Information Visualisation

Course Notes

Version of 08 Mar 2024

Ao.Univ.-Prof. Dr. Keith Andrews

ISDS
Graz University of Technology
Inffeldgasse 16c
A-8010 Graz

kandrews@iicm.edu

https://courses.isds.tugraz.at/ivis/ivis.pdf

Contents

List of Figures

List of Tables

Preface

I first starting working on information visualisation in 1992 as part of my PhD thesis [Andrews 1996], continuing through my professorial thesis (Habilitation) [Andrews 2002b]. I helped organise the very first conference in the field, the IEEE Symposium on Information Visualization in 1995, was programme co-chair in 2001 and 2002, and general chair in 2005.

These lecture notes have evolved over many years of giving talks and teaching short courses on various aspects of information visualisation at conferences and for industry. I taught the first dedicated course on Information Visualisation at Graz University of Technology in summer semester 2005 and have also taught a version of the course at FH Joanneum in Graz, and at various conferences.

I would like to thank my students and colleagues past and present for their many suggestions and corrections, which have helped to massage these notes into their current form.

Thanks and happy reading,

Keith Andrews

Graz, Austria, 08 Mar 2024

Credits

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

- Figure 4.3 is used with kind permission of Steve Eick, Visual Insights.
- Figure 4.5 is used with kind permission of Tom Erickson.
- Figure 5.12 is used with kind permission of Young Hyun, CAIDA.
- Figure 5.18 is used with kind permission of John Stasko, Georgia Tech.
- Figure 5.13 is used with kind permission of Matthias Kreuseler, University of Rostock.
- Figure 5.15 is used with kind permission of Jack van Wijk, Eindhoven University of Technology.
- Figure 6.9 was scanned from an original photograph with kind permission of Kim Fairchild.
- Figure 7.2 is used under the terms of the Copyright Notice of the University of Maryland (see page xii).
- Figure 8.3 is used with kind permission of Pacific Northwest Naional Laboratory.

The following figures are used under the terms of the ACM Copyright Notice (see page xii):

- Figure 4.2, extracted from CHI '91. Human factors in computing systems conference proceedings on Reaching through technology, pages 173-176.
- Figure 4.4, extracted from CHI 96 Electronic Proceedings, Videos.
- Figure 7.11, extracted from CHI 94 Electronic Proceedings, Videos.
- Figure 7.3, extracted from CHI 97 Electronic Proceedings, Demos.
- Figure 8.2, from the SIGIR '92 Proceedings.

University of Maryland Copyright Notice

ACM Copyright Notice

Chapter 1

Introduction

“ *Let my dataset change your mindset.* ”

[Hans Rosling, title of talk at TED@State, 03 Jun 2009 [Rosling 2009].]

Information visualisation (InfoVis) is the visual presentation of abstract information spaces and structures, together with accompanying interactions, so as to facilitate their rapid assimilation and understanding.

Visualisation

The broader field of visualisation has three main sub-fields:

- *SciVis*: Scientific Visualisation (SciVis) typically involves concrete (3d) objects, for example a medical scan of part of the body, or a simulation of air flow around an aircraft wing. SciVis visualisations often depict flows, volumes, and surfaces in (3d) space.
- *GeoVis*: Geographic Visualisation (GeoVis) is map-based. The data typically has inherent 2d or 3d spatial coordinates, and is generally shown in relation to a map.
- *InfoVis*: Information Visualisation (InfoVis) deals with *abstract* information structures, such as hierarchies, networks, or multidimensional spaces.

Data Visualisation (DataVis) = InfoVis + GeoVis.

Visual Analytics = DataVis (frontend) + Analytics (backend).

Information Visualisation

InfoVis ≠ SciVis or GeoVis:

- In SciVis, the visual representation (geometry) is generally given, suggested by objects in the data. [Concrete objects, geometry is given.]
- In GeoVis, the visual representation (geometry) is generally given, determined by spatial coordinates within the data. [Spatial coordinates, geometry is given.]
- In InfoVis, an appropriate visual representation must be (carefully) designed or “invented”. [Abstract structures, geometry is *chosen*.]

Visual Representation + Interaction

- The visual representation is only half the story.
- Interaction (navigational and manipulation) facilities are the other half.

Two Main Purposes

Interactive data visualisations are used for two main purposes:

- *Analysis*: *Exploratory* visualisations help researchers to explore and analyse unfamiliar datasets.
- *Presentation*: *Explanatory* visualisations present results and insights to a wider audience.

For numerous examples of each kind, see my talk at TEDxGraz 2015 [Andrews 2015].

1.1 References

Books (InfoVis)

++ Tamara Munzner; *Visualization Analysis and Design*; CRC Press, 26 Nov 2014. ISBN 1466508914 (com, uk) [Munzner 2014] `https://cs.ubc.ca/~tmm/vadbook/` [4 physical copies and online full text via TUB.]

++ Ward, Grinstein, and Keim; *Interactive Data Visualization: Foundations, Techniques, and Applications*; 2nd Edition, CRC Press, 29 May 2015. ISBN 1482257378 (com, uk) [Ward et al. 2015] [1 physical copy in TUB.]

++ Tominski and Schuhmann; *Interactive Visual Data Analysis*; CRC Press, 30 Apr 2020. ISBN 0367898756 (com, uk) [Tominski and Schuhmann 2020]

++ Colin Ware; *Visual Thinking for Information Design*; 2nd Edition, Morgan Kaufmann, 14 Jul 2021. ISBN 0128235675 (com, uk) [Ware 2021]

\+ Colin Ware; *Information Visualization: Perception for Design*; 4th Edition, Morgan Kaufmann, 11 Mar 2020. ISBN 0128128755 (com, uk) [Ware 2020] [5 physical copies in TUB.]

\+ Bob Spence; *Information Visualization: An Introduction*; Springer, 3rd Edition, 14 Dec 2014. ISBN 3319073400 (com, uk) [Spence 2014] doi:10.1007/978-3-319-07341-5 [PDF + epub via TUB SpringerLink.]

\+ Alberto Cairo; *The Functional Art*; New Riders, 2012. ISBN 0321834739 (com, uk) [Cairo 2012] [Online full text via TUB.]

\+ Alberto Cairo; *The Truthful Art*; New Riders, 2016. ISBN 0321934075 (com, uk) [Cairo 2016] [Online full text via TUB.]

\+ Card, MacKinlay, Shneiderman; *Readings in Information Visualization : Using Vision to Think*; Morgan Kaufman, 1999. ISBN 1558605339 (com, uk) [Card et al. 1999]

Books (Practical Guides)

++ Stephen Few; *Show Me the Numbers*; 2nd Edition, Analytics Press, 01 Jun 2012. ISBN 0970601972 (com, uk) [Few 2012]

++ Stephen Few; *Now You See It: An Introduction to Visual Data Sensemaking*; 2nd Edition, Analytics Press, 15 Apr 2021. ISBN 1938377125 (com, uk) [Few 2021]

\+ Stephen Few; *Information Dashboard Design*; 2nd Edition, Analytics Press, 15 Aug 2013. ISBN 1938377001 (com, uk) [Few 2013]

\+ Cole Nussbaumer Knaflic; *Storytelling with Data*; Wiley, 02 Nov 2015. ISBN 1119002257 (com, uk) [Nussbaumer Knaflic 2015]

\+ Danyel Fisher and Miriah Meyer; *Making Data Visual: A Practical Guide to Using Visualization for Insight*; O'Reilly, 12 Jan 2018. ISBN 1491928468 (com, uk) [Fisher and Meyer 2018]

\+ Andy Kirk; *Data Visualisation*; 2nd Edition, Sage Publications, 08 Jul 2019. ISBN 1526468921 (com, uk) [Kirk 2019]

\+ Edward Tufte; *Seeing with Fresh Eyes*; Graphics Press, 2020. ISBN 1930824009 (com, uk) [Tufte 2020]

\+ Edward Tufte; *The Visual Display of Quantitative Information*; 2nd Edition, Graphics Press, 2001. ISBN 0961392142 (com, uk) [Tufte 2001]

\+ Edward Tufte; *Envisioning Information*; Graphics Press, 1990. ISBN 0961392118 (com, uk) [Tufte 1990]

\+ Edward Tufte; *Visual Explanations*; Graphics Press, 1997. ISBN 0961392126 (com, uk) [Tufte 1997]

◦ Edward Tufte; *Beautiful Evidence*; Graphics Press, 2006. ISBN 0961392177 (com, uk) [Tufte 2006]

◦ Robert Harris; *Information Graphics*; Oxford University Press, 2000. ISBN 0195135326 (com, uk) [Harris 2000]

Books (Applications)

◦ Julie Steele and Noah Iliinsky; *Beautiful Visualization: Looking at Data Through the Eyes of Experts*; O'Reilly, 21 Jun 2010. ISBN 1449379869 (com, uk) [Steele and Iliinsky 2010]

◦ James J. Thomas and Kristin A. Cook; *Illuminating the Path: The Research and Development Agenda for Visual Analytics*; 184-page report, August 2005. `http://nvac.pnl.gov/agenda.stm` ISBN 0769523234 (com, uk)

◦ Martin Dodge and Rob Kitchin; *Mapping Cyberspace*; Routledge, 2000. ISBN 0415198844 (com, uk) [Dodge and Kitchin 2000]

◦ Jin-Ting Zhang; *Visualization for Information Retrieval*; Springer, Nov 2007. ISBN 3540751475 (com, uk) [J.-T. Zhang 2007]

◦ Chaomei Chen; *Information Visualisation and Virtual Environments*; Springer, 1999. ISBN 1852331364 (com, uk) [Chen 1999]

◦ Chaomei Chen; *Information Visualization: Beyond the Horizon*; 2nd Edition, Springer, May 2006. ISBN 184628340X (com, uk)

◦ Vladimir Geroimenko and Chaomei Chen; *Visualizing the Semantic Web*, 2nd Edition; Springer, 2005. ISBN 1852339764 (com, uk) [Geroimenko and Chen 2005]

◦ Fayyad et al; *Information Visualization in Data Mining and Knowledge Discovery*; Morgan Kaufmann, 2001. ISBN 1558606890 (com, uk) [Usama Fayyad 2001]

◦ Richard Saul Wurman; *Information Architects*; Watson-Guptill, 1997. ISBN 1888001380 (com, uk)

[Wurman 1997]

- ◦ Alberto del Bimbo; *Visual Information Retrieval*; Morgan Kaufmann, 1999. ISBN 1558606246 (com, uk) [del Bimbo 1999]
- ◦ Jorg Blasius and Michael Greenacre; *Visualization of Categorical Data*; Academic Press, 1998. ISBN 0122990455 (com, uk) [Blasius and Greenacre 1998]
- ◦ Teuvo Kohonen, T. S. Huang, and M. R. Schroeder; *Self-Organizing Maps*; 3rd Edition, Springer, 2000. ISBN 3540679219 (com, uk) [Kohonen 2000]
- ◦ Okabe et al; *Spatial Tessellations*; 2nd Edition, Wiley, 2000. ISBN 0471986356 (com, uk) [Okabe et al. 2000]

Podcasts

- \+ Andy Kirk; *Explore Explain*; Video podcast. `https://visualisingdata.com/podcast/` `https://youtube.com/@explore_explain`
- \+ Enrico Bertini and Moritz Stefaner; *Data Stories*; Podcast about data visualisation. `datastori.es`
- \+ Jonathan Schwabish; *PolicyViz Podcast*; `https://policyviz.com/podcast/`
- \+ Cole Nussbaumer Knaflic; *Storytelling with Data Podcast*; `https://storytellingwithdata.com/podcast`
- \+ Alli Torban; *Data Viz Today*; Monthly podcast. `dataviztoday.com`

Online Resources

- ++ *Multiple Views: Visualization Research Explained*; `https://medium.com/multiple-views-visualization-research-explained`
- ++ Robert Kosara; *EagerEyes*; `eagereyes.org`
- ++ Reddit; *Data Is Ugly*; `https://reddit.com/r/dataisugly/`
- ++ Reddit; *Data Is Beautiful*; `https://reddit.com/r/dataisbeautiful/`
- \+ Andy Kirk; *Visualising Data*; `visualisingdata.com`
- \+ David McCandless; *Information is Beautiful*; `informationisbeautiful.net`
- \+ Nadieh Bremer; *Visual Cinnamon*; `visualcinnamon.com`
- \+ Neil Richards; *Questions in Dataviz*; `questionsindataviz.com`
- ◦ Cole Nussbaumer Knaflic; *Storytelling with Data*; `storytellingwithdata.com`
- ◦ Nathan Yau; *Flowing Data*; `flowingdata.com`
- \+ Makeover Monday; `makeovermonday.co.uk`
- ◦ Jonathan Schwabish; *HelpMeViz*; `https://policyviz.com/helpmeviz/`
- ◦ Datawrapper; *Datawrapper Blog*; `blog.datawrapper.de`

- Severino Ribeccar; *The Data Visualisation Catalogue*; Overview of chart types. `datavizcatalogue.com`
- ferdio; *Data Viz Project*; Overview of chart types. `datavizproject.com`
- Alberto Cairo; *The Functional Art*; `thefunctionalart.com`
- Manuel Lima; *Visual Complexity*; `visualcomplexity.com`
- Michael Friendly; *Gallery of Data Visualization*; `https://datavis.ca/gallery/`
- *InfoVis Wiki*; `infovis-wiki.net`
- *InfoVis.org Mailing List*; `https://infovis.org/pipermail/infovis/`

Journals

++ Information Visualization; Sage; ISSN 1473-8716 `https://journals.sagepub.com/home/ivi`

++ IEEE Computer Graphics and Applications; ISSN 0272-1716 `https://publications.computer.org/cga/`

++ IEEE Transactions on Visualization and Computer Graphics; ISSN 1077-2626 `https://publications.computer.org/tvcg/`

- Visual Informatics; ISSN 2468-502X `https://sciencedirect.com/journal/visual-informatics`
- Journal of Visualization and Interaction (JoVI); ISSN 2794-5502 `journalovi.org`

++ *Nightingale*; The Journal of the Data Visualization Society `nightingaledvs.com` [More magazine-style.]

Conferences

++ IEEE Vis. Formerly three separate co-located conferences: InfoVis, VAST, and SciVis. The first IEEE Symposium on Information Visualization (InfoVis) was in 1995. The main conference in the field, low acceptance rate (26% in 2023), very focussed, high quality papers. `ieeevis.org`
[The Vis conference talks are here: `https://youtube.com/c/IEEEVisualizationConference/`]

++ EuroVis (Eurographics/IEEE Symposium on Visualization). Since 1999, formerly VisSym. High quality, quite low acceptance rate (25% in 2021). `eurovis.org`
[The EuroVis 2023 are on YouTube and are linked from the programme: `https://conferences.eg.org/eurovis2023/for-attendees/program/`]

\+ Outlier. Annual Conference of the Data Visualization Society. More practitioner than academic. `outlierconf.com`
[The Outlier conference and other talks are here: `https://youtube.com/@DataVisualizationSociety/playlists`]

- IV (International Conference on Information Visualisation). Since 1997. Broad in scope, fairly high acceptance rate. `graphicslink.co.uk` Proceedings published with IEEE: `http://ieeexplore.ieee.org/xpl/conhome.jsp?punumber=1000370`
- PacificVis (IEEE Pacific Visualization Symposium). `pvis.org`
- Information+ Conference; `informationplusconference.com`
- See Conference, Germany. Largely German-speaking. `see-conference.org`

◦ IVAPP (International Conference on Information Visualisation Theory and Applications). ivapp.scitevents.org

◦ Some papers at CHI, AVI, UIST.

