right is largely the same as in the first

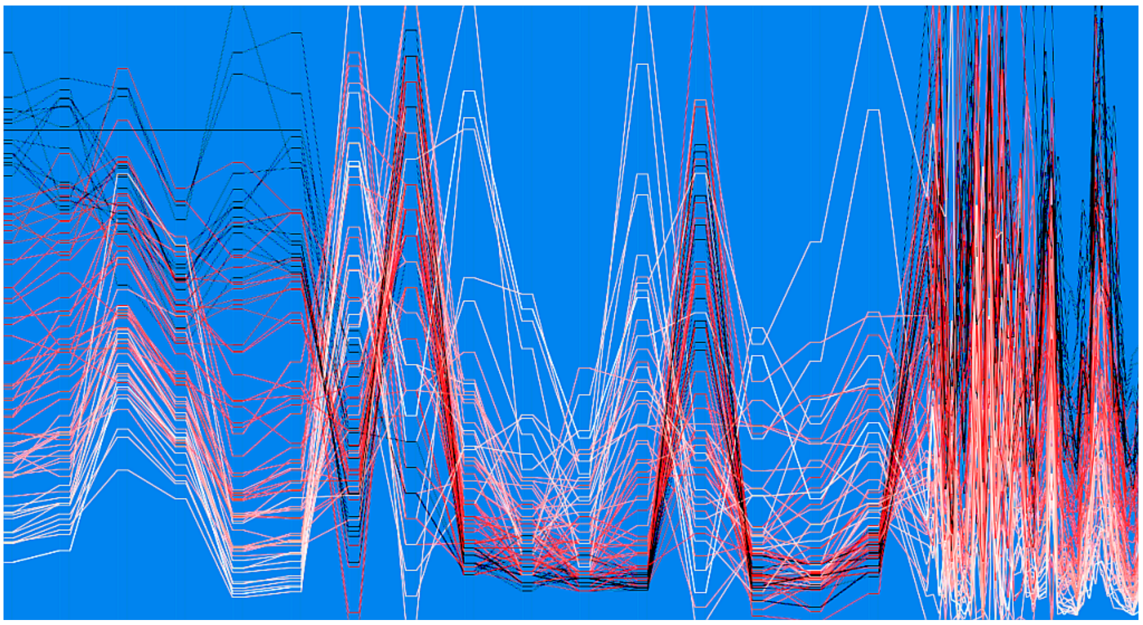


Figure 3.16: Colour shading is a parallel coordinates operation in which one dimension is selected by the user and every polyline is then assigned a colour within a colour range according to the record's data value in that dimension. In this example, colour shading is performed on the first dimension, and the colour range is defined as black-red-white. The higher a record's data value in the first dimension, the darker its polyline. This aids in spotting correlations between dimensions. Here, for example, the polylines' colour distribution on the right largely match that of the first dimension, so a user can deduce that records with higher values in the first dimension tend to have higher values in the last few dimensions as well. The image was adapted from InfoScope [Brodbeck and Girardin, 2003].

dimension; records with higher values in the first dimension tend to have higher values in the last few dimensions as well.

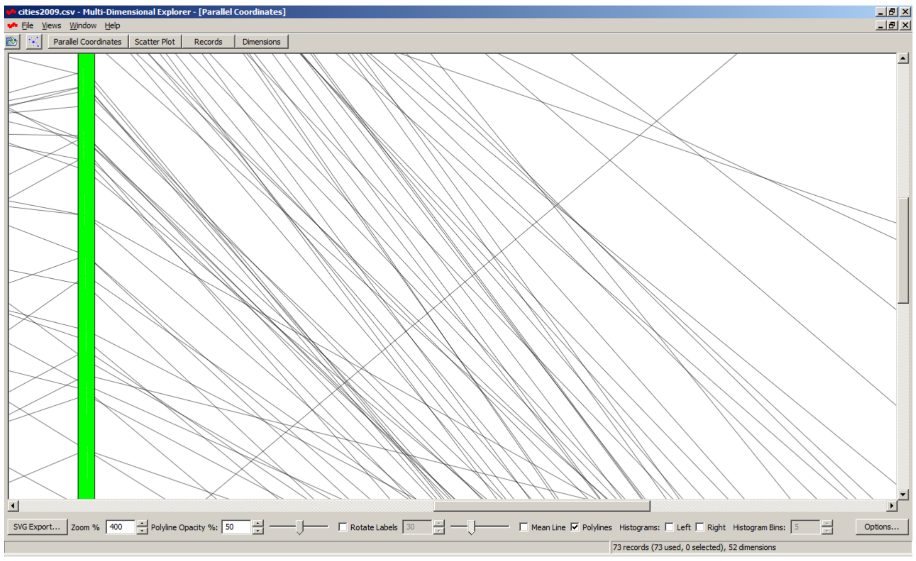
Colour shading is similar to selecting records. The difference is that selections result from the user's interest in a particular *record*, or group of records, whereas colour shading is useful when the user is interested in a *dimension* as a whole and how that dimension generally relates to other dimensions.

3.4.6 Zooming

Bauer et al. name zooming as the final step in using parallel coordinates for data analysis. Indeed, as parallel coordinates polylines are infinitely thin by definition, they can always be rendered with a thickness of exactly 1 pixel, regardless of the zoom level of the entire visualisation. This can help discern polylines placed very close to each other. Figure 3.17 shows the zoomed region of a parallel coordinates visualisation.

However, if users just need a quick way to identify individual records in crowded areas of the display, zooming may not be a desirable solution, because it requires users to temporarily sacrifice their complete overview of the data and to constantly zoom in and out. This is a rather tedious way to "follow" a polyline along all axes. Temporarily selecting a record and then deselecting it again just to see its entire polyline in a crowded display mixes different tasks and concerns.

A better approach to provide the user with a record's details on demand is to temporarily *focus* it when the mouse pointer is hovering above any of its polyline segments. Focussing means highlighting the polyline with another different colour (not the one used for selected records) and showing the corresponding record's individual data values on the crossings between polylines and axes. Figure 3.18 shows a focussed record in a crowded parallel coordinates visualisation.



Zoom % 400 Polyline Opacity %: 50 ☐ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5

73 records (73 used, 0 selected), 52 dimensions

Figure 3.17: A parallel coordinates display at a zoom level of 400%. With zooming, users can more easily discern polylines drawn close to each other. Lines are infinitely thin by definition, that is, they can always be drawn with a thickness of 1 pixel, irrespective of the zoom level. This helps in detecting patterns in otherwise overly crowded areas of the parallel coordinates visualisation.

See also Section 3.2 for discussion of techniques to solve problems caused by overlapping polylines.

3.5 Software Applications

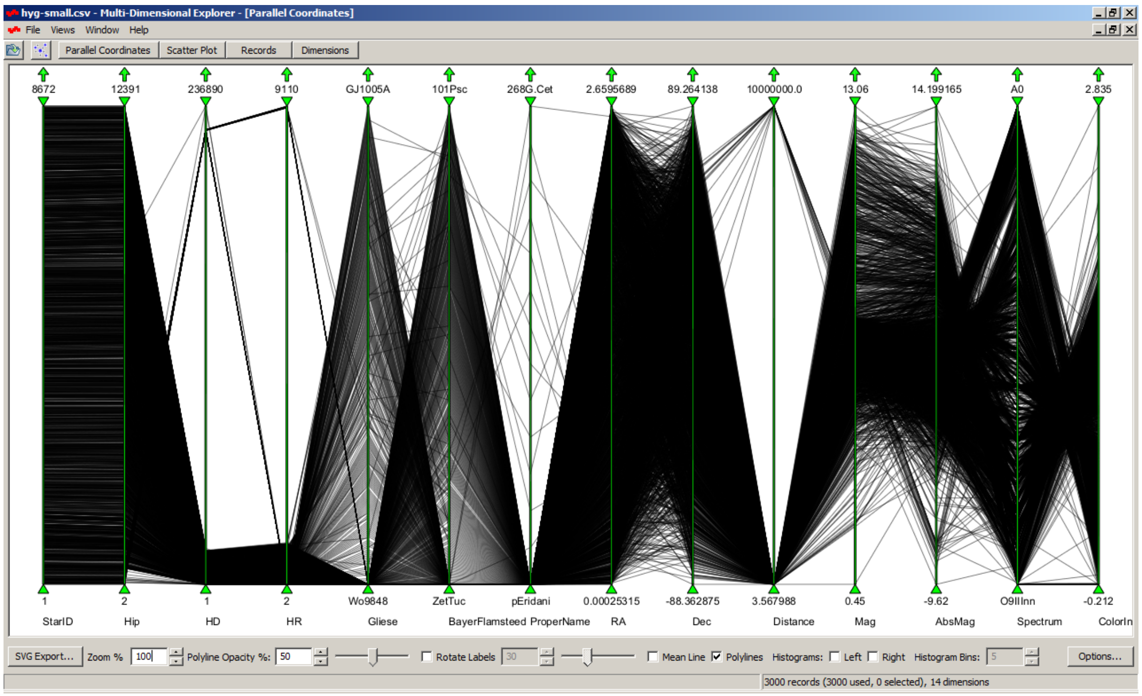
This section gives an overview of existing software solutions for parallel coordinates visualisations. Each application is introduced separately, and particular features, strengths and weaknesses are highlighted. Parallel coordinates are simple enough to implement, but still each software application reviewed in this section turns out to be different:

- **Features:** Applications may offer certain features not found in competitors. For instance, Parallax features automatic visual classification, XmdvTool can animate data along a time dimension, and GGobi has extensive statistical tools.
- **Purpose:** Some of the applications also differ in their general scope and purpose. InfoScope is particularly aimed at exploring data with a geographical aspect, whereas Picviz was developed for use in the field of network security. Situvis was developed in the context of conflict analysis.
- **Interaction:** Finally, applications differ in the way users can interact with the display. For example, parvis features two-phase rendering to keep the software responsive while the user manipulates the visualisation. Caleydo has angular brushing.

Table 3.2 lists the reviewed software applications. Software which turned out to be more feature-rich with regards to parallel coordinates was given more space than the other tools. When software is available for download (or direct online use) on the Internet, a web address is given in its bibliography entry.

3.5.1 MDVS

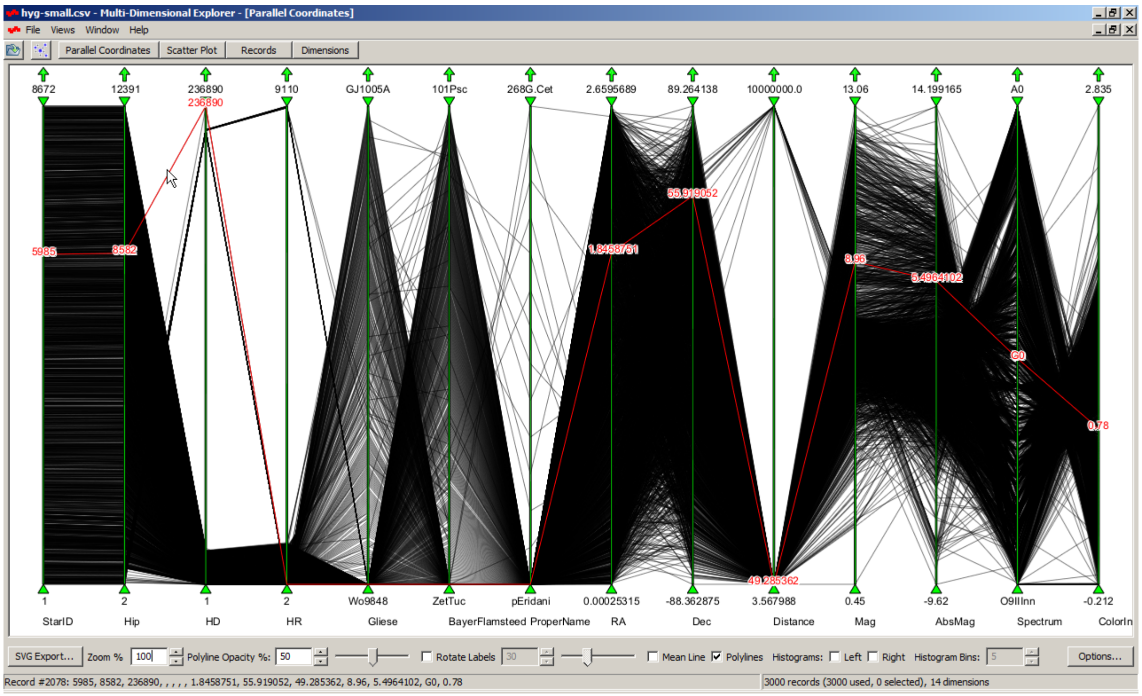
The Multi-Dimensional Visualisation System (MDVS) was made by Hackl [2010] as an extension of the Java [Oracle, 2011] desktop application MultiDimensional MetaData Visualization System (MD^{2}VS)



Zoom % 100 Polyline Opacity %: 50 ☐ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5

3000 records (3000 used, 0 selected), 14 dimensions

(a) Before focussing



Zoom % 100 Polyline Opacity %: 50 ☐ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5

Record #2078: 5985, 8582, 236890, , , , , 1.8458751, 55.919052, 49.285362, 8.96, 5.4964102, G0, 0.78

3000 records (3000 used, 0 selected), 14 dimensions

(b) After focussing

Figure 3.18: Focussing is a more user-friendly way than zooming to discern individual records in a crowded parallel coordinates visualisation. (a) shows 3000 records and 14 dimensions from the stellar data set by [Nash, 2006]. On the top area between the second and third axis, one of the polyline segments stands out, but it is impossible to follow its path in the rest of the display, because it is overlapped by thousands of other polylines. On (b), the mouse pointer is hovering above the line segment between the second and third axis, which temporarily focusses the polyline, highlighting it in red and showing its individual data values.

Name	Characteristics
MDVS	Intuitive usage
InfoScope	Support for geographical dimensions
parvis	Performance gains by two-phase rendering
Parallax	Visual classification, selection mechanisms
Situvis	Conflict analysis, pairing with graphs
Picviz	Aimed at network security
GGobi	Extensive statistical tools
XmdvTool	Time animation, hierarchical clustering
VisDB	Offers other visualisations
Caleydo	Aimed at medical science
OECD eXplorer	OECD-specific analyses, direct online use
Protovis	Implemented entirely in JavaScript and SVG
VizCraft	Aimed at Aircraft Design
Liquid Diagrams	Integration into Google Docs, SVG export

Table 3.2: A summary of parallel coordinates software reviewed in this thesis. For each of the tools, main characteristics are named.

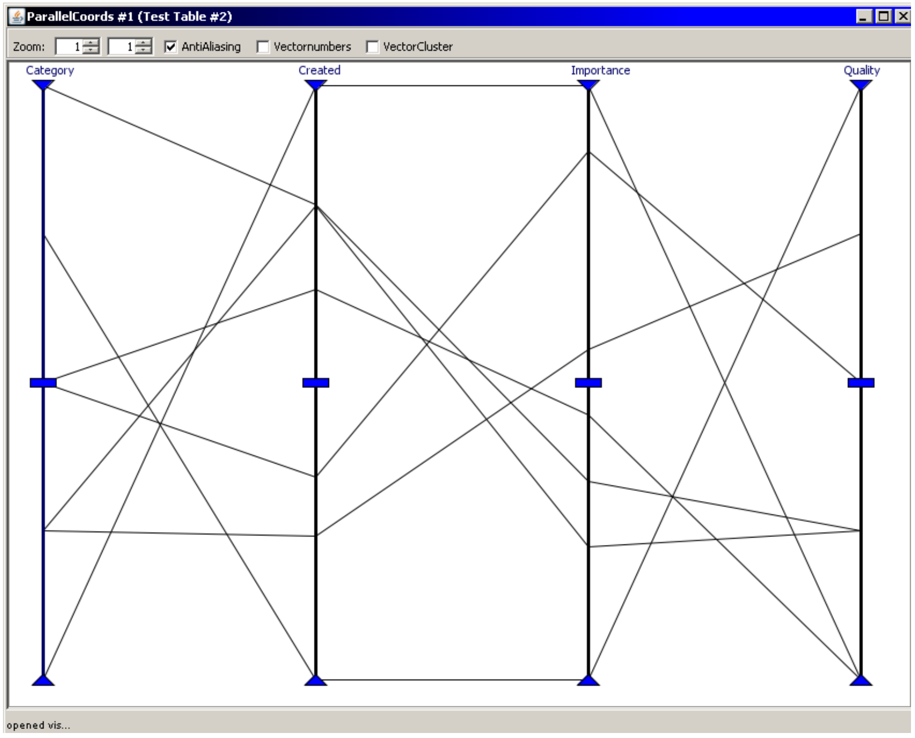
previously developed by Mader [2007]. The original MD^{2}VS application lacked a parallel coordinates visualisation. It had, however, been designed with potential extensions for further visualisation schemes in mind. MDVS therefore integrated a parallel coordinates component. Figure 3.19 is an example of a test data set visualised with parallel coordinates in MDVS. The component offers the following user interaction features:

- Filtering. In order to render a record "unused", the user has to restrict the dimension by dragging the blue triangles located on the top and bottom of the corresponding axes. All records whose lines do not pass through the now restricted vertical area will be considered unused and appear greyed out.
- Record Selection. Records which are not unused can be selected and deselected, either by clicking the corresponding lines, or by drawing a selection rectangle with the mouse. Selected records appear in blue, unselected ones in black. Figure 3.19 shows the difference between unused, unselected, and selected records.
- Dragging Axes. The horizontal position of each axis can be changed by dragging and dropping the header text with the mouse.
- Tooltip Information. When the user moves the mouse pointer over a record and leaves it there for a few seconds, the record's actual data values are displayed on each axis.

3.5.2 InfoScope

InfoScope is a commercial, closed-source Java desktop application, made by Brodbeck and Girardin [2003] and distributed by the Macrofocus company. A free test version can be obtained from the company's web site. The test version, however, can only be used with demo data sets provided by Macrofocus. Figure 3.20 shows the tool.

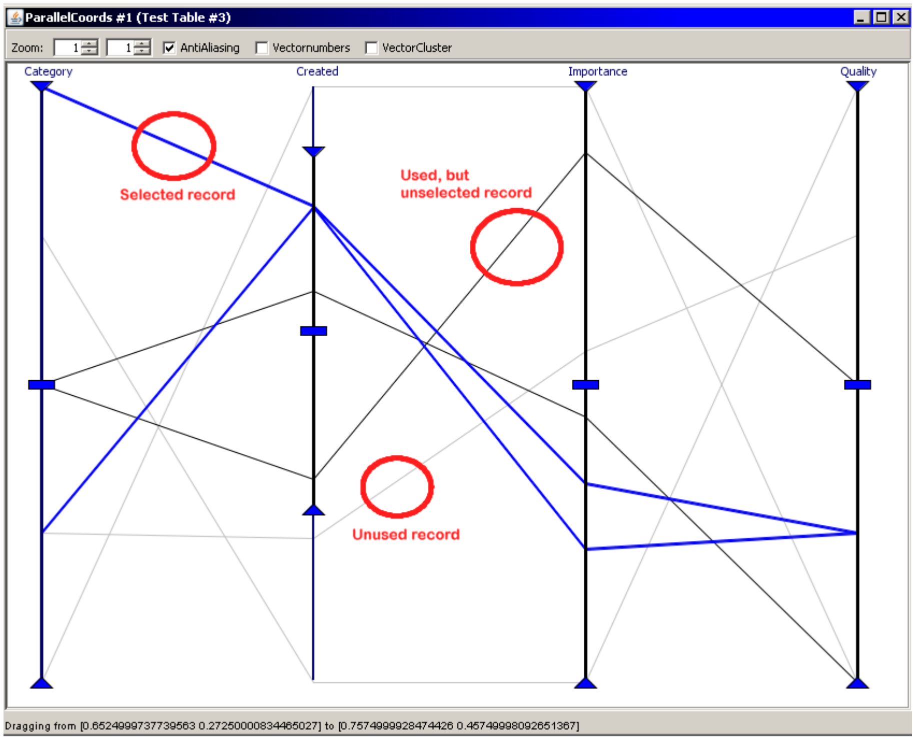
For data input, the software uses proprietary `.mis` files. It is a binary format, but the professional version of InfoScope provides *InfoScope Distiller*, a tool for conversion of simple text files into `.mis` files [Macrofocus, 2010]. Data sets can be read by opening files from the local file system or by downloading them from Macrofocus servers directly from within the application.


ParallelCoords #1 (Test Table #2)

Zoom: 1 1 [✓ AntiAliasing] Vectornumbers VectorCluster

opened vis...

(a) All records are used, none are selected.


ParallelCoords #1 (Test Table #3)

Zoom: 1 1 [✓ AntiAliasing] Vectornumbers VectorCluster

Dragging from [0.6524999737739563 0.27250000834465027] to [0.7574999928474426 0.45749998092651367]

(b) Some records are unused or selected.

Figure 3.19: The parallel coordinates component in MDVS [Hackl, 2010] visualising a test data set with dimensions "Category", "Created", "Importance" and "Quality". (a) shows all records are used and unselected. However, as (b) shows, records can also be in different states. When unused because of a restricted dimension axis, they appear grey. When in use, they can be either selected (blue) or unselected (black).

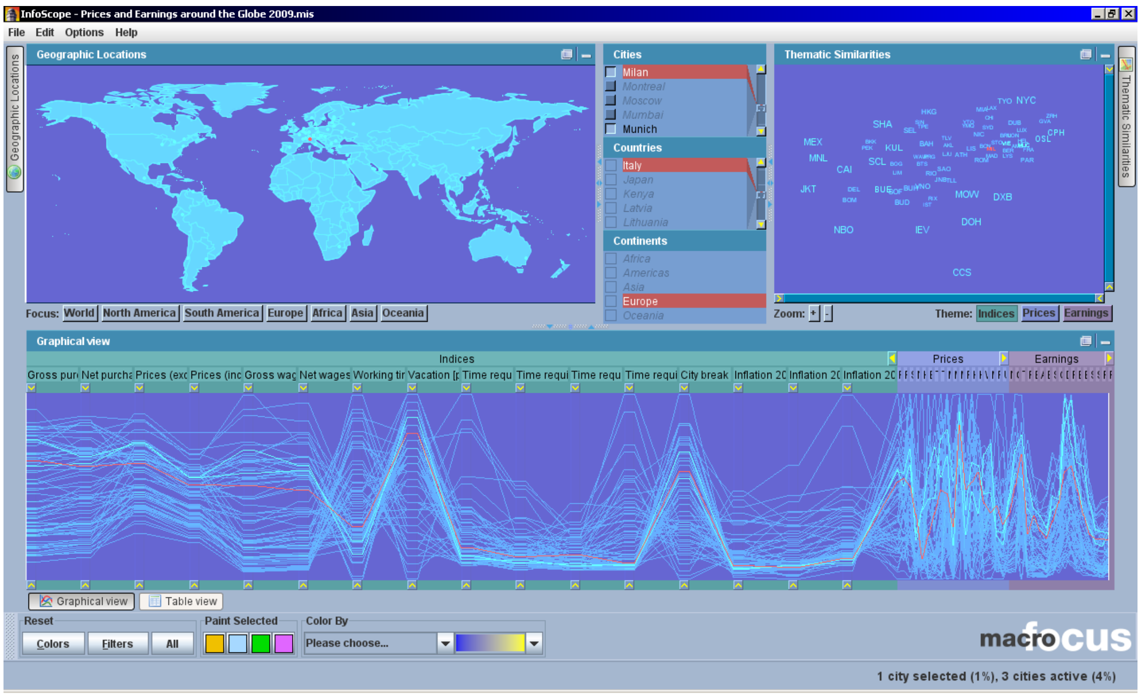


Figure 3.20: Macrofocus InfoScope, a commercial visualisation application written in Java, aimed at data with a geographical dimension. Depending on the nature of the data set, the parallel coordinates display is synchronised with a geographical map. In this example, the data is about cities spread across the globe; the lines highlighted in the parallel coordinates display correspond to the cities shown on the world map. The city of Milan corresponds to the red dot in the centre of Europe and to the red (selected) polyline in the parallel coordinates display. Likewise, Vienna and Munich correspond to the light blue dots and to the light blue (active but not selected) polylines. Additionally, a thematic similarity map of the data is shown in the right top corner.

InfoScope is aimed at data with a *geographical* dimension, such as data for a set of cities, because the geographical location of records is shown on a map in an extra window. The nature of the map and whether it is shown at all depends on the data. Examples of demo data sets provided by Macrofocus include “Prices and Earnings around the Globe” [UBS, 2009], which uses a map of the whole world, and “Swiss Cities Ranking” [l’Agefi, 2003], which uses a map just of Switzerland. The other additional visualisation provided is a thematic similarity map, which is calculated so as to place cities with similar characteristics near to one another using techniques such as force-directed placement [Fruchterman and Reingold, 1991].

The central parallel coordinates visualisation component fixes the order of dimensions. Axes cannot be reordered, nor can single axes be removed from the view. Nevertheless, dimensions are grouped into categories; this categorisation is reflected in the visualisation, since the user can visually “broaden” a category. The dimension axes belonging to the category are then separated by wider spacing, while the other categories are narrower.

InfoScope distinguishes between *active* and *selected* records. Arrows controlling filtering are placed at the top and bottom of each axis. These arrows can then be moved up and down, restricting active (that is, selectable) records to those whose lines run through the vertical area, the *interval*, between the arrows. These active records are selected by clicking on their lines in the parallel coordinates visualisation. Multiple records can be selected by pressing the Ctrl key while clicking. Upon selection, records appear in a different colour, and the geographical and thematic similarity visualisations are updated accordingly. Similarly, the selection is synchronised with a standard tabular view of the data.

The other selection type found in InfoScope introduces an additional visual information channel in the graphical display by means of *colour shading*. One dimension axis can be selected for this feature via the “Color by” dropdown menu, upon which each record polyline is coloured according to its value in the selected dimension. The colour shading scheme itself can be chosen, too. For example, one can choose shading from black to red, such that lower values tend more towards black while higher values tend more towards red.

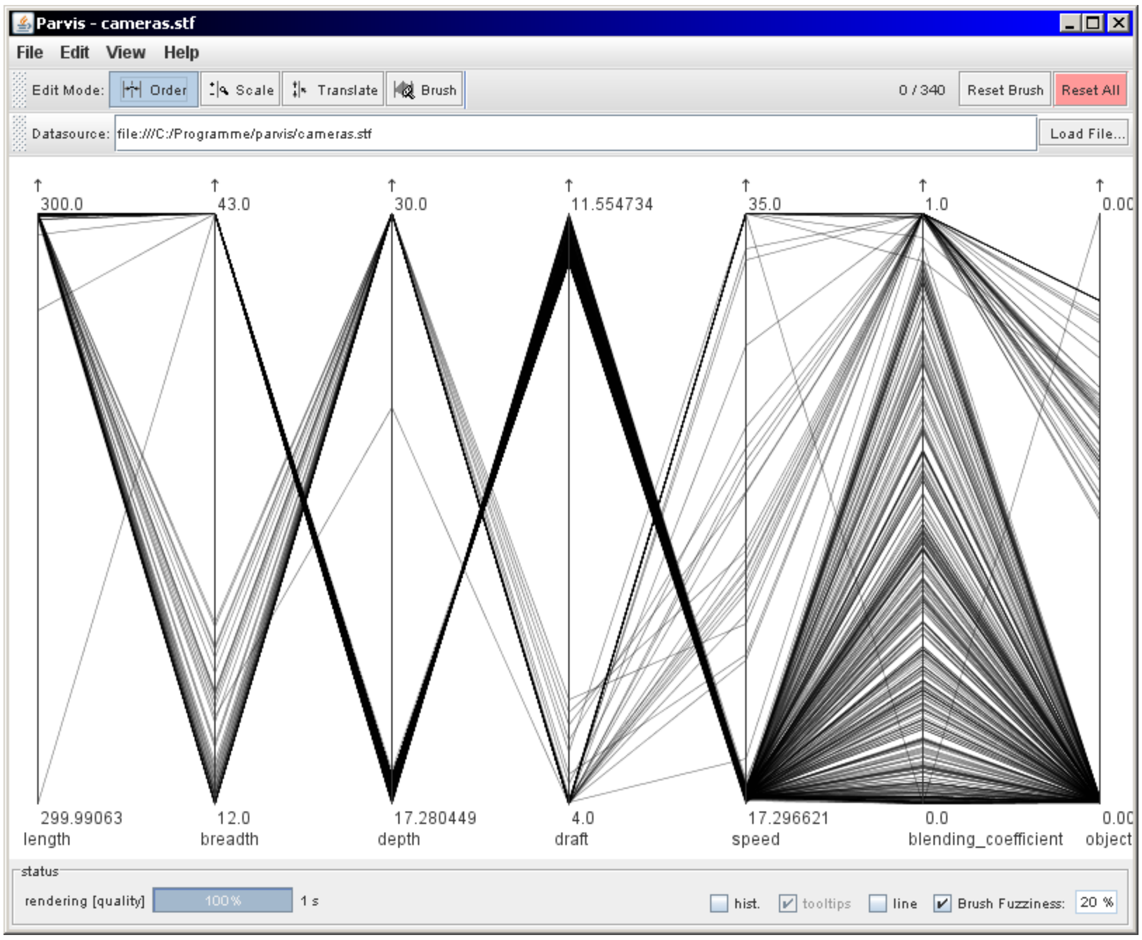
There is no zooming available for the parallel coordinates visualisation; its size always depends on the window size. On the positive side, anti-aliasing can optionally be turned on. Records are optionally focussed when hovering over their lines with the mouse pointer and, simultaneously, tooltips showing the record’s data values appear.

3.5.3 parvis

parvis is an open-source Java desktop application developed by Ledermann [2003]. It is a general-purpose parallel coordinates visualisation tool without any particular application area. The text-based `.STF` file format is used for data input. At the time of writing, the project is discontinued. Although the latest release version number is only 0.3.1, parvis is a mature and usable piece of software. Figure 3.21 shows the tool.

Dimensions in the display can be reordered freely by horizontally dragging the axes, but an axis cannot be repeated or removed from the display. Individual axes can be translated and scaled vertically. There is, however, no way to zoom the entire display.

When the “tooltips” option is activated, records are focussed when moving over them with the mouse pointer, and the record’s data values appear as tooltips over the data points on the axes. Selecting the records, however, is a rather complex operation, because the only selection type supported by parvis is *angular brushing*. Records cannot be selected by a simple single click, by creating an axis interval, or by drawing a rectangle.



Datasource: file:///C:/Programme/parvis/cameras.stf

length	breadth	depth	draft	speed	blending_coefficient	object
300.0	43.0	30.0	11.554734	35.0	1.0	0.0
299.99063	12.0	17.280449	4.0	17.296621	0.0	0.0

Figure 3.21: parvis is an open-source Java desktop application for general-purpose parallel coordinates visualisation; displaying here the well-known cars data set [Ramos and Donoh, 1983]. This figure illustrates progressive rendering, one of parvis' special features to enhance speed and usability. While an axis is being moved by dragging it horizontally with the mouse, the visualisation is updated immediately without anti-aliasing. It is then progressively replaced by anti-aliased lines while the application stays responsive, allowing the user to continue work without interruption. The bar at the bottom left of the window shows the current rendering progress.

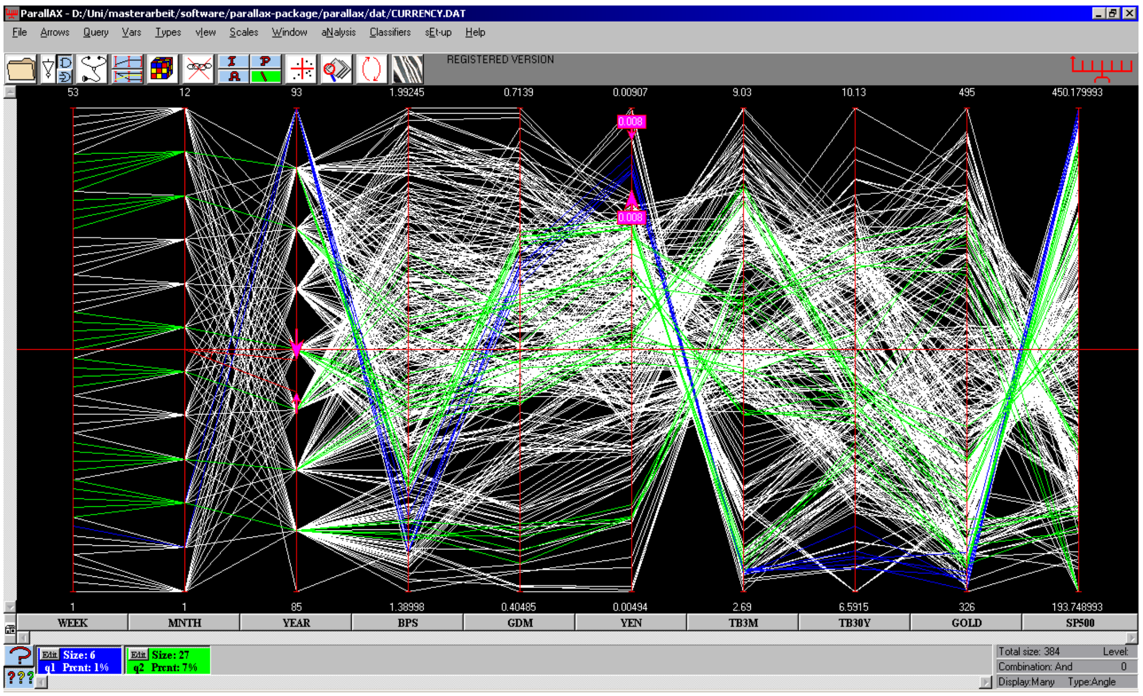


Figure 3.22: Parallax, a commercial, closed-source desktop application featuring parallel coordinates. This figure shows a combination of two different query types on a financial data set. Records appearing in green have been selected by an angle query on the "Year" axis; blue ones have been selected by an interval query on the "Yen" axis. Basic queries can be combined into more complex ones by logical AND, OR and NOT operators. Parallax also features automatic visual classification.