◦ OpenVis. Annual conference, open-source tools for datavis, held in Boston, USA [ran from 2013 to 2018]. openvisconf.com

Professional Organisations

++ Data Visualization Society; datavisualizationsociety.com
[20,000+ members and very active Slack channels (datavizsociety.slack.com after approval)]

Local Organisations

\+ On Data and Design Vienna; Many of the events are online. https://meetup.com/ondataanddesign-vienna/ ondataanddesign.com

InfoVis Companies

Suppliers of infovis toolkits and components:

- Tableau; tableau.com [Tableau was acquired by Salesforce on 01 Aug 2019 for $15.7 billion.]
- Qlik; qlik.com
- Microsoft Power BI; powerbi.microsoft.com
- Spotfire; https://tibco.com/products/tibco-spotfire [Spotfire was acquired by Tibco in May 2007 for $195 million.]
- Datawrapper; datawrapper.de
- Flourish; flourish.studio
- Inxight; https://web.archive.org/web/20080501144431/http://www.inxight.com/
[Initially spun off from Xerox, Inxight was acquired by BusinessObjects in May 2007. BusinessObjects was acquired by SAP in Oct 2007.]
- The Hive Group; hivegroup.com [The Hive Group was merged into Visual Action in Jan 2015.]
- Panopticon; panopticon.com
- macrofocus; macrofocus.com
- Maya Viz; mayaviz.com [Maya Viz was acquired by General Dynamics in Apr 2005.]
- OmniViz; omniviz.com [OmniViz was acquired by BioWisdom in Feb 2007. BioWisdom was acquired by Instem in Mar 2011.]
- AVS; avs.com
- NComVA; ncomva.com [NComVA was acquired by Qlik in 2013.]
- Advizor Solutions; advizorsolutions.com [Formerly Visual Insights, was renamed Advizor Solutions in 2003.]

- magnaview; `magnaview.com`
- Uncharted Software; `uncharted.software` [Formerly Oculus Info, was renamed Uncharted Software in 2015.]
- Tom Sawyer Software; `tomsawyer.com`
- yWorks; `yworks.com`
- ILOG; `ilog.com` [ILOG was acquired by IBM in Jan 2009.]
- Periscopic; `periscopic.com`
- Stamen Design; `stamen.com`
- datavisyn; in Linz; `datavisyn.io` [Located in Linz, Austria. Co-founded by Marc Streit and Alex Lex.]

Video: Stephen Few

- Stephen Few; *Now You See It*; 58-minute video [Few 2008] [14:12–27:00]

Video: Hans Rosling

- Hans Rosling; *Stats That Reshape Your World View*; 20-minute video [Rosling 2006] [00:00–18:54] [Video: `https://ted.com/talks/hans_rosling_the_best_stats_you_ve_ever_seen`]
- Demos are available at `gapminder.org`.
- Source code (Angular 6, Electron) is available from `https://github.com/Gapminder/gapminder-offline`

[Hans Rosling passed away on 07 Feb 2017.]

1.2 Why Visualise?

Table vs Line Chart

Compare the table of numbers in Table 1.1 with the visual representation (a line chart) of the same data in Figure 1.1.

- It is much easier to see trends and patterns in the visual representation.
- It is easier to make comparisons in the visual representation.
- It is easier to read off exact data values in the tabular representation (although you could, for example, display exact values upon mouseover in an interactive version of the line chart).

Attentive vs Pre-Attentive Processing

View Figure 1.2 and count the number of 3s. Then do the same with Figure 1.3.

- Text and numbers have to be processed attentively, which requires cognitive effort and proceeds in serial (slow).
- Certain visual attributes can be processed pre-attentively, which happens without conscious effort and in parallel (fast).

Month	*Salesperson A*	*Salesperson B*
2012-01	28366	23274
2012-02	27050	21732
2012-03	29463	23845
2012-04	32561	28732
2012-05	28050	24023
2012-06	30100	26089
2012-07	22343	19026
2012-08	21506	17903
2012-09	24664	19387
2012-10	28842	23490
2012-11	30621	25873
2012-12	36254	28490

Table 1.1: Sales for 2012 in € by salesperson (ficticious sales data). Compare the sales figures of the two salespeople. Can you spot a trend?

Figure 1.1: Sales for 2012 in € by salesperson. Line chart of the same sales data. It is much easier to see the trends and compare the data, when it is presented visually.

175496490872545628327267094621
635280462905702676727325929055
561548569586711934907152874596
596289748716229184490082538851
180265490932887579802909278921
872634890928895000283058985889
927756990049828005987761883115

Figure 1.2: Count the number of 3s. Attentive processing requires conscious effort and proceeds serially.

175496490872545628327267094621
635280462905702676727325929055
561548569586711934907152874596
596289748716229184490082538851
180265490932887579802909278921
872634890928895000283058985889
927756990049828005987761883115

Figure 1.3: Count the number of 3s. Colour is a pre-attentive attribute. By encoding the target 3s in red, they can be rapidly processed by the human visual system pre-attentively. Pre-attentive processing occurs without conscious effort and in parallel.

	v$_1$		**v$_2$**		**v$_3$**		**v$_4$**	
	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4
	10.00	8.04	10.00	9.14	10.00	7.46	8.00	6.58
	8.00	6.95	8.00	8.14	8.00	6.77	8.00	5.76
	13.00	7.58	13.00	8.74	13.00	12.74	8.00	7.71
	9.00	8.81	9.00	8.77	9.00	7.11	8.00	8.84
	11.00	8.33	11.00	9.26	11.00	7.81	8.00	8.47
	14.00	9.96	14.00	8.10	14.00	8.84	8.00	7.04
	6.00	7.24	6.00	6.13	6.00	6.08	8.00	5.25
	4.00	4.26	4.00	3.10	4.00	5.39	19.00	12.50
	12.00	10.84	12.00	9.13	12.00	8.15	8.00	5.56
	7.00	4.82	7.00	7.26	7.00	6.42	8.00	7.91
	5.00	5.68	5.00	4.74	5.00	5.73	8.00	6.89
mean	**9.00**	**7.50**	**9.00**	**7.50**	**9.00**	**7.50**	**9.00**	**7.50**
sd	**3.3166**	**2.0316**	**3.3166**	**2.0317**	**3.3166**	**2.0304**	**3.3166**	**2.0306**

Table 1.2: The four variables known as Anscombe's Quartet look almost identical if only standard summary statistics such as mean and standard deviation (sd) are considered.

Anscombe's Quartet

- Table 1.2 shows Francis Anscombe's 1973 dataset [Anscombe 1973; Wikipedia 2013; Kosara 2011] with four variables in x and y.
- Standard summary statistics such as mean and standard deviation are almost identical for all four variables.
- However, when plotted graphically, as shown in Figure 1.4, the four variables are revealed to be very different.

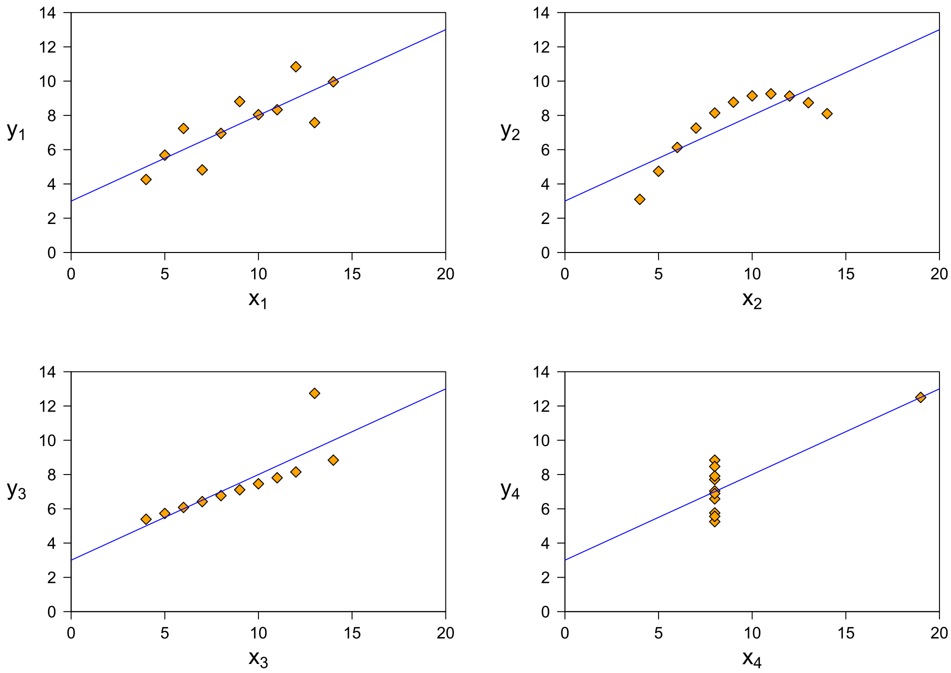


Figure 1.4: The four variables in Anscombe's Quartet have almost identical summary statistics (mean, standard deviation, etc.). However, when plotted graphically, they are revealed to be rather different in nature.

1.3 Visual Lies

Sometimes, visualisations can be (deliberately) deceptive or misleading.

Resources

++ Alberto Cairo; *How Charts Lie*; W. W. Norton, 15 Oct 2019. ISBN 1324001569 (com, uk) [Cairo 2019]

+ Alberto Cairo; *Graphics Lies, Misleading Visuals*; Chapter 5 of New Challenges for Data Design, 27 Dec 2014. [Cairo 2014]

+ Nathan Yau; *How to Spot Visualization Lies*; 09 Feb 2017. [Yau 2017]

+ Katie Notopoulos; *13 Graphs That Are Clearly Lying*; 03 Oct 2014. `https://buzzfeed.com/katienotopoulos/graphs-that-lied-to-us` [Notopoulos 2014]

+ *WTF Visualizations*; `viz.wtf` [WTF 2017]

+ Reddit; *Data is Ugly*; `https://reddit.com/r/dataisugly/`

◦ David Shere and Hannah Groch-Begley; *A History Of Dishonest Fox Charts*; `http://mediamatters.org/research/2012/10/01/a-history-of-dishonest-fox-charts/190225`

◦ Mushon Zer-Aviv; *Disinformation Visualization: How to Lie with DataVis*; 31 Jan 2014. [Zer-Aviv 2014]

+ Darrell Huff; *How to Lie with Statistics*; Reissue Edition, W. W. Norton, 17 Oct 1993. ISBN 0393310728

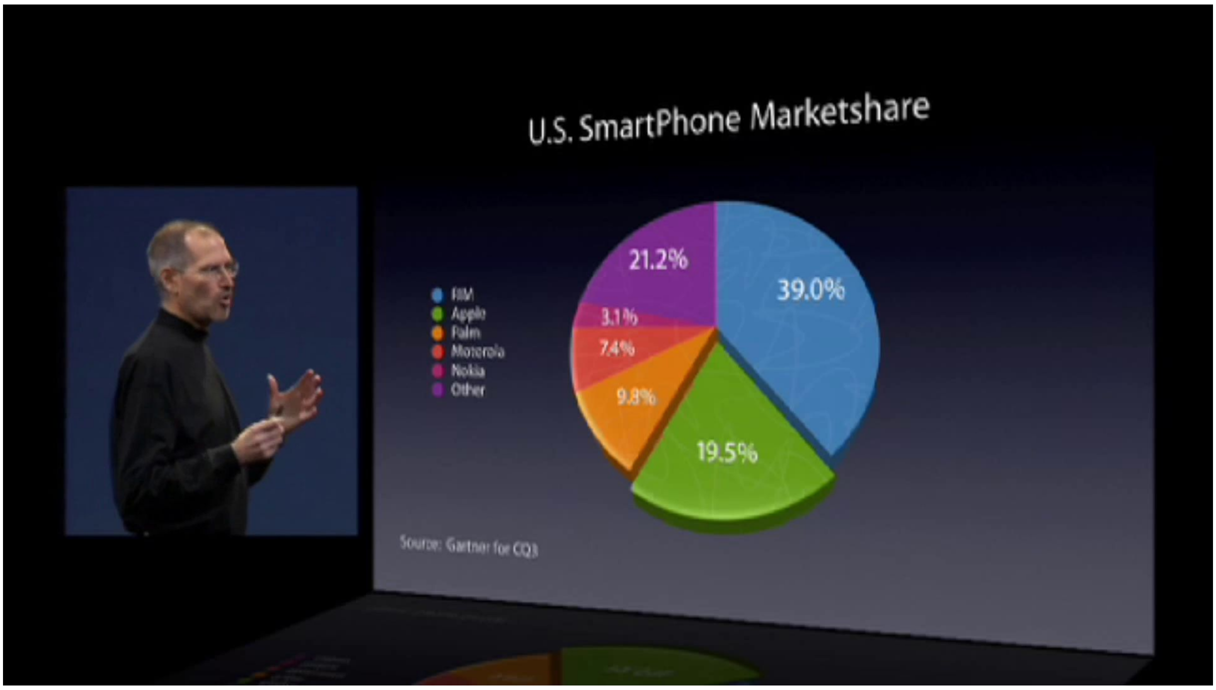


Figure 1.5: Steve Jobs' 3d pie chart [Jobs 2008, 00:09:42].

(com, uk) [Huff 1993]

Misuse of 3D Perspective

- Surely, no-one would ever misuse 3d perspective to give a false impression?
- In his Macworld 2008 keynote speech [Jobs 2008, 00:08:24], Steve Jobs showed a 3d pie chart of US smartphone market share data by brand. Figure 1.5 shows the original slide and Figure 1.6 is a reconstruction of Jobs' 3d pie chart. Table 1.3 shows the raw data in a table. [Video: `https://youtu.be/i9XU6wk_mWY?t=08m24s`]
- The "Apple" slice of 19.5% is at the bottom of the pie chart and is tilted towards the viewer, making it appear much larger than the "Other" slice of 21.2% at the top.
- A fairer representation would be to use a standard 2d pie chart (see Figure 1.7), or even better a bar chart (see Figure 1.8) of the same data.
- As Jack Schofield of the Guardian points out [Schofield 2008], the graphic is cleverly deceptive in at least two other ways as well:
  - Splitting market share by brand emphasises Apple. A more honest appraisal would be to split by operating system (OS), since certain OSes are used by several brands.
  - At the time, Symbian dominated the world smartphone market share, but was weak in the US, so showing only US data places Apple in the best light.

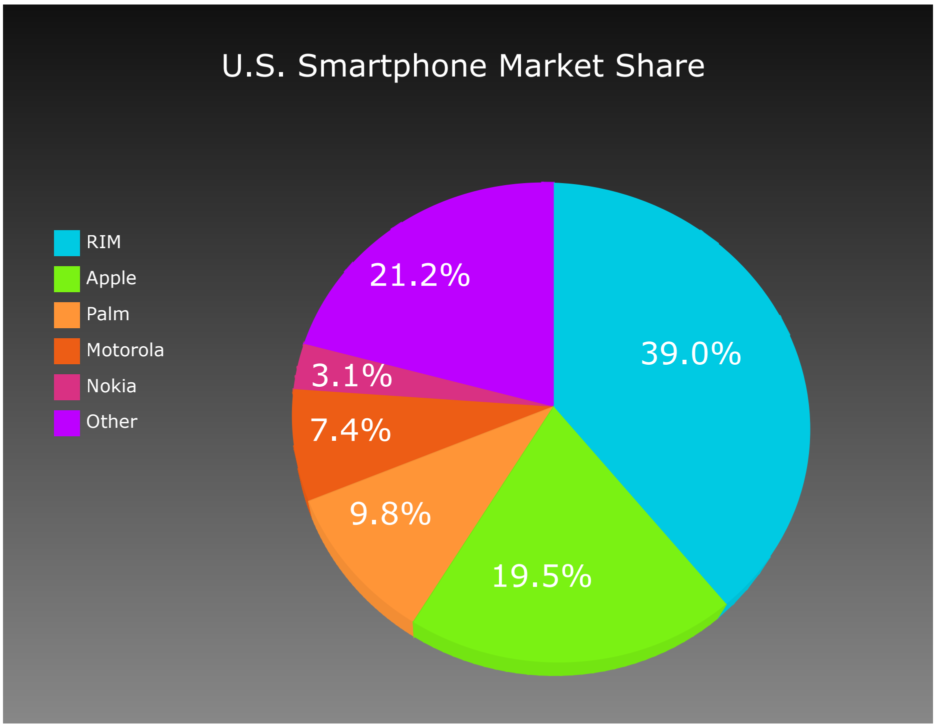


Figure 1.6: A reconstruction of Steve Jobs' 3d pie chart, with 3d perspective making the lower segment appear larger than it should. [Chart created by Keith Andrews with LiquidDiagrams [Andrews and Lessacher 2010].]

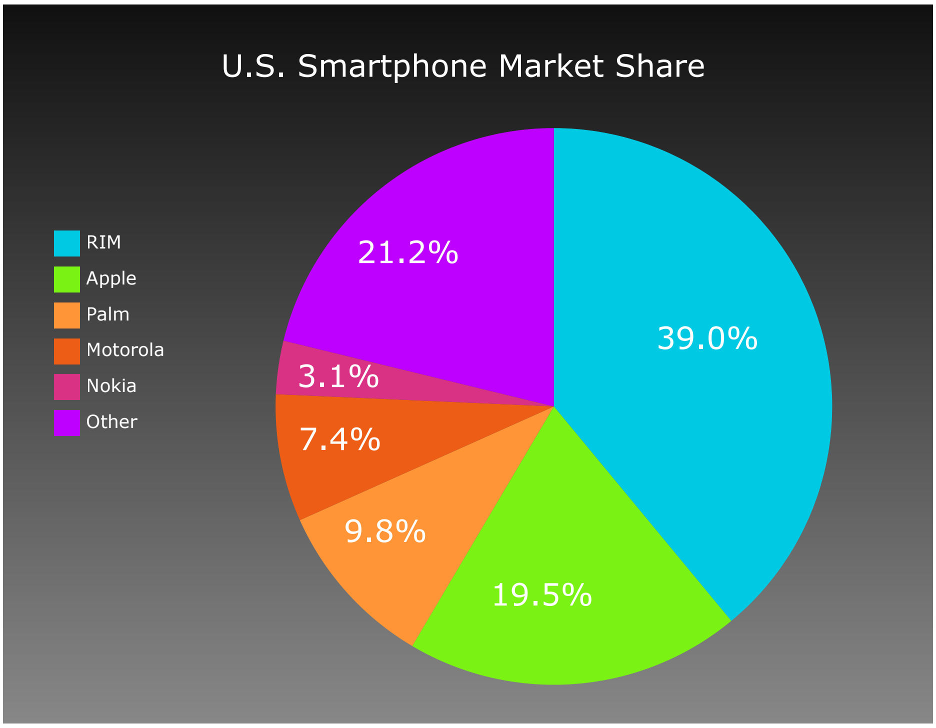


Figure 1.7: A standard, flat 2d pie chart of the data. [Chart created by Keith Andrews with LiquidDiagrams [Andrews and Lessacher 2010].]

Manufacturer	Market Share (%)
RIM	39.0
Apple	19.5
Palm	9.8
Motorola	7.4
Nokia	3.1
Other	21.2

Table 1.3: Steve Jobs' pie chart data showing U.S. smartphone market share for Q3 2007 as given by Gartner.

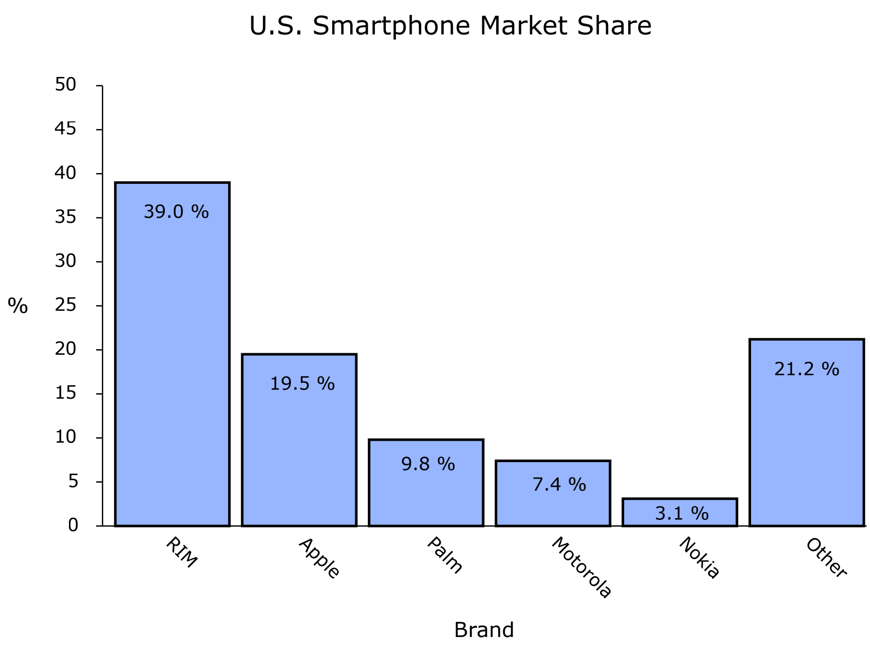


Figure 1.8: A bar chart of the data. [Chart created by Keith Andrews with LiquidDiagrams [Andrews and Lessacher 2010].]

Video: Noah Iliinsky

- Noah Iliinsky; *Data Visualizations Done Wrong*; ORDcamp 2012 Ignite Talk, 5-minute video [Iliinsky 2012] Clips from [Video: `https://youtu.be/lb7JaPIeEE4`].

1.4 General Concepts of Information Visualisation

General concepts which appear over and again in information visualisation.

Visualisation Pipeline

In Chapter 1 of their Readings volume, Card et al. [1999, page 17] describe a reference model for visualisation, shown in Figure 1.9:

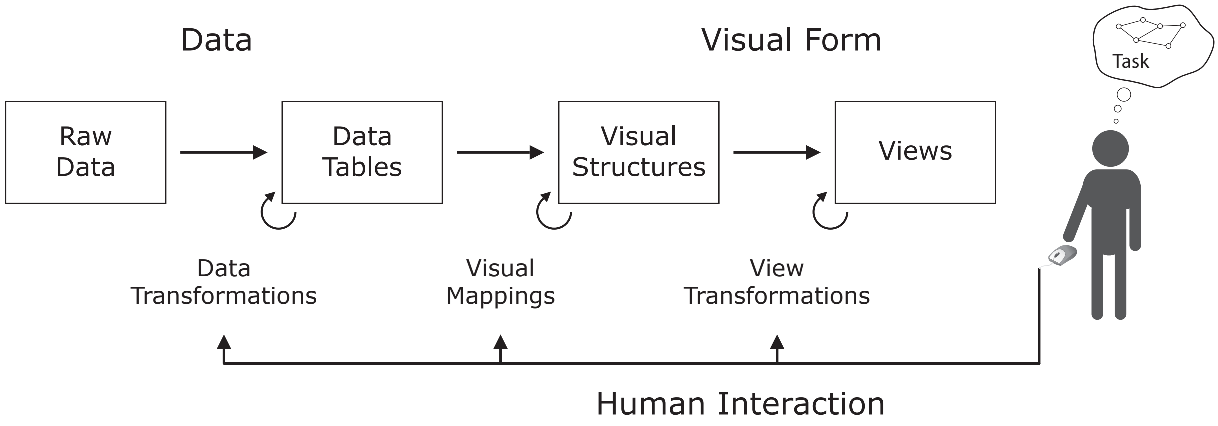


Figure 1.9: The visualisation pipeline. [Redrawn by Keith Andrews from the original in Card et al. [1999, page 17].]

- It describes the mapping of data to visual to support human interaction.
- It has become known as the visualisation pipeline.

The Information Visualisation Mantra

Ben Shneiderman's information visualisation mantra:

> "Overview, zoom and filter, details on demand"

Repeated ten times, once for each project where this principle was re-discovered. . .

From [Shneiderman 1996].

Utilising Human Visual Perception

Humans have remarkable perceptual abilities:

- to scan, recognise, and recall images rapidly.
- to rapidly and *automatically* detect patterns, outliers, and changes in size, colour, shape, movement, or texture.

Text-based interfaces require cognitive effort to understand their information content.

Information visualisation seeks to present information visually, in essence to offload cognitive work to the human visual perception system.

Visualisation + Interaction

- *Interaction*: being able to explore and manipulate the view is just as important as the underlying visual representation.
- *Object Constancy*: Smoothly animate transitions over about 1 sec. Eliminates the need for re-assimilation of the scene [Robertson et al. 1991a].

Focus-plus-Context

Focus on one or more areas of interest, while maintaining the surrounding context (but not in as much detail). Specific examples of focus-plus-context techniques include:

- *Overview-plus-Detail*: Two separate, but synchronised, windows or panes: an overview window (context) and a detail window (focus).
- *3d Perspective*: Focus items are in the foreground, with the context in the background.
- *Fisheye View*: A geometric distortion (like a magnifying glass) is applied over the area of interest [Furnas 1981; Furnas 1986]. The focus in the centre is enlarged, while the surrounding context is made smaller.
- *Focus-and-Blur*: Focus items are (optically) in focus, while context items are blurred.

Guaranteed Visibility

Landmarks in the visualisation which are important to the user's understanding remain visible at all times.

Edge Bundling

In node-link visualisations, there are sometimes so many edges that visual clutter results:

- Edge bundling [Holten 2006; Lhuillier et al. 2017] ties edges with similar paths together visually to reduce clutter.
- It is like applying cable ties to a bunch of computer network cables which follow the same path.
- In Figure 1.10, naive straight-line connections clutter the diagram.
- In Figure 1.11, edge bundling ties edges with similar paths together.

Excentric Labels

Sometimes, there is not enough room inside a visualisation to properly label individual elements:

- To avoid clutter, *excentric labels* [Fekete and Plaisant 1999; Welz 1999, pages 57 and 81] are drawn outside of the main visualisation and connected to the corresponding elements by lines.

See Figure 1.12.

Small Multiples

A *small multiple* is a table (lattice or grid) of charts or plots, using the the same axes and scale for comparision. For example:

- The term was coined by Tufte [2001, page 170] and defined as "... a series of graphics, showing the same combination of variables indexed by changes in another variable."
- For example, a scatterplot matrix is a table of scatterplots showing all pairwise combinations of variables, as shown in Figure 1.13.

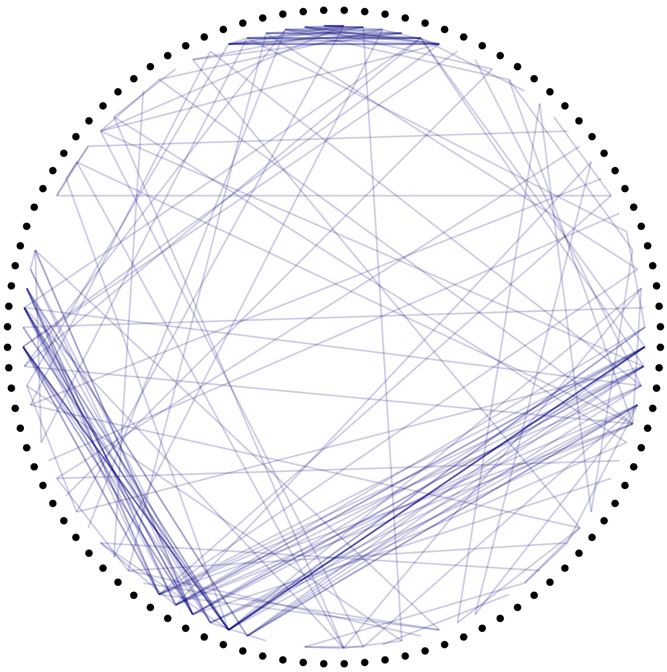


Figure 1.10: Naive straight-line connections. [Figure made by Keith Andrews using sample R code from Holtz [2017]] .

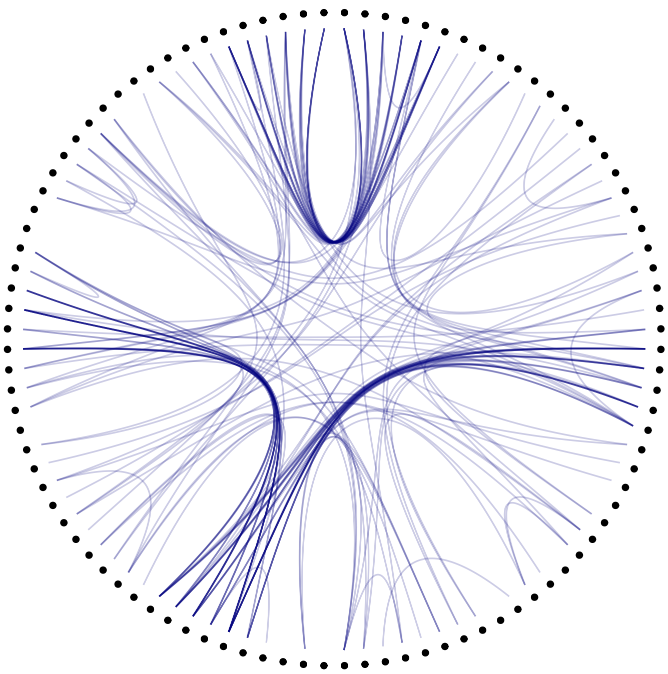


Figure 1.11: Edge bundling ties edges with similar paths together. [Figure made by Keith Andrews using sample R code from Holtz [2017]] .

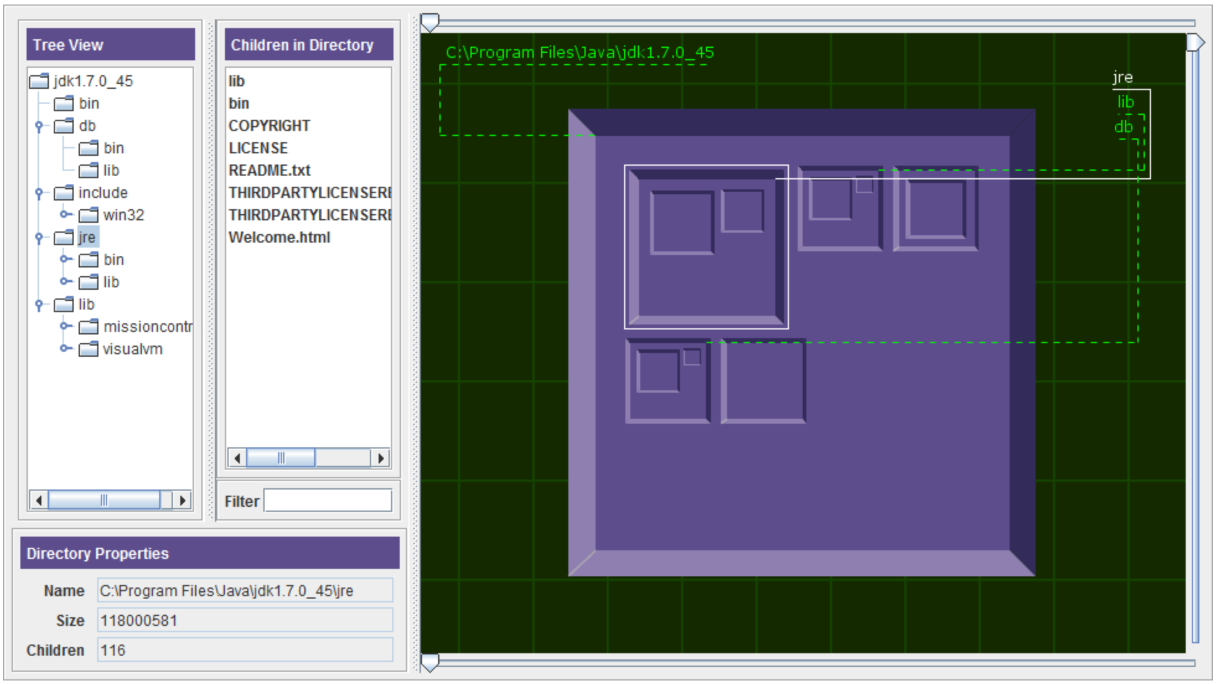


Figure 1.12: Excentric labels are drawn outside of the main visualisation and connected to the corresponding elements by lines. In the JExplorer tree browser, excentric labels are used to label the selected folder, its parent, and (some) siblings. [Screenshot made by Keith Andrews.]