The most distinguishing feature of parvis is *progressive rendering*. To enhance usability of the application even for large data sets, rendering is performed in two steps. While the user modifies the display, such as by dragging an axis or by selecting records with the mouse, a fast and low-quality (no anti-aliasing) version of the visualisation is displayed immediately. It is then replaced progressively by anti-aliased lines which are generated in the background. This way, the system *remains responsive* while the user still performs operations with the mouse. Work can be continued without interruption. The other performance advantage gained from this, is that most of the time, the expensive generation of the high-quality display can be terminated immediately, as long as the user keeps moving the mouse pointer.

A further distinguishing feature of parvis are *axis histograms*, which visualise the density of records on an axis' interval. parvis also allows the free choice of all colours in the parallel coordinates visualisation. On the negative side, there is no synchronised table view of the data set.

3.5.4 Parallax

Parallax is a parallel coordinates visualisation desktop application developed by Inselberg [2010a]. It is a commercial, closed-source software package. Inselberg [2009, pp. 382-416] gives a walkthrough of the application, explaining its various features. Figure 3.22 shows Parallax.

For file input, Parallax uses simple text files with the default file name ending .DAT. In these files, records are separated by line breaks, while elements within a record are separated by spaces. There are only numerical values, no enumerations or strings. One can, however, denote undefined (null) values in the input data set. In the visualisation, these values appear below the bottom of their corresponding axes. Parallax allows users also to create new .DAT files. In order to do so, the current selection is "isolated", which is to say that all records currently not selected by any query are removed from the data set. The remaining records may then be saved as a new file.

Axes can be reordered and removed freely, but any axis may appear only once. The application, however, automatically generates a list of all meaningful *axis permutations* to choose from, based on the observation in Inselberg [2009, pp. 389-390] that few permutations are needed to obtain all possible adjacent pairs of axes. In addition to this convenience feature, Parallax also features vertical flipping of axes. Parallax has scatter plot and histogram visualisations. In the scatter plot display, record selections are synchronised with the parallel coordinates display. It is also possible to select records from within the scatter plot display by drawing a multi-sided polygon encompassing the desired points.

Parallax features a comprehensive structured querying mechanism, which can be viewed as a two-layered system:

- On the first layer, queries can be named and be associated with a particular colour. Any number of such queries can be created. The results of each query, that is, the colouring of records, can be shown separately or in combination with those of other queries.

- On the second layer, a query is itself composed of “queries”. Thus, the word “query” actually has a double meaning in Parallax. Queries on this second layer comprise *interval*, *pinch*, *angle* and *relative complement* queries:

  - A *pinch* query is defined by an upper and lower arrow placed anywhere between two axes. As the horizontal position of the arrows may be moved as well, this must actually be considered an invisible selection *line*. Those records whose polylines intersect with the invisible line are selected.
  - The *interval* query can likewise be considered a special case of the pinch query in which upper and lower bound arrows have to be placed exactly on an axis.
  - *Angle* queries, defined between two axes, constitute a range of angles. An angle is measured from the left axis line. For example, the minimum allowed angle might be 30 degrees, the maximum allowed angle 45 degrees. Now, if a polyline segment between the two axes has an angle of 35 degrees from the left line, then it is included in that range, and the record is selected. Figure 3.15 illustrates the concept, which Hauser et al. [2002] call “angular brushing”. In order to define such a query in Parallax, the user has to click the “A” button in the tool bar, then click on an axis line in the parallel coordinates visualisation; two purple arrow handles appear on the axis line. They can be dragged up and down to define the angle range.
  - A *relative complement* query is defined by the complement of two first-layer queries. If, for instance, the user chooses the relative complement between (first-layer) queries A and B, then the result of this (second-layer) query are all records selected in A but not in B.

  Second-layer queries are combined logically with *AND*, *OR* and *NOT* operators to form a first-layer query.

Parallax offers an undo feature for some of its operations, which represents an important plus in terms of usability. On the downside, the application’s display quality suffers from the lack of anti-aliasing. The colour scheme can only be partially changed. Furthermore, a number of bugs detract from a flawless user experience. Most importantly, zooming results in seemingly random display errors to the point of rendering the application unstable, and dialogue windows for choosing a query’s associated colours will not always open. The former error is acknowledged in the manual and may disappear in future versions of the application (1.0 at the time of writing).

3.5.5 Situvis

Situvis is an open-source parallel coordinates visualisation software package developed by Clear et al. [2009] within the *Processing* programming environment [Fry and Reas, 2010]. The tool is meant to be used for modelling behaviour patterns and for conflict analysis, although it could also be used more generally for all kinds of input data. It operates on text-based `.tsv` files.

Originally, before the software was labelled "Situvis", its most particular feature was to pair parallel coordinates with a node-like graph visualisation of the same data set. Figure 3.23 shows a comparison of the current software with its predecessor, which was given the name "paired parallel coordinates". It was based on the observation by Shannon et al. [2008] that parallel coordinates are not particularly good at visualising *relationships between records*. The graph visualisation component, however, has been removed and is no longer present in the current Situvis software.

User interaction in Situvis is relatively limited. Axes can be reordered, but an axis cannot be removed or repeated. When the user moves the mouse pointer over an axis, a tooltip shows the value corresponding to the mouse pointer location. Records can be selected by intersecting their polylines with a line the user draws by dragging the mouse over the visualisation. The records' actual values, however, are not displayed. There is no table view of the data, either.

Apart from the line intersection feature, selecting records is based on the concept of "situations." A situation is a named selection, composed of constraints defined on each dimension. The way a constraint is defined depends on the nature of the dimension, the type of which can either be numerical or an enumeration of strings. Constraints for numerical dimensions are defined in terms of lower and upper bounds, while constraints for enumerations are defined as a subset of allowed values. The graphical user interface, however, provides no way of defining situations; they have to be defined manually in the tool's input text files.

Besides the parallel coordinates visualisation, there is a list of all currently defined situations. Each entry in the list can be activated separately, which results in the situation and all the records it encompasses being visualised, using the colour defined for that situation. The user may then expand or narrow the situation for axes with real values, and toggle allowed values for axes with enumerations. Where situations cross, colours are mixed automatically, the tool's main purpose being conflict analysis.

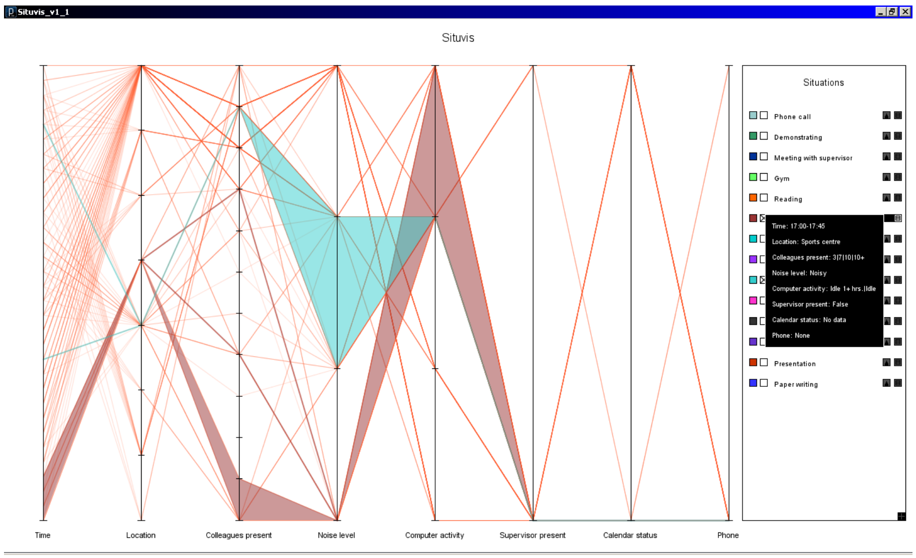
3.5.6 Picviz

Picviz is an open-source C library originally made by Tricaud et al. [2011] and implemented itself with the Cairo [2010] graphics library. The developers also provide ready-to-use command-line interface (CLI) and graphical user interface (GUI) frontends. At the time of writing, the project is still in its beta phase. Figure 3.24 shows the GUI frontend of Picviz.

Although Picviz can be used as a general-purpose parallel coordinates visualisation tool, its actual purpose, as explained by Tricaud and Saadè, is *network security*. A tool to convert server logs into the tool's own *Picviz Graph Description Language* (PGDL) file format is provided. PGDL is a text-based graph description language [Picviz, 2010].

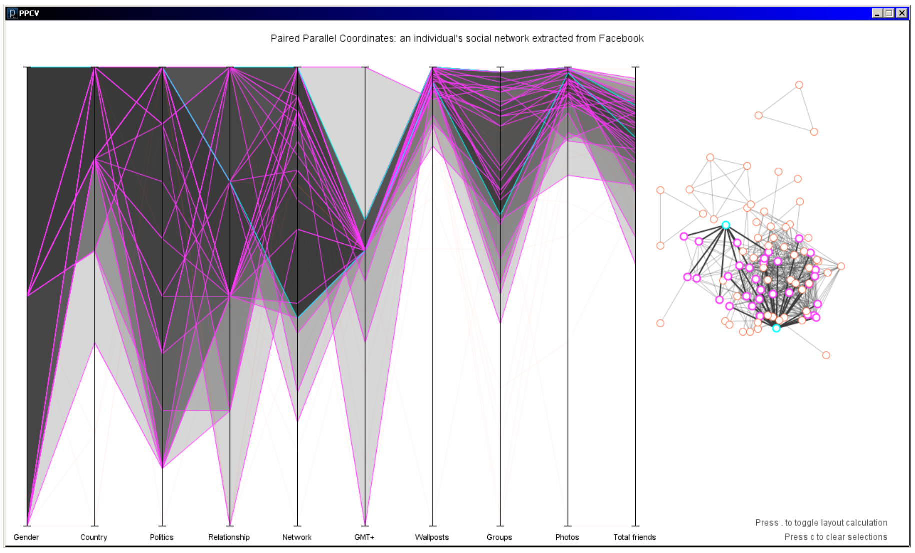
The introductory example given by the Picviz developers is to analyse Hypertext Transfer Protocol (HTTP) server logs. Records represent different requests, dimensions include information such as a request's Uniform Resource Locator (URL), Internet Protocol (IP) address, HTTP level, request method, and the user agent string. The authors then go on to show how one can immediately spot particularities in the correlations between request methods and URLs, or between IP addresses and user agents [Tricaud and Amaducci, 2009].

The Picviz GUI gives users complete control over the order of dimension axes. Axes may also appear



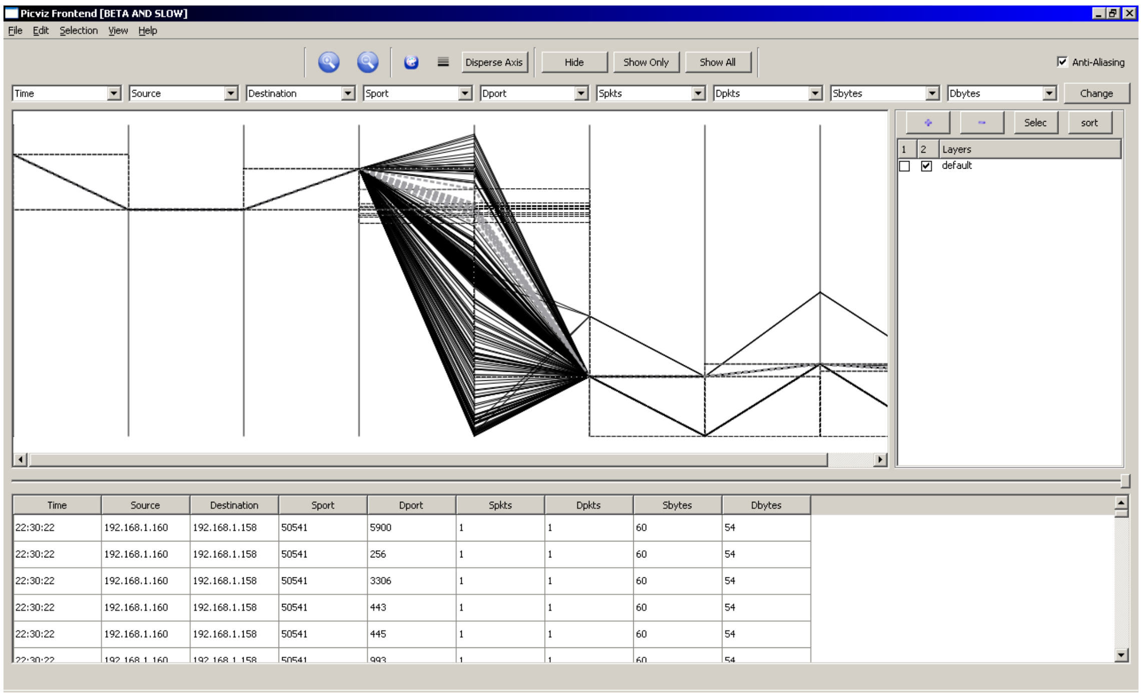
Time: 17:00-17:45
Location: Sports centre
Colleagues present: 3|7|10|10+
Noise level: Noisy
Computer activity: Idle 1+ hrs.|Idle
Supervisor present: False
Calendar status: No data
Phone: None

(a) Current Version of Situvis


PPCV
Paired Parallel Coordinates: an individual's social network extracted from Facebook
Gender
Country
Politics
Relationship
Network
GMT+
Wallposts
Groups
Photos
Total friends
Press : to toggle layout calculation
Press c to clear selections

(b) Paired Parallel Coordinates

Figure 3.23: Situvis [Clear et al., 2009] is an open-source software package developed within the Processing programming environment, featuring parallel coordinates visualisation. Although envisioned as a tool for modelling user behaviour patterns, it can be used for all kinds of applications. (a) shows what the software currently looks like. Previous versions of Situvis, as shown in (b), pair parallel coordinates with a graph visualisation, based on the observation that parallel coordinates are not particularly good at visualising relations between individual records. The graph visualisation does exactly that; its nodes represent records, its edges represent relations between them. Selections in both visualisations are synchronised, with turquoise indicating a selection. Turquoise nodes in the graph correspond to turquoise lines in the parallel coordinates display. Purple nodes and lines represent records directly related to the selected ones. This image shows an example of a social network data set in which each record represents a user on Facebook. (Note that both images shown here have been inverted to increase legibility.)



Time	Source	Destination	Sport	Dport	Spkts	Dpkts	Sbytes	Dbytes
22:30:22	192.168.1.160	192.168.1.158	50541	5900	1	1	60	54
22:30:22	192.168.1.160	192.168.1.158	50541	256	1	1	60	54
22:30:22	192.168.1.160	192.168.1.158	50541	3306	1	1	60	54
22:30:22	192.168.1.160	192.168.1.158	50541	443	1	1	60	54
22:30:22	192.168.1.160	192.168.1.158	50541	445	1	1	60	54
22:30:22	192.168.1.160	192.168.1.158	50541	993	1	1	60	54

Figure 3.24: The standard GUI frontend of Picviz, an open-source C library aimed specifically at applying parallel coordinates visualisation to network security. The data set shown here is scanned network traffic. Grey lines represent selected records. In addition, dashed rectangles are drawn around selected records dimension-wise.

more than once; an axis cannot, however, be hidden completely other than by replacing it with a different axis. Instead of selecting records by defining intervals on or between axes, Picviz employs a generalised approach; one can draw a selection *rectangle* with the mouse to enclose desired polylines. Selected records can then be coloured individually. Other than that, the colours used in the display cannot be changed. Sets of records can however be saved as "layers" and subsequently be hidden from the view. This compensates for the lack of a feature to aggregate selections directly with the mouse, such as by pressing the Shift or Ctrl key while clicking.

As a severe limitation, the Picviz GUI makes it difficult to analyse the actual values of selected records. There is a table displaying the whole data set, but selections in the table and the parallel coordinates visualisation are *not* synchronised. In fact, the table itself is completely inactive. Values are only displayed as tooltips on the visualisation itself when the user places the mouse pointer on a record's polyline. For any more complicated task, the CLI frontend has to be used.

Finally, anti-aliasing can optionally be turned on to give users the choice to trade speed for display quality. Additionally, zooming is supported, and the visualisation can be exported as a Portable Network Graphics (PNG) file.

3.5.7 GGobi

GGobi is a general-purpose visualisation desktop application suitable for statistical analysis of multivariate data [Cook and Swayne, 2007]. It is written in C, using the GTK+ toolkit [GTK+ Team, 2010], and can read Extensible Markup Language (XML) and comma-separated values (CSV) text files. GGobi is open-source and can be downloaded for free. The application evolved from the older XGobi project [Swayne et al., 2007]. Figure 3.25 shows the tool.

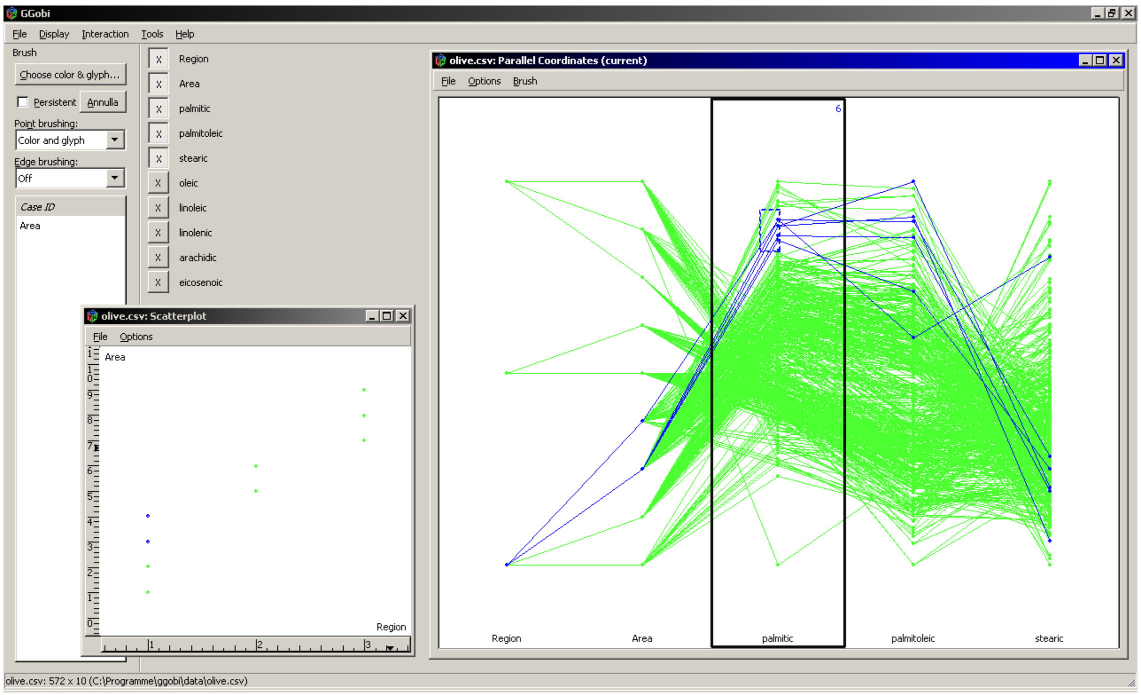


Figure 3.25: GGobi, an open-source GTK+ application featuring parallel coordinates visualisation. The tool offers various other visualisation types and synchronises selections and data manipulations in each of them. Here, parallel coordinates are shown with a scatter plot of the first two dimensions. GGobi's most distinguishing feature is a set of extensive data manipulation and statistical tools. (Note that parts of this image have been inverted to increase legibility.)

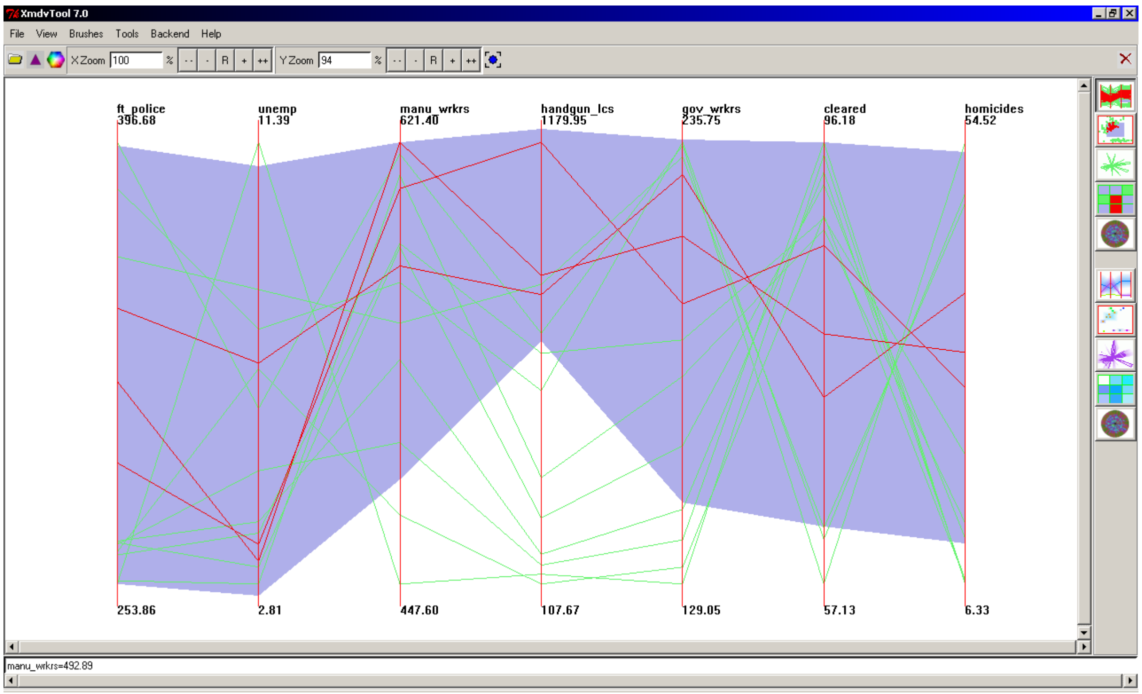
GGobi features not only parallel coordinates, but also scatter plots, time series, and bar charts. The visualisations are synchronised: record selections and data manipulations in one of them trigger an immediate update of the others. There is also a table view of the input data set (called "data viewer"), which is, however, only partially synchronised with the visualisations.

User interaction in the parallel coordinates visualisation itself is rather limited. In order to select records, the user must move a fixed-size rectangle over the the data points – *not* the lines connecting the points! In order to aggregate selections, a checkbox labelled "consistent" has to be checked while records are selected. On the positive side, the application gives users complete control over the way a selection is displayed. Colour, style and thickness of a selected record's lines can be chosen freely. Additionally, dimension axes can be reordered and removed from the display. They cannot, however, be repeated.

In order to identify individual records, the user has to activate the "Identify" interaction mode and move the mouse pointer over the record's lines. The record will be focussed, and tooltips showing the record's actual data values will appear. A particular feature of GGobi's parallel coordinates is to change the visualisation's entire orientation, so that axes appear as horizontal lines, as opposed to the traditional way of displaying them vertically. The application does not feature anti-aliasing or zooming.

GGobi's most distinguishing feature is not directly related to its parallel coordinates visualisation component. It is the tool's extensive set of data manipulation and statistical tools. Examples of such tools include the following [Swayne et al., 2006]:

- Data in each dimension can be transformed, standardised, and sorted.
- Random noise can be added.
- Records can be selected automatically according to defined rules ("automatic brushing").



```
manu_wrkrs=492.89
```

Figure 3.26: XmdvTool's parallel coordinates component. XmdvTool is an open-source C++ application suitable for general-purpose visualisation of multivariate data. The interior of the grey polygon behind the lines defines an interval on each axis and thus the current record selection. XmdvTool also features clustering ("hierarchical parallel coordinates") for large data sets and animation for data sets in which one dimension represents time.

- The data set can be sampled ("subsetting").

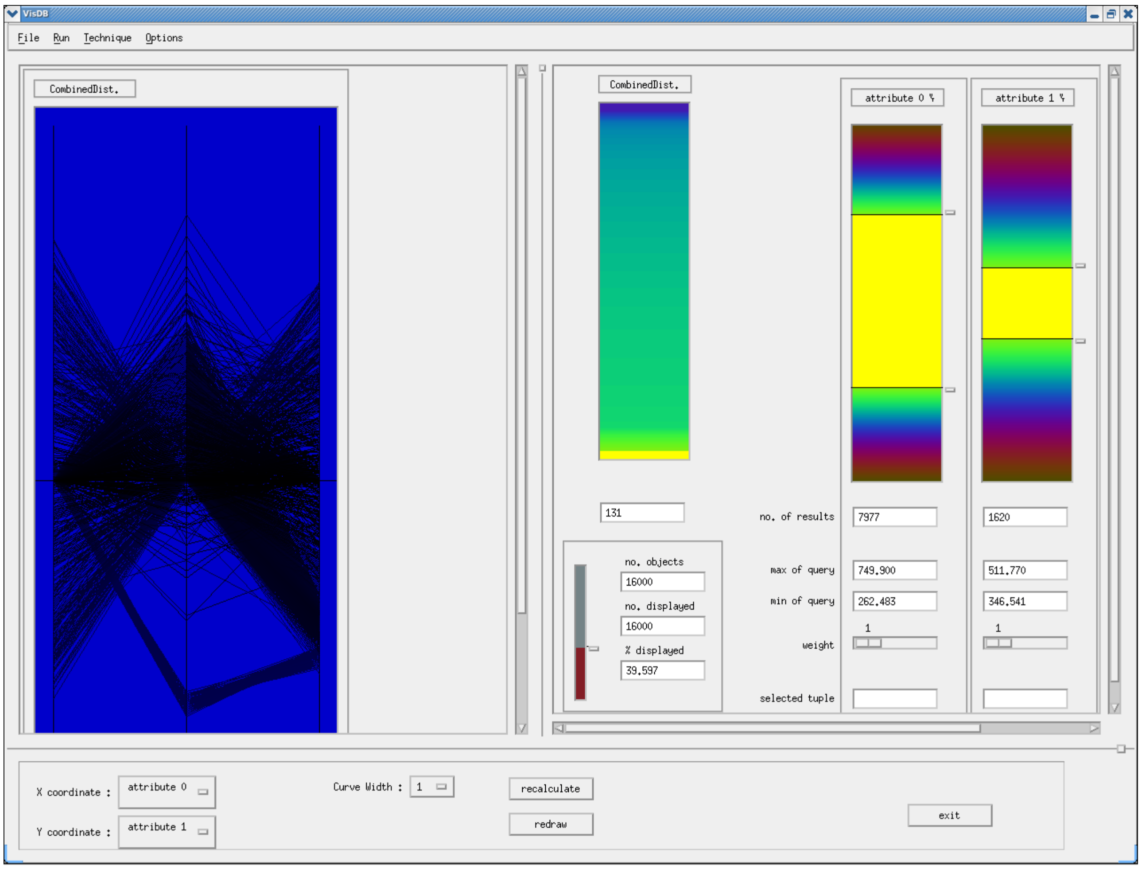
All of these manipulations immediately update the parallel coordinates display and all other visualisations.

3.5.8 XmdvTool

XmdvTool is an open-source application for general-purpose data visualisation, implemented in C++, using OpenGL [Shreiner, 2009; Khronos Group, 2011a] and Tcl/Tk [2010]. It features scatter plots, star glyphs, dimensional stacking, and parallel coordinates. For each of its visualisation schemes, XmdvTool also features a *hierarchical* view, that is, clustering [Rundensteiner et al., 2007; XmdvTool, 2010]. XmdvTool uses text-based `.okc` files for data input. It also provides an output facility: selected records can be saved as a subset into a new `.okc` file, which can then be reopened later for further processing.

Dimension axes can be freely reordered and removed from the display, but cannot be repeated. Aside from manual reordering, the tool also features a number of algorithms to order axes computationally. Furthermore, the space between axes can be stretched with the "distortion" feature.

Selecting records in the tool's parallel coordinates component is performed via combined interval definitions on each axis. When the user moves the mouse over the visualisation, the application's status bar displays the dimension closest to the mouse pointer, along with the value corresponding to the mouse pointer's current vertical position. Clicking then sets the upper or lower bound of the interval to be defined on that axis. The intervals are represented by a grey polygon whose vertices lie on the axes. Consequently, the interior of the polygon contains the polylines of all selected records. Figure 3.26 shows an example of this record selection method. Up to four different selection polygons can be created



		attribute 0	attribute 1
131	no. of results	7977	1620
no. objects: 16000	max of query	749.900	511.770
no. displayed: 16000	min of query	262.483	346.541
% displayed: 39.597	weight	1	1
	selected tuple		

X coordinate : attribute 0
Y coordinate : attribute 1
Curve Width : 1

Figure 3.27: VisDB's parallel coordinates component. A data set with three dimensions is visualised on the left side. The right side of the screen contains user interaction elements controlling the number of records displayed as well as the vertical stretching of each axis.

at the same time and combined with logical operators *AND*, *OR* and *NOT*, in order to create complex selections.

Time series animation is a special feature of XmdvTool. If one of the data set's dimensions can be considered to represent time, then the data set can be animated as a series of visualisations changing over time.

XmdvTool allows zooming both horizontally and vertically. Despite the application using OpenGL, the multiple visualisations it produces are not anti-aliased. Another downside of the software is that, although record selections are maintained across different visualisation schemes, the multiple visualisations cannot be shown together at the same time.

3.5.9 VisDB

VisDB is a general-purpose visualisation tool, written in C++ using Motif [2000]. It was developed at the Institute for Computer Science at the University of Munich to support "the exploration of large databases" [Keim and Kriegel, 1994; Keim et al., 2002]. The software features various visualisation techniques in addition to parallel coordinates. Figure 3.27 shows the application running on Linux and displaying three-dimensional data. The input format is a plain text file in which dimensions are separated by spaces and records by line breaks. This is the format of the example data file which comes with the software; no further documentation is given on file input formats.

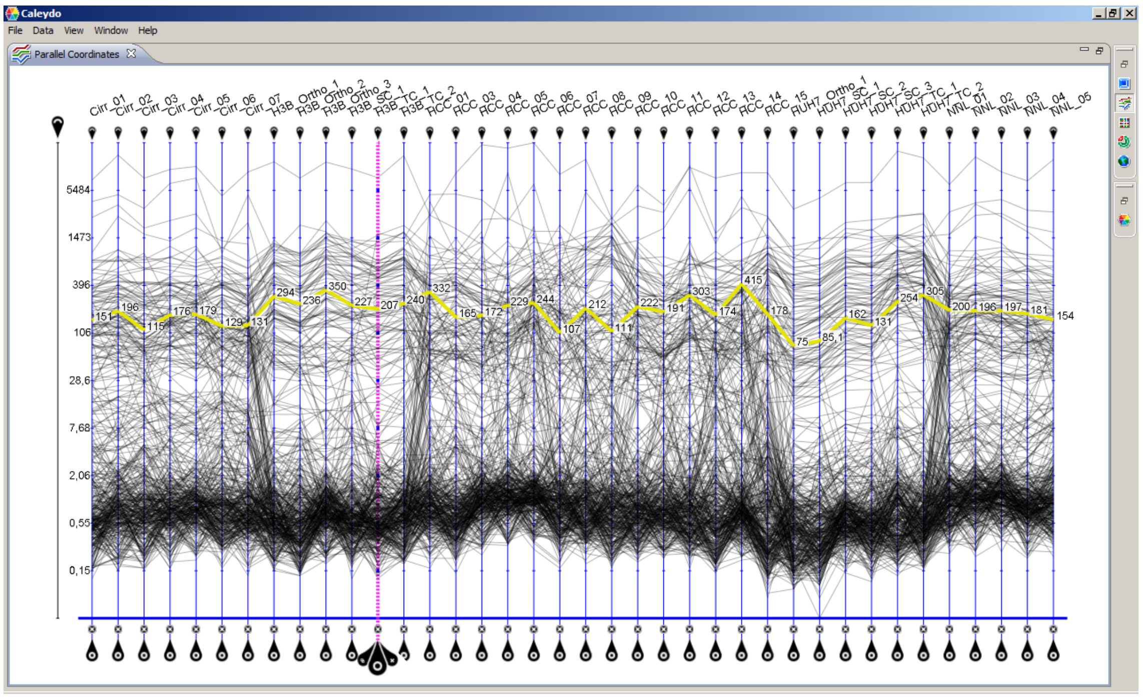


Figure 3.28: Caleydo [Lex et al., 2010], an OpenGL-based Java tool aiding in the analysis of multi-dimensional data in a medical domain (gene expression data). Its parallel coordinates component offers various interaction features, including angular brushing. The record currently under the mouse is focussed (yellow in this image), and tooltips with the record's values appear.

VisDB offers only limited user interaction for its parallel coordinates component. Records cannot be selected or brushed. Axes cannot be moved or hidden. The visualisation's size is fixed. The application does support reducing the number of records displayed and vertically stretching any of the axes.

3.5.10 Caleydo

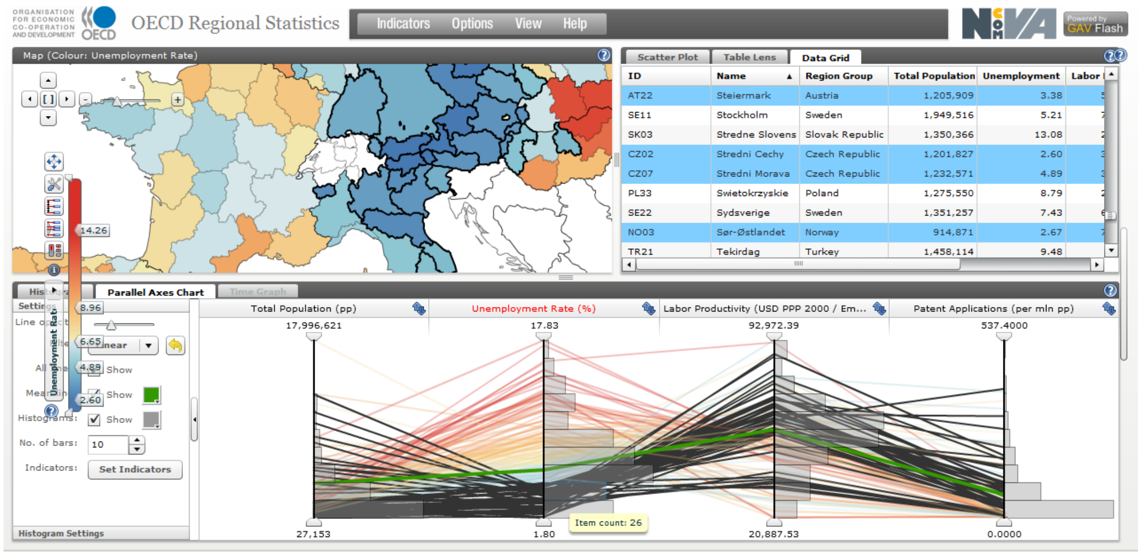
Caleydo is an information visualisation framework by Lex et al. [2010], implemented in Java [Oracle, 2011] and OpenGL [Shreiner, 2009; Khronos Group, 2011a], rooted in medical and genetic science, although it can be used for any kind of multi-dimensional data. Other than parallel coordinates, it features a number of additional visualisation methods suitable for its scientific problem domain: heat maps and a radial hierarchy. Different visualisations can be shown arranged next to each other in a special 3D view called a *bucket*. Figure 3.28 shows Caleydo's parallel coordinates component.

Axes in the parallel coordinates view can be rearranged, hidden, and repeated freely. Records can be selected individually or grouped via angular brushing.

3.5.11 OECD eXplorer

OECD eXplorer is a free online tool provided by the Organisation for Economic Co-operation and Development (OECD) for visual analysis of regional statistics [Organisation for Economic Co-operation and Development, 2011; Jern, 2009]. It is implemented in Flash [Adobe, 2011]. The software is made for OECD-specific data, but custom data can be loaded by users in the form of plain text files. This feature is not really made for data completely unrelated to OECD statistics, but in practise one can adapt any data set to be read correctly by OECD eXplorer.

Other than parallel coordinates, the software features scatter plot and table lens visualisations. There is a data grid which displays records and dimensions in tabular form, and (very suitable for this domain)



ID	Name	Region Group	Total Population	Unemployment	Labor
AT22	Steiermark	Austria	1,205,909	3.38	5
SE11	Stockholm	Sweden	1,949,516	5.21	7
SK03	Stredne Slovens	Slovak Republic	1,350,366	13.08	2
CZ02	Stredni Cechy	Czech Republic	1,201,827	2.60	3
CZ07	Stredni Morava	Czech Republic	1,232,571	4.89	3
PL33	Swietokrzyskie	Poland	1,275,550	8.79	2
SE22	Sydsverige	Sweden	1,351,257	7.43	6
NO03	Sør-Østlandet	Norway	914,871	2.67	7
TR21	Tekirdag	Turkey	1,458,114	9.48	

Line colour: | Linear
All lines: Show
Mean line: Show
Histograms: Show
No. of bars: 10
Indicators: Set Indicators

Figure 3.29: OECD eXplorer, an online tool provided by the Organisation for Economic Co-operation and Development [2011], features parallel coordinates visualisation for regional statistical data. Every record in the data set belongs to a region, and there is a geographical map to aid data analysis. This example screenshot was made from a visualisation of a European subset of data, with the parallel coordinates view showing four of the dimensions: total population, unemployment rate, labour productivity, and patent applications. Histograms are displayed on each axis and can be used to select groups of records. Records with low unemployment rates have been selected, which shows how they are generally related to regions with low population and high labour productivity.

a geographical map of the data. Figure 3.29 shows the OECD eXplorer visualising statistics about unemployment rates with parallel coordinates and a linked geographical map of Central European regions.

Standard parallel coordinates features include changing polyline opacity, flipping axes, free reordering, hiding axes, and setting interval filters on any axis. Colours can be freely customised. The minimum and maximum value can be specified for every axis. As for special features, there are *histograms* on the axes, their width depending on the number of records in the corresponding axis interval. Groups of records are selected by clicking on histograms. There is also a mean line, that is, a special polyline representing the average value of every dimension.

On the negative side, axes cannot be repeated, and there are no tooltips for polylines, regardless of whether they are selected or not.

3.5.12 Protovis

Protovis [Bostock and Heer, 2009] is a toolkit implemented entirely in JavaScript and SVG [Mozilla Developer Network, 2011; Ramani et al., 2008]. Its creators maintain that its high level of abstraction compared to many other low-level graphics libraries is a distinct advantage for the development of information visualisation software. Protovis also includes parallel coordinates, as shown in Figure 3.30.

Given that Protovis is meant to run in a web browser and makes extensive use of scripting, performance is an issue. User interaction is very limited compared to other parallel coordinates software as well. Records are coloured from red to blue relative to their value in one of the dimensions, which the user selects by clicking on the respective axis. Dragging on an axis with the mouse creates an interval in which records are selected. The data values of selected records are not shown anywhere.

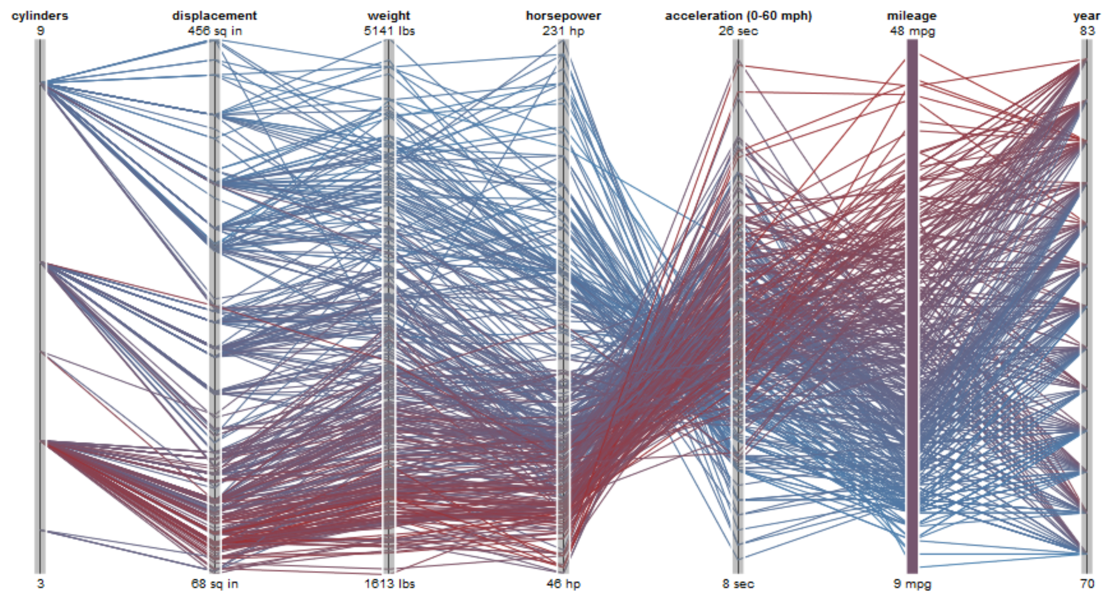


Figure 3.30: Parallel coordinates in Protovis [Bostock and Heer, 2009], a toolkit implemented in JavaScript and SVG. This example shows Protovis running in a web browser and visualising the commonly used cars data set by Ramos and Donoh [1983]. Performance is an issue with web-based implementations of parallel coordinates, and interaction methods are more limited than in other software.

3.5.13 VizCraft

VizCraft is an information visualisation tool written by Goel [1999], applying parallel coordinates to the domain of aircraft design but made such that any kind of multi-dimensional data can be used with it. It is implemented as a Java [Oracle, 2011] applet and can be used online from the official web page. Figure 3.31 shows VizCraft visualising a small fictional test data set created by the tool's author.

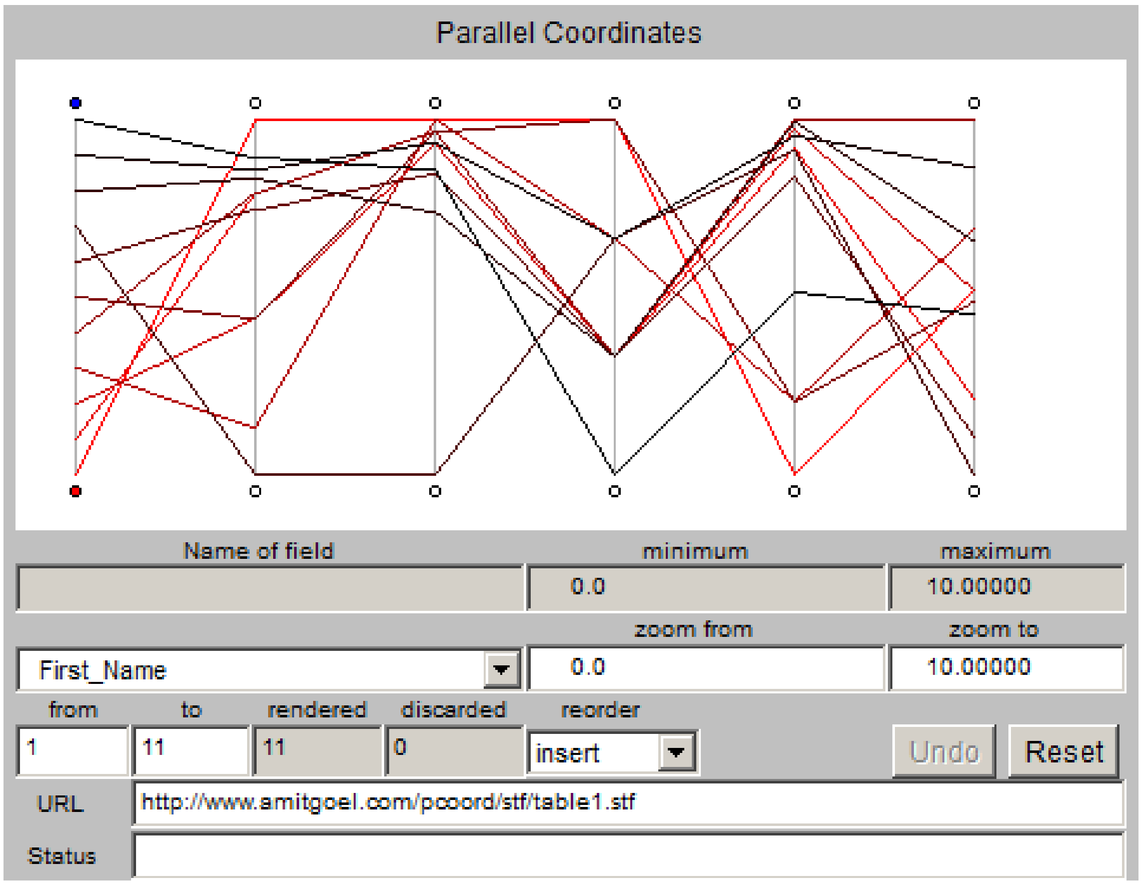
Interaction is very limited in VizCraft. Axes can be moved by dragging them with the mouse, and they can be vertically zoomed. In addition to that, an axis can be chosen as the "active" one by clicking on it, leading to records being coloured from black to red relative to their value in the corresponding dimension. Selecting records, or obtaining detailed information about the records in general, is entirely absent from the software's interface.

3.5.14 Liquid Diagrams

Liquid Diagrams provide parallel coordinates and a number of other visualisation techniques as a Google Docs Gadget [Google, 2011]. They were implemented by Andrews and Lessacher [2010]. The idea is that a user enters data into a Google Docs spreadsheet and then inserts the gadget to visualise it, as shown in Figure 3.32. All of this happens online, with no installation of additional software required.

The parallel coordinates component of Liquid Diagrams features extensive support for user interaction. Axes can be dragged horizontally with the mouse to reorder dimensions. An axis can also be flipped by clicking on a small arrow above it. Polylines are selected by simply clicking on them.

Furthermore, there are triangular handles on the top and bottom of each axis, which can be dragged vertically by the user to define a range on the corresponding dimension; all polylines not going through that range are greyed out and cannot be selected (as a minor problem, the tool does not make sure that greyed-out lines are drawn below the others).



Name of field	minimum	maximum
	0.0	10.00000
	zoom from	zoom to
First_Name	0.0	10.00000

from	to	rendered	discarded	reorder
1	11	11	0	insert

URL http://www.amitgoel.com/pcoord/stf/table1.stf

Status

Figure 3.31: Parallel coordinates in VizCraft [Goel, 1999], a visualisation tool written in the context of aircraft design, implemented as a Java applet. Interaction in this tool is restricted to moving axes, vertically zooming axes, and designating one axis as the reference for colouring of records.

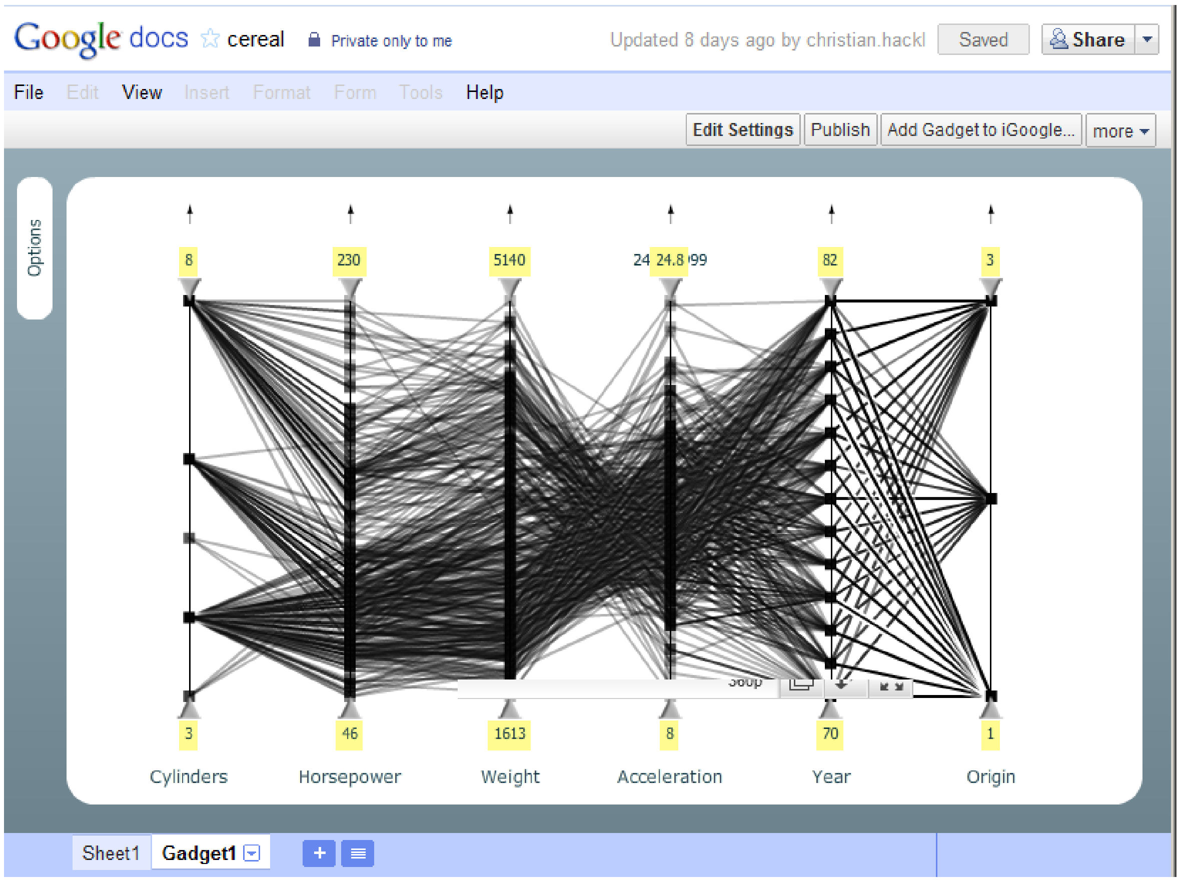


Figure 3.32: The parallel coordinates component of Liquid Diagrams by Andrews and Lessacher [2010], a set of gadgets to be used in Google Docs. Given the nature of the tool, it can be used anywhere where web access exists. It features extensive support for user interaction and SVG export. This figure shows the tool visualising the well-known cars data set [Ramos and Donoh, 1983].

There are also some options for customisation of the visualisation, such as colours and fonts for various labels. The most powerful of those options is to choose the *colour scheme* of the polylines such that every record is given an individual colour. This works well for small data sets with few records, because the colours are more easily distinguishable.

Performance is an issue with Liquid Diagrams. Since the gadget is implemented in Flash and runs inside a web browser, it cannot always deliver the speed and responsiveness required for fluent interactive analysis of data. On the other hand, there is also the unique feature of exporting the visualisation as an SVG file. This makes it particularly easy to embed a parallel coordinates visualisation inside other documents or presentations or to edit it outside of Google Docs.

Chapter 4

Multi-Dimensional Explorer

"We are the champions, O Bjarne!
And we'll keep compiling till the end!"

[Herb Sutter at SD Best Practices, 2008]

This chapter is about the software application Multi-Dimensional Explorer (MDE), which was written for this thesis. It implements parallel coordinates, a visualisation technique discussed in Chapter 3; that chapter also discusses previously developed tools. MDE learned from them by building upon their strengths and useful ideas, while at the same time avoiding some of their pitfalls.

Although MDE is a general-purpose visualisation tool, designed to be extensible with additional visualisation schemes and not dependent on any concrete visualisation scheme, its focus is on parallel coordinates. It is a desktop application with a graphical user interface supporting interaction (that is, not only displaying static images). MDE is designed to be as cross-platform as possible. Performance is a major requirement, which is why OpenGL [Shreiner, 2009; Khronos Group, 2011a] was chosen as the main rendering engine.

Section 4.1 outlines the software design principles of MDE and documents the environment in which it was developed. Section 4.2 discusses the individual modules of the MDE source code. Section 4.3 compares MDE to other parallel coordinates software discussed previously.

Chapter 5 then discusses two selected areas in MDE's software design, which are particularly complex in the overall architecture. Appendix A is a manual for MDE end users and explains all of its features in detail. Appendix B gives future developers detailed information on how to extend MDE with new visualisations.

4.1 Software Architecture

MDE is written in C++, conforming to the 2003 ISO standard of the language [International Organization for Standardization, 2003]. No C++0x features [International Organization for Standardization, 2010] are used. Such features are already available in many C++ compilers and might keep some parts of the source code more concise and could in fact be employed in future versions of MDE, but the new language standard is still too much of a work in progress, and its implementations are still too experimental to meet MDE's goal of being a robust and reliable piece of software.

The C++ code of MDE follows generally accepted principles of good software engineering in C++ as defined by Meyers [1996, 1997], using standard design patterns by Gamma et al. [1994]. The major principles in MDE's software design and implementation are:

1. Use of the C++ standard library whenever possible [Josuttis, 1999]. For example, no use of a custom string class instead of `std::string`.

2. Compliance with the C++ language standard to ease porting MDE to other platforms; no use of proprietary compiler extensions.

3. Heavy use of the Non-Virtual Interface (NVI) idiom [Sutter, 2001]. Public member functions are preferably non-virtual, delegating to *virtual or pure virtual private* member functions. Protected member functions are preferably non-virtual as well.

4. Liberal use of the `assert` macro for safe termination of the application in face of programing errors, rather than throwing exceptions. Exceptions are reserved for exceptional problems not caused by errors in MDE's source code, and in certain cases for a simple means of reporting errors from recursive functions. In other cases, function return values are deemed appropriate. Assertions are *not* turned off in release builds of MDE – this is on purpose!

5. Restriction of object-oriented features (virtual functions) to cases where run-time polymorphism is actually needed. Specifically, `mde::presentation::structure::VisualisationElement` and `mde::data::Point` are examples of two classes whose instances can semantically belong to different types, but this typing is not expressed in terms of derivation and overriding virtual functions.

C++ was chosen for this project for a number of reasons. Its expressiveness and abstraction features ease the creation of complex software applications. Unlike other high-level languages, however, C++ does not impose any cost in performance gains in trade for these advantages. Performance is one of the major goals in the development of MDE, and the fact that C++ compiles code to native executables accessing the underlying operating system without any intermediate layers, providing for closer vicinity to hardware, makes the language more than apt for a desktop visualisation application. Other than that, C++ is one of the most used programming languages in computer science and software engineering, which means that extensive documentation and support from a large community are available.

MDE was developed with Microsoft Visual C++ 2010 Express Edition [Microsoft, 2010b], which is available for free on Microsoft's official website. The source code package of MDE contains a solution file which developers can use to build MDE with all necessary compiler switches and automatically execute unit tests. Doxygen [van Heesch, 2011] is used for documentation at source code level; all necessary means to build documentation in various formats at class and function level are provided.

Note that MDE was tested only with Microsoft Visual C++ 2010 Express Edition on Windows XP and Windows 7. Porting MDE to different platforms or different compilers such as GCC [Free Software Foundation, 2011] is an example of future work. However, MDE's design principles mentioned above, paired with the cross-platform compatibility of all 3rd party libraries involved, inevitably ease any such undertaking significantly.

MDE's source code is divided into seven modules. Each module resides in a distinct namespace or sub-namespace. `mde` is the parent namespace; it contains no direct members of its own. All names of classes, functions or other C++ entities are contained in one of the sub-namespaces. Table 4.1 gives an overview of the modules. Modules Data, Data Input, Presentation, Presentation Structure and Options are meant to be built as libraries which are then linked to by Application and Test, the two executables.

MDE depends also on a number of 3rd party libraries:

- MDE's graphical user interface (GUI) is implemented with the cross-platform wxWidgets library, version 2.8.11 [wxWidgets, 2010].

Module Name	**Purpose**	**C++ Namespace**
Application	Application-specific components, such as the help menu or status bar.	`mde::application`
Data	Data matrix storage, normalisation and access synchronisation.	`mde::data`
Data Input (submodule of Data)	Reading data from external sources, such as files.	`mde::data::input`
Presentation	Data presentation, such as visualisation windows and rendering backends.	`mde::presentation`
Presentation Structure (submodule of Presentation)	Logical structure of visualisations, such as geometrical line and circle definitions; SVG creation.	`mde::presentation::structure`
Options	Program options management, such as storing an internal options tree.	`mde::options`
Test	Unit tests.	`mde::test`

Table 4.1: Modules of MDE's source code. Each of them resides in a distinct namespace or sub-namespace of its own. `mde` is the parent namespace; it contains no direct members of its own. All names of classes, functions or other C++ entities are contained in one of the sub-namespaces. With the exception of Application and Test, all modules are meant to be compiled to libraries. Application and Test are meant to be compiled to executables, statically linking the libraries created from the other modules.

- Visualisation windows use OpenGL, version 1.1, for rendering [Shreiner, 2009; Khronos Group, 2011a]. Note that wxWidgets features integrated OpenGL support.

- OpenGL font support is enabled by FTGL, version 2.1.3 [Maddock, 2008]. FTGL depends itself on the FreeType 2 library [FreeType, 2010]. Mapping between font names and font file paths is handled in a platform-dependent way. Therefore, text in OpenGL visualisations is currently only enabled in Windows, where the Win32 API is used directly to retrieve a list of available fonts and their corresponding file paths. On other platforms, no text appears. See also Chapter 5.

- TinyXML++, version 2.5.4 [Thomason et al., 2010], is used to read MDE's options file in Extensible Markup Language (XML) format [Bray et al., 2008].

- The Boost libraries, version 1.43.0, are used by MDE for a variety of features throughout the entire source code [Boost, 2010].

- UnitTest++, version 1.4, is used for unit tests [Llopis and Nicholson, 2011].

Apart from the fact that Application has to link to all libraries, there are a number of conceptual dependencies, visualised in Figure 4.1.

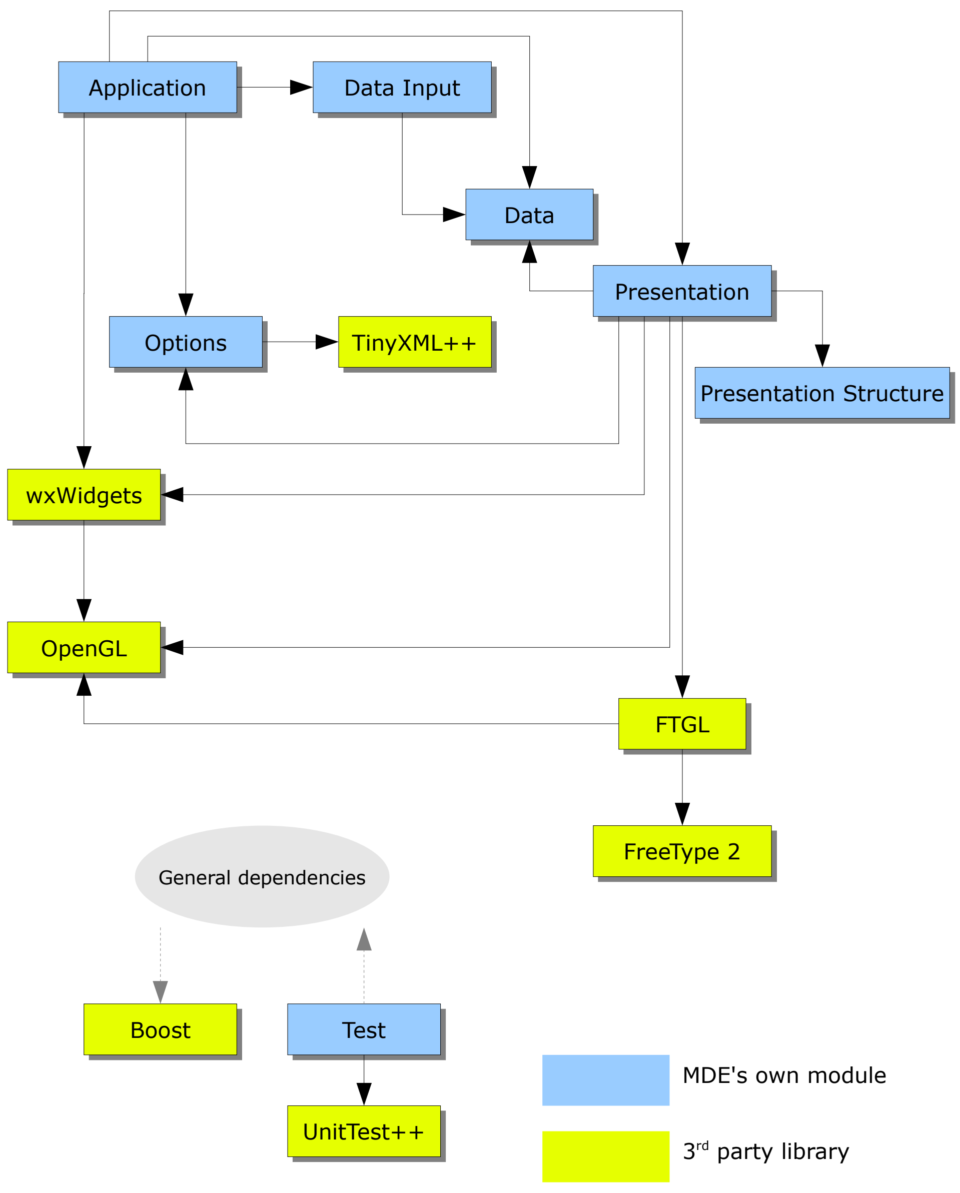


Figure 4.1: Visualisation of the dependencies between MDE's modules and 3rd party libraries. An arrow indicates that a module needs to know about another module or 3rd party library. The Boost libraries are used throughout the entire application, more as an extension of the C++ standard library than a separate module, so dependencies on them are not documented explicitly. Module Test contains tests of all other modules (or is designated to contain tests of all other modules in future versions of MDE), so conceptually it needs to know about *all* of the other modules and libraries. Apart from the fact that these conceptional dependencies exist, modules Application and Test are statically linked to the library files created from all other modules, because they are compiled into executable files.

4.2 Modules

This section discusses each of the modules in MDE's software architecture in detail. The order in which modules appear in this section is not related to their importance or "level" in the general design, but is simply alphabetical. For reasons of readability (and in accordance with C++ rules), names of classes and free-standing functions in this section are not written with the full namespace prefix. For example, `mde::presentation::DataView` is written as `DataView` in the Data subsection and as `presentation::DataView` in the other subsections.

4.2.1 Application

This module contains components which are not of general use, but belong to the concrete MDE GUI application: specific windows, menus, bars, and dialogues. Its central class is `MainWindow`, which represents the main window of MDE; the parent of any other windows which might be opened. The module depends on all of the Data, Data Input, Presentation and Options modules, in the following way:

- The data storage and synchronisation mechanisms of Data are used to provide a central point of reference to the data set which is accessed by visualisation subwindows.
- Data Input is used to link file-open dialogues to actual file-parsing mechanisms.
- Presentation provides the contents of visualisation subwindows in the GUI.
- General program options are defined and maintained via the Options module.

wxWidgets [2010] is the GUI framework used by MDE. It provides an abstract interface equal across different platforms, internally implementing it by direct access to the operating system's Application Programming Interface (API). This aids in achieving platform-specific look and feel, increasing usability of a software application.

Much startup initialisation code is found in the constructor of `MainWindow`, a class derived from wxWidget's `wxMDIParentFrame` to enable the Multiple Document Interface paradigm [Microsoft, 2010a]. The class allocates and stores one instance for each of the `data::Holder`, `options::Tree` and `options::Synchroniser` classes. Those are never deleted, nor should they, in order to avoid order of destruction issues at program termination. Note that this does *not* constitute a memory leak, as memory usage is constant.

Note how the module uses abstract, application-independent components from Options and integrates them into the GUI using `OptionsDialog` and related Application classes. This way of interaction between the modules can be described such that `OptionsDialog` acts as visual frontend of the Options module.

Which subwindows can be opened by `MainWindow` and consequently, the contents of the toolbar and Views menu, are determined by querying `presentation::DataFactoryGroup`. It returns information about visualisations offered by the application and provides `MainWindow` with pointers to `presentation::DataViewFactory`. When a user wishes to open a visualisation window, the factory is used to instantiate concrete `presentation::DataView` subclasses, using the Factory Method design pattern by Gamma et al. [1994]. The subclass instance is then put into a new instance of `DataViewMDIChildFrame`, the base class for MDE subwindows, and equipped with references to the centralised instances of `data::Holder` (to allow it to access the data set) and `options::Synchroniser` (to grant it access to program options).

How visualisation takes place and what the user can do in a subwindow is the concern of module Presentation. Table 4.2 gives an overview of all classes, functions, and enumerations used by module Application.

Name	**Purpose**
`Application`	Main application class for wxWidgets.
`CsvCharacterControl`	Character option control for `CsvFileReaderDialogue`.
`CsvFileReaderDialogue`	Dialogue window for CSV file import.
`CsvFileReaderWithDialogue`	Creates a `data::Matrix` from a CSV file with user interaction.
`DataViewMdiChildFrame`	`wxMDIChildFrame` used as parent window of `presentation::DataView`.
`MainMenuBar`	Menu bar for `MainWindow`.
`MainStatusBar`	Status bar for `MainWindow`.
`MainToolBar`	Tool bar for `MainWindow`.
`MainWindow`	Top-level window of MDE.
`MainWindowItemInformation`	Appearance information for `MainWindow` menus and toolbar.
`MainWindowItems`	Group of `MainWindowItemInformation` instances.
`OptionColourControl`	`wxColourPickerCtrl` replacement
`OptionColourTextControl`	Specialised text control for colour codes.
`OptionControl`	Control on an `OptionsPanel`.
`OptionEnumerationControl`	Control for choosing enumeration value.
`OptionFontControl`	Control for choosing font option.
`OptionsDialogue`	Options dialogue.
`OptionsDialoguePanel`	Page in an `OptionsDialogue`.
`RecentFiles`	Container storing paths of recently opened files.
`RecentFilesIterator`	Iterator for `RecentFiles`.
`MainWindowIdentifier`	Identifiers for tool bar and menu items in `MainWindow`.
`createDefaultFileReaderGroup()`	Creates default `data::input::FileReaderGroup`.
`createOptionsFileError()`	Creates options file error message.
`handleException()`	Displays current exception's error message.
`itemIdentifierDataViewHighest()`	Highest of all "add data view" menu item identifiers.
`itemIdentifierDataViewLowest()`	Lowest of all "add data view" menu item identifiers.
`openFile()`	Opens file with data for a `data::Matrix`.
`serialiseMdiChildFrames()`	Generates string from `DataViewMdiChildFrame` instances' position and size.

Table 4.2: The classes, enums and free-standing functions of MDE's Application module.

4.2.2 Data

This module contains data structure components and means to manipulate them, independent of their visual or textual representation. It also features mechanisms to intercept modifications of the data and notify other parts of the software of any such changes. Data is entirely self-contained and does not know about or depend on any of the other modules.

The way MDE internally represents multi-dimensional data and how it is stored and synchronised is explained in Figure 4.2. Class `Matrix` stores `std::vector` of `Point` for representing matrix fields. A union member variable is used in `Point` to store for each field either a `double` value for real number dimensions, or an `int` value for integer number and enumeration dimensions. In the latter case, the value is the index of the enumeration value. Information pertaining to entire dimensions is stored by `Matrix` in a separate collection of `Dimension` instances.

`Holder` is, for most of MDE's other source code sections, the only way to communicate with `Matrix`. It permits only non-modifying operations on it, providing a const reference to `Matrix`. Among those are `pointString()` and `pointNormalised`, used to obtain a string representation of a field or its normalisation in the range [0.0,1.0], irrespective of the corresponding dimension's type. Figure 4.3 explains the difference between obtaining string representations and normalised values and how those operations are related to the way `Matrix` stores and structures data.