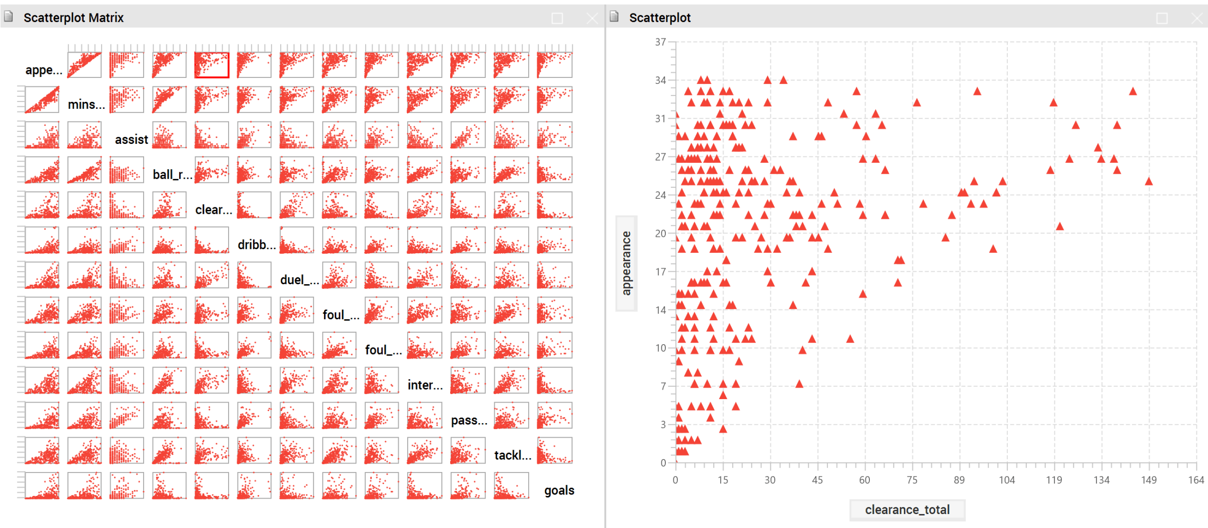


Figure 1.13: The scatterplot matrix on the left shows all pairwise combinations of 13 performance variables about players from 16 clubs in five top European leagues in the 2017/18 season. The scatterplot on the right shows number of appearances plotted against total clearances. Players are represented by red triangles. [Screenshot made by Keith Andrews using mVis [Chegini et al. 2019].]

1.5 Types of Information

- **Linear**: Tables, program source code, alphabetical lists, chronologically ordered items, etc.
- **Hierarchies**: Tree structures.
- **Networks**: General graph structures, such as hypermedia node-link graphs, semantic networks, webs, etc.
- **Multidimensional**: Metadata attributes such as type, size, author, modification date, etc. Items with n attributes become points in n-dimensional space.
- **Feature Spaces**: From information retrieval (IR), a *feature vector* represents each object in a collection. For collections of text documents, word frequencies are used to construct a term vectors. The feature space is projected to two or three display dimensions.
- **Query Spaces**: objects laid out according to their affinity with particular (combinations of) query terms.
- **[Spatial]**: Inherently 2d or 3d data such as floor plans, maps, CAD models, etc. with an obvious, natural geometric visual representation. [Not the focus of this course.]

Video: David McCandless

- David McCandless; *The Beauty of Data Visualization*; 18-minute video [McCandless 2010] [00:00–07:28, 17:09–17:54] [Video: https://ted.com/talks/david_mccandless_the_beauty_of_data_visualization]
- More examples of his work are at informationisbeautiful.net.

Video: Tamara Munzner

- Tamara Munzner; *Visualization Analysis and Design*; 6.5 hours of video, VAD course at UBC Oct 2021, with slides. [Munzner 2021]. https://cs.ubc.ca/~tmm/vadbook/#videos https://cs.ubc.ca/~tmm/talks/vad/VAD-2021.pdf
- The 22 prerecorded segments are also listed in this YouTube playlist: https://youtube.com/playlist?list=PLT4XLHmqHJBeB5LwmRmo6ln-m7K3lGvrk
- Other talks and materials here: https://cs.ubc.ca/~tmm/vadbook/

Chapter 2

Visual Perception

“ We see more with our mind than our eyes. ”

[Connie Malamed, Visual Language for Designers, 2009 [Malamed 2009, page 25]]

References

++ Colin Ware; *Visual Thinking for Design*; 2nd Edition, Morgan Kaufmann, 14 Jul 2021. ISBN 0128235675 (com, uk) [Ware 2021]

++ Colin Ware; *Information Visualization: Perception for Design*; 4th Edition, Morgan Kaufmann, 11 Mar 2020. ISBN 0128128755 (com, uk) [Ware 2020]

++ Christopher Healey and James Enns; *Attention and Visual Memory in Visualization and Computer Graphics*; IEEE Transactions on Visualization and Computer Graphics (TVCG), Jul 2012. doi:10.1109/TVCG.2011.127 [C. G. Healey and Enns 2012]

\+ Stephen Few; *Tapping into the Power of Visual Perception*; Chapter 5 of *Information Dashboard Design*; 2nd Edition, Analytics Press, 15 Aug 2013. ISBN 1938377001 (com, uk) [Few 2013, Chapter 5]

\+ Connie Malamed; *Visual Language for Designers: Principles for Creating Graphics That People Understand*; Rockport Publishers, Jun 2009. ISBN 1592537413 (com, uk) [Malamed 2009]

\+ Christopher Chabris and Daniel Simons; *The Invisible Gorilla: And Other Ways Our Intuition Deceives Us*; Harper Collins, Mar 2011. ISBN 000731731X (com, uk) [Chabris and Simons 2011b]

◦ Richard Gregory; *Eye and Brain*; 5th Edition, Princeton University Press, 1997. ISBN 0691048371 (com, uk) [Gregory 1997]

◦ Brian Wandell; *Foundations of Vision*; Sinauer Associates, 1995. ISBN 0878938532 (com, uk) [Wandell 1995]

◦ Bruce, Green, and Georgeson; *Visual Perception*; 4th Edition, Psychology Press, 2003. ISBN 1841692379 (com, uk) [Bruce et al. 2003]

Online Resources

++ Christopher Healey; *Perception in Visualization*; `https://www.csc2.ncsu.edu/faculty/healey/PP/` [C. Healey 2009]

++ Stephen Few; *Tapping the Power of Visual Perception*; Blog article, 04 Sept 2004. https://perceptualedge.com/articles/ie/visual_perception.pdf [Few 2004]

++ Stephen Few; *Data Visualization for Human Perception*; Chapter 35 of The Encyclopedia of Human-Computer Interaction, 2nd Ed, 2014. https://interaction-design.org/encyclopedia/data_visualization_for_human_perception.html [Few 2014]

∘ Steven Bradley; *What Designers Should Know About Visual Perception and Memory*; Blog article, 07 Mar 2011 https://vanseodesign.com/web-design/visual-perception-memory/ [Bradley 2011]

Bandwidth of the Senses

- based on work by Tor Nørretranders.
- McCandless [2010, 00:09:05–00:09:54] TED 2010 video. [Video: https://youtu.be/5Zg-C8AAIGg?t=09m10s]

2.1 Human Vision

The eyes sample the environment 3–4 times per second, building up a picture of what is there in our mind:

- Fixation: a brief stationary period when visual information is sampled.
- Saccade: a period of rapid eye movement to a new location.

  [Video: https://dailymotion.com/video/x6md3za?start=2006]

  We actually see with our mind:

- What we see depends not only on what is actually there, but also on what we expect to see and where our attention is directed.
- "What you see is what you need"

Selective Attention

We perceive only what the mind attends to:

- Selective Attention Test (basketball passes) by Dan Simons and Chris Chabris [Simons and Chabris 1999a; Chabris and Simons 2011b; Chabris and Simons 2011a].
- Original video [Simons and Chabris 1999b] [Video: https://youtu.be/vJG698U2Mvo].
- Based on on work originally done by Ulric Neisser at Cornell University in the 1970s [Bazerman and Tenbrunsel 2016; Neisser 1979].
- The Door Study (workmen with door) by Dan Simons and Dan Levin [Simons and Levin 1998a; Simons and Levin 1998b] [Video: https://youtu.be/FWSxSQsspiQ]. BBC door experiment [Video: https://dailymotion.com/video/x6md3za?start=2620].
- Multi-Colour Card Trick by Richard Wiseman [Wiseman 2008] [Video: https://youtu.be/5HkGSrY1N9Y].

Colour Perception

Colour perception is influenced, among other things, by:

- (Assumed) prescence of shadows. [Video: https://youtu.be/XGG01xTYSoo?t=1s] [Video: https://youtu.be/z9Sen1HTu5o?t=24s]
- (Assumed) colour of light sources. [Video: https://youtu.be/uBSXjMIOUls] [Video: https://youtu.be/kc1GjIAFdMA]

Depth Perception

- Perspective, chair.
- Perspective, room.
- Perspective, rail lines. [Video: https://dailymotion.com/video/xq1rfl?start=736]

2.2 Visual Input Takes Priority

- Sight overrides hearing (McGurk effect). [Video: https://youtu.be/G-1N8vWm3m0?t=26s]
- Sight can override touch (rubber hand). [Video: https://youtu.be/Qsmkgi7FgEo?t=01m40s]

Visual Working Memory

The capacity of visual working memory is limited to 3–4 simple shapes [Vogel et al. 2001].

2.3 Preattentive Processing

Certain visual attributes can be processed preattentively (in parallel rather than serially) by the human visual system.

They "pop out" of the screen at you (without conscious effort).

When a visual target is encoded using a preattentive attribute, the time to locate it remains constant, regardless of the number of distractors.

Preattentive Attributes (Pop-Out Features)

The following attributes are pre-attentive:

- Colour hue (see Figure 2.1).
- Colour intensity (luminance) (see Figures 2.2 and 2.3).
- Line length (see Figure 2.4).
- Line width (see Figure 2.5).
- 2d spatial position (see Figure 2.6).

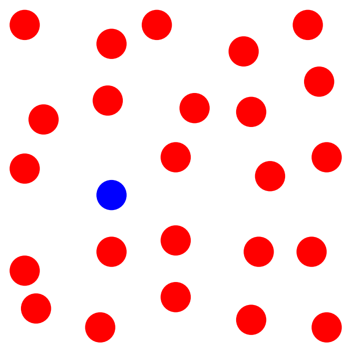


Figure 2.1: Colour hue is preattentive.

- Orientation (see Figure 2.7).
- Size (see Figure 2.8).
- Shape (see Figure 2.9).
- Added mark (see Figure 2.10).
- Enclosure (see Figure 2.11).
- Lack of enclosure (see Figure 2.12).
- Curvature (see Figure 2.13).
- Focus and blur (see Figure 2.14).
- 3d depth (see Figure 2.15).
- Flicker (blinking) (see Figure 2.16).
- Velocity of motion (see Figure 2.17).
- Direction of motion (see Figure 2.18).

  Some preattentive attributes are perceived more readily (are perceptually stonger) than others.

Conjunctions

Beware when using multiple encodings in one display:

- Most preattentive attributes cannot be combined while still remaining pre-attentive.
- Conjunctions of motion, depth, colour hue, and orientation remain pre-attentive.

  See Figures 2.19 and 2.20.

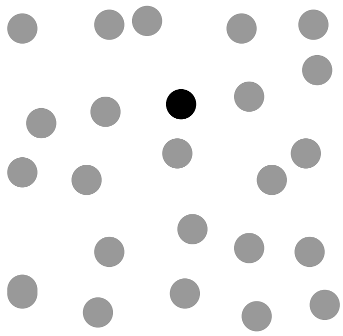


Figure 2.2: Colour intensity is preattentive.

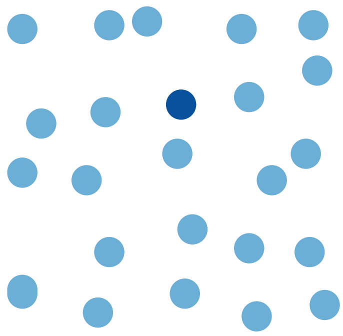


Figure 2.3: Colour intensity is preattentive.

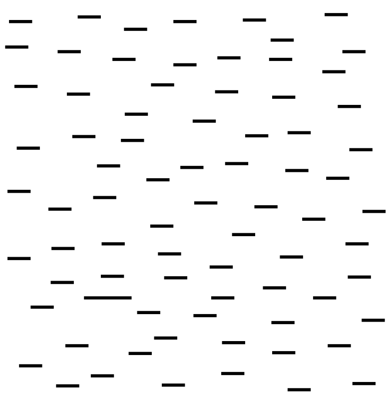


Figure 2.4: Line length is preattentive.

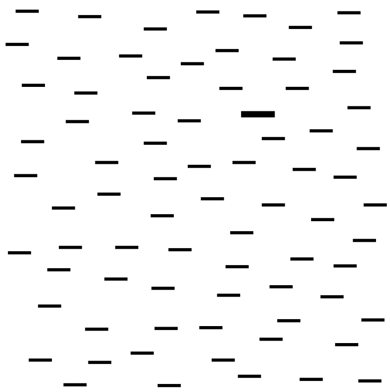


Figure 2.5: Line width is pre-attentive.

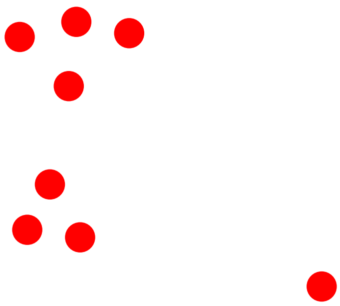


Figure 2.6: 2D spatial position is preattentive.

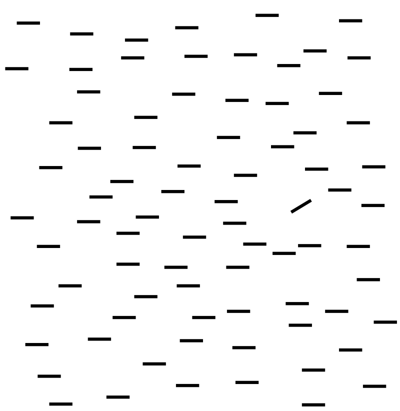


Figure 2.7: Orientation is preattentive.

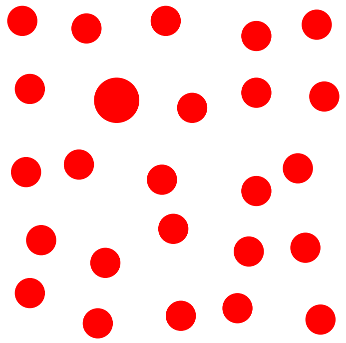


Figure 2.8: Size is preattentive.

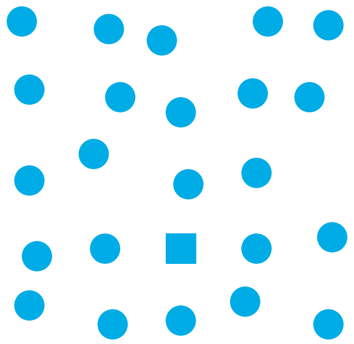


Figure 2.9: Shape is preattentive.

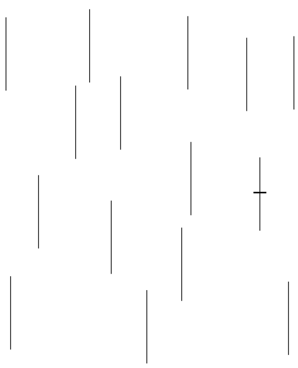


Figure 2.10: An added mark is preattentive.