Modifying operations of `Matrix` are mirrored in the interface of `Holder`, which intercepts the calls and notifies any registered `Observer` instances. This is a classical application of the Observer design pattern by Gamma et al. [1994]. After sending the notification, `Holder` delegates the operation to `Matrix`. This is similar to the Proxy design pattern by Gamma et al. [1994], but in the case of MDE, the approach is not object-oriented because there is no run-time polymorphism involved.

Data is stored in class `Matrix` after it has been loaded (see the Data Input module discussed in Section 4.2.3. The constructor of `Matrix` is templatised in order to achieve complete flexibility with any data sources.

Filters on dimensions are maintained by `Holder`, which stores a collection of `DimensionFilter` instances separately for each dimension in its encapsulated matrix. A filter restricts a dimension to a subrange or subset of values. This way, filters determine which records are considered "used" and which ones are considered "unused". There are two different ways of defining a filter:

- Using a percentage range. Since the normalised complete range of data in a dimensions is always (0.0, 1.0), a filter of this type is defined as a pair of double values. For example, a filter might be (0.1, 0.9), which means that any record whose normalised point in that dimension is less than 0.1 or greater than 0.9 will be considered unused.

- Using a set of allowed values. This mode can only be applied to dimensions of type enumeration. A `DimensionFilter` defined as such contains a set of "used" enumeration indices. A record's enumeration index in the corresponding dimension must be an element of that set; otherwise, it is considered unused.

The design of this module generally assumes that there will be many records and few dimensions, which is why no effort is made to optimise dimension-specific data or algorithms, whereas such considerations have been taken into account for efficient mass-storage of records. This is the reason class `Point` uses a union. To mitigate security problems related to the use of unions in C++, access to the data inside of `Point` is restricted exclusively to `Matrix`.

Table 4.3 gives an overview of all classes, free-standing functions, enums and typedefs found in the Data module.

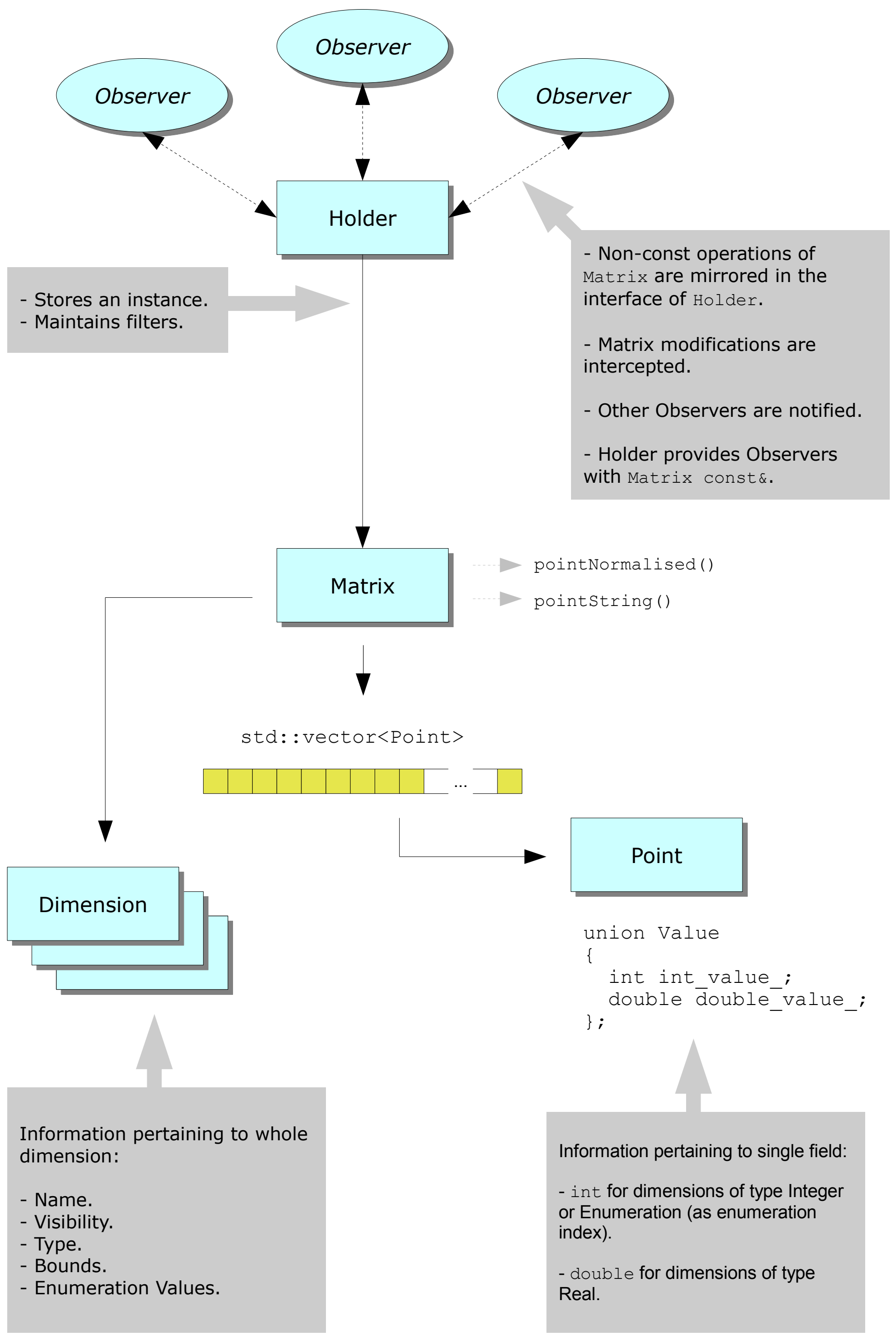

Observer
Observer
Observer
Holder
- Stores an instance.
- Maintains filters.
- Non-const operations of Matrix are mirrored in the interface of Holder.
- Matrix modifications are intercepted.
- Other Observers are notified.
- Holder provides Observers with Matrix const&.
Matrix
pointNormalised()
pointString()
std::vector<Point>
...
Point
Dimension
union Value
{
int int_value_;
double double_value_;
};
Information pertaining to whole dimension:
- Name.
- Visibility.
- Type.
- Bounds.
- Enumeration Values.
Information pertaining to single field:
- int for dimensions of type Integer or Enumeration (as enumeration index).
- double for dimensions of type Real.

Figure 4.2: Multi-dimensional data storage and synchronisation in MDE's Data module. Internally, class `Matrix` stores a `std::vector<Point>`. `Point` represents a field and stores either a `double` value for real number dimensions, or an `int` value for integer number and enumeration dimensions. In the latter case, the value is the index of the enumeration value. `Matrix` also stores information about entire dimensions in a separate collection of `Dimension` instances. Almost all of MDE operates only on `Matrix const&`, using methods like `pointString()` and `pointNormalised()` to obtain a string representation of a field or its normalisation in the range (0.0,1.0), irrespective of its dimension's type. Modifying operations are mirrored in the interface of class `Holder`, which delegates them to `Matrix` and reports the change to any registered `Observer`.

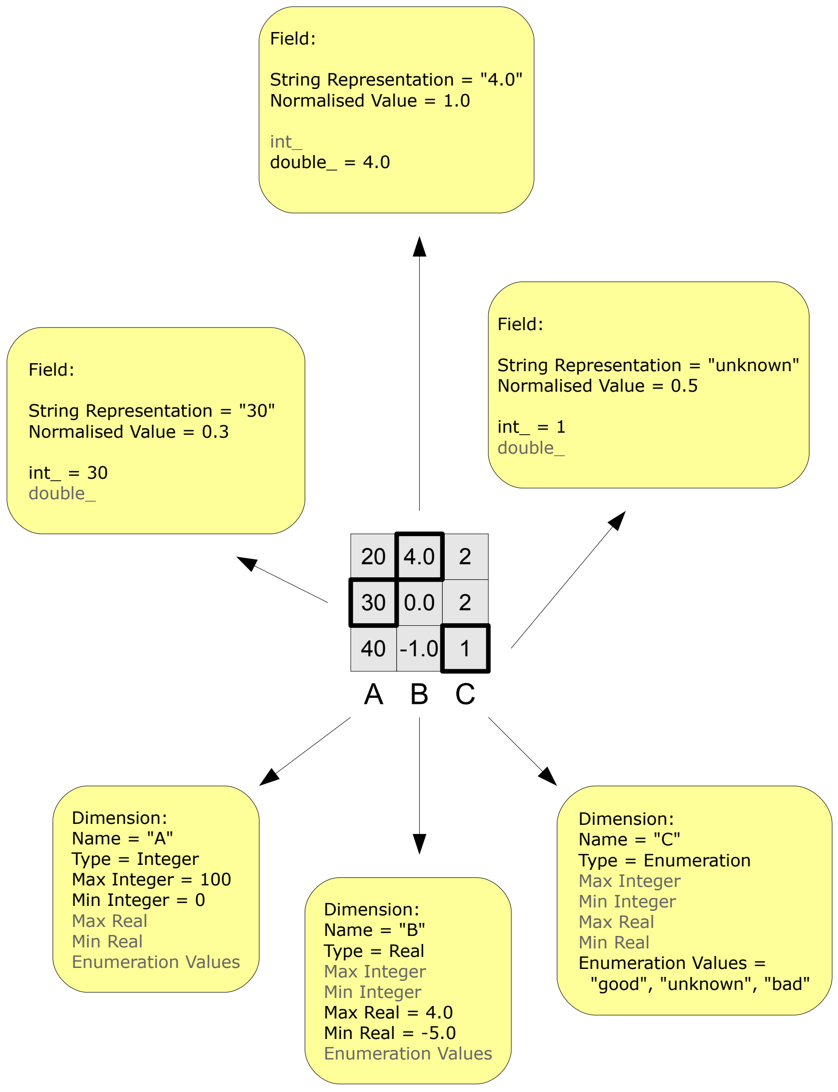
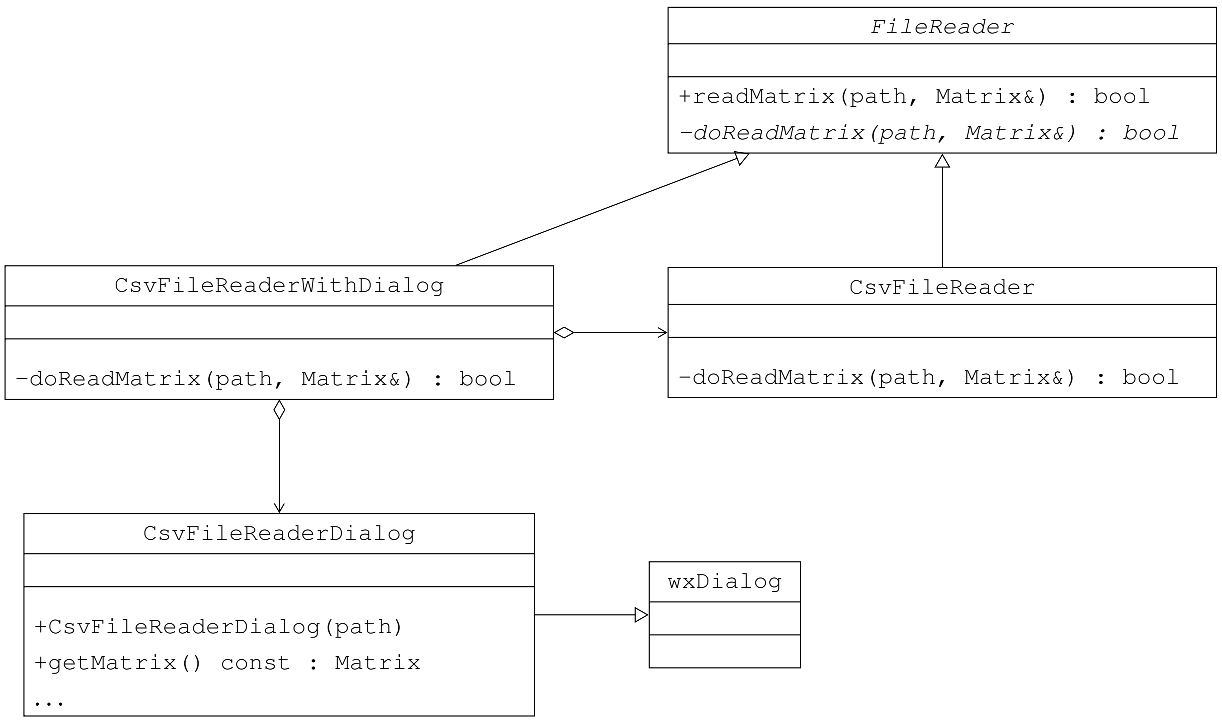


Figure 4.3: Every field stored in a `Matrix` is presented to the outside world in a unified manner; either as a string representation or as a normalised value in the range (0.0,1.0). This is a safe interface to a more complex internal structure. Every instance of `Dimension` is either of type Integer, Real or Enumeration, and according to that type different member variables both in `Dimension` and in corresponding `Field` objects are either active or inactive. In this example, dimension “A” is of type Integer and therefore stores maximum and minimum integer values to define its range. Those are used for normalising individual values. “30” here is normalised to 0.3. “B” works similarly for real numbers. “C” is of type Enumeration and therefore stores a vector of possible values, an index into that vector stored in individual fields. In this example, “1” is stored in the last field, leading to a string representation of “unknown” and a normalisation value of 0.5.

Name	**Purpose**
`Change`	Records data manipulations made via `Holder`.
`Dimension`	Represents a data dimension.
`DimensionFilter`	Restriction of records to a subset in one of the dimensions.
`DimensionIndex`	Index of a dimension in `Matrix`.
`DimensionPosition`	Position of a dimension in `Matrix` when dimensions are rearranged.
`Exception`	Base exception for data-related errors.
`Holder`	Filters and synchronisation for `Matrix`.
`HolderBatchCommit`	Commits multiple data changes in one batch.
`IllegalInputRowLengthException`	Exception when an input row has too few or too many fields
`Observer`	Observes `Holder`.
`Point`	Field of `Matrix`.
`PointConversionException`	Exception when `Matrix` construction fails due to conversion error
`PointStringConverter`	Converts strings to `Point` instances.
`RecordState`	State of a record in `Matrix`.
`addDefaultFiltersToHolder()`	Adds default, limitless filters to `Holder`.
`dimensionFilterDescription()`	Textual representation of `DimensionFilter`.
`getUsedRecordIndices()`	Applies `DimensionFilter` range to a dimension, obtaining records not excluded through the filters.
`prettyReal()`	Pretty representation of real number.
`typeDescription()`	Text description of a `Type`.

Table 4.3: The classes, enums, typedefs and free-standing functions of MDE's Data module.



FileReader
+readMatrix(path, Matrix&) : bool
-doReadMatrix(path, Matrix&) : bool
CsvFileReaderWithDialog
-doReadMatrix(path, Matrix&) : bool
CsvFileReader
-doReadMatrix(path, Matrix&) : bool
CsvFileReaderDialog
+CsvFileReaderDialog(path)
+getMatrix() const : Matrix
...
wxDialog

Figure 4.4: This class diagram shows how the part of MDE responsible for importing CSV files is implemented. `data::input::FileReader` is an abstract base class to read any kind of files into `data::Matrix` instances. `data::input::CsvFileReader` is derived from it, implementing its pure virtual `doReadMatrix()` member function. `application::CsvFileReaderWithDialog` adapts `data::input::CsvFileReader` for GUI-specific use, implemented in terms of `application::CsvFileReaderDialog` – the "Import Wizard" from the user's point of view. This designs completely separates parsing and interpreting CSV files (a concern of module Data Input) from the provision of related GUI elements to the user (the concern of module Application).

4.2.3 Data Input

This module is a sub-module of Data. It contains tools to read data from external sources and use it in the creation of new `mde::data::Matrix` instances. The templatised non-default constructor of class `data::Matrix` can be seen as the link between the parent and child module.

The central component of the module is the abstract base class `FileReader`. Inside the Data Input module, the only concrete derived class is `CsvFileReader`, an implementation for reading comma-separated value (CSV) files. This is because the current version of MDE only supports CSV for input. The implementation relies on `boost::escaped_list_separator` from Boost [2010] to break up input lines into tokens.

Outside of module Data Input, in module Application, `application::CsvFileReaderWithDialog` is another derivee of `FileReader`. It is implemented in terms of `CsvFileReader` and adds a GUI dialogue (the "Import Wizard" from the end user's point of view). This is an application of the Adaptor design pattern by Gamma et al. [1994]. Figure 4.4 is a class diagram of this part of MDE's architecture, crossing module boundaries. Table 4.4 lists all classes and functions of the Data Input module.

4.2.4 Options

This module contains the means to load, save and query both options chosen by the user, such as colours for selected, used, or unused records, and options saved automatically without the user noticing, such as the paths of recently opened files. Options is self-contained and does not depend on any other MDE

Name	**Purpose**
`CannotOpenFileException`	Exception when a file cannot be opened for reading.
`CsvFileReader`	Creates a `Matrix` from a CSV file.
`CsvParsingOptions`	Options for CSV parsing.
`FileReader`	Creates a `Matrix` from a file.
`FileReaderGroup`	`FileReader` instances with associated file name endings.
`IsDefaultValidLine`	`TextStreamInput`'s default functor to determine whether to skip lines.
`TextStreamInput`	Provides `TextStreamInputIterator` pair for `Matrix` creation from a `std::istream`.
`TextStreamInputIterator`	Iterates over a `std::istream` and turns each line into a `TextStreamInputLine`.
`TextStreamInputLine`	Tokenises a line of text for `Matrix` input.
`TooFewColumnsInCsvLineException`	Exception when a CSV line contains too few columns.
`TooManyColumnsInCsvLineException`	Exception when a CSV line contains too many columns.
`guessCsvParsingOptions()`	Guesses `CsvParsingOptions` suitable for a specific CSV file.
`makeDimension()`	Creates a `Dimension` by analysing text input.
`makeDimensionImplementation()`	Implementation of `makeDimension()`.

Table 4.4: The classes and free-standing functions of MDE's Data Input module.

modules. Options are persistently stored in an Extensible Markup Language (XML) file [Bray et al., 2008], and the TinyXML++ library by Thomason et al. [2010] is used for parsing it. No library is used for writing XML, because the process of writing XML is too simple to justify adding yet another 3rd party library to MDE.

The module is built around a tree for cascading option values, similar to the logic of Cascading Style Sheets [Çelik et al., 2010]. Its central component is class `Tree`, which stores an internal tree of `Node` objects. For every option available in the application, a `Definition` object exists, including information about an option's name, description, type and default value. A collection of `Definition` objects is contained within each `Node`. All definitions are automatically inherited.

In addition to that, each `Node` also contains values for definitions. Values are simply strings; whether their contents are valid or not depends on the `Definition` they are assigned to. Every `Node` *must* contain a value for each of its own definitions and *may* contain a value for each of its inherited definitions. This is how values are overridden. `Node`'s own and inherited values can be read and modified uniformly. The class will recognise if the definition of a particular value is inherited or not.

In order to prevent inheritance of unused options, or inheritance of options which would be meaningless for a subnode (imagine a "Rendering Engine" option in a base node which is not used by a subnode representing a plain text panel), inherited options have to be made visible explicitly by calling `setVisibleInheritedOptions()`.

Figure 4.5 gives a fictional example of an options tree whose root element contains the two general options background_colour and label_font. Furthermore, it contains two subnodes My View and Your View. Your View contains no new definitions or overridden values, while My View contains a special option dot_size and overrides background_colour. This leads to the following options being available and values being set for them:

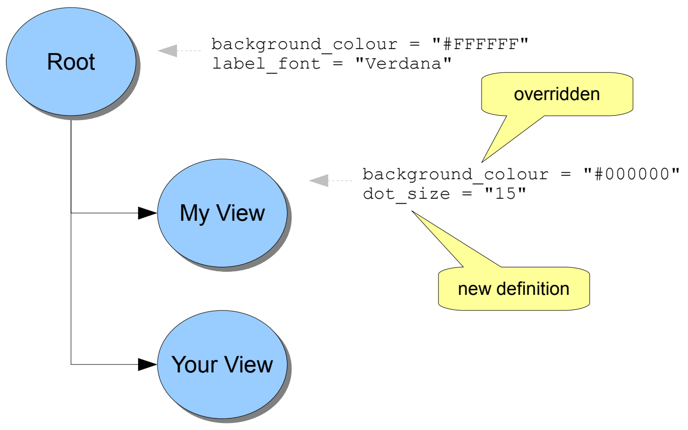


Figure 4.5: MDE's tree-based options mechanism supports inheritance and overriding. In this example, Root, My View and Your View are `Node` objects, Root being the parent of the other two. Root contains two options background_colour and label_font, which the others inherit. My View overrides the parent value of background_colour and adds dot_size, an option definition of its own.

- Root: background_colour = "#FFFFFF", label_font = "Verdana"
- My View: background_colour = "#000000", label_font = "Verdana", dot_size = "15"
- Your View: background_colour = "#FFFFFF", label_font = "Verdana"

As this example shows, which definitions are available and which values they are currently set to depends on which node is being queried! In common Design Patterns terminology [Gamma et al., 1994], `Tree` acts as a *Facade* for the more complex `Node` class. Clients of `Tree` are not completely oblivious of `Node`, but they only have to deal with const references, not with pointers or non-const references if they do not explicitly request them.

Class `Synchroniser` encapsulates `Tree`, giving access only to its const interface. Modifying operations such as `changeValue()` are intercepted so that registered `Observer` objects can be notified before the call is delegated to `Tree`. This is the same design as in `data::Holder`, implementing the Observer design pattern by Gamma et al. [1994].

As for the technical structure of the tree, a `Node` knows its children and its parent, both via pointers. A leaf node has an empty children collection, while a root node stores the null pointer as its parent. Table 4.5 lists all classes, free-standing functions, and enums of module Options.

4.2.5 Presentation

This module contains components responsible for visual and textual presentation of the data structures in module Data. Additionally, it depends on the Presentation Structure module, which it uses to create and maintain the geometrical structure of its visualisations, and on the Options module to maintain user settings such as the colour of selected records.

Name	**Purpose**
`BatchChange`	Commits many option changes in one batch.
`Change`	Changes made via `Synchroniser`.
`ChildrenCountsDifferException`	Exception for differing children counts in `checkEqual()`'s node comparison
`Definition`	Defines an option.
`DefinitionCountsDifferException`	Exception for differing definition counts in `checkEqual()`'s node comparison
`DefinitionNamesOrTypesDifferException`	Exception for differing definition names or types in `checkEqual()`'s node comparison
`DuplicateNodeKeyException`	Exception for duplicate node keys in options file
`EnumerationValues`	Values for enumerated options.
`Exception`	Base exception for option-related errors.
`InvalidDefaultValueException`	Exception for a `Definition`'s invalid default value
`InvalidIntegerException`	Exception for when an integer string in the options file is invalid
`InvalidValueException`	Exception for when a value in the options file is invalid for its definition
`Node`	Node in `Tree`.
`NodeKeysDifferException`	Exception for differing node keys in `checkEqual()`'s node comparison
`NoRootException`	Exception for when the options file has no root.
`Observer`	Observes `Synchroniser`.
`OptionsFileCannotBeOpenedException`	Exception for when the options file cannot be opened.
`OptionsFileNotFoundException`	Exception for when the options file cannot be found.
`ParsingException`	Exception for XML code that cannot be parsed.
`Synchroniser`	Synchronises options across different `Observer`s.
`Tree`	Manages cascading options.
`TreeStructuresNotEqualException`	General, abstract exception for `checkEqual()`.
`UnknownTypeException`	Exception for unknown types in the options file.
`ValueForUnknownDefinitionException`	Exception for values of unknown options in options file.
`Type`	Type of an option.
`checkEqual()`	Checks two `Node` objects and their descendents for an equal structure.
`getAvailableFonts()`	Retrieves fonts available on the system.
`getDefaultFontName()`	Retrieves default font name.
`getFontDirectory()`	Retrieves the system directory for font files.
`getFontPath()`	Retrieves the complete path of a font file.
`readOptionsFile()`	Reads the options file.
`readXml()`	Reads options XML code.
`writeXml()`	Writes options XML code.

Table 4.5: The classes, free-standing functions, and enums of MDE's Options module.

MDE can be extended with additional visualisations by subclassing the abstract `Visualisation` base class, which is itself a specialisation of the more general abstract `DataView`. The abstract class `Data View` is implemented for non-visual ways of data presentation in the sense of no graphical rendering. `InteractiveVisualisation` is a predefined derivee of `Visualisation` providing interaction with the mouse and keyboard for the user of a visualisation window.

`DataView` is derived from the `wxPanel` class of the wxWidgets framework, but multiply inherits also `data::Observer` and `options::Observer`, so that all views will always be notified when data changes occur in one of them, and when program options have been modified by the user. Multiple inheritance is used in a safe manner here due to `data::Observer` and `options::Observer` being defined as pure interface classes. It is necessary that they never directly or indirectly derive from `wxPanel` (or `wxPanel`'s parent classes) to avoid a diamond class hierarchy [Meyers, 1997].

The way MDE separates data from presentation concerns is similar to the widely recognised Model-View-Controller (MVC) software architecture pattern; however, using the definition of Buschmann et al. [1996, pp. 140-141], MDE lacks a separate controller component and is thus more an application of the "Document-View" pattern. As Buschmann et al. explain, *"In several GUI platforms, window display and event handling are closely interwoven. (...) You can combine the responsibilities of the view and the controller from MVC in a single component by sacrificing the exchangeability of controllers. (...) The view component of Document-View combines the responsibilities of controller and view in MVC, and implements the user interface of the system. As in MVC, loose coupling of the document and view components enables multiple simultaneous synchronized but different views of the same document."* This description fits MDE's architecture. wxWidgets not only draws windows, but also provides input event handling (the responsibility of the controller in MVC). Module Data corresponds to the "document" component and module Presentation corresponds to the "view" component.

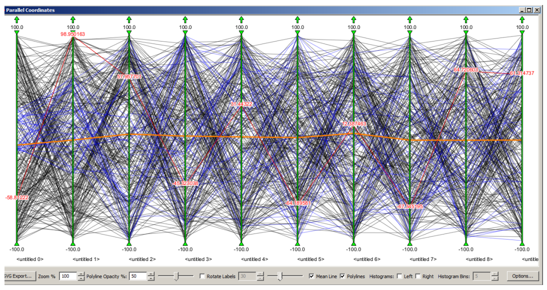
Module Presentation contains four concrete presentation subclasses, which are made known to the rest of MDE via `DataViewFactoryGroup`:

- `ParallelCoordinatesVisualisation`, derived from `InteractiveVisualisation`, visualises data with parallel coordinates (see Chapter 3).
- `ScatterPlotVisualisation`, derived from `InteractiveVisualisation`, visualises data with a Scatter Plot (see Chapter 2).
- `RecordsTableDataView`, derived from `DataView`, shows individual records in a tabular form.
- `DimensionTableDataView`, derived from `DataView`, gives an overview of the dimensions in the data set.

Figure 4.6 shows how these concrete subclasses are presented to the user in MDE's GUI. Figure 4.7 is a class diagram showing the inheritance relationships.

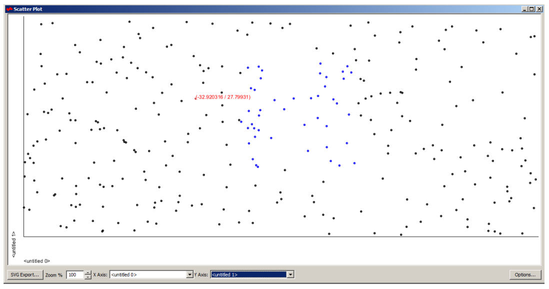
`Visualisation` works with normalised window coordinates in the range [0.0,1.0]. The point of origin, (0.0,0.0) is the lower left corner of a visualisation window. This means subclasses do not have to cope with window size and that their visualisations are automatically scalable. In some cases, however, it is still desirable to translate relative to absolute coordinates and vice versa; for example when determining whether the mouse pointer is close enough to some element of the visualisation, or to implement minimum pixel sizes for otherwise freely stretchable elements. To fulfil those needs, `Visualisation` offers the methods `toPixelsX()`, `toPixelsY()`, `toRelativeX()` and `toRelativeY()`.

Subclasses of `Visualisation` (directly or indirectly via `InteractiveVisualisation`), such as `Parallel CoordinatesVisualisation`, override private virtual methods and are implemented in terms of the protected non-virtual methods of `Visualisation`. Furthermore, `Visualisation` automatically creates and



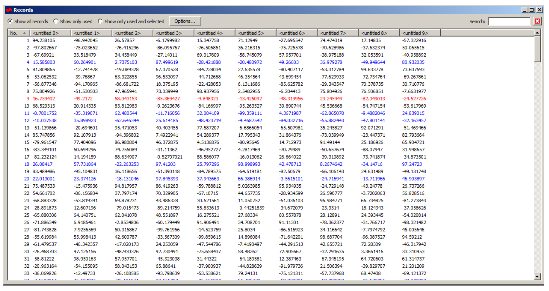
SVG Export... Zoom % 100 Polyline Opacity %: 50 ☐ Rotate Labels 30 ☑ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5 Options...

(a) ParallelCoordinatesVisualisation



SVG Export... Zoom % 100 X Axis: <untitled 0> Y Axis: <untitled 1> Options...

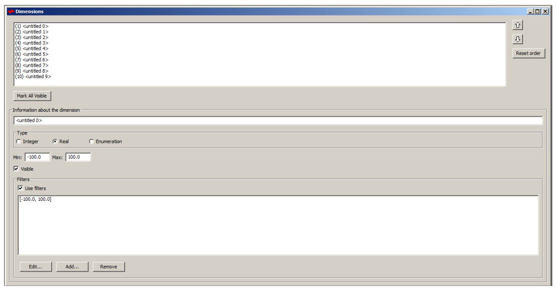
(b) ScatterPlotVisualisation


Records

(• Show all records) (Show only used) (Show only used and selected) Options... Search:

No.	<untitled 0>	<untitled 1>	<untitled 2>	<untitled 3>	<untitled 4>	<untitled 5>	<untitled 6>	<untitled 7>	<untitled 8>	<untitled 9>
1	94.238105	-96.942045	26.57857	-6.1799982	15.347758	71.12949	-27.695547	74.474319	17.14835	-57.322916
2	-97.802667	-75.023652	-76.415296	-86.095767	-76.506851	36.216315	-75.725578	-70.628986	-37.632374	50.065615
3	-67.69921	33.518479	34.458449	-27.14011	69.017609	-58.745079	57.957701	-38.975188	32.053591	-40.958892
4	15.585803	60.264901	2.7375103	87.499619	-28.421888	-20.480972	49.26603	36.979278	-49.949644	80.932035
5	81.804865	-12.741478	-19.089328	67.070528	-84.228034	22.635578	-80.407117	-53.312784	99.633778	73.607593
6	-53.062532	-39.76867	63.322855	96.533097	-44.712668	46.354564	43.699454	-77.629933	-72.734764	-69.267861
7	-56.877346	-94.170965	-86.681722	18.375195	-22.428053	6.1311686	-85.625782	-29.343547	70.378735	30.710776
8	75.804926	-51.530503	47.965941	73.039949	98.937956	2.5482955	-6.204413	75.804926	76.506851	-7.6631977
9	16.739402	-49.2172	58.043153	-85.369427	-9.848323	-13.425092	-48.319956	23.245949	-82.049013	-24.527726
10	68.529313	20.914335	83.812983	-9.2623676	-84.166997	-95.263527	39.890744	45.536668	-54.747154	-53.617969
11	-8.7801752	-35.319071	62.480544	-11.716056	32.084109	-99.359111	4.3671987	-62.865078	-9.4882046	24.839015
12	-10.037538	35.898923	-62.645344	25.614185	-48.423719	-4.4587542	-84.032716	-55.882443	-47.801141	-32.163457
13	-51.139866	-20.694601	95.471053	40.403455	77.587207	-6.6866054	-65.507981	35.245827	92.071291	-51.469466
14	85.747856	92.107913	-94.396802	7.4922941	54.289377	17.795343	31.864376	-73.039949	-23.447371	82.793664
15	-79.961547	77.404096	86.980804	46.372875	4.5136876	-80.95645	14.712973	91.49144	25.186926	65.904721
16	-83.349101	50.694296	74.755089	-31.11362	-46.952727	4.2817469	-70.79989	-50.657674	-88.07947	31.998657
17	-82.232124	14.194159	88.634907	-0.52797021	88.586077	-16.013062	26.664022	-39.310892	-73.741874	-34.873501
18	26.08417	57.731864	-22.263253	97.41203	25.797296	98.998993	42.478713	8.2674642	-34.14716	97.24723
19	83.489486	-95.104831	36.118656	-51.390118	-84.789575	-64.519181	-82.50679	-66.106143	24.631489	-49.131748
20	22.013001	23.374126	-18.131046	97.845393	37.943663	66.386914	-3.5615101	-24.716941	-13.711966	46.903897
21	75.487533	-15.475936	94.817957	86.419263	-59.788812	5.0263985	95.934935	-24.729148	-43.24778	26.737266
22	54.661702	-86.156804	37.797174	70.329905	-67.10715	44.657735	-28.934599	26.590777	-3.7202063	56.828516
23	-68.883328	-53.819391	69.878231	43.986328	30.521561	11.050752	-51.036103	96.984771	66.734825	-81.273843
24	-28.891873	12.607196	-79.015473	-89.214759	55.833613	-0.44251839	-34.672079	-23.3314	18.124943	-37.058626
25	-65.880306	64.140751	62.041078	48.551897	16.275521	27.68334	60.557878	28.12891	24.393445	-54.020814
26	-71.886349	6.9185461	-2.8534806	-60.179449	91.906491	34.708701	91.11301	-78.362377	-31.766717	-98.321482
27	-81.743828	7.9256569	50.315867	-99.761956	-14.523759	25.8034	-86.516923	34.116642	-7.7974792	45.005646
28	-55.619984	55.998413	42.600787	-33.567309	-99.859615	14.896084	-71.642201	98.687704	-96.087527	94.59212
29	-61.479537	-46.342357	-17.020173	24.253059	-47.544786	-7.4190497	-44.291513	42.655721	72.28309	-46.317942
30	-26.468703	97.125156	-48.930326	92.730491	-75.658437	58.48262	72.905667	-32.291635	3.3661916	33.310953
31	-58.81222	98.950163	57.957701	-45.323038	31.44322	-64.189581	12.387463	-67.345195	64.720603	61.314737
32	-20.963164	-54.155095	58.043153	65.88641	-37.900937	-44.828639	-91.979736	21.506394	-39.829707	21.201209
33	-36.069826	-12.49733	-26.108585	-93.798639	-53.538621	79.24131	-75.121311	-57.737968	68.47438	-69.121372

(c) RecordTableDataView


Dimensions

(1) <untitled 0>
(2) <untitled 1>
(3) <untitled 2>
(4) <untitled 3>
(5) <untitled 4>
(6) <untitled 5>
(7) <untitled 6>
(8) <untitled 7>
(9) <untitled 8>
(10) <untitled 9>

Reset order

Mark All Visible

Information about the dimension

<untitled 0>

Type

(Integer) (• Real) (Enumeration)

Min: -100.0 Max: 100.0

☑ Visible

Filters

☑ Use filters

[-100.0, 100.0]

Edit... Add... Remove

(d) DimensionTableDataView

Figure 4.6: The concrete subclasses of MDE's abstract base class `DataView`. (a) parallel coordinates drawn by `ParallelCoordinatesVisualisation`, (b) a scatter plot drawn by `ScatterPlotVisualisation`. Those two classes are indirectly derived from `DataView` via `Visualisation` and `InteractiveVisualisation`. On the other hand, `RecordTableDataView` shown in (c), and `DimensionTableDataView`, shown in (d), are direct implementations of textual representations of the data set.

maintains an instance of `structure::VisualisationStructure`, a structured collection of geometrical definitions explained in Subsection 4.2.6.

MDE can likewise be configured to use different *implementations* for the visualisations it renders to the screen, by subclassing the abstract `VisualisationImplementation` base class and providing a factory to instantiate it by subclassing `VisualisationImplementationFactory`; this is in accordance with the Factory Method design pattern described by Gamma et al. [1994]. `VisualisationImplementation` itself is an extension of `wxWindow`.

The module contains two implementations of `VisualisationImplementation`:

- `VisualisationImplementationOpenGL` is MDE's main rendering engine. It is implemented in terms of OpenGL [Shreiner, 2009; Khronos Group, 2011a].
- `VisualisationImplementationGraphicsRenderer` is an alternative engine which uses the operating system's standard Application Programming Interface (API) for graphics drawing. This class should be considered more as a proof-of-concept for MDE's software architecture supporting different rendering backends. It is much slower than the OpenGL backend.

The relationship between `Visualisation` and `VisualisationImplementation` is such that the former instantiates an instance of the latter; `Visualisation` is the graphical frontend, `Visualisation Implementation` is the backend. This is a classical application of the Bridge design pattern by Gamma et al. [1994]. System-specific and low-level graphics operations are the concern of `Visualisation Implementation`, while `Visualisation` is concerned with providing a protected interface with which derived classes can build concrete visualisation schemes.

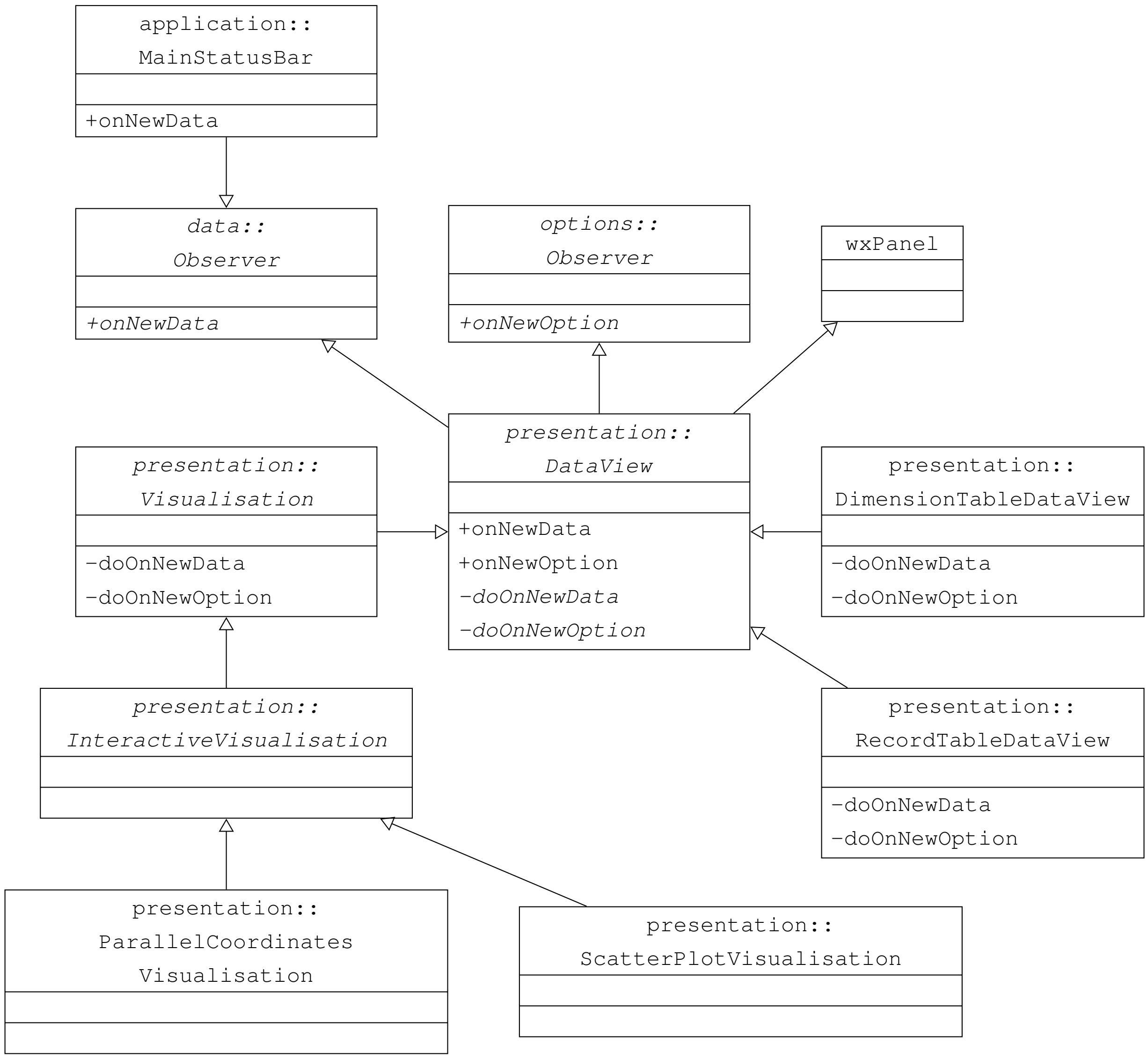


Figure 4.7: The class hierarchy in MDE pertaining to visualisation. The central component is the abstract class `DataView` in the Presentation module. It is a `wxPanel` specialisation, derived also from observers in both the Data and the Options module, so that all `DataView` instances are kept up to date with changes in data or program options. `RecordTableDataView` and `DimensionTableDataView` implement `DataView` directly. `Visualisation` extends `DataView` for data presentation involving the rendering of graphics. `InteractiveVisualisation`, still abstract, adds mouse and keyboard interaction mechanisms. `ParallelCoordinatesVisualisation` and `ScatterPlotVisualisation` are concrete subclasses of it. In module Application, `MainStatusBar` is yet another implementor of `data::Observer`, keeping MDE's status bar up to date. See Figure 4.8 for the further separation of `Visualisation` into frontend and backend.

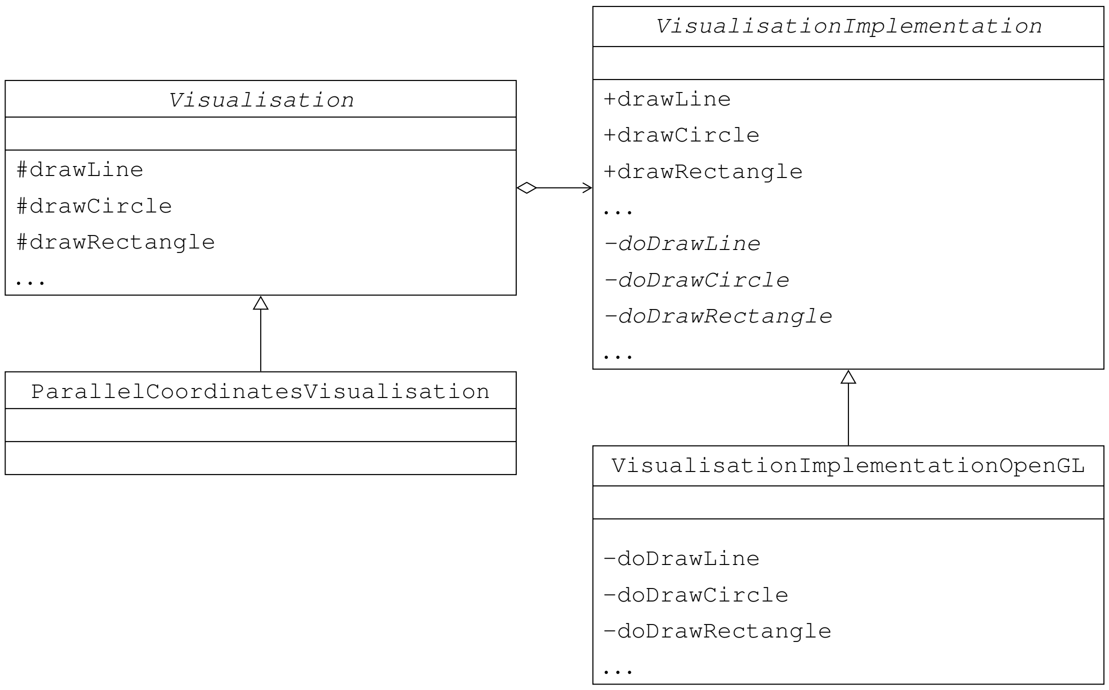


Figure 4.8: This class diagram shows the bridging between visualisation frontend and backend in MDE. `Visualisation`, the frontend, stores a pointer to `VisualisationImplementation`, the backend. Both classes are abstract; derivees of `Visualisation` are concerned with the logic of creating structured graphics, `VisualisationImplementation` is concerned with translating that logic into actual on-screen rendering. `ParallelCoordinatesVisualisation` and `VisualisationImplementationOpenGL` are given as examples of concrete subclasses here. If, for example, `ParallelCoordinatesVisualisation` needs to draw a line, then it calls the protected method `Visualisation::drawLine()`. The base class will delegate the call to `VisualisationImplementation::drawLine()`, from where it will be dispatched to the concrete rendering backend's `VisualisationImplementationOpenGL::doDrawLine()` function, which finally draws a line on the screen.

It follows that `Visualisation`-derived classes do not need to know how the visualisations they produce are implemented. Figure 4.8 is a class diagram of the bridge. In summary:

- `Visualisation` is implemented in terms of `VisualisationImplementation`.
- `Visualisation`'s only public method is its constructor, and is used by outside code to place visualisations into the application's general user interface.
- `Visualisation`'s protected methods are all non-virtual and are used by derived classes to build concrete visualisation schemes.
- `Visualisation`'s virtual private methods are to be implemented by derived classes (which constitutes an application of the Template Method design pattern by Gamma et al. [1994]). Those implementations are implemented in terms of the protected base class methods mentioned in the previous item.
- `Visualisation`'s non-virtual private methods are helper functions and wxWidgets event handlers.

`Visualisation` contains a breach of object-oriented pureness. It knows of the existence of its special base class `InteractiveVisualisation` and internally downcasts the `this` pointer to `Interactive Visualisation` in order to be able to call certain interaction-related functions. Those functions should not be used by anyone other than `Visualisation`, which is why they are private and `Interactive Visualisation` declares `Visualisation` a friend in order to grant access to them. `Visualisation` declares InteractiveVisualisation a friend, too, so that `InteractiveVisualisation` may access private functions of `Visualisation` not meant to be used further down in the inheritance hierarchy.

This breach of object-oriented pureness is justified by the fact that the separation into `Visualisation` and `InteractiveVisualisation` stems mainly from the desire to avoid a central class from becoming too huge. Their purposes are not entirely separated from each other, the result being mutual friendship.

Presentation is clearly the most complex of MDE's modules. Two particularly complex areas are pixel caching and rendering of fonts in OpenGL. These are discussed in detail in Chapter 5. See also Appendix A for more detailed information on how to add new `Visualisation` subclasses to MDE.

Table 4.6 is a list of the classes, structs, and free-standing functions of the Presentation module which are not related to any of the concrete `DataView` classes. Table 4.7, on the other hand, lists all components of the module related specifically to the parallel coordinates visualisation, the scatter plot visualisation, and the textual record and dimension views.

4.2.6 Presentation Structure

Presentation Structure, a sub-module of Presentation, contains the components responsible for the logical structuring of data presentations. This includes Scalable Vector Graphics (SVG) support [Eisenberg, 2002; Ramani et al., 2008]. Presentation Structure is entirely self-contained and does not depend on any other MDE module.

The structure of a presentation is different from the structure of data. A presentation's structure is defined in geometrical terms, such as the end points of lines or the centre and radius of circles, and related geometrical operations. The central class of the Presentation Structure module is `Visualisation Structure`, a collection of `VisualisationElement` instances with related operations for iteration and specific querying.

`VisualisationElement` has a memory-efficient internal implementation in the form of a discriminated union. Just as in the case of `data::Point`, the use of a union here is justified by the sheer number of objects which can be instantiated from this class. There may literally be millions of `Visualisation Element` objects, all created while the visualisation is also being rendered to the screen. For reasons of safety in face of union usage, however, `VisualisationStructure` alone is allowed to create new instances of `VisualisationElement`. Other parts of MDE can instantiate the class only indirectly via public methods of `VisualisationStructure`, such as `addLine()` or `addCircle()`.

The contents of `VisualisationStructure` are inspected for:

1. Geometrical operations with the current mouse pointer position in `InteractiveVisualisation`, such as finding out whether a particular `VisualisationElement` is under the mouse pointer.

2. Exporting a visualisation as an SVG file.

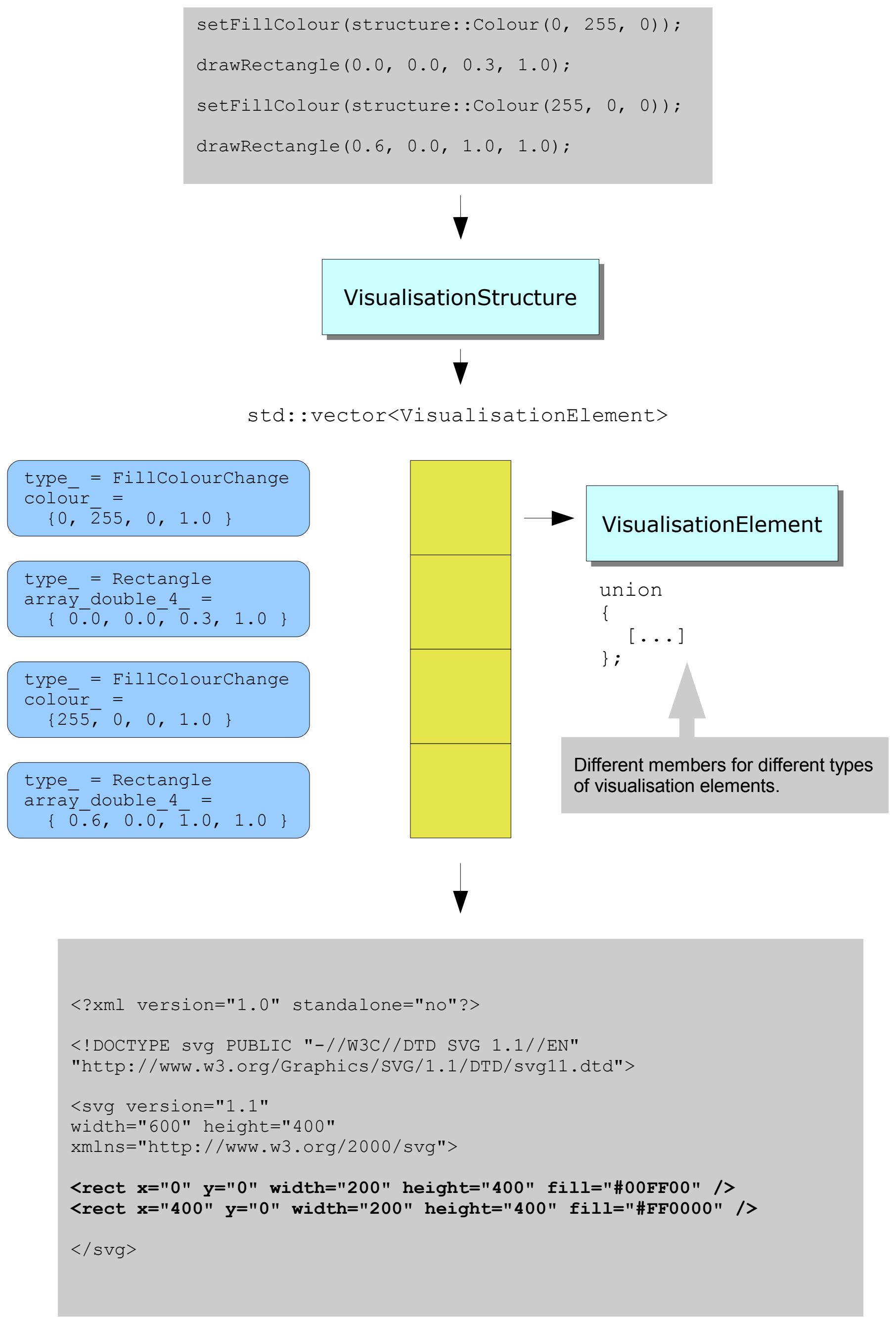
Figure 4.9 shows an example of what could be contained in a `VisualisationStructure` and how `buildSvg()` would transform the contents into SVG code. Table 4.8 lists all classes and functions of the Presentation Structure module. Functions `rgbToHsl()` and `hslToRgb()`, used for making an RGB colour lighter, are based on JavaScript code by Jackson [2008].

Name	Purpose
`DataView`	Base class for the display of data in a window.
`DataViewConstructionParameters`	Tuple of parameters for `DataView`'s constructor.
`DataViewFactory`	Creates `DataView` instances.
`DataViewFactoryGroup`	Group of `DataViewFactory` instances.
`DimensionFilterDialogue`	Dialogue for adding or editing a `data::DimensionFilter`.
`Exception`	Base exception for presentation-related errors.
`FontException`	Exception for font-related errors.
`InteractiveVisualisation`	`Visualisation` with mouse and keyboard interaction.
`NormalisedMousePosition`	Mouse coordinates in range (0.0, 1.0).
`NormalisedSelectionRectangle`	Rectangle with coordinates in range (0.0, 1.0) used for group selections in `InteractiveVisualisation`.
`OpenGLFontException`	Exception for OpenGL font errors.
`RecordIterationStrategy`	Defines order by which `Visualisation` iterates records to be rendered.
`RecordIterationUnusedFirst`	Defines record iteration order such that unused records go first.
`RecordIterationUnusedFirstSelected Last`	Defines record iteration order such that unused records go first, selected last.
`TimedSpinControl`	`wxSpinCtrl` emitting events also a few seconds after direct text modification
`TimedTextControl`	`wxTextCtrl` emitting timed modification events
`Visualisation`	Central visualisation component.
`VisualisationImplementation`	Class with which `Visualisation` is implemented.
`VisualisationImplementationFactory`	Singleton factory class for producing `VisualisationImplementation` objects.
`VisualisationImplementationGraphics Renderer`	Standard operating system graphics drawing backend.
`VisualisationImplementationOpenGL`	OpenGL rendering backend.
`VisualisationMustBeRebuiltEvent`	Event for when a visualisation must be rebuilt.
`Widget`	Interactive entity in an `InteractiveVisualisation` window.
`WidgetGroup`	Group of `Widget` instances in the same `InteractiveVisualisation` window.
`changeDimensionType()`	Changes dimension type with message boxes.
`iterationIndicesAreUnique()`	Checks record iteration indices for uniqueness.
`showDataViewError()`	Displays `DataView` error message.

Table 4.6: The general classes, structs, and free-standing functions of MDE's Presentation module.

Name	**Purpose**
`DimensionInformationWindow`	`DimensionTableDataViewSubwindow` for when a dimension is selected.
`DimensionTableDataView`	`DataView` in which dimension-specific information is shown and manipulated.
`DimensionTableDataViewFactory`	Creates `DimensionTableDataView` instances.
`DimensionTableDataViewSubwindow`	Panel on bottom of `DimensionTableDataView`.
`EnumerationDimensionInformationWindow`	`DimensionTableDataViewSubwindow` for when an enumeration dimension is selected.
`IntegerDimensionInformationWindow`	`DimensionTableDataViewSubwindow` for when an integer number dimension is selected.
`NoDimensionInformationWindow`	`DimensionTableDataViewSubwindow` for when no dimension is selected.
`ParallelCoordinatesAxis`	Means to interact with an axis in `ParallelCoordinatesVisualisation`.
`ParallelCoordinatesAxisMenu`	Menu for axes in `ParallelCoordinatesVisualisation`.
`ParallelCoordinatesFilterCircle`	Means to interact with set filters in `ParallelCoordinatesVisualisation`.
`ParallelCoordinatesFilterTriangle`	Means to interact with ranged filters in `ParallelCoordinatesVisualisation`.
`ParallelCoordinatesVisualisation`	`InteractiveVisualisation` with parallel coordinates.
`ParallelCoordinatesVisualisationFactory`	Creates `ParallelCoordinatesVisualisation` instances.
`RealDimensionInformationWindow`	`DimensionTableDataViewSubwindow` for when a real number dimension is selected.
`RecordTableDataView`	`DataView` with a text table of records.
`RecordTableDataViewFactory`	Creates `RecordTableDataView` instances.
`RecordTableDataViewListControl`	List view control for `RecordTableDataView`.
`ScatterPlotVisualisation`	`InteractiveVisualisation` with a scatter plot.
`ScatterPlotVisualisationFactory`	Creates `ScatterPlotVisualisation` instances.
`TableDataViewListControl`	`wxListView` with sorting by column, used in `RecordTableDataView`.

Table 4.7: Classes in MDE's Presentation module used for concrete data views, rather than the general mechanisms of the module.



```
setFillColour(structure::Colour(0, 255, 0));

drawRectangle(0.0, 0.0, 0.3, 1.0);

setFillColour(structure::Colour(255, 0, 0));

drawRectangle(0.6, 0.0, 1.0, 1.0);
```

VisualisationStructure
std::vector<VisualisationElement>
VisualisationElement
Different members for different types of visualisation elements.

```
type_ = FillColourChange
colour_ =
  {0, 255, 0, 1.0 }

type_ = Rectangle
array_double_4_ =
  { 0.0, 0.0, 0.3, 1.0 }

type_ = FillColourChange
colour_ =
  {255, 0, 0, 1.0 }

type_ = Rectangle
array_double_4_ =
  { 0.6, 0.0, 1.0, 1.0 }
```

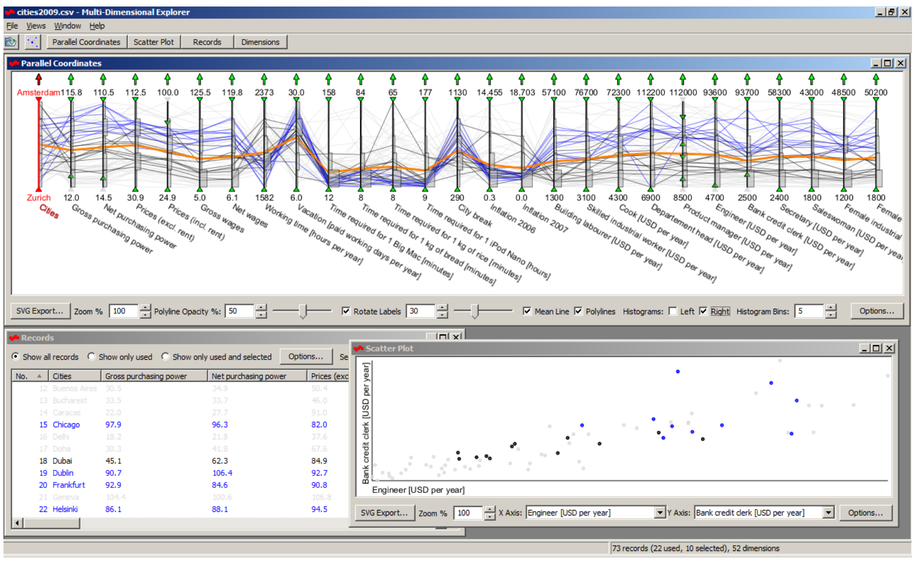
```
union
{
  [...]
};
```

```
<?xml version="1.0" standalone="no"?>

<!DOCTYPE svg PUBLIC "-//W3C//DTD SVG 1.1//EN"
"http://www.w3.org/Graphics/SVG/1.1/DTD/svg11.dtd">

<svg version="1.1"
width="600" height="400"
xmlns="http://www.w3.org/2000/svg">

<rect x="0" y="0" width="200" height="400" fill="#00FF00" />
<rect x="400" y="0" width="200" height="400" fill="#FF0000" />

</svg>
```

Figure 4.9: Class `VisualisationStructure` maintains the logical structure of visualisations. `Visualisation` contains an instance of it and fills it in operations called by subclasses. In this example, a subclass draws two rectangles of different colour. `VisualisationElement` instances are created, which are queried later by `buildSvg()` to create SVG code. All elements are defined in normalised coordinates. Only when the SVG is created, are the absolute width and height of the image specified. The resulting code shows that there is no direct mapping between `VisualisationElement` objects and SVG elements; the fill colour is changed twice, which results in individual `VisualisationElement` objects, whereas in the SVG, colours become attributes of corresponding `rect` tags.

Name	**Purpose**
`Colour`	RGB colour code.
`Exception`	Base exception for all errors related to presentation structure.
`InvalidColourException`	Exception when an invalid `Colour` is to be created.
`Rectangle`	Geometrical rectangle definition.
`Text`	Geometrical text definition.
`VisualisationElement`	Element of a `VisualisationStructure`.
`VisualisationStructure`	Collects `VisualisationElement` instances.
`VisualisationStructure GeometricalIterator`	Iterates over the geometrical elements of `VisualisationStructure`.
`VisualisationStructure Iterator`	Iterates over the elements of `VisualisationStructure`.
`boundsOutsideOfRectangle()`	Whether an element is entirely outside of a rectangle.
`buildSvg()`	SVG code from a `VisualisationElement` range.
`enclosedByRectangle()`	Whether an element is entirely within a rectangle.
`equal()`	Floating-point-aware equality comparison.
`greaterOrEqual()`	Floating-point-ware greater-than-or-equal-to comparison.
`hslToRgb()`	Converts from HSL to RGB.
`intersectsRectangle()`	Checks whether a `VisualisationElement` intersects a rectangle.
`lessOrEqual()`	Floating-point-aware less-than-or-equal-to comparison.
`lineSegmentsIntersect()`	Checks intersection of two line segments.
`rgbToHsl()`	Converts from RGB to HSL.
`svgCircle()`	SVG code for a circle.
`svgClipPath()`	SVG code for clipping.
`svgColour()`	SVG code for an RGB colour.
`svgEllipse()`	SVG code for an ellipse.
`svgLine()`	SVG code for a line.
`svgPolygon()`	SVG code for a polygon.
`svgRectangle()`	SVG code for a rectangle.
`svgText()`	SVG code for text.
`svgTriangle()`	SVG code for a triangle.

Table 4.8: The classes and free-standing functions of MDE's Presentation Structure module.


cities2009.csv - Multi-Dimensional Explorer
File Views Window Help
Parallel Coordinates
Scatter Plot
Records
Dimensions
Amsterdam
Zurich
Cities
Gross purchasing power
Net purchasing power
Prices (excl. rent)
Prices (incl. rent)
Gross wages
Net wages
Working time [hours per year]
Vacation [paid working days per year]
Time required for 1 Big Mac [minutes]
Time required for 1 kg of bread [minutes]
Time required for 1 kg of rice [minutes]
Time required for 1 iPod Nano [hours]
City break
Inflation 2006
Inflation 2007
Building labourer [USD per year]
Skilled industrial worker [USD per year]
Cook [USD per year]
Departement head [USD per year]
Product manager [USD per year]
Engineer [USD per year]
Bank credit clerk [USD per year]
Secretary [USD per year]
Saleswoman [USD per year]
Female industrial
Female
Scatter Plot
Bank credit clerk [USD per year]
Engineer [USD per year]

SVG Export... Zoom % 100 Polyline Opacity %: 50 ☑ Rotate Labels 30 ☑ Mean Line ☑ Polylines Histograms: ☐ Left ☑ Right Histogram Bins: 5 Options...

Records

(●) Show all records ( ) Show only used ( ) Show only used and selected Options...

No.	Cities	Gross purchasing power	Net purchasing power	Prices (exc
12	Buenos Aires	30.5	34.9	50.4
13	Bucharest	33.5	33.7	46.0
14	Caracas	22.0	27.7	91.0
15	Chicago	97.9	96.3	82.0
16	Delhi	18.2	21.8	37.6
17	Doha	30.3	41.8	67.6
18	Dubai	45.1	62.3	84.9
19	Dublin	90.7	106.4	92.7
20	Frankfurt	92.9	84.6	90.8
21	Geneva	104.4	100.6	106.8
22	Helsinki	86.1	88.1	94.5

SVG Export... Zoom % 100 X Axis: Engineer [USD per year] Y Axis: Bank credit clerk [USD per year] Options...

73 records (22 used, 10 selected), 52 dimensions

Figure 4.10: MDE visualising the Cities data set [UBS, 2009] in three different ways. The upper subwindow shows a parallel coordinates view of the data with some dimensions hidden. There are filters defined on some axes, turning a number of records unused (and shown in grey). Blue records are selected. Record states are synchronised across different visualisation windows, as is evident in both the scatter plot and the tabular records subwindow, which use the same colours for the states. The parallel coordinates subwindow features axis histograms and a mean line. The first axis is highlighted in red, meaning that the mouse pointer is currently hovering over it. The green arrows on top can be clicked to flip the axes.

4.2.7 Test

Module Test contains MDE's unit tests. Conceptually, all other modules are tested; it therefore depends on all of them. Furthermore, Test depends on UnitTest++ [Llopis and Nicholson, 2011], the unit test library used by MDE.

Every unit test's implementation resides in a `.cpp` file of its own. Header files in this module serve to reduce code duplication in cases where different unit tests need the same basic setup. The vast majority of unit tests are for the modules Data and Data Input. They are listed in Tables 4.9 and 4.10, respectively. Other unit tests are listed in Table 4.11.

4.3 Comparison With Other Tools

MDE differs from other parallel coordinates software both from the user and from the developer point of view. There are also many similarities, though. This is due to MDE combining features found in separate applications, which in turn allows users to analyse data with a single application rather than having to switch between tools while working on the same data set. Combining those features is not only an aggregation of functionality, it leads to new ways of working with data, because the set of features in a software application is more than the sum of its parts. In summary, what MDE contributes to the field of parallel coordinates is an integration of best user interaction practises found in previously developed tools. Figure 4.10 shows the MDE application window and some its features.

The following list discusses major differences with other tools in detail:

- MDE takes its user interface approach from **MDVS** [Hackl, 2010]. It provides a Multiple Document Interface (MDI) [Microsoft, 2010a] in which different visualisations reside in different subwindows. Textual overviews of individual records and individual dimensions are integrated consistently into this scheme. Record selection is achieved by drawing a selection rectangle with the

Name	**Purpose**
`TestChange`	Tests isolated `data::Change`.
`TestChangeDimensionType`	Tests changing dimension types in `data::Matrix`.
`TestChangeMatrixReplacement`	Tests `data::Change` for replacement of matrix in a `data::Holder`.
`TestChangeMinMax`	Tests changing min/max values in `data::Matrix`.
`TestChangeRecordState`	Tests changing record state in `data::Matrix`.
`TestCorrectPointStringConverter`	Tests `data::PointStringConverter` with correct decimal point characters.
`TestDefaultDimensionFilters`	Tests default instances of `data::DimensionFilter` for `data::Holder`.
`TestDimension`	Tests isolated `data::Dimension`.
`TestDimensionFilter`	Tests isolated `data::DimensionFilter`.
`TestDimensionIndexAndPosition`	Tests `data::DimensionIndex` and `data::DimensionPosition`.
`TestDimensionReordering`	Tests changing the dimension order in `data::Matrix`.
`TestDimensionReorderingAllAtOnce`	Tests changing the order of all dimension in `data::Matrix` at once.
`TestDimensionVisibility`	Tests hiding and showing dimensions.
`TestDimensionWrongType`	Tests wrong types for `data::Dimension`.
`TestFocusRecord`	Tests focussing of records.
`TestGetSmallestGreatestValues`	Tests retrieving smallest and greatest values from `data::Matrix` dimensions.
`TestHolderAddRemoveFilters`	Tests adding and removing `data::DimensionFilter` to `data::Holder`.
`TestHolderApplyFilters`	Tests applying `data::DimensionFilter` in `data::Holder`.
`TestHolderMatrixAssignment`	Tests basic assignment of `data::Matrix` to `data::Holder`.
`TestMatrixOutOfBounds`	Tests assertions for illegal indices in a `data::Matrix`.
`TestMatrixPointsAsStrings`	Tests string representation of `data::Matrix` fields.
`TestMatrixPointsNormalised`	Tests normalisation of `data::Matrix` fields.
`TestWrongPointStringConverter`	Tests `data::PointStringConverter` with wrong decimal point character.

Table 4.9: The unit tests in MDE's Test module testing components of module Data.