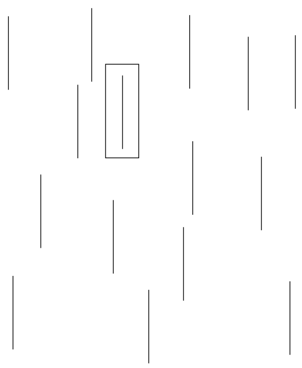


Figure 2.11: Enclosure is preattentive.

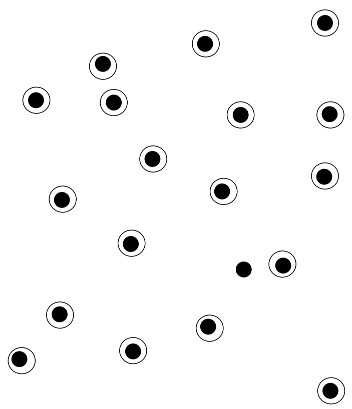


Figure 2.12: Lack of enclosure is preattentive.

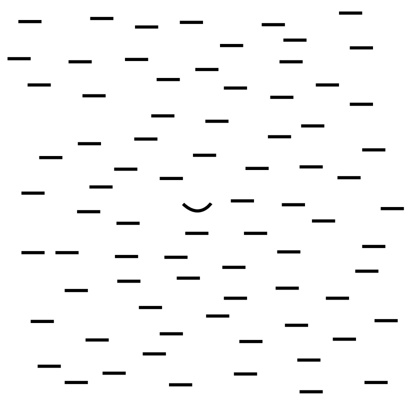


Figure 2.13: Curvature is preattentive.

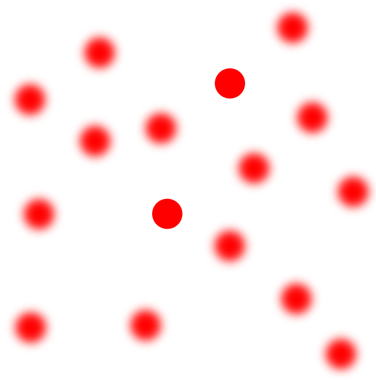


Figure 2.14: Focus and blur is preattentive.

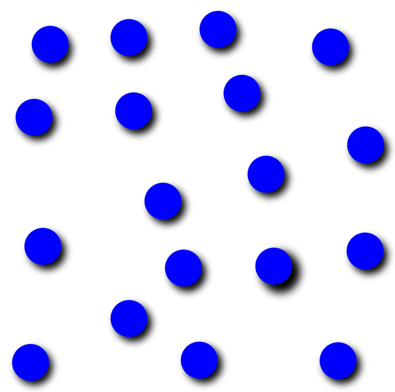


Figure 2.15: 3d depth is preattentive.

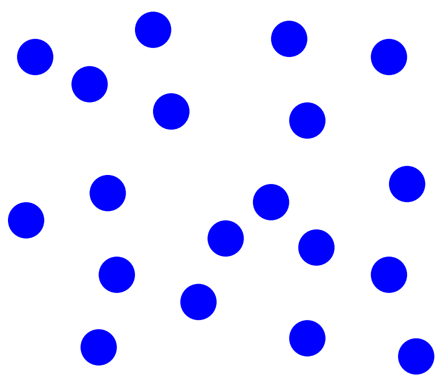


Figure 2.16: Flicker (blinking) is preattentive. [Figure is interactive, only works in HTML slides.]

Figure 2.17: Velocity of motion is preattentive. [Figure is interactive, only works in HTML slides.]

Figure 2.18: Direction of motion is preattentive. [Figure is interactive, only works in HTML slides.]

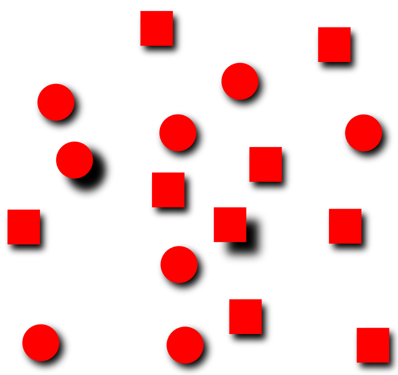


Figure 2.19: The conjunction of shape and depth remains preattentive.

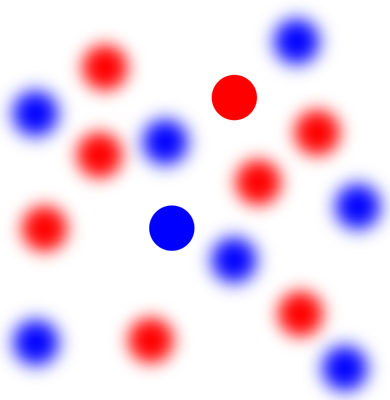


Figure 2.20: The conjunction of blur and colour hue remains preattentive.

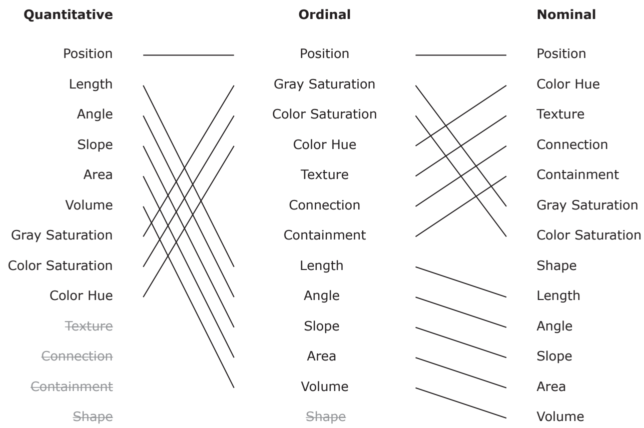


Figure 2.21: Some visual encodings work better than others, depending on the type of data. Encodings higher in each list are perceived more accurately. [Redrawn by Keith Andrews from Mackinlay [1988, Figure 9].]

2.4 Visual Encoding

References

++ Stephen Few; *The Visual Perception of Variation in Data Displays*; Visual Business Intelligence Newsletter, Oct 2016. `https://perceptualedge.com/articles/visual_business_intelligence/the_visual_perception_of_variation.pdf`

+ Jock Mackinlay; *Applying a Theory of Graphical Perception to the Graphic Design of User Interfaces*; Proc. UIST 1988. [Mackinlay 1988].

+ Peter Aldhous; *Data Visualization: Basic Principles*; `https://peteraldhous.com/ucb/2017/dataviz/week2.html`

Encoding Quantitative Values

Only two of the preattentive attributes can be perceived quantitatively with any accuracy:

- Line length.
- 2d spatial position.

Only these two can be used to accurately encode continuous quantitative numerical values, for example:

- location on a line graph (2d spatial position).
- location on a scatter plot (2d spatial position).
- length of a bar in a bar graph (line length).

Perceiving Continuous Differences

Differences in colour intensity and size can be perceived to a limited degree:

- one shade of grey is lighter than another
- one circle is larger than another

but not by how much.

It is hard to compare them accurately on a continuous scale:

- This shade of grey is 10% lighter than that one.
- This slice of a pie chart is 5% smaller than that one.

In practice, about 5 distinct shades of gray (or intensities of any single colour hue) can be distinguished.

Encoding Categories

Some preattentive attributes are more naturally non-continuous.

The following preattentive attributes are particulary useful for encoding discrete categories:

- Colour hue (palette).
- Shape (fixed number of distinct glyphs).

Perceptually Distinguishable Colour Palettes

Choose colours from a HCL colour space `hclwizard.org` rather than HSV [Aisch 2011].

But, nowadays, use the oklch colour space:

- Geoff Graham; *Falling For Oklch: A Love Story Of Color Spaces, Gamuts, and CSS* Smashing Magazine, 28 Aug 2023. `https://smashingmagazine.com/2023/08/oklch-color-spaces-gamuts-css/`
- Andrey Sitnik and Travis Turner; *OKLCH in CSS: why we moved from RGB and HSL* 25 Oct 2022. `https://evilmartians.com/chronicles/oklch-in-css-why-quit-rgb-hsl`
- Cameron Chapman; *Color Theory For Designers, Part 2: Understanding Concepts And Color Terminology* Smashing Magazine, 20 May 2021. `https://smashingmagazine.com/2010/02/color-theory-for-designers-part-2-understanding-concepts-and-terminology/`

Chapter 3

History of Information Visualisation

References

++ Sandra Rendgen; *History of Information Graphics*; Taschen, 08 May 2019. ISBN 3836567679 (com, uk) [Rendgen 2019]

++ Michael Friendly and Howard Wainer; *A History of Data Visualization and Graphic Communication*; Harvard University Press, 08 Jun 2021. ISBN 0674975235 (com, uk) [Friendly and Wainer 2021]

++ Isabel Meirelles; *Design for Information*; Rockport, 01 Oct 2013. ISBN 1592538061 (com, uk) [Meirelles 2013]

\+ Theodore W. Pietsch; *Trees of Life*; Johns Hopkins University Press, 02 May 2013. ISBN 1421411857 (com, uk) [Pietsch 2013]

\+ Manuel Lima; *The Book of Trees*; Princeton Architectural Press, 08 Apr 2014. ISBN 1616892188 (com, uk) [Lima 2014]

\+ Kruja et al; *A Short Note on the History of Graph Drawing*; Proc. Graph Drawing (GD 2001). [Kruja et al. 2002]

\+ Jacques Bertin; *Semiology of Graphics*; ESRI Press, 2010. ISBN 1589482611 (com, uk) [Bertin 2010] [Reprint]

\+ Jacques Bertin; *Sémiologie graphique*; Editions de l'Ecole des Hautes Etudes en Sciences, 1999. ISBN 2713212774 (com, uk) [Bertin 1999] [In French]

Online Resources

++ Michael Friendly and Daniel J. Denis; *Milestones in the History of Thematic Cartography Statistical Graphics, and Data Visualization*; 2018. `https://datavis.ca/milestones/`

◦ Pat Hanrahan; *To Draw a Tree*; InfoVis 2001 keynote talk, Oct 2001. `https://graphics.stanford.edu/~hanrahan/talks/todrawatree/`

3.1 Diderot and d'Alembert

- Denis Diderot and Jean le Rond d'Alembert, 1751.

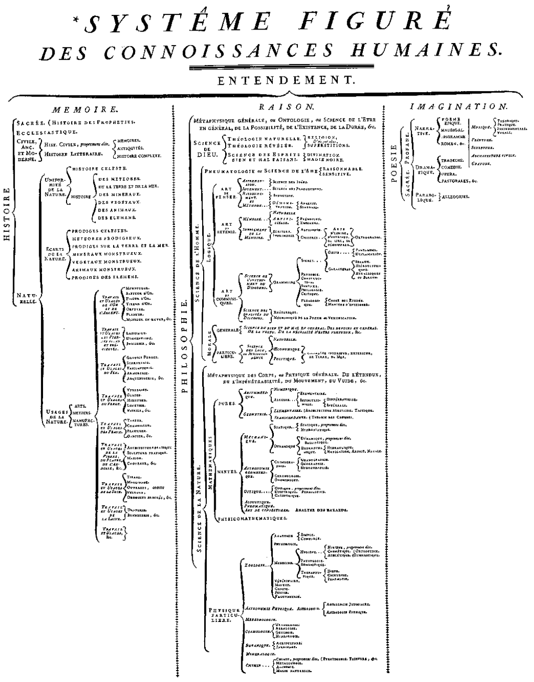


Figure 3.1: The tree of Diderot and d'Alembert. [Image from Wikimedia Commons [Diderot and le Rond d'Alembert 1751c]]

- A taxonomy of human knowledge, called the "Figurative System of Human Knowledge".
- Inspired by Francis Bacon's taxonomy from 1620 [Bacon 1620].
- Also known as "The tree of Diderot and d'Alembert" [Diderot and le Rond d'Alembert 1751b].
- The top three branches are Memory, Reason, and Imagination.

Figurative System of Human Knowledge (1751)

- Produced as the table of contents for the "Encyclopedia, or a systematic dictionary of the sciences, arts, and crafts" published in 1751 [Diderot and le Rond d'Alembert 1751a].
- Shown in Figure 3.1.

3.2 Joseph Priestley

Joseph Priestley was an English scientist and theologian:

- He produced some of the first timeline charts [Sheps 1999].
- In 1765, he produced his Chart of Biography, a historical timeline of around 2000 people, divided into six horizontal bands (categories) such as "Poets and Artists", "Mathematicians and Physicians", and "Statesmen and Warriors".
- In 1769, he produced the New Chart of History, shown in Figure 3.2. It spans 3000 years of history from 1200 BC to 1800 AD with 16 horizontal bands corresponding to geographical regions.

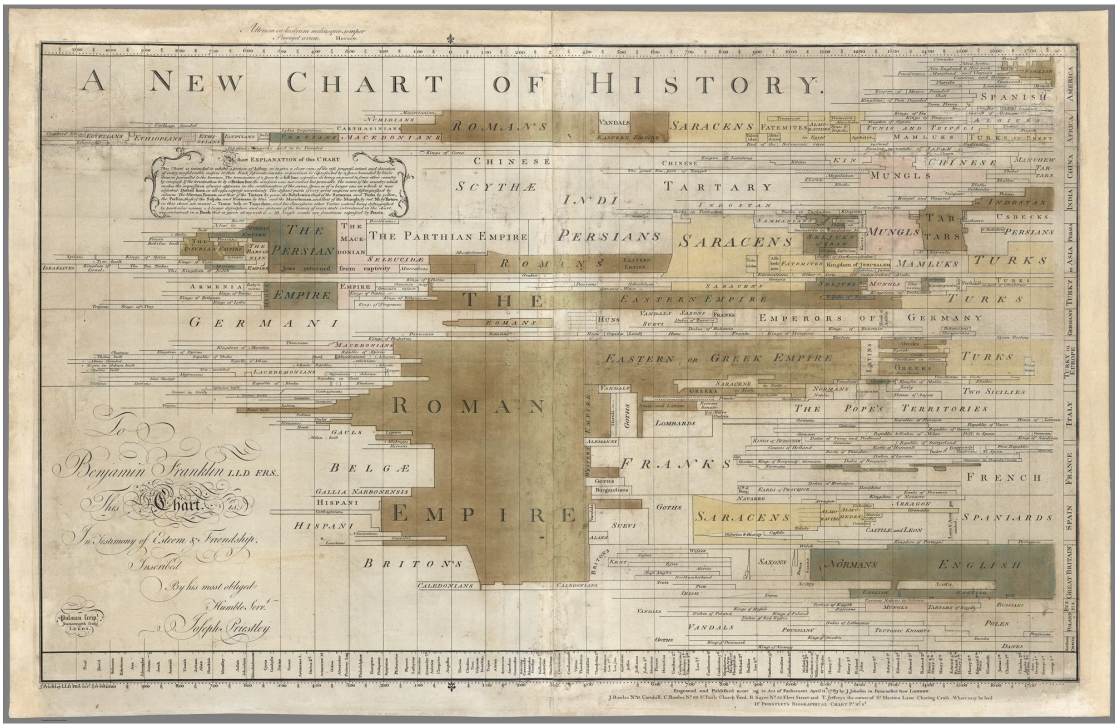


Figure 3.2: Joseph Priestley's New Chart of History from 1769. [Image from the David Rumsey Map Collection. Image copyright © 2000 by Cartography Associates. Used under the terms of Creative Commons CC BY-NC-SA 3.0.]

3.3 William Playfair

William Playfair was a Scottish engineer and economist:

- He is considered the founder of statistical graphics, inventing among other things the line chart, area chart, pie chart, and bar chart.
- An example of an area chart can be seen in Figure 3.3, taken from the 3rd edition of his Commercial and Political Atlas [Playfair 1801a].
- Two examples of a pie chart can be seen in Figure 3.4, taken from his Statistical Breviary [Playfair 1801b].