Name	**Purpose**
`TestCsvFileReaderFirstLineCaptions`	Tests `data::input::CsvFileReader` with first line as captions.
`TestCsvFileReaderSimple`	Tests `data::input::CsvFileReader` with simple file.
`TestCsvFileReaderWrongFilename`	Tests `data::input::CsvFileReader` with wrong filename.
`TestCsvFileReaderWrongParameters`	Tests `data::input::CsvFileReader` with wrong parameters.
`TestFileReaderGroup`	Tests `data::input::FileReaderGroup`.
`TestIsDefaultValidLine`	Basic tests for `data::input::IsDefaultValidLine`.
`TestMakeDimensionSimpleColumns`	Tests `data::input::makeDimension()` with simple input.
`TestMatrixCreationFromStream`	Tests creation of `data::Matrix` from stream.
`TestMatrixCreationRowTooLong`	Tests creation of `data::Matrix` with input row being too long.
`TestMatrixCreationRowTooShort`	Tests creation of `data::Matrix` with input row being too short.
`TestTextStreamInput`	Basic tests for `data::input::TextStreamInput`.
`TestTextStreamInputComplex`	Complex tests for `data::input::TextStreamInput`.
`TestTextStreamInputEmpty`	Tests empty string input for `data::input::TextStreamInput`.
`TestTextStreamInputOnlyInvalidLines`	Tests invalid lines input for `data::input::TextStreamInput`.

Table 4.10: The unit tests in MDE's Test module testing components of module Data Input.

Name	**Purpose**
`TestColour`	Basic tests for `presentation::structure::Colour`.
`TestOptionDefinition`	Basic tests for `options::Definition`.
`TestOptionNode`	Tests for isolated `options::Node`.
`TestOptionsChange`	Tests isolated `options::Change`.
`TestReadXml`	Tests `options::readXml()`.
`TestRecentFiles`	Tests `application::RecentFiles`.
`TestRecordIteration`	Tests `presentation:: RecordIterationStrategy`.
`TestTestOptionsTree`	Basic tests for `options::Tree`.
`TestVisualisationElement Algorithms`	Tests C++ standard algorithms on `presentation::structure::VisualisationStructure`.
`TestVisualisationElementLine Intersection`	Tests `presentation::structure:: intersectsRectangle()`.
`TestVisualisationElementOrdering`	Tests order of `presentation::structure:: VisualisationElement` elements.
`TestVisualisationElementType Equality`	Tests type equality of `presentation::structure:: VisualisationElement`.
`TestVisualisationElementValues`	Tests return values of `presentation::structure:: VisualisationElement` methods.
`TestVisualisationStructure Iterator`	Tests iterators of `presentation::structure:: VisualisationStructure`.
`TestVisualisationStructureRecords`	Tests record handling of `presentation::structure:: VisualisationStructure`.

Table 4.11: The unit tests in MDE's Test module testing components of modules Application, Presentation, Presentation Structure and Options.

mouse, filters are set on dimensions by vertically dragging triangles on an axis. However, MDVS uses standard operating system functions to draw its graphics and is thus much slower than MDE, which uses an OpenGL backend.

- **InfoScope** [Brodbeck and Girardin, 2003], too, has a similar user interface. Dimension filters are set by dragging triangles on axes; however, group selection of records is not as easy to achieve as in MDE with its simple selection rectangle approach. However, MDE lacks InfoScope's special support for geographical dimensions.

- **parvis** [Ledermann, 2003] features axis histograms very much like those found in MDE. Its multi-phase rendering of the parallel coordinates visualisation, however, takes a different approach. parvis draws a non-anti-aliased preview for visualisation areas about to be modified by current user actions and does not redraw areas which will not be touched. MDE acknowledges that redrawing of same graphics on the same area is a performance bottleneck, but defines multiple rendering phases which are cached internally as arrays of pixel data. Anti-aliasing can be globally turned off as an option, though this has turned out to be of little use in terms of higher performance. MDE's approach is more abstract and can thus be used to optimise other visualisation methods as well.

- **Parallax** [Inselberg, 2010a] offers more sophisticated record selection techniques than MDE, such as angular brushing. It has also a unique approach to the handling of empty fields in the input data, which MDE simply transforms to 0. Setting filters on dimensions (called "interval queries" in Parallax) works in a similar manner. MDE, however, uses more interaction-oriented means of dynamically adapting its visualisations. For example, in MDE dimensions can be moved and flipped with simple mouse operations instead of requiring the user to open separate dialogue windows and menus. Parallax' lack of anti-aliasing support means that there is no way to change the opacity of polylines, whereas polyline opacity can be freely modified in MDE.

- **Situvis** by Clear et al. [2009] does not feature much user interaction, and it is generally more difficult for the user to maintain an overview of the relationship between the parallel coordinates view and the details of the data it visualises. The graph visualisation featured in previous versions of Situvis is absent from MDE. However, MDE uses the same approach to define filters on enumeration dimensions by having the user click dots on an axis corresponding to individual elements of the enumeration. In addition to that, MDE also provides range filters for enumerated dimensions.

- **Picviz** [Tricaud et al., 2011] is meant to be used in the context of network security, while MDE is a general-purpose visualisation tool for multi-dimensional data. Picviz generally offers few user interaction features compared to MDE. It is not possible to set filters on dimensions or to move or flip axes. The rendering backend does not use anti-aliasing. However, the mechanism of selecting records by drawing a rectangle with the mouse is the same as in MDE.

- **GGobi** [Cook and Swayne, 2007] offers statistics tools absent from MDE. Its way of synchronising data in different visualisation views is similar, though. MDE, on the other hand, provides feature-rich user interaction not found in GGobi, such as simple record selection and aggregation of selections or zooming of the display. Another major difference is MDE's support for anti-aliasing.

- **XmdvTool** [XmdvTool, 2010] features clustering and time series animation; two features not found in MDE. It uses OpenGL as its rendering backend, but in contrast to MDE disables anti-aliasing. MDE makes it easier to select and identify individual records, as visualisations can be viewed next to each other and are also synchronised with textual record and dimension tables absent from XmdvTool.

- **VisDB** by Keim et al. [2002] offers a set of different synchronised visualisations, just like MDE, but it provides little support for user interaction. MDE features many ways of selecting records, defining filters, moving and flipping dimensions, and zooming; all of this is absent from VisDB.

- **Caleydo** by Lex et al. [2010] is rooted in medical science, whereas MDE is general-purpose software, which makes it simpler to use for data analysis in other domains without distraction by features useful only for Caleydo's original purpose. Caleydo, in contrast to MDE, features angular brushing, but does not have a simple mouse selection rectangle mechanism like MDE.

- **OECD eXplorer** [Organisation for Economic Co-operation and Development, 2011], too, is rooted in a particular domain, namely statistics of regions around the world. MDE is general-purpose and thus accepts anything as input data, while special measures have to be taken to load custom data into OECD eXplorer (which will still try to interpret it as OECD statistics data). The other major difference is that OECD eXplorer is implemented as an online Flash application, whereas MDE is a native desktop application. OECD eXplorer's mean line and histogram features have been integrated into MDE. However, in OECD eXplorer, groups of records cannot be selected by a drawing a rectangle, but are selected by clicking on the axis histograms.

- **Protovis** [Bostock and Heer, 2009] offers almost none of the interaction features of MDE. From an implementation point of view, its use of JavaScript and SVG is radically different from MDE, which is a desktop application written in C++ and using OpenGL. However, MDE allows users to export visualisations as SVG files.

- **VizCraft** by Goel [1999] offers almost none of MDE's features, either. It is targeted at aircraft design and implemented as a Java applet, in contrast to MDE's general-purpose approach and C++ implementation.

- **Liquid Diagrams** [Andrews and Lessacher, 2010] is an online tool integrated into Google Docs, which is yet another example of an approach radically different from MDE. This difference in implementation also means that while Liquid Diagrams have the advantage of being available everywhere, they do not have any way to access graphics hardware directly like MDE with its OpenGL backend; consequently the software performs more slowly than MDE.

Chapter 5

Selected Details of the Implementation

"Hic sunt dracones!"

["Here be dragons!" – Latin phrase labelling dangerous unknown territories on medieval maps]

Chapter 4 discusses the Multi-Dimensional Explorer (MDE) software application from a software engineer's point of view. This chapter describes two areas of the software architecture which deserve special attention due to their complexity. Section 5.1 discusses the multi-layered caching mechanism of MDE, Section 5.2 explains how MDE manages to embed text in graphics.

The context of this chapter is the Presentation module. In order to increase legibility, class names are not prefixed by `presentation::`. For example, `Visualisation` refers to `presentation::Visualisation`.

5.1 Multi-Phase Caching

The `Visualisation` and `VisualisationImplementation` classes of MDE's Presentation module are responsible for drawing graphics in visualisation windows. As visualisations in MDE are dynamic, they change often, whenever the user modifies some parameters of the visualisation or uses its interaction features. Recreating the entire visualisation from scratch every time a minimal change occurs is not feasible. This is particularly true in the case of `ParallelCoordinatesVisualisation`, the parallel coordinates component of MDE, with its large variety of interaction mechanisms. The scatter plot visualisation, implemented in `ScatterPlotVisualisation`, is much simpler.

The parallel coordinates visualisation is also more complex than the scatter plot visualisation for the sheer number of graphics primitives which are drawn. Visualising N records and M dimensions requires N x $(M - 1)$ lines to be drawn in parallel coordinates, whereas a scatter plot only draws N glyphs (dots, or other icons) for any given number of dimensions.

For these two reasons, `ParallelCoordinatesVisualisation` shall serve as the motivating example for this section. However, MDE is also designed to be independent of any particular visualisation scheme. Therefore, any optimisation mechanism in its software architecture has to be defined in abstract, general terms. `VisualisationImplementationOpenGL`, the main rendering engine of MDE implements those mechanisms in OpenGL [Shreiner, 2009; Khronos Group, 2011a] and is used as an example throughout the rest of this section. `VisualisationImplementationGraphicsRenderer` is not considered.

Optimisation of MDE's rendering performance is built on the idea of caching the pixels of a visualisation after pre-defined steps. Concrete subclasses of `Visualisation` know about those steps and can structure the creation of their visualisations accordingly. Three such steps are identified:

1. Rendering the *background* of a visualisation. The background includes elements which are likely to be unaffected by the most common forms of user interaction. In the case of parallel coordinates, axis labels, minimum and maximum value labels as well as flipping arrows on top of each axis are considered the visualisation's background. These elements do not change often.

2. Drawing the *main contents* of a visualisation on top of its background. This is when graphical elements for individual records are drawn. In the case of parallel coordinates, polylines for unused, used and selected records, as well as the mean line, histograms and filter handles. These elements change more often than the background, as record states are modified by the user selecting records and adjusting filters on dimensions.

3. Drawing the *overlay* of a visualisation on top of its background and main contents. This is for temporary changes of a visualisation as the user moves the mouse pointer over it. In the case of parallel coordinates, focussing of records and displaying tooltips for them, as well as drawing highlighted axes elements and filter handles, and displaying a semi-transparent copy of an axis while it is being dragged with the mouse.

Figure 5.1 gives a better idea of how these steps translate to visualisation phases. Unused records are part of the main contents, rather than the background, due to the observation that the manipulation of filters is a frequent user action in parallel coordinates; if the change of a record's state triggered a rebuild of the entire visualisation, then the filter handles would not be responsive enough. The drawback of this approach is the (less likely but still possible) use case when filters are not used much, while record selections change often, because in this case continuously redrawing the same polylines for unused records is wasteful. Accounting to both cases through a more flexible design involving a dynamic number of visualisation phases is an example of future work on MDE, see also Chapter 6.

As for the implementation of this design, `VisualisationImplementationOpenGL` contains two `std::vector<unsigned char>` member variables in which the pixel output of the first and second step is cached. `background_` stores the background of the visualisation, `pixels_` stores its main contents. What follows is a documentation of how and in which parts of the source code the caching takes place.

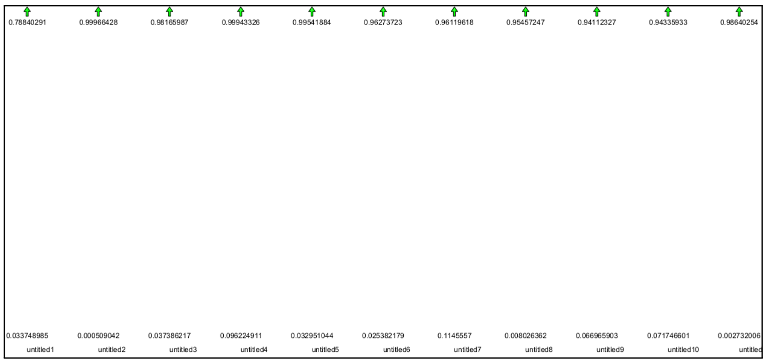
When a visualisation window is first created or when any changes in data or options occur, `presentation::Visualisation` calls `prepareForNewData()` and `prepareForNewOption()`, two of its non-pure virtual private member functions. The default implementations do nothing, but derived classes may override them to take custom preparations for rebuilding a visualisation or parts of it. For example, `ParallelCoordinatesVisualisation` updates its custom GUI controls, such as the polyline opacity slider or the check boxes for mean line and histograms.

`Visualisation` then starts the process of rebuilding its visualisation (or parts of it) by sending the custom `wxEVT_VISUALISATION_MUST_BE_REBUILT_AFTER_DATA_CHANGE` event to itself and handling it in function `onVisualisationMustBeRebuiltAfterDataChange()`.

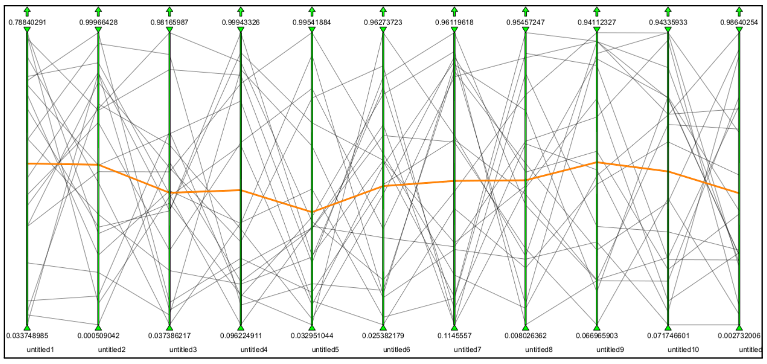
The nature of the change dictates how `Visualisation` proceeds. The `data::Change` and `options::Change` objects are inspected to decide on further action.

- If the change is more comprehensive than just a change of the record currently being focussed, then `rebuildVisualisation()` is called. Subsequently, in `VisualisationImplementationOpenGL::doClear()`, the `pixels_` cache is cleared. The `background_` cache remains, for now, untouched.

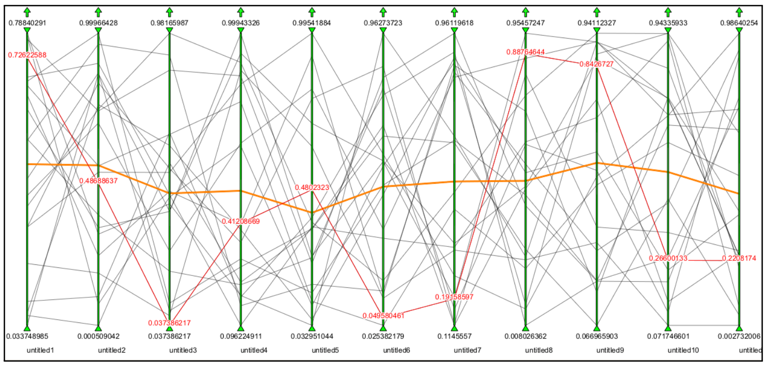
  `Visualisation` commences `wxEVT_IDLE` event handling, which means `onIdle()` is called repeatedly until all records of the input data set have been processed. This design keeps the window responsive while extremely comprehensive data sets are being visualised.



(a) Background



(b) Main Contents



(c) Overlay

Figure 5.1: In MDE, rendering performance is optimised by breaking it up into three steps. In (a), the background of a parallel coordinates visualisation is drawn; this comprises dimension names as well as minimum and maximum labels and flipping arrows on each dimension. In (b), the main contents (polylines, mean line and filter handles here), are drawn on top of the background. In (c), the overlay is drawn by rendering a red highlighted copy of the polyline under the mouse and adding temporary tooltips with the corresponding record's values. Unused records are put into the middle layer, rather than the background layer, due to the observation that the manipulation of filters is a frequent user action in parallel coordinates; if the change of a record's state triggered a rebuild of the entire visualisation, then the entire visualisation would have to be rebuilt every time a filter handle was used, resulting in a slow and unresponsive user interface.

As long as there are still records to be processed, `createVisualisation()` is called. This function first checks the number of records which have been processed already; if it is 0 and if no background cache exists (performed by inspecting the boolean `background_cached_` variable, which is initially `false`), then further control is delegated to the virtual function `visualisationFirstStep()`, which concrete subclasses implement to render the background of the visualisation. Subclasses can also clear the background cache by calling `clearBackgroundCache()`, if they find that data or option changes have invalidated it.

When `ParallelCoordinatesVisualisation` has finished creating the background, `VisualisationImplementationOpenGL` caches the current pixel output by saving it in its `background_` member variable. `Visualisation` sets `background_cached_` to `true`.

If `createVisualisation()` is called with an active background cache, the `renderBackground()` method of `VisualisationImplementationOpenGL` is called first, pasting the cached background pixels on the window, followed by a call to `visualisationFirstStep()` with any actual rendering disabled.

Subsequently, the virtual member function `partiallyCreateVisualisation()` is called for each record, and the likewise virtual member function `visualisationLastStep()` is called to complete the visualisation. `VisualisationImplementationOpenGL` can now cache the complete scene in `pixels_`.

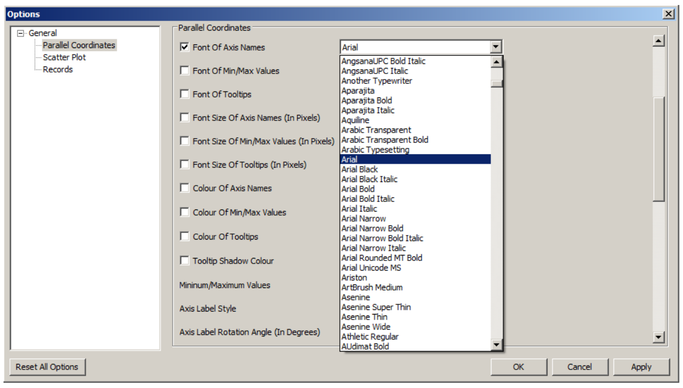
- If only focussing changed, `Visualisation` just calls its `renderVisualisationToScreen()` function. It first instructs `VisualisationImplementationOpenGL` to paste its `pixels_` cache to the screen and calls the virtual member function `createOverlay()`. That function does nothing in the base class but is overridden in `InteractiveVisualisation` to handle features like focussing records under the mouse. If, for example, a parallel coordinates polyline is focussed, then the highlighted polyline is drawn on top of the entire cached scene. The results of applying the overlay are *not* cached, because overlay graphics are inherently temporary, so there would be no sense in storing them persistently.

5.2 Rendering TrueType Fonts in OpenGL

OpenGL has no direct support for rendering text, because text exists a higher abstraction level than the problems OpenGL solves and which are much closer to the graphics hardware. Software engineers requiring text to be drawn with OpenGL therefore choose from a number of very different available solutions to meet their specific needs [Khronos Group, 2011b].

The solution employed by MDE is to use the FTGL library [Maddock, 2008]. It enables programmers to draw text specifying a font file from which to read character shape definitions. FTGL supports TrueType fonts [Apple, 2002], allows any geometrical operations to be applied to rendered text and, alternatively, supports a less flexible but faster type of text rendering. Geometrical operations are needed for rotated axis labels in MDE's parallel coordinates visualisation; the faster but less flexible type of rendering is used to display non-rotated axis labels.

The complexity arising with MDE's use of the FTGL library is two-folded. First, some way to map from a font's *name* (that which a user sees in the end user interface) to the *path* of its file in the operating system's file system is required. Second, the font file must be integrated into the OpenGL visualisation with the library's Application Programming Interface (API). These two aspects are discussed in the following subsections.



Parallel Coordinates

- [✓] Font Of Axis Names: Arial
- [ ] Font Of Min/Max Values
- [ ] Font Of Tooltips
- [ ] Font Size Of Axis Names (In Pixels)
- [ ] Font Size Of Min/Max Values (In Pixels)
- [ ] Font Size Of Tooltips (In Pixels)
- [ ] Colour Of Axis Names
- [ ] Colour Of Min/Max Values
- [ ] Colour Of Tooltips
- [ ] Tooltip Shadow Colour

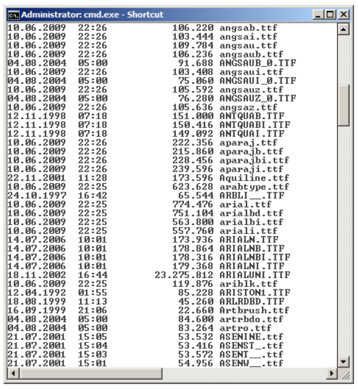
Mininum/Maximum Values

Axis Label Style

Axis Label Rotation Angle (In Degrees)

AngsanaUPC Bold Italic
AngsanaUPC Italic
Another Typewriter
Aparajita
Aparajita Bold
Aparajita Italic
Aquiline
Arabic Transparent
Arabic Transparent Bold
Arabic Typesetting
Arial
Arial Black
Arial Black Italic
Arial Bold
Arial Bold Italic
Arial Italic
Arial Narrow
Arial Narrow Bold
Arial Narrow Bold Italic
Arial Narrow Italic
Arial Rounded MT Bold
Arial Unicode MS
Ariston
ArtBrush Medium
Asenine
Asenine Super Thin
Asenine Thin
Asenine Wide
Athletic Regular
AUdimat Bold

(a) Font Names



```
10.06.2009  22:26           106.220 angsab.ttf
10.06.2009  22:26           103.444 angsai.ttf
10.06.2009  22:26           109.784 angsau.ttf
10.06.2009  22:26           106.236 angsaub.ttf
04.08.2004  05:00            91.688 ANGSAUB_0.TTF
10.06.2009  22:26           103.408 angsaui.ttf
04.08.2004  05:00            75.060 ANGSAUI_0.TTF
10.06.2009  22:26           105.592 angsauz.ttf
04.08.2004  05:00            76.280 ANGSAUZ_0.TTF
10.06.2009  22:26           105.636 angsaz.ttf
12.11.1998  07:18           151.000 ANTQUAB.TTF
12.11.1998  07:18           150.416 ANTQUABI.TTF
12.11.1998  07:18           149.092 ANTQUAI.TTF
10.06.2009  22:26           222.356 aparaj.ttf
10.06.2009  22:26           215.860 aparajb.ttf
10.06.2009  22:26           228.456 aparajbi.ttf
10.06.2009  22:26           239.596 aparaji.ttf
22.11.2001  11:28           173.596 Aquiline.ttf
10.06.2009  22:25           623.628 arabtype.ttf
24.10.1997  16:42            65.544 ARBLI___.TTF
10.06.2009  22:25           774.476 arial.ttf
10.06.2009  22:25           751.104 arialbd.ttf
10.06.2009  22:25           563.800 arialbi.ttf
10.06.2009  22:25           557.760 ariali.ttf
14.07.2006  10:01           173.936 ARIALN.TTF
14.07.2006  10:01           178.864 ARIALNB.TTF
14.07.2006  10:01           178.316 ARIALNBI.TTF
14.07.2006  10:01           179.368 ARIALNI.TTF
18.11.2002  16:44        23.275.812 ARIALUNI.TTF
10.06.2009  22:25           119.876 ariblk.ttf
12.04.1992  01:55            85.228 ARISTON1.TTF
18.08.1999  11:13            45.260 ARLRDBD.TTF
16.09.1999  21:06            22.660 Artbrush.ttf
04.08.2004  05:00            84.600 artrbdo.ttf
04.08.2004  05:00            83.264 artro.ttf
21.07.2001  15:05            53.532 ASENINE.ttf
21.07.2001  15:04            53.416 ASENST_.ttf
21.07.2001  15:03            53.572 ASENT__.ttf
21.07.2001  15:01            54.956 ASENW__.ttf
```

(b) Font Files

Figure 5.2: No obvious mapping exists between font names and font file paths. (a) shows an option control in MDE displaying all available font names to the user. (b) demonstrates that the corresponding files have very different names which follow no logical scheme. For this reason, programmers must employ platform-specific means of determining the paths of font files.

5.2.1 Mapping from Name to File Path

Font names, as they are displayed to the end user of an application, do not correspond at all to file names in the file system. For example, "Arial" may correspond to the file path `C:\Windows\Fonts\arial.ttf` on a Windows installation, but for obvious reasons this cannot generally be assumed. Unavailability of any such logical mapping between name and path poses a problem to MDE, because the full path of a font file is needed to draw text with the FTGL library. Figure 5.2 shows the difference between font names and font paths.

wxWidgets is no help in this regard, either, because although it features many font-related components, it does not contain functionality for retrieving the path of a font. Therefore, this is an area where MDE has to resort to platform-specific implementations. Any such platform-specific dependencies are encapsulated in the implementations of the two functions `getAvailableFonts()` and `getFontDirectory()`. They are not exposed to other components of MDE. The following part of this documentation assumes a Microsoft Windows platform and availability of the Windows API [Microsoft, 2010c].

A font path consists of two parts: the directory path and the file name. For example, in `C:\Windows\Fonts\arial.ttf`, the directory path is `C:\Windows\Fonts`. In order to retrieve it, MDE's `getFontDirectory()` function uses the Windows API function `SHGetSpecialFolderLocation()`, passing the predefined value `CSIDL_FONTS` as an argument.

`getAvailableFonts()`, on the other hand, creates, statically stores, and returns a const reference to a `std::map` in which keys are font names and values are corresponding file names. The directory is *not* contained in the map's values! For example, key "Arial" might refer to value "arial.ttf", rather than `C:\Windows\Fonts\arial.ttf`.

The Windows registry has to be used to identify all the available font names and their corresponding file names, because the relationships are stored there at key `HKEY_LOCAL_MACHINE\\SOFTWARE\\Microsoft\\WindowsNT\\CurrentVersion\\Fonts`. The key is opened with `RegOpenKeyEx()`, followed by a series of calls to `RegEnumValue()` and `RegQueryValueEx()` to retrieve font names and filenames. Any entry whose name does not end with " (TrueType)" or whose filename does not end with ".ttf" is excluded from the results, because this is the easiest way to retrieve only TrueType fonts.

Clients of `getAvailableFonts()` and `getFontDirectory()` are oblivious to these system-specific low-level intricacies. They operate instead on safe C++ constructs like `std::map`, `std::string` and `boost::filesystem::path`. Consequently, porting the mechanism to other platforms requires no modification of client code.

5.2.2 Drawing Text

Having obtained a map of all available fonts with corresponding file paths, FTGL can be used to draw text respecting the user's font choice. All use of FTGL in MDE (just as any OpenGL-specific MDE functionality in general) is encapsulated in class `VisualisationImplementationOpenGL`. Two different classes for FTGL font rendering are used in the two overloaded versions of `doDrawText()`:

- `FTGLTextureFont` is used in the overload taking a `rotation` parameter for drawing potentially rotated text.
- `FTGLPixmapFont` is used in the overload taking no such parameter for the drawing of non-rotated text because its implementation is faster.

In both cases, an instance of the corresponding FTGL class is dynamically allocated via a `boost::shared_ptr`. This is a costly operation which should not be repeated every time text is drawn. Therefore, performance is optimised by caching the instances, inserting them into a `std::map` which maps font filenames to either `boost::shared_ptr<FTGLTextureFont>` or `boost::shared_ptr<FTGLPixmapFont>`. Having now at its disposal an instance of the proper FTGL font class, `doDrawText()` just uses its `FaceSize()` and `Render()` high-level methods to draw text on the current OpenGL visualisation.

For `FTGLTextureFont`, the class used for rotated text, the implementation is slightly more complex because OpenGL matrix transformations are involved. First, the identity matrix is loaded by calling the OpenGL function `glLoadIdentity()`. It is then modified by `glOrtho()` such that the desired text coordinates become the point of origin. Afterwards, the projection matrix is rotated using `glRotatef()`. At this point, the rotated piece of text is drawn. When the operation has finished, it restores the previous projection matrix. Figure 5.3 shows the geometry of text rotation.

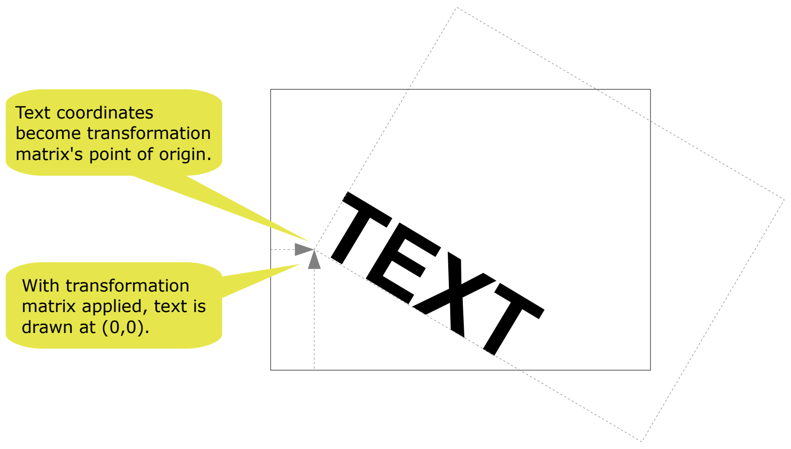

Text coordinates become transformation matrix's point of origin.
With transformation matrix applied, text is drawn at (0,0).
TEXT

Figure 5.3: MDE uses OpenGL's transformation matrix mechanism to rotate text drawn with the `FTGLTextureFont` class. An identity matrix is first positioned such that the desired text coordinates correspond to its point of origin. It is then rotated. Finally, text is drawn at position (0,0) of the transformation matrix, visualised here as the rotated rectangle around the text. The operation is completed by restoring the previous transformation matrix.

Chapter 6

Conclusion and Future Work

"To them and their posterity will we commit our future. They will continue the voyages we have begun, and journey to all the undiscovered countries, boldly going where no man... where no one has gone before."

[James T. Kirk in Star Trek VI – "The Undiscovered Country", 1991]

This thesis began with an introduction to information visualisation in Chapter 2. It placed information visualisation in a historical context and demonstrated that the concept existed long before computers were invented. Furthermore, it defined the term "information visualisation" to distinguish it from general data visualisation. Geographical visualisation was given as a prime example of visualisation often falsely attributed to the field of information visualisation.

Having defined the precise scientific meaning of multi-dimensional information visualisation, a number of popular techniques were introduced: scatter plots, histograms, star plots and similarity maps. The growing importance of user interaction was outlined; usability is becoming an ever greater concern in this area.

With all this context established, Chapter 3 explained parallel coordinates. Ever since Alfred Inselberg reintroduced the technique in the second half of the 20th century, it has become ever more popular and more widely-used. Parallel coordinates are a unique information visualisation technique, because they impose no theoretical limit on the number of dimensions which can be displayed at the same time. The thesis explained why parallel coordinates work like this and why they differ from any orthogonal approach.

However, the thesis also outlined problems with parallel coordinates. The most important problem is that large amounts of data result in the visualisation being cluttered with lines. As the thesis demonstrates, many techniques to mitigate this problem have been invented by the scientific community; the solution proposed is usually to combine records or lines into clusters. Random sampling, using neural networks, or using time animation have all been suggested as extensions to the basic parallel coordinates technique.

This thesis explained also how to *use* parallel coordinates. It first discussed basic interaction features and then reviewed a large number of software applications featuring parallel coordinates to demonstrate that the basic concept of the technique has been implemented in many different ways. The thesis reviewed each of the software applications' strengths and weaknesses, making it an ideal starting point for anyone willing to try exploratory data analysis with parallel coordinates and looking for the proper tool to solve the task at hand.

At the same time, there is a great variety of applications of parallel coordinates. This is demonstrated by this thesis as well, because the software reviewed covers many different domain areas, ranging from conflict analysis, network security, and regional statistics to medical science. Other than that, technical aspects of the implementations differ, too. Some of the tools are classical desktop applications, others are embedded into web pages for online access. In short, this thesis shows parallel coordinates' versatility both from the end user's and the software engineer's point of view. Performance turned out to be a common problem in the parallel coordinates software reviewed. However, as previously discussed, user interaction is becoming ever more important in information visualisation. The "best" clustering technique has yet to be found. As a result, existing software tools do not handle large data sets in a satisfactory manner for the end user of an application.

The Multi-Dimensional Explorer (MDE) software was developed for this thesis and was discussed in Chapter 4. MDE is faster than traditional parallel coordinates software by its choice of implementation tools (C++ and OpenGL) and by applying a variety of optimisation techniques coming from software engineering. Furthermore, MDE combines interaction features found in other parallel coordinates visualisation software, creating new usage scenarios. Unlike a number of other, more academic or experimental toolkits, MDE is meant to be used for real data analysis and has been designed and developed with usability in mind.

Chapter 5 discussed some particularly complex aspects of MDE's design, including the multi-level caching mechanism and the difficulties in embedding text into OpenGL visualisations. Both are important for a usable parallel coordinates visualisation, of course. The structure of parallel coordinates makes them apt for caching, and text is needed to display axis names or informative tooltips.

The future of parallel coordinates is hard to predict. On the one hand, the basic approach of arranging axes next to each other on a plane is going into ever new directions: 3D parallel coordinates and curves instead of polylines have been proposed and tested in prototypes. On the other hand, parallel coordinates are already a useful technique as they are. They should be embraced much more by software engineers as well as usability engineers to create robust, fast, reliable and usable implementations. MDE is a starting point for this. Although the software performs very fast already, many additional techniques are not used and might be tested in future.

Most importantly, MDE does not employ OpenGL display lists and uses basic pixel operations for its caching mechanism, rather than relying on texture operations. Both of those techniques promise further performance gains. Additionally, MDE's caching mechanism currently supports only a fixed number of cache levels – the mechanism could instead be generalised to support n cache levels, which would certainly prove interesting for interactive parallel coordinates visualisations where operations often update only a horizontal subrange of the screen when axes are being moved.

Another use for a dynamic number of cache levels is to put polylines for unused records into an intermediate layer between the background and the main contents. The current design always considers unused records part of the main contents. This keeps the user interface responsive when filter handles are being dragged with the mouse (because the background does not have to be recreated), but sacrifices performance gains which would be obtained otherwise for the case when a user has finished setting his or her filters and continues modifying only selections (because in this case the current implementation of MDE redraws the same unused record lines over and over). An intermediate layer would combine responsiveness with additional performance gains at the cost of slightly increased memory consumption.

MDE does not currently feature clustering, either. This is partly due to the fact that little research has gone so far into the translation of parallel coordinates' typical user interaction features to a clustered display. For example, how should MDE's record selection rectangle work with clusters? What does it mean to drag filter handles on a dimension when records are clustered? What should be highlighted and which tooltip values should appear when the user moves the mouse pointer over a cluster? In fact, the entire user interaction scheme has to be redefined when clustering is present; extensive usability tests should be performed to gain more insights in this area, rather than implementing one's own ideas without taking the end user into account.

Similar considerations hold for colour shading, which MDE does not yet implement. Colour shading conflicts with record selection, because both operations modify the colour of the polylines. What exactly do users expect when they select records in a parallel coordinates visualisation with activated colour shading? Should the selected polylines just become blue, ignoring the colour range? Or should the colour of selected records follow a different shading range? And how intuitive is an application with such heavy overloading of the colour information channel? Again, it seems advisable to perform user testing, possibly with a prototype, to see how this feature should be implemented to aid in exploratory data analysis.

Parallel coordinates have stood the test of time in the fast moving world of computer science. They are certainly here to stay. Let us apply our knowledge in other areas of software engineering to make them faster, better and more usable.

Appendix A

MDE User Guide

"Just TU it."

[Motto of Graz University of Technology alias TU Graz]

This is the user manual of the Multi-Dimensional Explorer (MDE) software, an interactive information visualisation desktop application for the exploratory analysis of multi-dimensional data. MDE was developed in 2011 by Christian Hackl for his Master's thesis ("Exploratory Data Analysis with Parallel Coordinates and the Multi-Dimensional Explorer") at Graz University of Technology. It documents MDE from the end user's point of view. Future developers of MDE who might want to extend the tool should instead use the MDE Developer Guide.

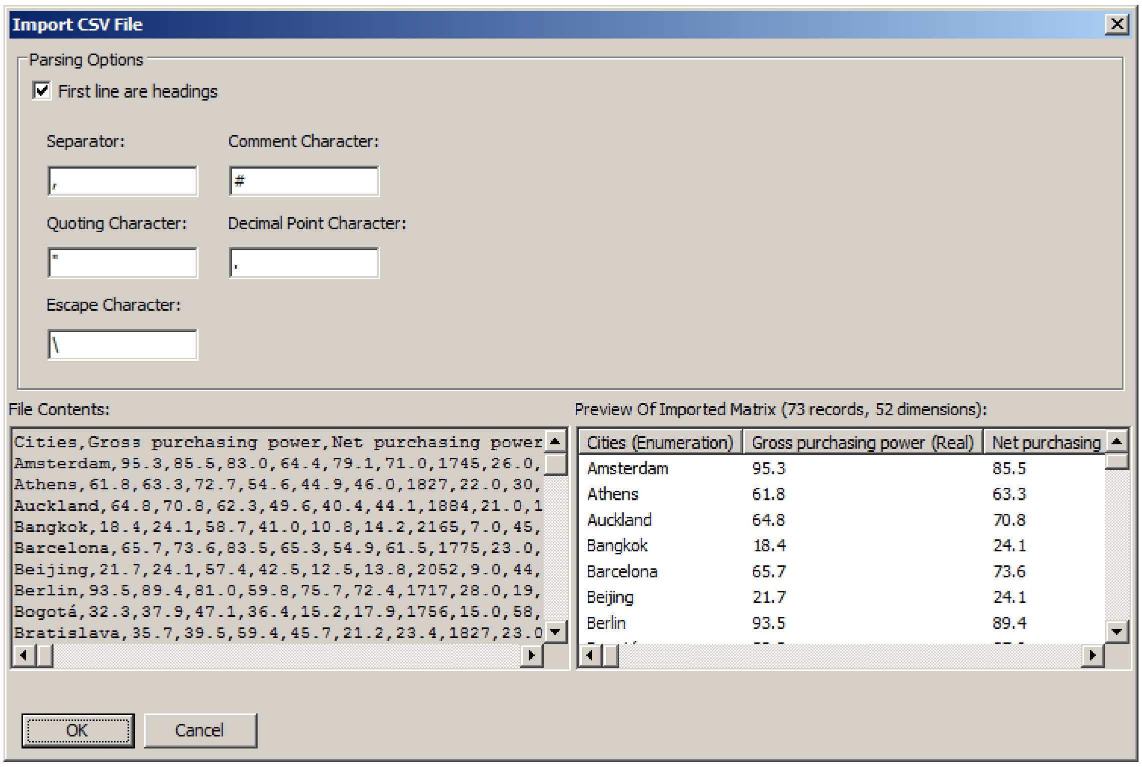
No setup is needed for MDE. All it takes to use the software are its `.exe` file (on Windows) and a CSV file to be opened. There is no "installer" for MDE. A file in which program options are stored persistently, `options.xml`, is created automatically in the same directory as the executable. MDE does not modify the Windows registry.

All examples given in this manual use the well-known cities data set by UBS, a collection of information about prices and earnings around the globe, turned into a CSV file using the conversion mechanism of Macrofocus InfoScope.

A.1 Loading Data

Data is loaded into MDE by pressing the Open File button on the tool bar or by selecting the appropriate item from the File menu. There is also a tool bar button and a menu item for generating *random* data, although this feature might be more useful for developers testing visualisations rather than actual end users. Upon selecting a CSV file to be opened, MDE opens a dialogue window like the one shown in Figure A.1, in which CSV parsing parameters can be overruled in case the application did not succeed in automatically detecting the correct separators, comment characters, quoting characters, decimal point characters, and escape characters.

Upon clicking OK, the data is loaded and will automatically be visualised as parallel coordinates. Every view of the data resides in its own MDE subwindow. A new view can be opened by clicking one of the Parallel Coordinates, Scatter Plot, Records and Dimensions buttons on the tool bar, or by selecting the corresponding items in the Views menu. Almost all of MDE's user interaction takes place in the view subwindows. They are discussed in subsequent sections.



Import CSV File

Parsing Options

[✓] First line are headings

Separator: ,

Comment Character: #

Quoting Character: "

Decimal Point Character: .

Escape Character: \

File Contents:

```
Cities,Gross purchasing power,Net purchasing power
Amsterdam,95.3,85.5,83.0,64.4,79.1,71.0,1745,26.0,
Athens,61.8,63.3,72.7,54.6,44.9,46.0,1827,22.0,30,
Auckland,64.8,70.8,62.3,49.6,40.4,44.1,1884,21.0,1
Bangkok,18.4,24.1,58.7,41.0,10.8,14.2,2165,7.0,45,
Barcelona,65.7,73.6,83.5,65.3,54.9,61.5,1775,23.0,
Beijing,21.7,24.1,57.4,42.5,12.5,13.8,2052,9.0,44,
Berlin,93.5,89.4,81.0,59.8,75.7,72.4,1717,28.0,19,
Bogotá,32.3,37.9,47.1,36.4,15.2,17.9,1756,15.0,58,
Bratislava,35.7,39.5,59.4,45.7,21.2,23.4,1827,23.0
```

Preview Of Imported Matrix (73 records, 52 dimensions):

Cities (Enumeration)	Gross purchasing power (Real)	Net purchasing
Amsterdam	95.3	85.5
Athens	61.8	63.3
Auckland	64.8	70.8
Bangkok	18.4	24.1
Barcelona	65.7	73.6
Beijing	21.7	24.1
Berlin	93.5	89.4

Figure A.1: The "Import Wizard", which MDE shows to the user upon selection of a CSV file to be opened for visualisation. If MDE did not succeed in detecting the correct separators, comment characters, quoting characters, decimal point characters or escape characters, the user can override these parameters. The left part of the window shows the plain text contents of the input file, the table on the right part is a preview of how it will be interpreted.

A.2 Parallel Coordinates View

The parallel coordinates view visualises multi-dimensional input data with the parallel coordinates visualisation technique, which involves arranging axes in parallel to each other on a plane, each axis representing one of the dimensions. Records are represented by polylines connecting the axes. Figure A.2 shows MDE implementing the concept.

A number of general display options for parallel coordinates can be changed in MDE using the controls in the view's subwindow. From left to right:

- An SVG Export button with which the visualisation is saved as an SVG file.
- A Zoom spin control for selecting the visualisation's zoom level.
- Controls to change the opacity of the polylines (50% by default).
- Controls to change the angle by which axis names are rotated, or to turn rotation off completely and instead truncate names so that they do not overlap.
- Controls to individually turn on and off polylines, the mean polyline, and axis histograms.
- An Options button to fine-tune further options, such as the colours of individual visualisation elements.

Figure A.3 shows these controls. Controls for SVG export, zooming and the Options button make sense for all graphical views and therefore appear also in the scatter plot visualisation.

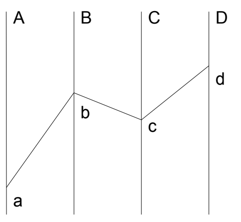
The first thing a user will want to do with a parallel coordinates visualisation displaying many dimensions is to hide some of the axes. This can be done in MDE by drawing a selection rectangle with the mouse in the display area above or below the polylines. Axes under the rectangle are selected and are displayed in a different colour, as shown in Figure A.4. It is now possible to right click on any of the selected dimensions to open a context menu with a Hide item. This is how a group of axes can be hidden from the view at once.

Figure A.5 shows what the user can do with each axis of the parallel coordinates visualisation. An axis can be flipped by clicking on the arrow symbol on top of each axis, as shown in Figure A.6. Filters can be defined on dimensions by dragging the triangles on the axis line; this results in polylines outside of the range becoming "unused" and thus displayed in grey. Furthermore, the entire axis can be moved horizontally by grabbing one of its top or bottom elements with the mouse and dragging it around. This is so that the user can change the order in which dimensions appear in the parallel coordinates visualisation.

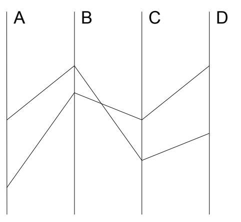
It is also possible to define more than one filter for an axis. Filters can be fine-tuned by right-clicking on one of their handles and choosing "Edit Filter...". An additional filter type exists for Enumeration dimensions, such as the "Cities" dimension of the Cities data set, which contains the names of cities. Filters for such dimensions can define a *set* of allowed values. A circle is drawn for each value of the enumeration. Allowed values are represented by filled circles. Circles can be clicked to toggle whether that value is allowed or disallowed. Figure A.7 shows what a Set filter for the "Cities" dimension looks like.

MDE's parallel coordinates view features histograms, as shown in Figure A.8. Histograms can be turned on and off individually for both sides of an axis by clicking on the respective check box at the bottom of the visualisation window. They represent the number of records in individual subranges of an axis; the number of bins to be displayed on an axis is changed via the "Histogram Bins" spin control.

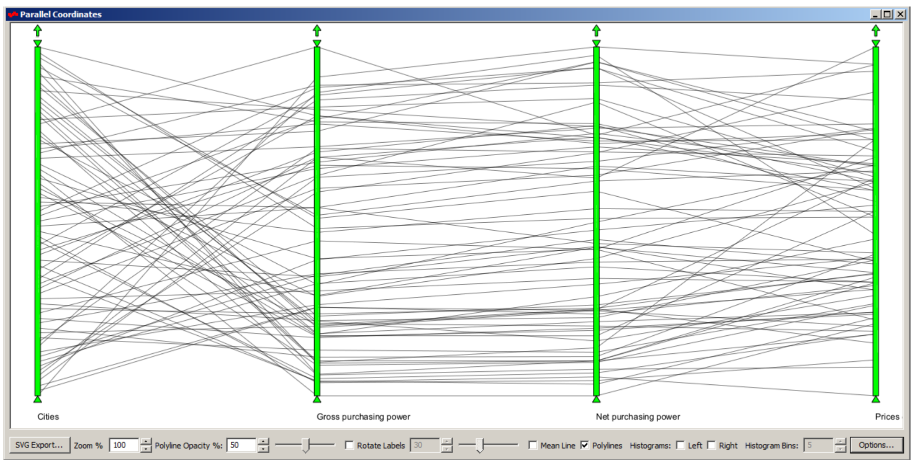
Presumably, the most common user interaction feature of MDE's parallel coordinates3 is the selection of records. When a polyline is clicked, the record it belongs to is selected. A group of polylines



(a) One four-dimensional record in parallel coordinates



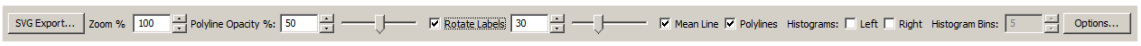
(b) Two four-dimensional records in parallel coordinates



Zoom % 100 Polyline Opacity %: 50 ☐ Rotate Labels 30 ☐ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5

(c) Parallel coordinates in MDE

Figure A.2: The concept of parallel coordinates is to arrange axes in parallel to each other on a plane. (a) shows a four-dimensional record p visualised with a vector of three connected lines at coordinates a, b, c and d on axes A, B, C and D, respectively. This demonstrates how the technique can be used to display records with any number of dimensions as long as there is enough horizontal space. In (b), two four-dimensional records are visualised with parallel coordinates. (c) shows MDE's parallel coordinates component implementing the concept, visualising 73 records and 4 dimensions.



Zoom % 100 Polyline Opacity %: 50 ☑ Rotate Labels 30 ☑ Mean Line ☑ Polylines Histograms: ☐ Left ☐ Right Histogram Bins: 5

Figure A.3: The controls shown by MDE on the bottom of a parallel coordinates visualisation window allow users to modify certain aspects of the visualisation. SVG Export saves the visualisation as an SVG file, the Zoom spin control serves to zoom the visualisation; polyline opacity can be controlled by both a spin control and the slider next to it; the rotation of axis name labels can be chosen or turned off completely; mean line, polylines and histograms can be individually turned on and off. Finally, there is an Options button to fine-tune further aspects of the parallel coordinates visualisation.

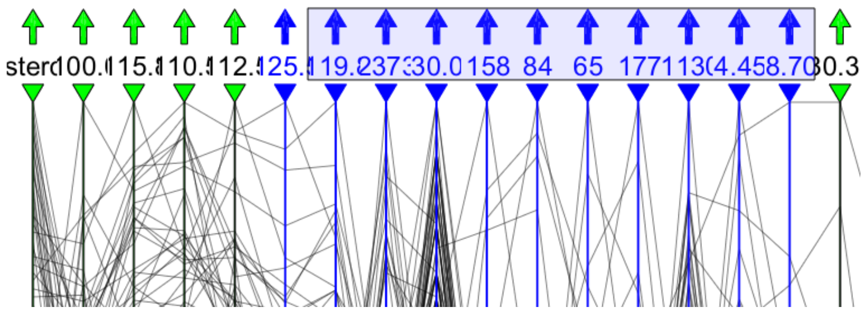
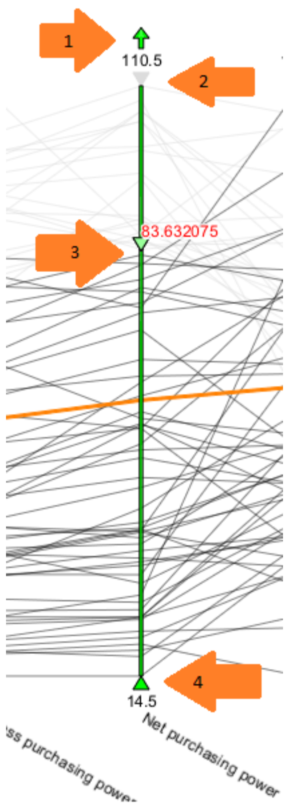
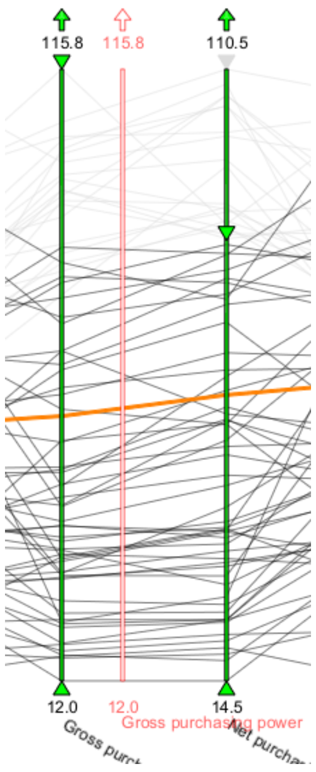


Figure A.4: In MDE's parallel coordinates visualisation, a group of axes can be selected by dragging a rectangle with the mouse in the display area above or below the polylines. The user can then right-click on any of the axes to open context menu with which all selected axes can be hidden at once.



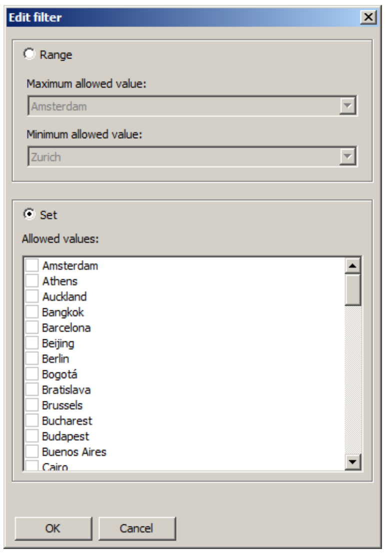
(a) Clickable Parts of an Axis.



(b) Moving an Axis.

Figure A.5: A parallel coordinates axis in MDE presents a number of interaction features to the user. Clickable parts of an axis are shown in (a). The arrow on top (1) can be clicked to toggle flipping. The triangles on top and bottom can be dragged to define filtered ranges on the polylines. (2) displays the original triangle position; (3) is the filter handle currently being dragged (the upper limit of the range is shown above it, too). (4) is the bottom handle of the range filter. (b) shows an axis being dragged horizontally with the mouse. The minimum and maximum value of the dimension are shown at the top and bottom of each axis as well.

Figure A.6: A parallel coordinates axis in MDE can be flipped upside down by clicking on the arrow symbol above each axis. The arrow direction changes as well.



Edit filter

( ) Range

Maximum allowed value:

Amsterdam

Minimum allowed value:

Zurich

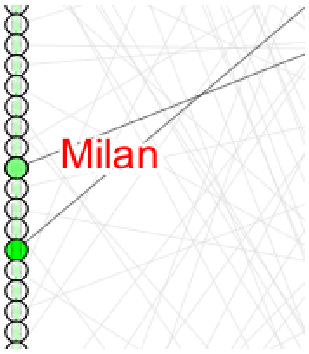
(•) Set

Allowed values:

- [ ] Amsterdam
- [ ] Athens
- [ ] Auckland
- [ ] Bangkok
- [ ] Barcelona
- [ ] Beijing
- [ ] Berlin
- [ ] Bogotá
- [ ] Bratislava
- [ ] Brussels
- [ ] Bucharest
- [ ] Budapest
- [ ] Buenos Aires
- [ ] Cairo

OK Cancel

(a) Editing a Filter



(b) Circles of a Set Filter

Figure A.7: MDE supports not only range filters on dimensions, but also set filters for enumerations. In (a), a range filter is turned into a set filter. (b) shows the graphical representation of a set filter: filled circles are drawn for allowed values of the enumeration, empty circles are drawn for disallowed ones. The circles can be clicked to toggle the state.

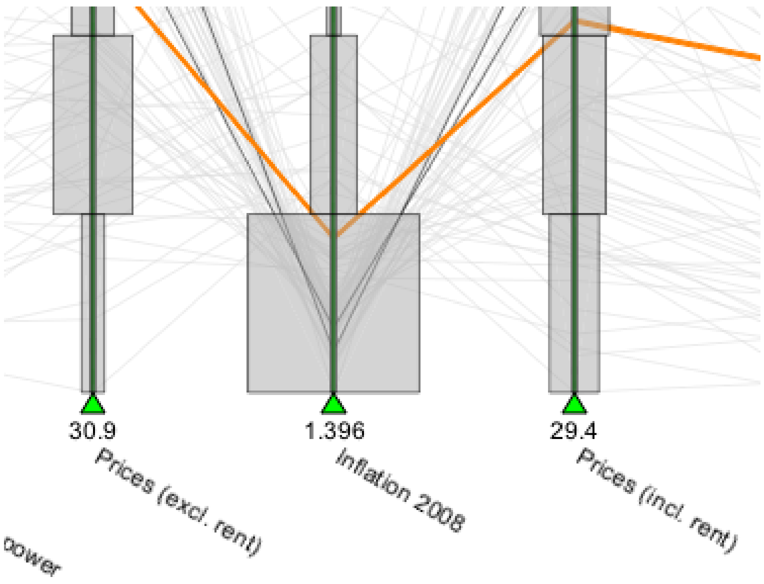


Figure A.8: Histograms can be turned on and off in MDE's parallel coordinates visualisation. They can be shown either left of each axis, right of each axis, or on both sides. The colours and opacity of histogram bins as well as the number of bins to be displayed on each axis can be changed by the user.

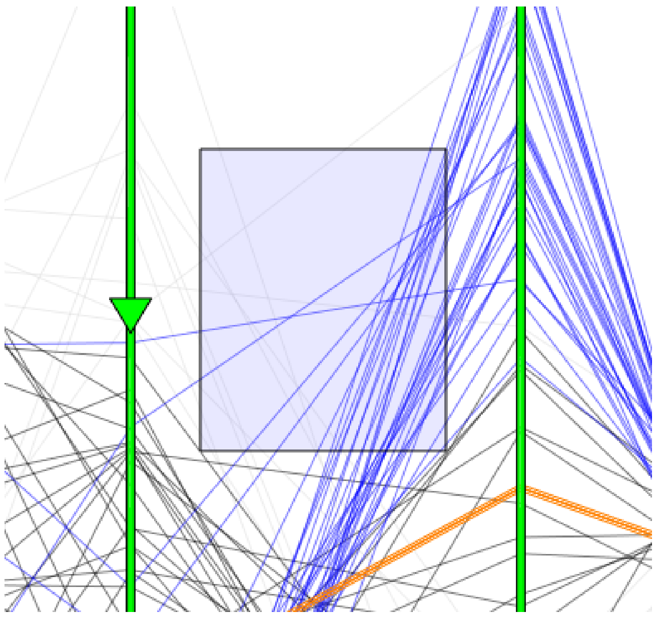


Figure A.9: In MDE's parallel coordinates visualisation, polylines are selected by dragging a rectangle with the mouse. All records belonging to one of the polyline segments under that rectangle change their state and become selected, which is visualised by drawing them in blue. This example also shows how unused records are not included in the selection, regardless of whether they are under the selection rectangle or not.

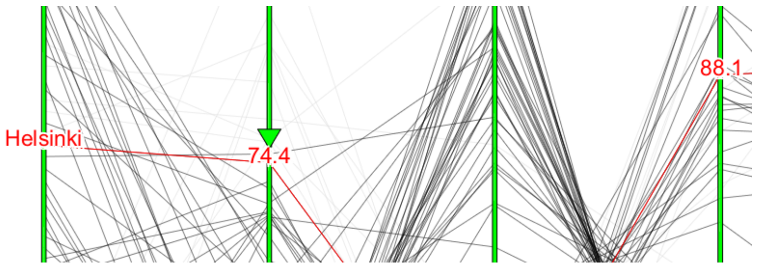


Figure A.10: When the user moves the mouse pointer over a polyline in MDE's parallel coordinates visualisation, that line is displayed in red. With some delay (the default being 1 second), tooltips showing the corresponding record's individual values appear on each axis.

(and thus, a group of records) can be selected by drawing a rectangle with the mouse, as shown in Figure A.9. When the user moves the mouse pointer over a polyline, it is focussed by drawing it in red. After some delay (1 second by default), tooltips showing the corresponding record's actual values on each axis appear as well, as shown in Figure A.10.

A.3 Scatter Plot View

A scatter plot is a two-dimensional visualisation technique for multi-dimensional input data. Any two of the input data dimensions are chosen by the user to represent the horizontal and vertical axes of the plot. Data points are then plotted according to their values in the two selected dimensions. Figure A.11 shows MDE's scatter plot component.

MDE synchronises the states of records across all of its views. Records selected or turned unused in the parallel coordinates visualisation are selected or unused in the scatter plot view as well – and vice versa. The same applies to focussing records and to hiding entire dimensions. However, there

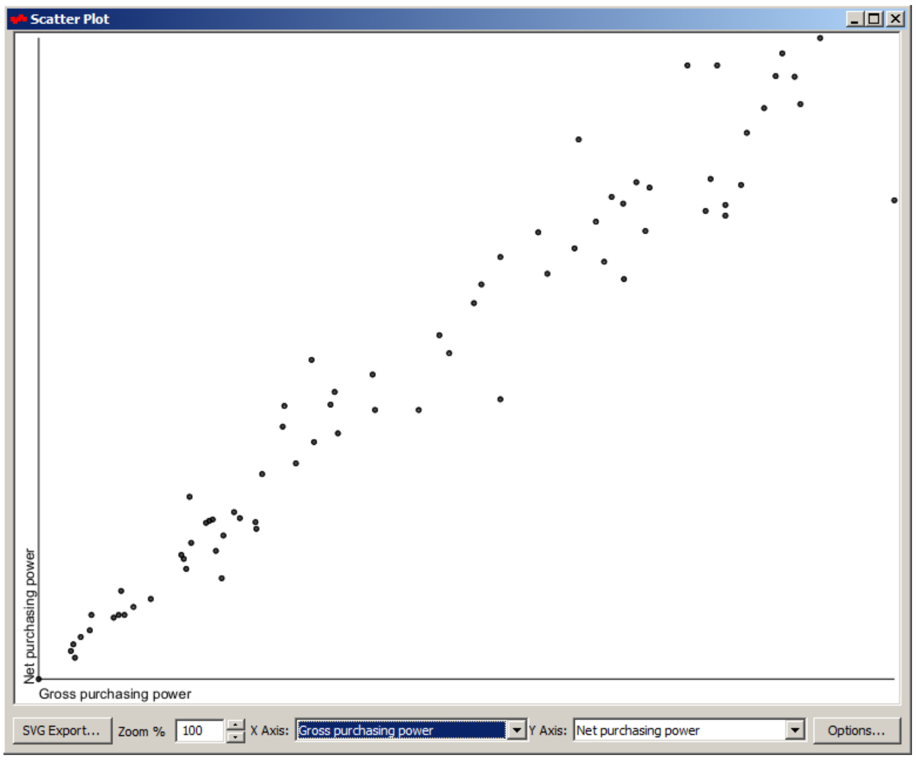


Figure A.11: A scatter plot is a standard 2D visualisation technique in which two dimensions of a multi-dimensional data set are selected to represent the horizontal and vertical axes of the window. Data points are then plotted on the window according to their values in the selected dimensions.

are also properties specific to individual visualisations. For example, the scatter plot has no notion of polyline opacity, so there is also no setting for it. Figure A.12 shows an example of record states being synchronised across different views.

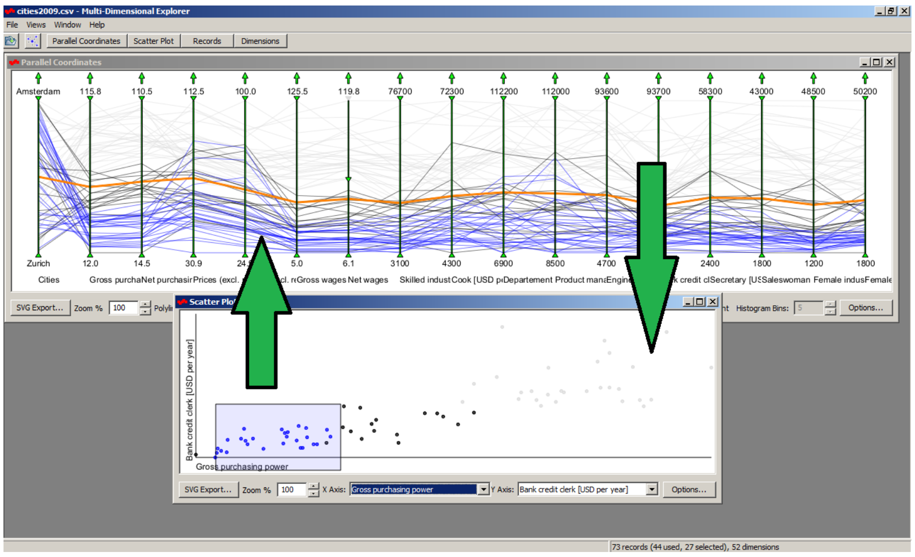
The two dimensions to be visualised in the scatter plot are chosen with the controls at the bottom of the window. This is also the location of the SVG Export button, the zoom control, and the Options button to fine-tune some display options.

A.4 Records View

The records view is a textual tabular representation of the input data. It therefore does not feature zooming or SVG export. However, record states and its colour scheme are synchronised with other visualisations. Figure A.13 shows a Records window displaying unused records in grey, selected ones in blue, and the focussed one in red; just like in the parallel coordinates and scatter plot visualisations.

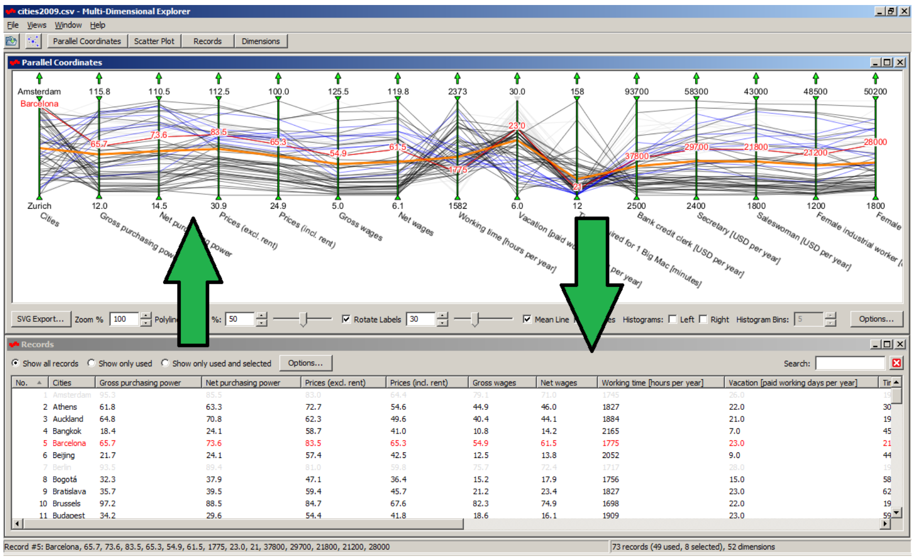
Furthermore, the order of columns in the records table is synchronised with that in the parallel coordinates display. The table can be sorted by clicking on one of its headers. Note that the *order of records* is an attribute specific to the records view. Other views have no notion of an order relationship between records.

The records view also features incremental search. Users can type text in the text field at the top right of the window. As they type, the records shown in the table are restricted to those with at least one field containing the typed text. Another useful feature of the records view is the ability to show only used, or only used and selected, records. This feature is enabled by clicking on the radio buttons on top of the window. An example of using it is to click on “Show only used” and then set filters on


cities2009.csv - Multi-Dimensional Explorer
File Views Window Help
Parallel Coordinates
Scatter Plot
Records
Dimensions
SVG Export...
Zoom %
X Axis: Gross purchasing power
Y Axis: Bank credit clerk [USD per year]
Options...

73 records (44 used, 27 selected), 52 dimensions

Figure A.12: MDE synchronises the states of records across different visualisation windows. This example shows a parallel coordinates view and a scatter plot view opened at the same time. Records which have become "unused" by setting a filter in the parallel coordinates window are displayed using grey polyline in the parallel coordinates window and using grey dots in the scatter plot window (as can be seen in the right part of the window). The user draws draws a rectangle in the latter, selecting all records whose dots are under it; this turns the dots blue. Corresponding polylines in the parallel coordinates are now displayed in blue as well.