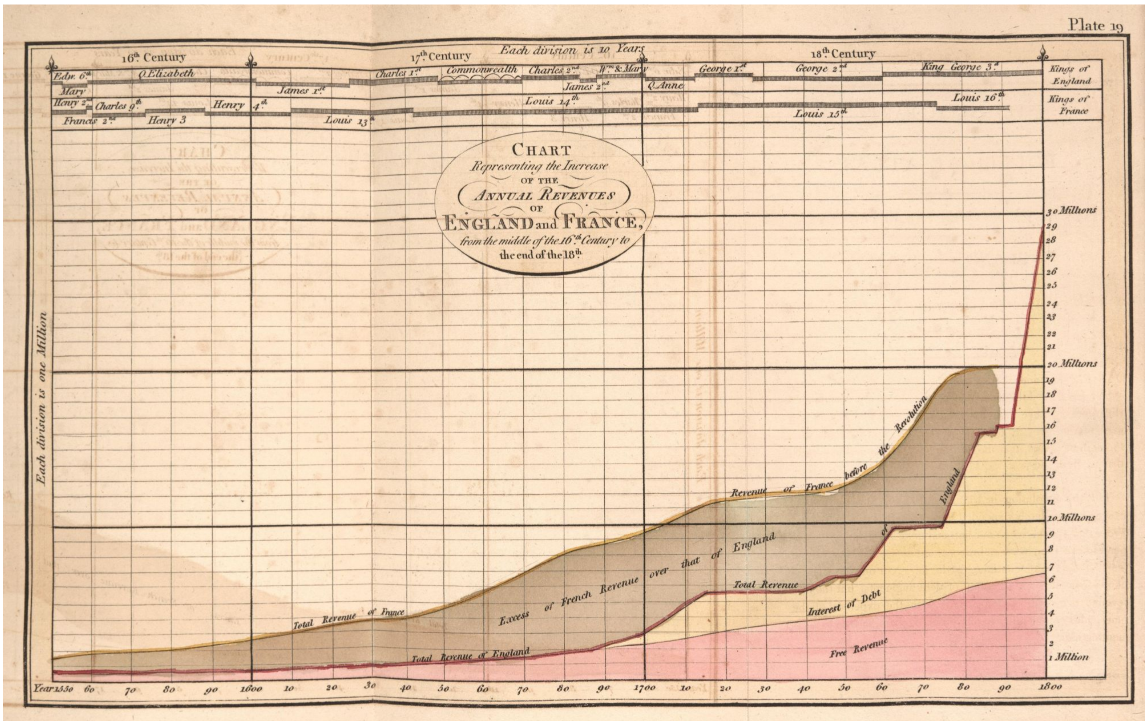


Figure 3.3: One of William Playfair's area charts, this example from the 3rd edition of his Commercial and Political Atlas. [Schoenberg Center for Electronic Text and Image (SCETI). Used under the terms of Creative Commons CC BY 2.5.]

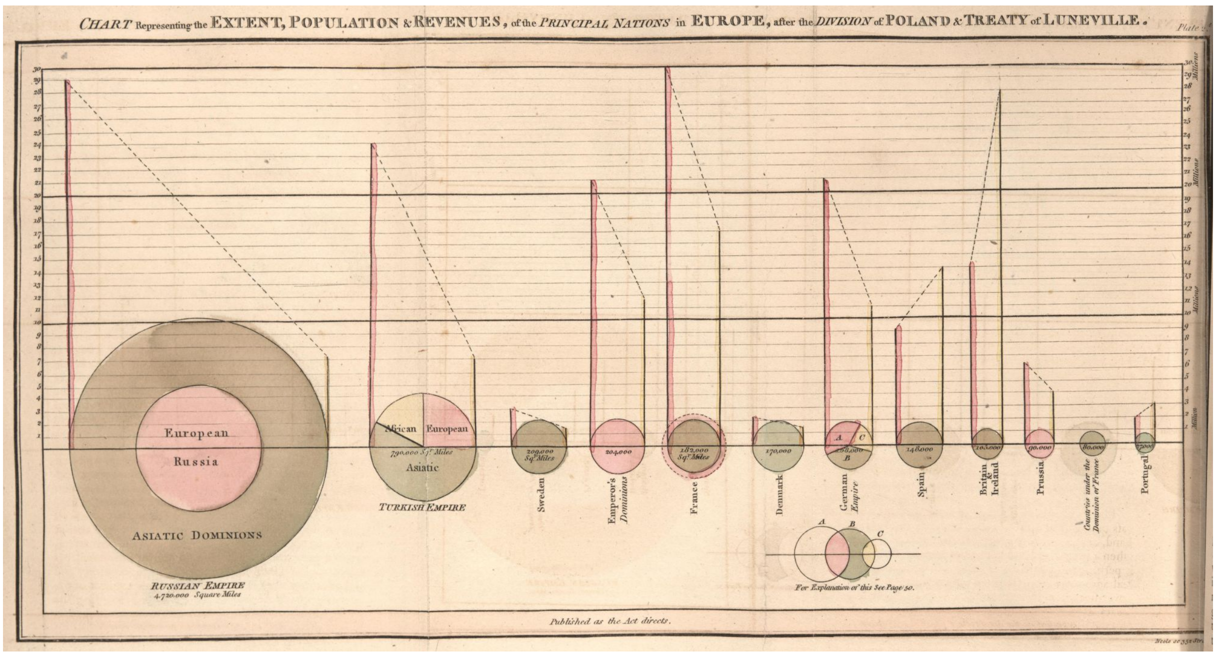


Figure 3.4: Two examples of a pie chart within this graphic from William Playfair's Statistical Breviary. [Schoenberg Center for Electronic Text and Image (SCETI). Used under the terms of Creative Commons CC BY 2.5.]

3.4 Edmund Cooper and John Snow

London Cholera Map (1854)

- In Sep 1854, a cholera epidemic hit the Golden Square area of London around Broad Street (St. James' parish).
- The first spot map of cholera deaths is usually attributed to Dr. John Snow, 1854, [Frerichs 2009], but in fact an earlier spot map was drawn by Edmund Cooper and presented on 26 Sept 1854, some 3 months earlier [Brody et al. 2000].
- Edmund Cooper was an engineer at the Metropolitan Commission of Sewers. Public complaints had linked the sewers to the cholera outbreak.
- Cooper plotted cholera deaths at addresses on a spot map, and used the map as an analytical tool to deduce that addresses near sewer holes did not exhibit higher numbers of deaths.
- Upto this time, cholera was thought to be an airborne disease, although Snow himself had long postulated a waterborne link.
- In popular retellings, such as Tufte [1997, pages 27–37] and Henig [1996, pages 1–2], Snow *first* plotted the deaths on a spot map (see Figure 3.5), and then used the map to discover a higher clustering of deaths around the Broad Street water pump. The handle on the Broad Street pump was removed, and the epidemic subsided.
- In fact, as recounted in Brody et al. [2000], Snow first presented a spot map on 04 Dec 1854, almost 3 months *after* the outbreak.
- Snow's map was not used as an analytical tool, but rather as an illustration after the event, to illustrate his finding that cholera was a waterborne disease.
- Workers in the nearby brewery, which had its own water (and beer) supply, were largely unaffected.
- Not really InfoVis, more GeoVis, since it is based on an underlying map.

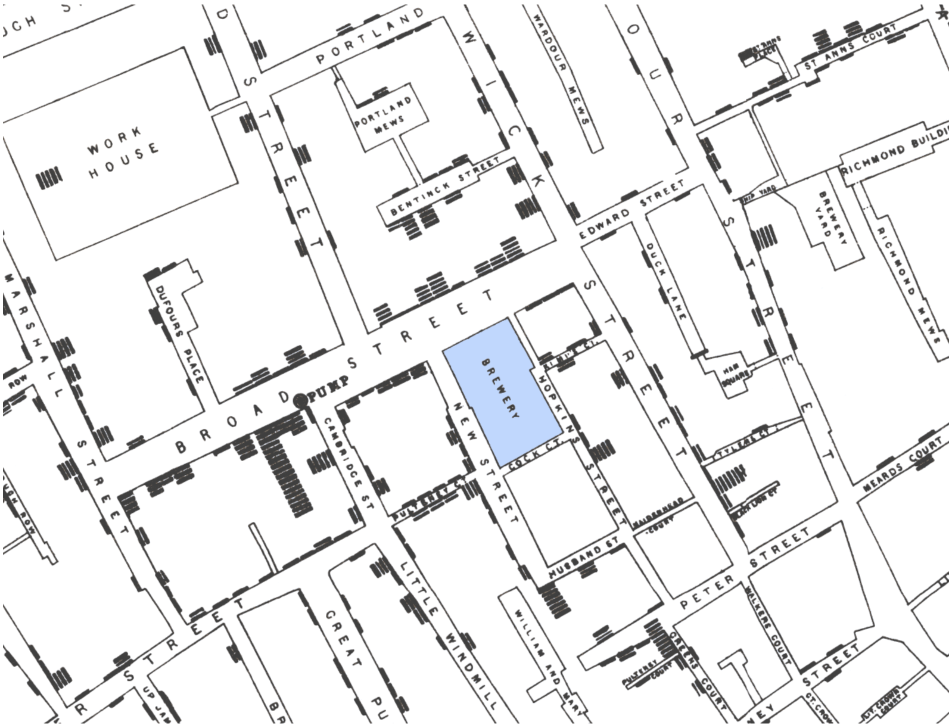


Figure 3.5: Snow's London cholera map.

3.5 Florence Nightingale

- Famous British nurse and statistician.
- She used a number of statistical graphics to illustrate her data and support her argument for health care reform [Small 1998].

Bat's Wing Diagram (1858)

- Shows changes over time for a small number of variables.
- In this case, the number of deaths from three different causes over a 12-month period, as shown in Figure 3.6.
- The time points are shown as 12 equally spaced radial lines (one for each month, winter at the bottom).
- The number of deaths is proportional to the length of the radial line (length-proportional).
- However, the coloured shading in of the areas (incorrectly) suggests to the viewer that the diagram is area-proportional.

Wedge Diagram (1858)

- Florence Nightingale, 1858.
- After criticism that her bat's wing diagram could be misleading, Nightingale redesigned it as a wedge diagram, shown in Figure 3.8.

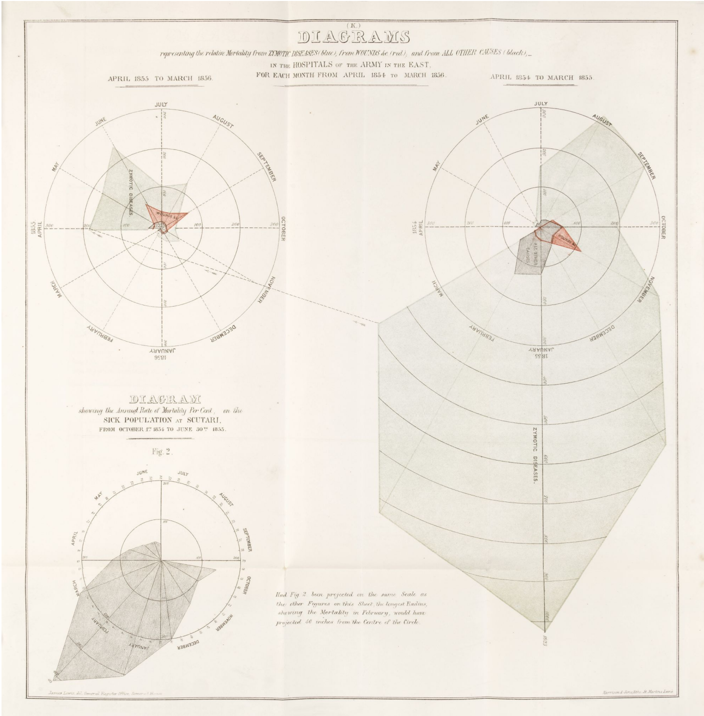


Figure 3.6: Florence Nightingale's original bat's wing diagram. [Image from the Wellcome Library, London. Used under the terms of Creative Commons CC BY-NC 2.0 UK.]

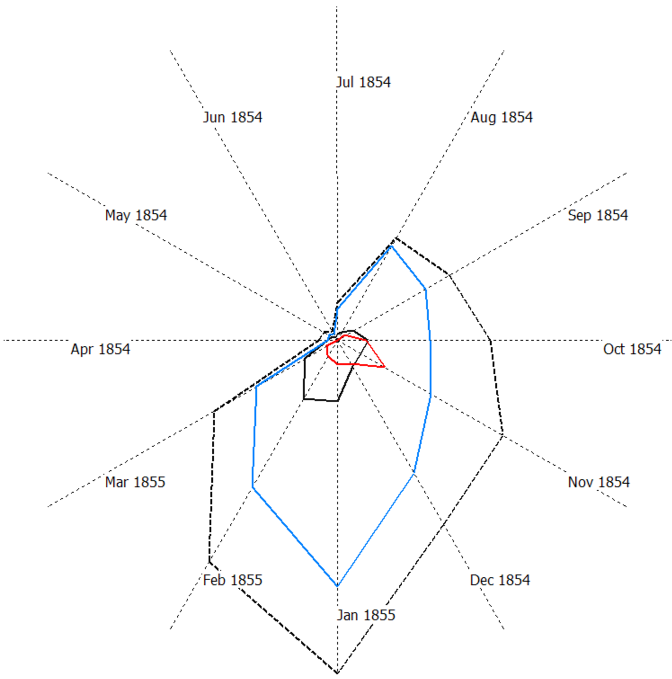


Figure 3.7: Modern bat's wing diagram.

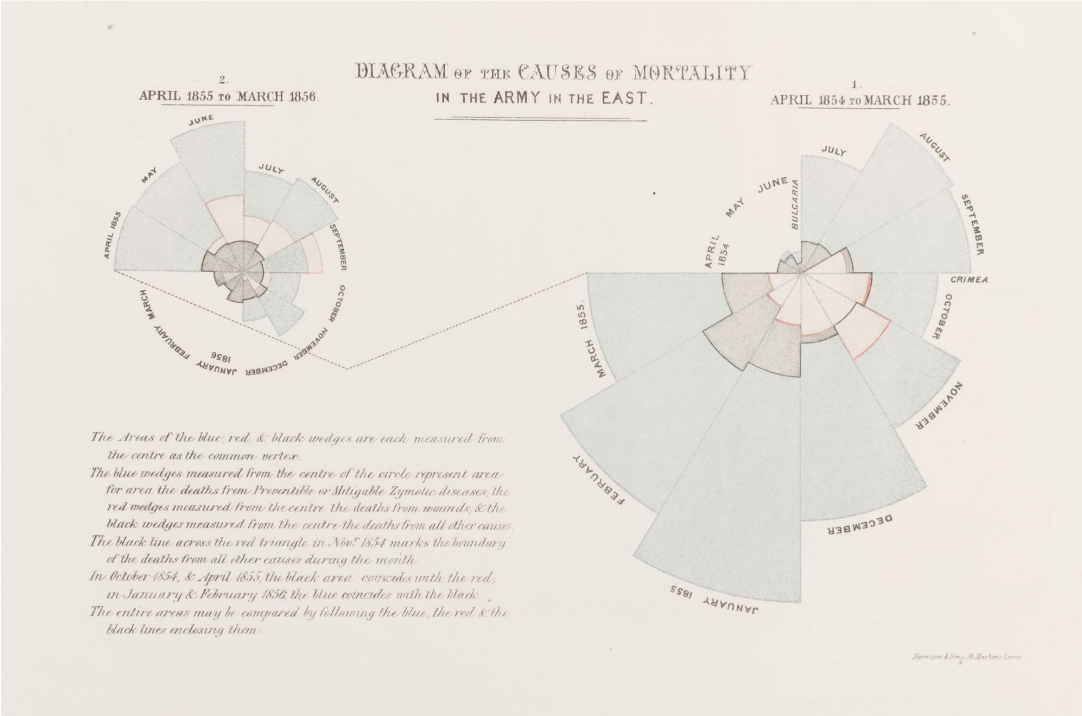


Figure 3.8: Florence Nightingale's original wedge diagram. [Image from the Wellcome Library, London. Used under the terms of Creative Commons CC BY-NC 2.0 UK.]

- Now, the number of deaths is actually proportional to the coloured shaded areas.
- However, there are some problems with occlusion, depending on the drawing order of the wedges.
- I use the name wedge diagram, following Small [1998]. It is sometimes also called a polar area diagram or a rose diagram. [It is also sometimes *incorrectly* referred to as a coxcomb diagram [Small 1998].]

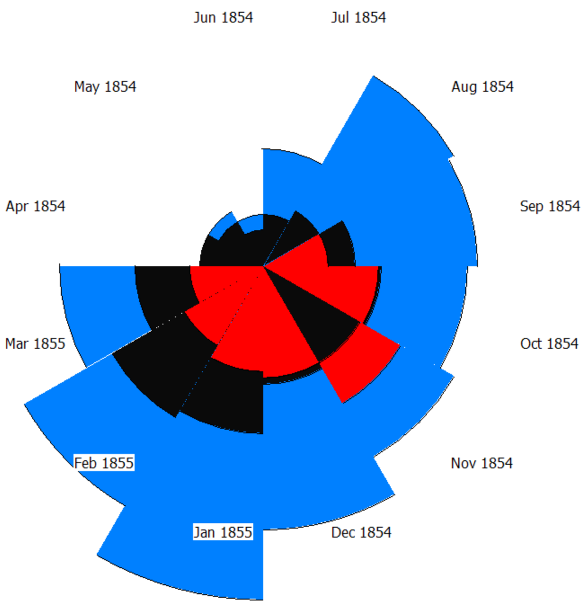


Figure 3.9: Modern wedge diagram.

3.6 Charles Minard

Diagram of Napoleon's Russian Campaign (1861)

- Charles Joseph Minard, 1861.

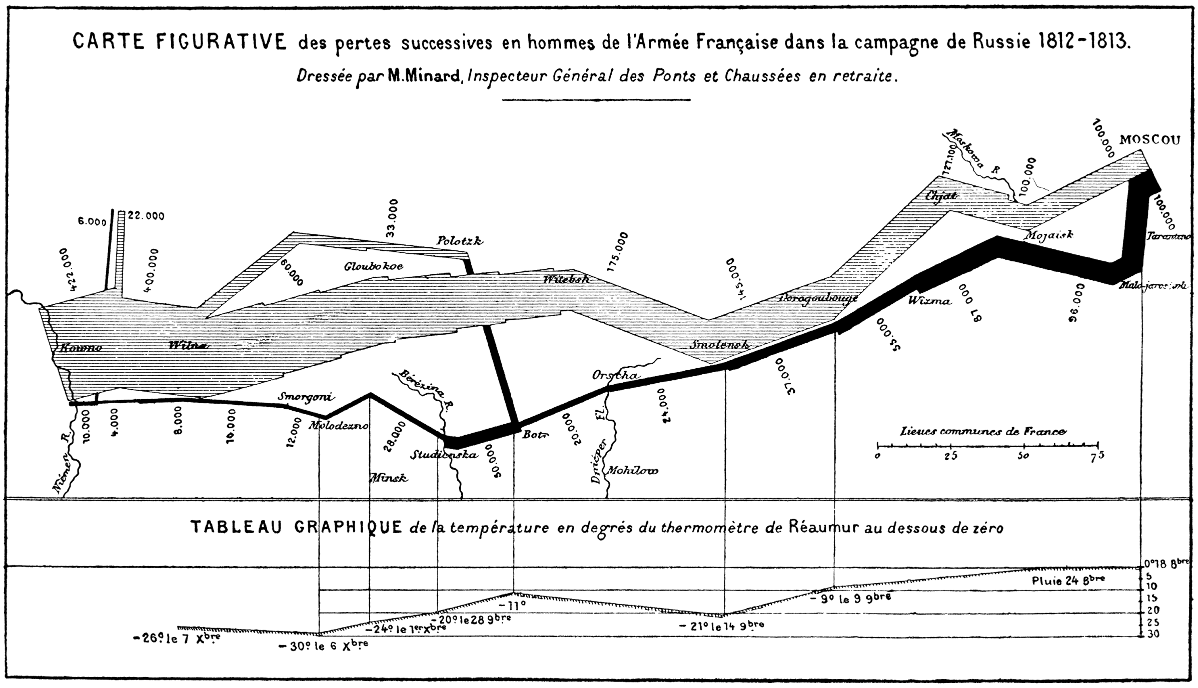


Figure 3.10: Minard's Map

3.7 Fletcher Hewes and Henry Gannett

Fletcher Hewes and Henry Gannett produced the 1883 edition of Scribner's Statistical Atlas of the United States [Hewes and Gannett 1883]:

- Plate 151 of the Atlas is shown in Figure 3.11.
- It shows a ranking of the then 47 states, according to ten dimensions.
- Each state appears once in each ranking and its instances are connected by a line, an early form of parallel coordinates plot.
- The darker blue boxes indicate the position of the United States as a whole.

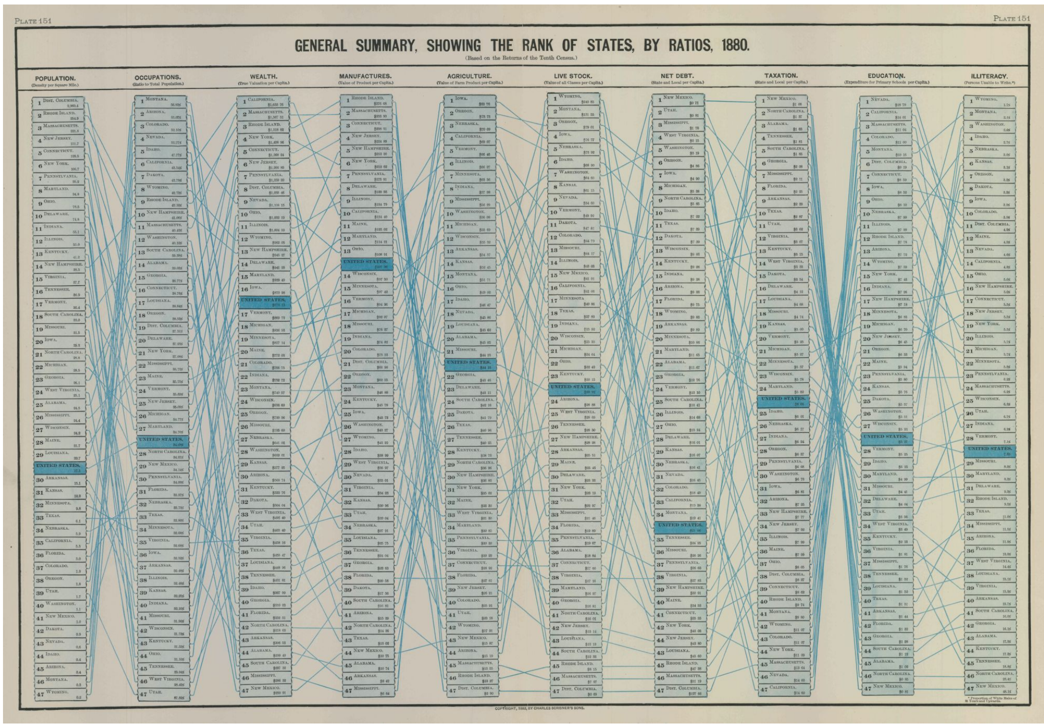


Figure 3.11: Hewes' and Gannett's parallel coordinates from [Image kindly provided by the Library of Congress, Geography and Map Division.]

3.8 Marey and Ibry (1878)

In his 1878 book [Marey 1878], Entienne Jules Marey published a graphic train schedule:

- The schedule is shown in Figure 3.12, which is taken from the 2nd Edition of the book [Marey 1885, page 20].
- He attributes the graphic to a Mr. Ibry, who is reported to have been deputy chief operating officer of the railway from Paris to Rouen [Wainer et al. 2013, page 56].
- Ibry had apparently been using this kind of display since at least 1846.
- As Wainer et al. [2013] describe, similar graphic train schedules had also been published in Russia in 1854.

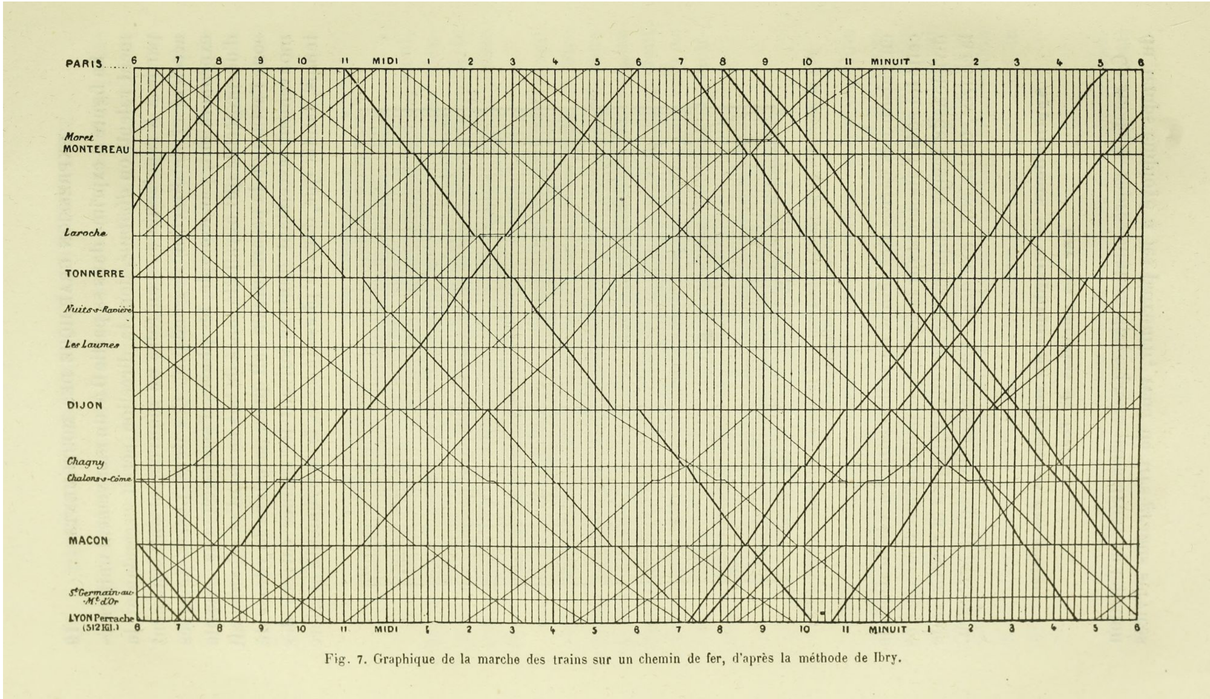


Fig. 7. Graphique de la marche des trains sur un chemin de fer, d'après la méthode de Ibry.

Figure 3.12: Marey's graphic train schedule, which he attributes to Ibry. [Image from the Internet Archive, in the public domain.]

3.9 Paul Otlet

Radial tree visualisation(s).

3.10 Jaques Bertin

Reorderable Matrix

- Jaques Bertin created a physical device for reordering matrices called Domino, see Figure 3.13.
- It is decribed in more detail by Henry [2008, page 78].
- Reconstructed in 2014 `https://aviz.fr/diyMatrix/`.
- Review paper and web app version at `https://aviz.fr/bertifier`.

Figure 3.13: Bertin's reorderable matrix. [Photograph used with kind permission of Jean-Daniel Fekete.]

Chapter 4

Visualising Linear Structures

Linearly structured information:

- alphabetical lists
- program source files
- chronological lists
- ranked search results

4.1 Bifocal Display

- Invented by Robert Spence and Mark Apperley in 1980 [Spence and Apperley 2018; Apperley et al. 1982]
- Separate focus and context areas. See Figure 4.1.
- Video at `http://www.ee.ic.ac.uk/r.spence/BobsVideos_files/V11BiFocal%20Office%20copy.mov` (save first and then play).

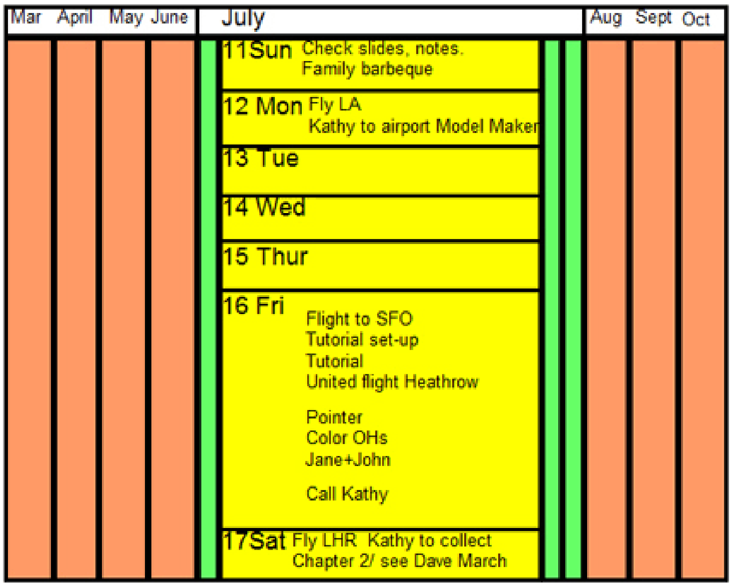


Figure 4.1: The bifocal calendar has a focus area in the middle and context areas to the left and right. [Courtesy of Bob Spence, placed under a Creative Commons Attribution-NoDerivs 3.0 Unported (CC-Att-ND-3) licence.]

4.2 Perspective Wall

- Xerox PARC, 1990.
- 3d perspective technique for linear information.
- Focus on the front panel and context in the side panels. See Figure 4.2.
- CHI'91 paper [Mackinlay et al. 1991] and video [Robertson et al. 1991b]. `https://youtu.be/hYUZbrWtCZg`
- US Patent 5339390 [Robertson et al. 1994b].

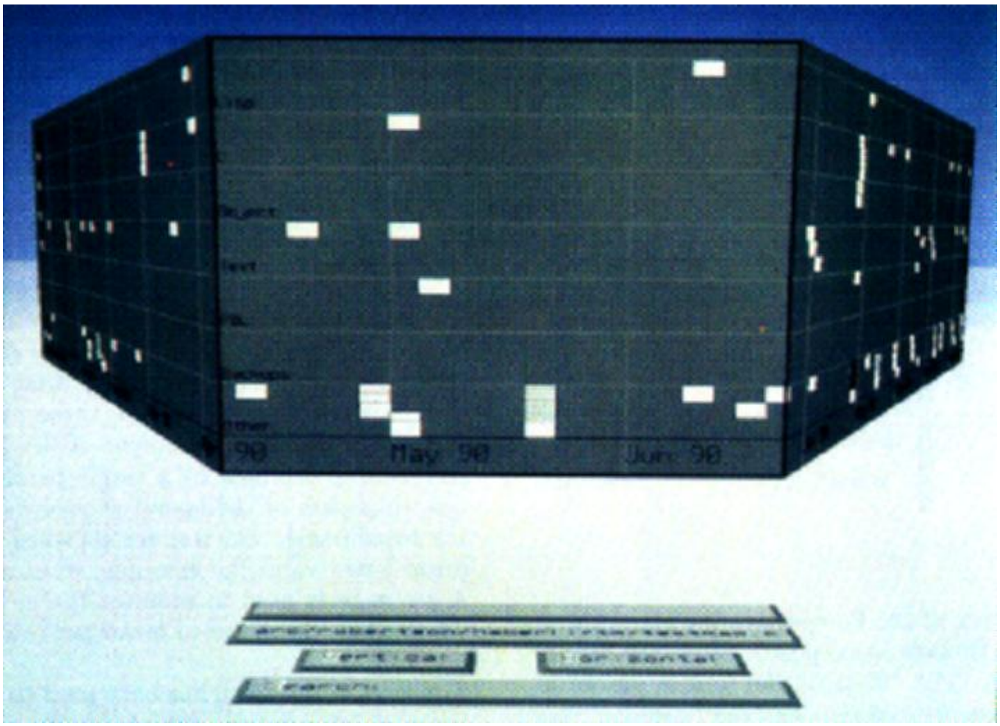


Figure 4.2: The perspective wall spreads linearly structured information across a wall from left to right. 3d perspective provides focus on the central segment of interest. [Copyright © by the Association for Computing Machinery, Inc.]