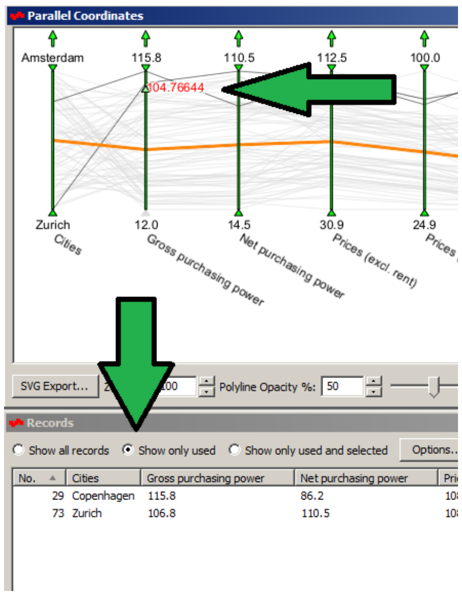
Show all records / Show only used / Show only used and selected

No.	Cities	Gross purchasing power	Net purchasing power	Prices (excl. rent)	Prices (incl. rent)	Gross wages	Net wages	Working time [hours per year]	Vacation [paid working days per year]	Tir
1	Amsterdam	95.3	85.5	83.0	64.4	79.1	71.0	1745	26.0	19
2	Athens	61.8	63.3	72.7	54.6	44.9	46.0	1827	22.0	30
3	Auckland	64.8	70.8	62.3	49.6	40.4	44.1	1884	21.0	19
4	Bangkok	18.4	24.1	58.7	41.0	10.8	14.2	2165	7.0	45
5	Barcelona	65.7	73.6	83.5	65.3	54.9	61.5	1775	23.0	21
6	Beijing	21.7	24.1	57.4	42.5	12.5	13.8	2052	9.0	44
7	Berlin	93.5	89.4	81.0	59.8	75.7	72.4	1717	28.0	19
8	Bogotá	32.3	37.9	47.1	36.4	15.2	17.9	1756	15.0	58
9	Bratislava	35.7	39.5	59.4	45.7	21.2	23.4	1827	23.0	62
10	Brussels	97.2	88.5	84.7	67.6	82.3	74.9	1698	22.0	19
11	Budapest	34.2	29.6	54.4	41.8	18.6	16.1	1909	23.0	59

Record #5: Barcelona, 65.7, 73.6, 83.5, 65.3, 54.9, 61.5, 1775, 23.0, 21, 37800, 29700, 21800, 21200, 28000

73 records (49 used, 8 selected), 52 dimensions

Figure A.13: MDE's records view is a table in which records are presented in textual form. The states of records are synchronised with all other views. This example shows selected records in blue, unused ones in grey, and the focussed one (Barcelona) in red. This matches exactly the colours in the parallel coordinates window above.



( ) Show all records [✓ Show only used] ( ) Show only used and selected

No.	Cities	Gross purchasing power	Net purchasing power	Pri
29	Copenhagen	115.8	86.2	10
73	Zurich	106.8	110.5	10

Figure A.14: MDE's records view allows users to display only relevant records in the table. For example, if users are interested only in seeing entries of used records, they can click on "Show only used". This image shows the user setting a ranged filter on the "Gross purchasing power" dimension in the parallel coordinates window, leading to only Copenhagen and Zurich being included. The records view now only shows these two records.

dimensions using the handles in the parallel coordinates window. This gives an immediate overview of which records are included in the range and which are not. Figure A.14 shows what this looks like in MDE. Visual properties of the records view can be customised by clicking on the Options button.

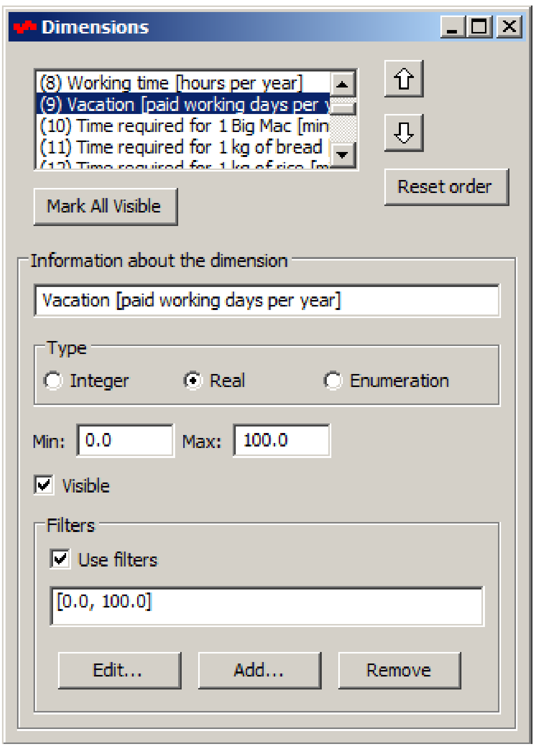
A.5 Dimensions View

MDE's dimensions view is used to fine-tune information about dimensions, rather than individual records. It is synchronised with the other views in terms of data pertaining to entire dimensions: name, type, visibility, order, minimum and maximum values, and filters. All these attributes of a dimension can be changed in this window, and the effect of any change becomes immediately visible in all other windows. Figure A.15 shows the modification of a dimension's minimum and maximum values causing the corresponding axis in the parallel coordinates visualisation to be updated.

The bottom part of the window consists of controls with which the user can update, remove, or add filters. Although the parallel coordinates visualisation features the same mechanisms, the dimensions window is more appropriate for setting precise filters. For example, setting a filter's upper limit to 13.14 is difficult in the parallel coordinates window, whereas in the dimensions window, the exact value can be typed in. Unlike other views, the dimensions window has no special options associated with it.

A.6 Options

All visual attributes of MDE can be customised in options dialogues. The options dialogue window is opened via the Options... item in the Views menu. It presents a hierarchy of option pages with general options at the top; the parallel coordinates, scatter plot and records views have their own pages (the dimensions view does not, because there are no visual options associated with it).


Dimensions

(8) Working time [hours per year]
(9) Vacation [paid working days per y
(10) Time required for 1 Big Mac [min
(11) Time required for 1 kg of bread
(12) Time required for 1 kg of rice [m

Mark All Visible
Reset order

Information about the dimension

Vacation [paid working days per year]

Type: Integer [✓ Real] Enumeration

Min: 0.0 Max: 100.0

[✓ Visible]

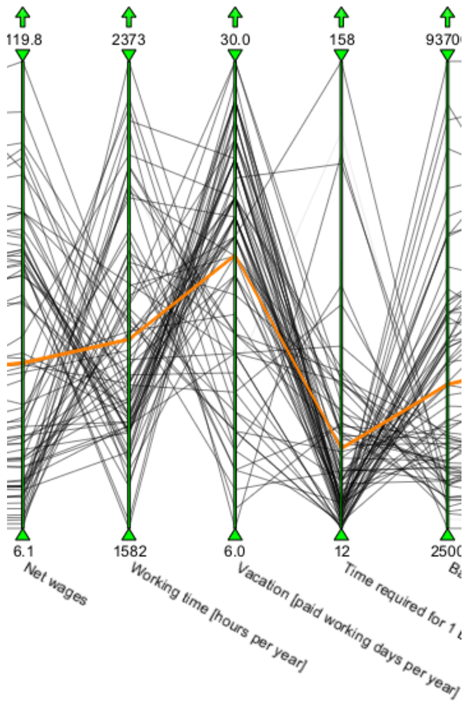
Filters

[✓ Use filters]

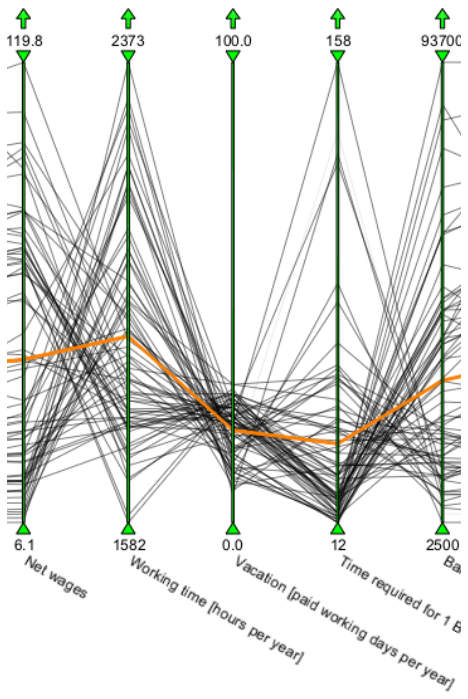
[0.0, 100.0]

Edit... Add... Remove

(a) Dimensions Window



(b) Axis Before Change



(c) Axis After Change

Figure A.15: MDE's dimensions view, shown in (a), is used to fine-tune information about entire dimensions. In this example, the user modified the minimum and maximum value of the "Vacation" dimension. This is all synchronised with the parallel coordinates visualisation. Before the modification, the dimension ranged from 6 to 30, as shown in (b). After the change, as shown in (c), it ranges from 0 to 100.

Many options are inherited in this hierarchy and can optionally be overridden. For example, the general colour to use for selected records can either be set globally on the General page or individually for each category of views. All option definitions and the currently chosen values are stored in `options.xml`. In addition, every *instance* of a view (that is, every single subwindow) has its own set of inherited options for temporary modification of options.

If, for example, a user opens a parallel coordinates visualisation and wants selected records to be displayed in green, then there are three ways to perform this task:

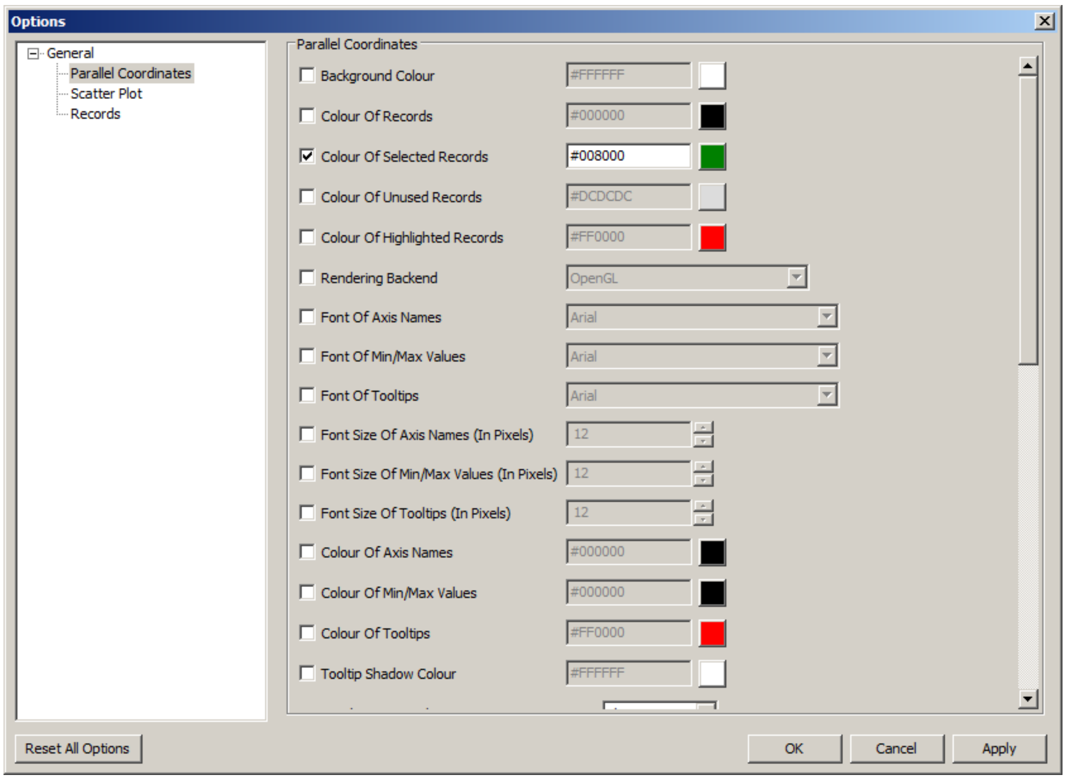
1. Open the options dialogue and change the Colour Of Selected Records option on the General page. This will lead not only to all parallel coordinates windows displaying green polylines but also all scatter plot windows displaying green dots and all records windows displaying green table rows for selected records.

2. Open the options dialogue, select the Parallel Coordinates entry and override the Colour Of Selected Records option *only* for parallel coordinates windows. Figure A.16 shows how to do this. By default, all inherited general options use the original value; in order to override an option and specify a custom colour, the check box to the left has to be clicked first. This will lead to all parallel coordinates windows displaying green polylines for selected records but not cause any change in the other windows.

3. Click the Options... button in the current parallel coordinates window and override the option there. This will lead to only the current window being affected. Other parallel coordinates windows, and parallel coordinates windows opened later, are not affected. The modification is not stored in `options.xml`, either. However, a user can always choose to make the change persistent and apply it to *all* parallel coordinates windows by clicking the Set As Default button.

In MDE, colours can be specified either by typing their hexadecimal RGB code or by clicking the coloured button on the right, which brings up a standard colour dialogue window. Fonts are specified by choosing a font name from a list.

For the parallel coordinates and scatter plot visualisation, the rendering backend can be chosen, too. However, the default OpenGL backend will usually suffice. The alternative, called "Standard Renderer", does not require OpenGL but will perform much slower. "OpenGL with anti-aliasing disabled" will usually not bring performance gains justifying the requisite loss of alpha transparency. The Reset All Options button is used to reset all options in MDE to the factory defaults.


Options

- General
  - Parallel Coordinates
  - Scatter Plot
  - Records

Parallel Coordinates

☐	Background Colour	#FFFFFF	⬜
☐	Colour Of Records	#000000	⬛
☑	Colour Of Selected Records	#008000	🟩
☐	Colour Of Unused Records	#DCDCDC	⬜
☐	Colour Of Highlighted Records	#FF0000	🟥
☐	Rendering Backend	OpenGL	
☐	Font Of Axis Names	Arial	
☐	Font Of Min/Max Values	Arial	
☐	Font Of Tooltips	Arial	
☐	Font Size Of Axis Names (In Pixels)	12	
☐	Font Size Of Min/Max Values (In Pixels)	12	
☐	Font Size Of Tooltips (In Pixels)	12	
☐	Colour Of Axis Names	#000000	⬛
☐	Colour Of Min/Max Values	#000000	⬛
☐	Colour Of Tooltips	#FF0000	🟥
☐	Tooltip Shadow Colour	#FFFFFF	⬜

Figure A.16: General options can be overridden in MDE's options dialogue window. This example shows the user overriding the colour of selected records specifically for parallel coordinates views. By default, values inherited from the General page are used; in order to override them, the check box to the left has to be clicked first. Colours can be specified either by typing their hexadecimal RGB code or by clicking the coloured button on the right, which brings up a standard colour dialogue window.

Appendix B

MDE Developer Guide

"What you write, and how you write it, can change your life."

[Beppe Severgnini, L'italiano – Lezioni semiserie, 2008, p.10[1]]

This guide is meant for future developers of Multi-Dimensional Explorer (MDE), a software application developed in 2011 by Christian Hackl for his Master's thesis ("Exploratory Data Analysis with Parallel Coordinates and the Multi-Dimensional Explorer") at Graz University of Technology. It explains how to add new visualisations to MDE using a concrete but simple example. The audience of this developer guide are *not* end users of MDE. End users should instead refer to the User Guide.

The example of a new (imaginary) visualisation discussed in this guide is as follows: *for each record, a horizontal line across the full window width is displayed, its vertical position depending on the first dimension's data value, its colour depending on whether the corresponding record is used (black), unused (grey) or selected (blue).* Figure B.1 shows the desired result. Note that this is not a real information visualisation technique (or at least not a very useful one); the example was chosen for its simplicity so that the developer guide can concentrate on programming aspects.

B.1 Development Environment Setup

MDE's source code is managed by the Subversion (SVN) version control software [Apache Software Foundation, 2011]. After a fresh checkout of the repository, the following subdirectories appear:

- `application/`
- `data/`
- `data/input`
- `options/`
- `presentation/`
- `presentation/structure/`
- `test/`

[1]Italian Original: "Quello che scrivete, e come lo scrivete, può cambiare la vostra vita." (English translation by the author of this thesis.)

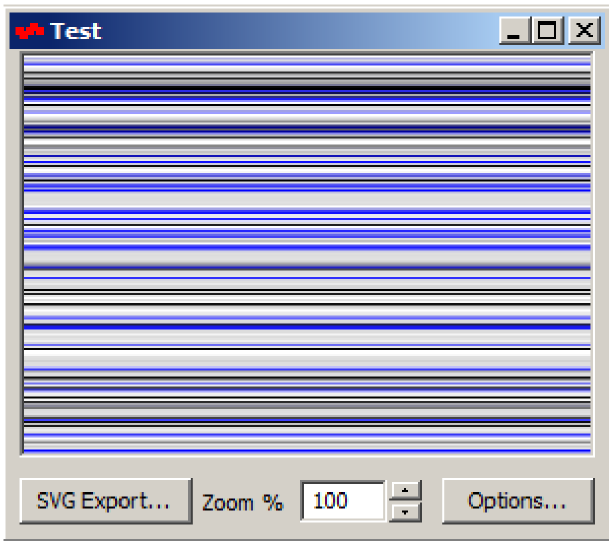


Figure B.1: An example of a new visualisation added to MDE. For each record of the data set, a horizontal line across the full window width is displayed, its vertical position depending on the first dimension's data value, its colour depending on whether the corresponding record is used (black), unused (grey) or selected (blue). This visualisation does not serve any practical purpose, but its simplicity makes it ideal for explaining the programming aspects of adding a new visualisation to MDE.

These contain the C++ source files of MDE (`.cpp` and `.h`), Microsoft Visual Studio project files (`.vcprojx`) as well as the Windows icon files (`.ico`) and Windows bitmap files (`.bmp`) needed by MDE's GUI frontend. Subdirectory `test` also contains `simple.csv` and a number of other plain-text files used by MDE's unit tests.

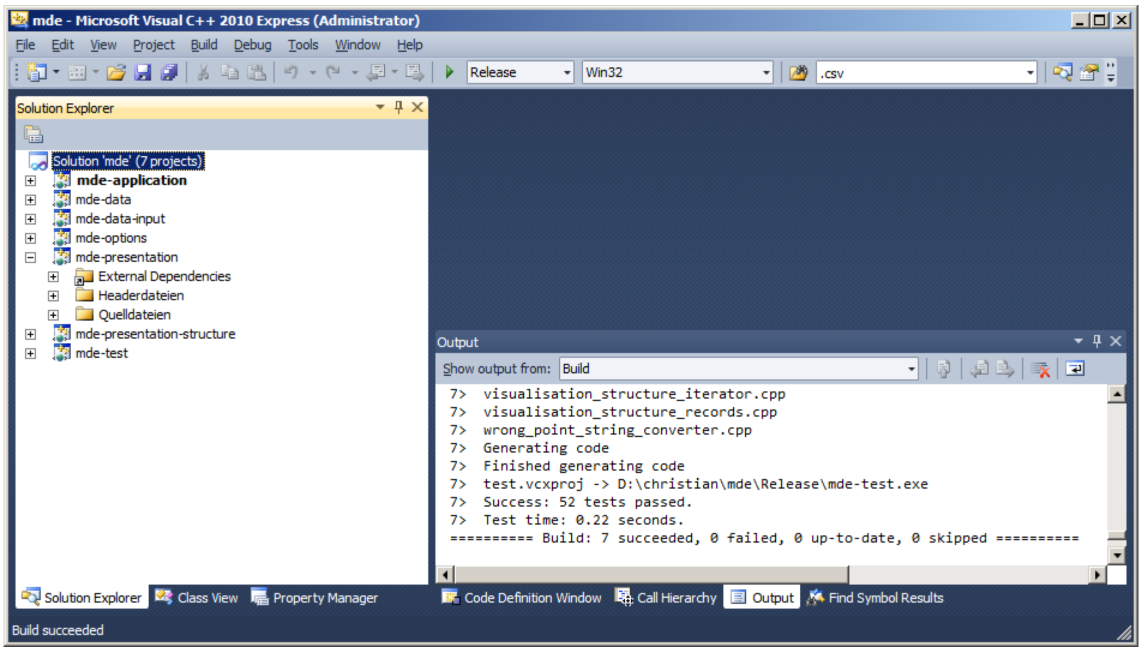
The root directory contains the Visual Studio solution file `mde.sln`, which can be used to quickly create MDE from scratch by opening it in Visual C++ 2010 [Microsoft, 2010b] and build the solution with one of the Release or Debug configurations. Before building MDE with the solution file provided, a developer must make sure that the following libraries are installed on his or her system:

- wxWidgets, version 2.8.11 [wxWidgets, 2010].
- Boost, version 1.43.0 [Boost, 2010].
- UnitTest++, version 1.4 [Llopis and Nicholson, 2011].
- FTGL, version 2.1.3 [Maddock, 2008].
- FreeType 2 [FreeType, 2010].
- TinyXML++, version 2.5.4 [Thomason et al., 2010].

The version numbers indicate those with which MDE was developed and tested. More recent versions may be used and should work if they are guaranteed to be backwards compatible.

It is necessary that all libraries mentioned above are built from source code. The reason for this requirement is that MDE itself is built with the non-default compiler switch `/MT` (Multi-Threaded Runtime Library). Therefore, any libraries used must have been built with the same compiler switch. Failure to do so will result in linker errors upon any attempt to build MDE.

SVN ignore lists have been set for all files and directories the build process might generate (such as various `Release` and `Debug` subdirectories, binaries or `.user` files). No attempts to commit any of those should be made.



```
7>  visualisation_structure_iterator.cpp
7>  visualisation_structure_records.cpp
7>  wrong_point_string_converter.cpp
7>  Generating code
7>  Finished generating code
7>  test.vcxproj -> D:\christian\mde\Release\mde-test.exe
7>  Success: 52 tests passed.
7>  Test time: 0.22 seconds.
========== Build: 7 succeeded, 0 failed, 0 up-to-date, 0 skipped ==========
```

Figure B.2: The Visual C++ development environment for MDE, after having opened the main solution file and performed a build with the Release configuration.

This guide assumes Microsoft Visual C++ Express Edition as the development environment. No full version of Microsoft Visual C++ is needed! Express Editions are provided free of charge by Microsoft and contain no technical restrictions in the compiler and debugger. Figure B.2 shows `mde.sln` opened in Visual C++ Express Edition 2010 and built with the Release configuration.

B.2 Preparing a New Visualisation

The new visualisation shall be named `TestVisualisation`, residing in namespace `presentation`, and it will be a subclass of `Visualisation`. Before implementing it, however, header and source files for it must be added to the solution. To do so, a developer first has to undertake these steps:

1. Create a header file called `test_visualisation.h` for the new visualisation in the `presentation` subdirectory. The easiest way to achieve this is to use the Solution Explorer, as shown in Figure B.3, by right-clicking on “Header Files” item of “mde-presentation” and selecting “Add” / “New Item”. In the dialogue window which appears, “Header File (.h)” must be chosen.

2. Create the associated source file `test_visualisation.cpp`, repeating the step from above but choosing instead the “Source Files” item of “mde-presentation” and choosing the “C++ File (.cpp)” entry in the dialogue window which appears. Due to wxWidgets’ reliance on platform-specific components in its implementation, it is imperative for this new source file to enable Microsoft’s language extensions, which are disabled by default in all files. This can be done on the file’s Language property page. Failure to do so will result in many seemingly unrelated compiler errors.

Listing B.1 is the header file for `TestVisualisation`. Listing B.2 is its source file. Note how the only requirement for the class is its constructor taking a `DataViewConstructionParameters` argument (because this is passed to the base constructor) and to implement the pure virtual private function `partiallyCreateVisualisation()`.

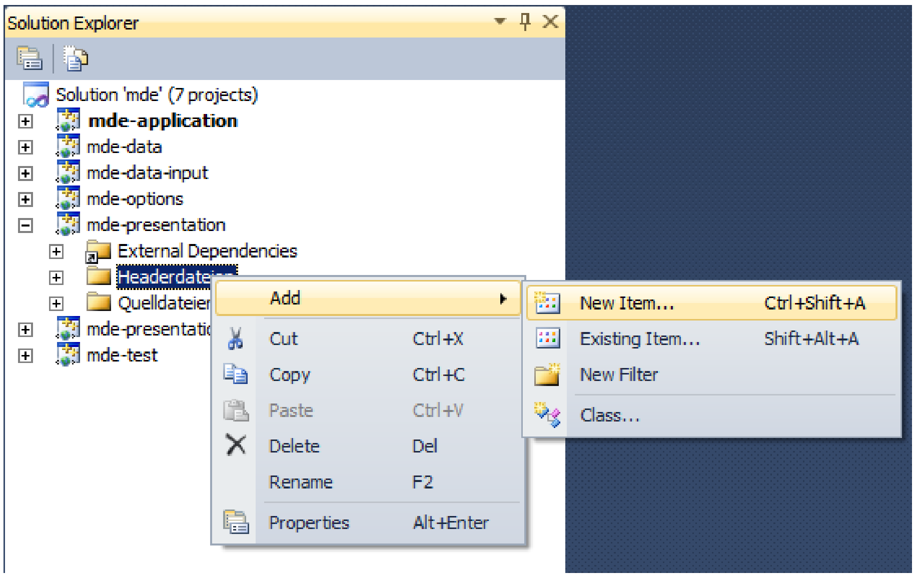


Figure B.3: The first step in adding a new visualisation to MDE is to create its header file in the Solution Explorer of Visual C++.

```cpp
#ifndef MDE_PRESENTATION_TEST_VISUALISATION_H_
#define MDE_PRESENTATION_TEST_VISUALISATION_H_

#include "visualisation.h"

namespace mde
{
  namespace presentation
  {
    class TestVisualisation : public Visualisation
    {
    public:
      TestVisualisation(DataViewConstructionParameters const &parameters)
          ;

    private:
      virtual void partiallyCreateVisualisation(int record_index);
    };
  }
}
#endif
```

Listing B.1: The header file for `TestVisualisation`. The class is derived from `Visualisation` and implements its pure virtual function `partiallyCreateVisualisation()`. The `DataViewConstructionParameters` parameter is just passed to the base constructor; `TestVisualisation` itself does not use it.

```
#include "test_visualisation.h"

namespace mde
{
  namespace presentation
  {
    TestVisualisation::TestVisualisation(DataViewConstructionParameters
        const &parameters) :
      Visualisation(parameters)
    {
    }

    void TestVisualisation::partiallyCreateVisualisation(int record_index
        )
    {
    }
  }
}
```

Listing B.2: The source file for `TestVisualisation`. The constructor passes `parameters` to the base constructor, while `partiallyCreateVisualisation()` currently does nothing. This is skeleton code for future `Visualisation`-derived MDE classes.

Now that the class exists, its existence must be made known to other components of MDE. `DataViewFactoryGroup` contains a list of all `DataView`-derived concrete classes. Including `TestVisualisation` there will automatically make it appear in MDE's main window tool bar and menu bar. In order to do so, a factory class producing `TestVisualisation` instances, derived from `DataViewFactory`, is required. The factory class will be called `TestVisualisationFactory`. Again, header files and source files as described above must be added to the Presentation project of the MDE solution.

The resulting factory code is shown in Listings B.3 and B.4. `withInstanceIndex()` is used so that MDE can keep track of the number of instances of a particular product. The list of option names created in the constructor and passed to the base factory class indicates which options `TestVisualisation` instances are going to use. It is important to include "rendering_backend" in the list, because every visualisation needs that option.

At this point, the factory class can be added to `DataViewFactoryGroup` by including its header file in `data_view_factory_group.cpp` and inserting a line in its constructor, pushing back a dynamically allocated instance of `TestVisualisationFactory` to `factories_`. The factory instance is never destroyed. This is on purpose! Developers should not falsely assume a memory leak here and attempt to needlessly delete the factories, because this can lead to dangerous order-of-destruction issues. Listing B.5 shows what the constructor of `DataViewFactoryGroup` looks like after the modification.

MDE now recognises the existence of the new visualisation in its user interface and displays appropriate buttons and items in its main window tool bar and menu, as shown in Figure B.4. Clicking on the tool bar and menu opens an empty window, as seen in Figure B.5. This is because `TestVisualisation` contains an empty implementation of `partiallyCreateVisualisation()`. The next section explains how to actually display something.

B.3 Implementing Visualisations

At this point, `TestVisualisation` has been created and embedded into MDE's graphical user interface. However, the visualisation does not yet display anything. To make graphics appear, its `partiallyCreate`

```
#ifndef MDE_PRESENTATION_TEST_VISUALISATION_FACTORY_H_
#define MDE_PRESENTATION_TEST_VISUALISATION_FACTORY_H_

#include "data_view_factory.h"

namespace mde
{
  namespace presentation
  {
    class TestVisualisationFactory : public DataViewFactory
    {
    public:
      TestVisualisationFactory();

    private:
      virtual DataView *doCreateDataView(DataViewConstructionParameters
          const &parameters);
      virtual std::string getName() const;
    };
  }
}
#endif
```

Listing B.3: The header file for `TestVisualisationFactory`. The class is derived from `DataViewFactory` and implements its pure virtual functions `doCreateDataView()` and `getName()`.

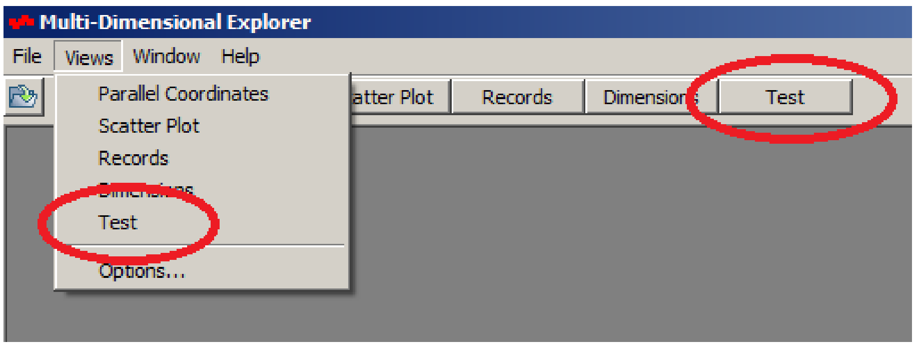


Figure B.4: The new visualisation in `TestVisualisation` automatically appears in MDE's tool bar and menu.

```cpp
#include "test_visualisation_factory.h"
#include "test_visualisation.h"
#include "data_view_construction_parameters.h"
#include <boost/assign/list_of.hpp>

namespace mde
{
  namespace presentation
  {
    TestVisualisationFactory::TestVisualisationFactory() :
      DataViewFactory(boost::assign::list_of
        ("records_colour")
        ("selected_records_colour")
        ("unused_records_colour")
        ("rendering_backend")
        ("background_colour")
      )
    {
    }

    DataView *TestVisualisationFactory::doCreateDataView(
        DataViewConstructionParameters const &parameters)
    {
      return new TestVisualisation(withInstanceIndex(parameters,
          productCounter()));
    }

    std::string TestVisualisationFactory::getName() const
    {
      return "Test";
    }
  }
}
```

Listing B.4: The source file for `TestVisualisationFactory`. The list of option names in the constructor of the factory indicates which options `TestVisualisation` instances are going to use.

```cpp
DataViewFactoryGroup::DataViewFactoryGroup() :
  factories_()
{
  factories_.push_back(new ParallelCoordinatesVisualisationFactory);
  factories_.push_back(new ScatterPlotVisualisationFactory);
  factories_.push_back(new RecordTableDataViewFactory);
  factories_.push_back(new DimensionTableDataViewFactory);
  factories_.push_back(new TestVisualisationFactory);
}
```

Listing B.5: The existence of `TestVisualisationFactory` is made known to the rest of MDE by allocating an instance of it in the constructor of `DataViewFactoryGroup` and adding it to its internal collection of factories. MDE will then automatically put appropriate items on its main window tool and menu bars.

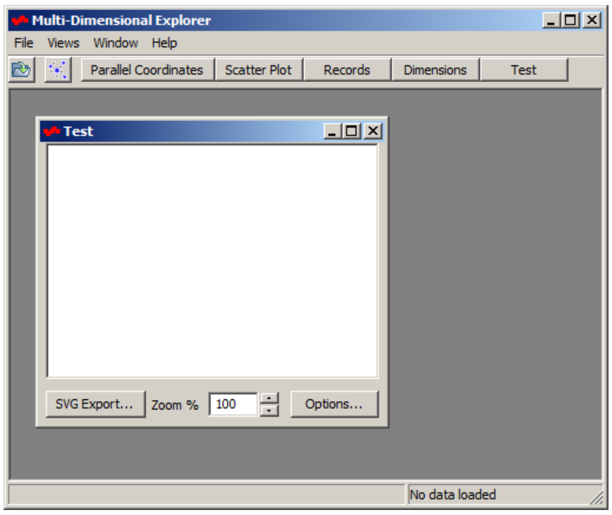


Figure B.5: With `partiallyCreateVisualisation()` doing nothing, `TestVisualisation` appears to the user as an empty window.

`Visualisation()` function must be implemented for real.

`partiallyCreateVisualisation()` is called by the `Visualisation` base class every time a record has to be rendered. The derived class, `TestVisualisation` in this example, uses the protected methods of `Visualisation` to implement the function, such as `drawLine()` or `drawRectangle()`. The input data to be visualised is accessed and can be modified via `dataHolder()`.

The goal of this guide is to create a visualisation displaying a horizontal line for every record. This requires four of `Visualisation`'s protected functions:

- `dataHolder()` to access the data.
- `drawLine()` to draw a line.
- `setStrokeColour()` to set a line's colour.
- `getOption()` to choose appropriate colours for different records.

Listing B.6 shows the source code for `TestVisualisation` to draw the corresponding lines.

This completes the developer guide. Other features of MDE graphics drawing are found in Christian Hackl's thesis and in the source code documentation. The implementations of `ParallelCoordinatesVisualisation` and `ScatterPlotVisualisation` serve as further reference.

```
#include "test_visualisation.h"
#include "../data/holder.h"

namespace mde
{
  namespace presentation
  {
    TestVisualisation::TestVisualisation(DataViewConstructionParameters
        const &parameters) :
      Visualisation(parameters)
    {
    }

    void TestVisualisation::partiallyCreateVisualisation(int record_index
        )
    {
      if (dataHolder().matrix().dimensionCount() > 0)
      {
        if (!dataHolder().isRecordUsed(record_index))
        {
          setStrokeColour(getOption("unused_records_colour"));
        }
        else if (dataHolder().matrix().recordState(record_index) == data
            ::Selected)
        {
          setStrokeColour(getOption("selected_records_colour"));
        }
        else
        {
          setStrokeColour(getOption("records_colour"));
        }

        drawLine(
          0.0, dataHolder().matrix().pointNormalised(data::DimensionIndex
              (0), record_index),
          1.0, dataHolder().matrix().pointNormalised(data::DimensionIndex
              (0), record_index)
        );
      }
    }
  }
}
```

Listing B.6: A complete example implementation for class `TestVisualisation`. Protected member functions of the base class are used to implement `partiallyCreateVisualisation()`, which is called individually for each record. `dataHolder()` accesses the input data, `setStrokeColour()` sets the line colour, `getOption()` determines appropriate colours for various record states, and `drawLine()` finally draws the line.

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