4.3 Seesoft

- AT&T Bell Labs, 1992.
- Focus + context technique for large amounts of source code.
- Lines of code are compressed down to rows of pixels. See Figure 4.3.
- Like hanging program listings on a wall several metres away.
- Zooming window supports several levels of zoom, from overview to lines of code.
- Articles [Eick et al. 1992; Ball and Eick 1996] and InterCHI'93 video [Steffen and Eick 1993].
- US Patent 5644692 [Eick 1997].

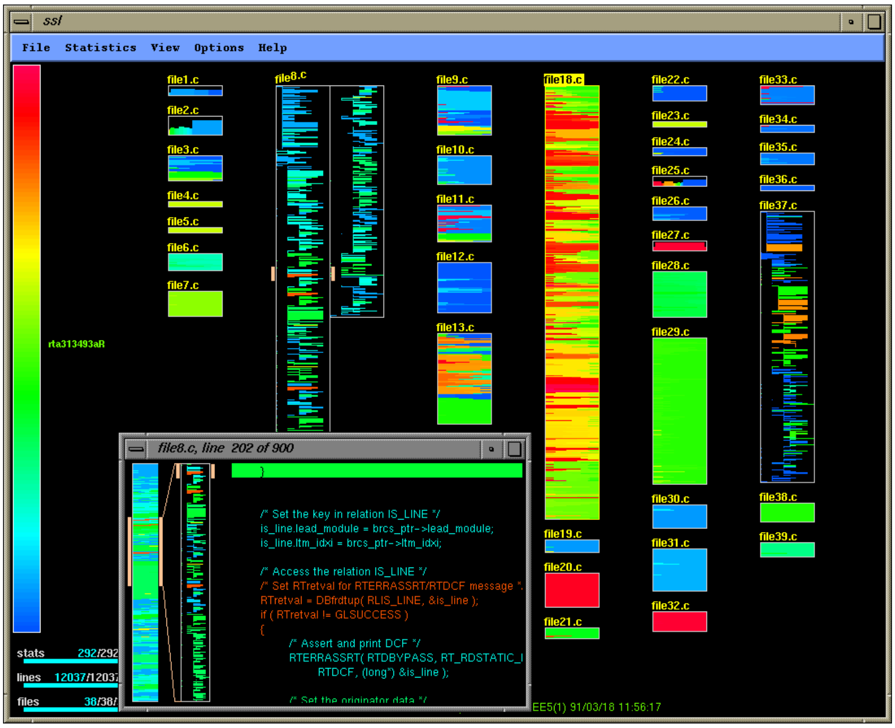


Figure 4.3: Seesoft visualising software consisting of 38 files comprising 12037 lines of code. The newest lines are shown in red, the oldest in blue, with a rainbow colour scale in between. [Image used with kind permission of Steve Eick, Visual Insights.]

4.4 Lifestreams

- Yale University, 1995.
- Streams of chronologically ordered items.
- AAAI 1995 paper [Freeman and Fertig 1995], CHI'96 video [Fertig et al. 1996], Wired article [Steinberg 1997].

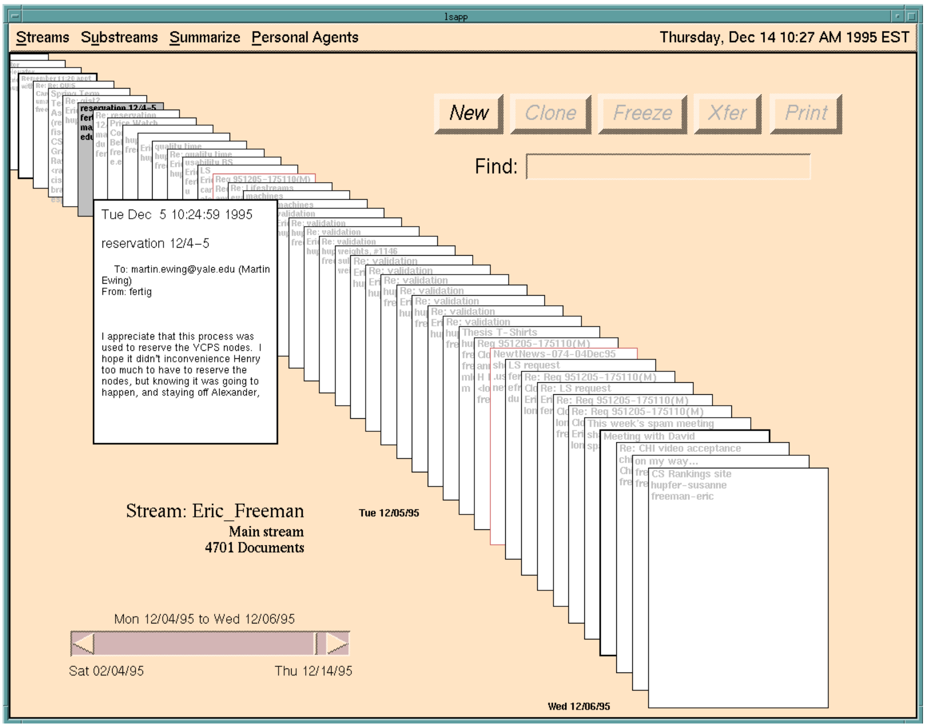


Figure 4.4: Lifestreams orders streams of item chronologically. It is possible to filter items into substreams. [Copyright © by the Association for Computing Machinery, Inc.]

4.5 Spiral of Ranked Items

- A spiral is a compact way of displaying a list of ranked items.
- GopherVR used a spiral to display search results. See Figure 4.5.
- 1994 draft version of paper for ED-MEDIA 95 [McCahill and Erickson 1994].

JUCS Spiral of Authors

- Journal of Universal Computer Science (JUCS), Graz University of Technology, 2009.
- High-profile authors in a sub-field of computer science are visualised in a spiral (in decreasing order of number of publications in that sub-field). See Figure 4.6.
- FIT 2009 paper [Afzal et al. 2009].

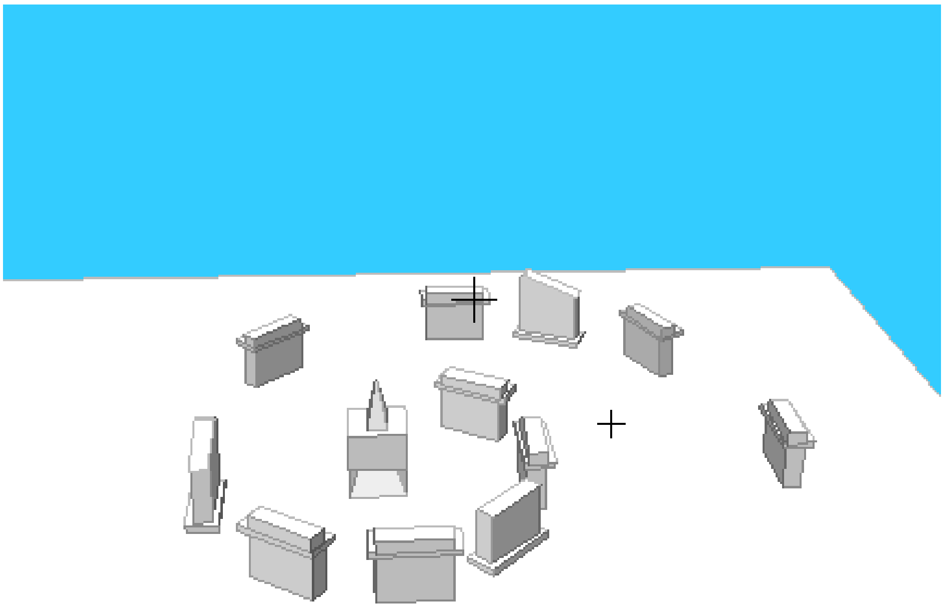


Figure 4.5: GopherVR spiral of search results. [Image used with kind permission of Tom Erickson]

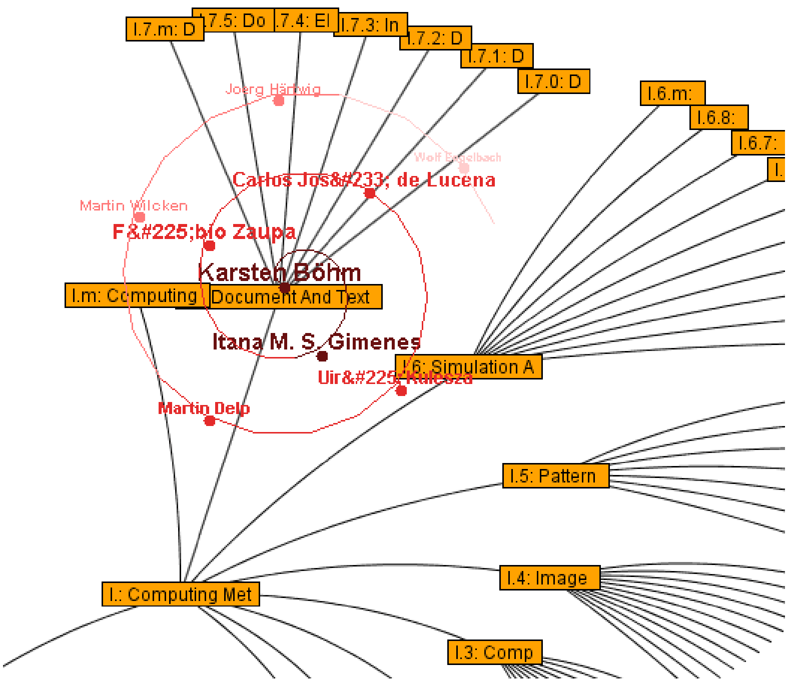


Figure 4.6: JUCS spiral of authors.

Chapter 5

Visualising Hierarchies

> *“ The organization of ideas and objects into categories and subcategories is fundamental to human experience. We classify to understand. Tree structures lie at the roots of our consciousness. ”*
>
> [Peter Morville, Ambient Findability, page 127, Sept. 2005.]

Hierarchies are extremely common:

- file systems
- library classification systems
- family trees

Many general graphs (networks) can also be transformed to a tree plus backlinks.

References

++ Hans-Jörg Schulz; *treevis.net: A Tree Visualization Reference*; IEEE Computer Graphics and Applications, Vol. 31, No. 6, 2011. [Schulz 2011]

++ Hans-Jörg Schulz et al; *The Design Space of Implicit Hierarchy Visualization: A Survey*; IEEE Transactions on Visualization and Computer Graphics, Vol. 17, No. 4, 2011. [Schulz et al. 2011]

+ Manuel Lima; *The Book of Trees*; Princeton Architectural Press, 08 Apr 2014. ISBN 1616892188 (com, uk) [Lima 2014]

+ Jürgensmann and Schulz; *A Visual Survey of Tree Visualization*; Best poster at IEEE InfoVis 2010. [Jürgensmann and Schulz 2010]

Online Resources

- Hans-Jörg Schulz; *A Visual Bibliography of Tree Visualization*; `treevis.net`

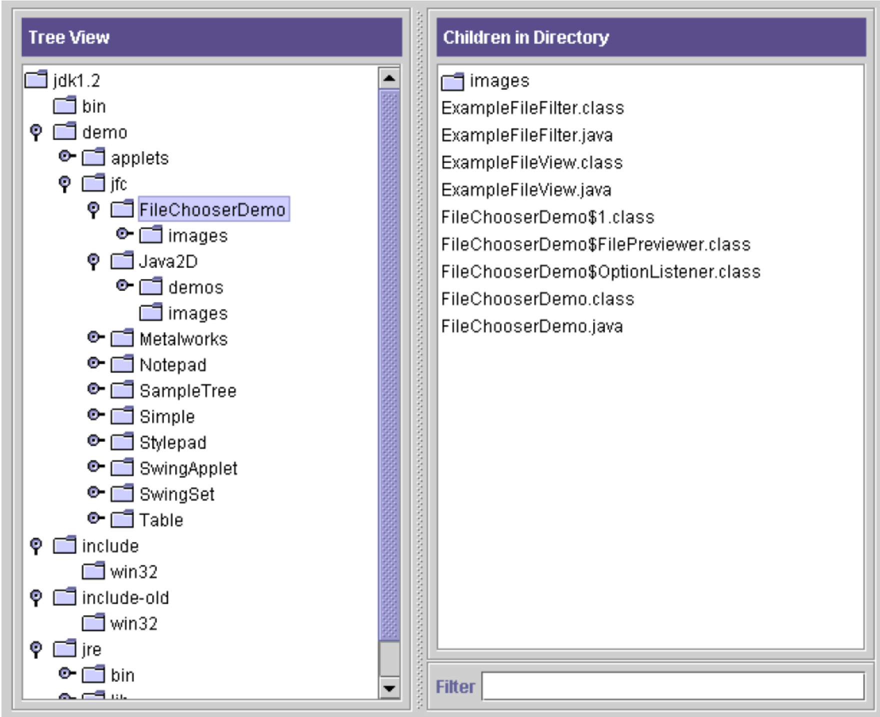


Figure 5.1: The Java Swing JTree tree view component. A view of directories on the left and their contents on the right.

5.1 Outliners

5.1.1 Tree Views

- Tree view on left shows structure, list view on right shows items (files, documents) at a particular level.
- Windows Explorer.
- Java Swing JTree component (see Figure 5.1).
- Harmony Collection Browser [Andrews 1996].

5.1.2 MagTree

- Andy Clark and Dave Smith, IBM, Jan 2001.
- File Magnitude Viewer (MagTree).
- Part of a tutorial on Java tree views [Smith and Clark 2001].
- Extends traditional tree view with preview of size statistics.
- Coloured pie indicates proportion of bytes in each subdirectory.
- Sizes are either relative to the root or relative to the parent.

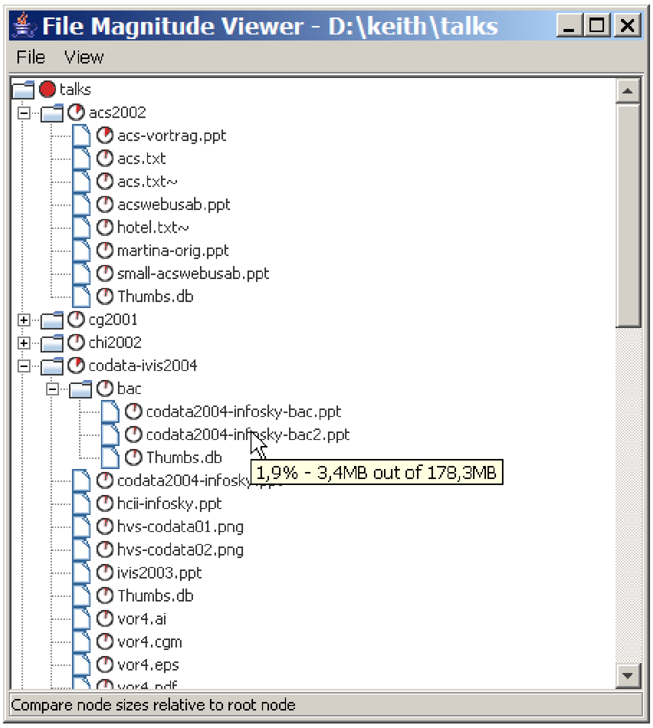


Figure 5.2: MagTree showing part of a file system hierarchy. Here, the sizes are all relative to the root.

5.1.3 WebTOC

- David Nation, Department of Defense and HCIL, 1997.
- Generates tree view of web site.
- Extends traditional tree view by overlaying supplementary statistical information.
- Coloured bars indicate proportion of various media types, shadows indicate number of files.
- HFweb 1997 paper [Nation et al. 1997] and CHI'98 video [Nation 1998].

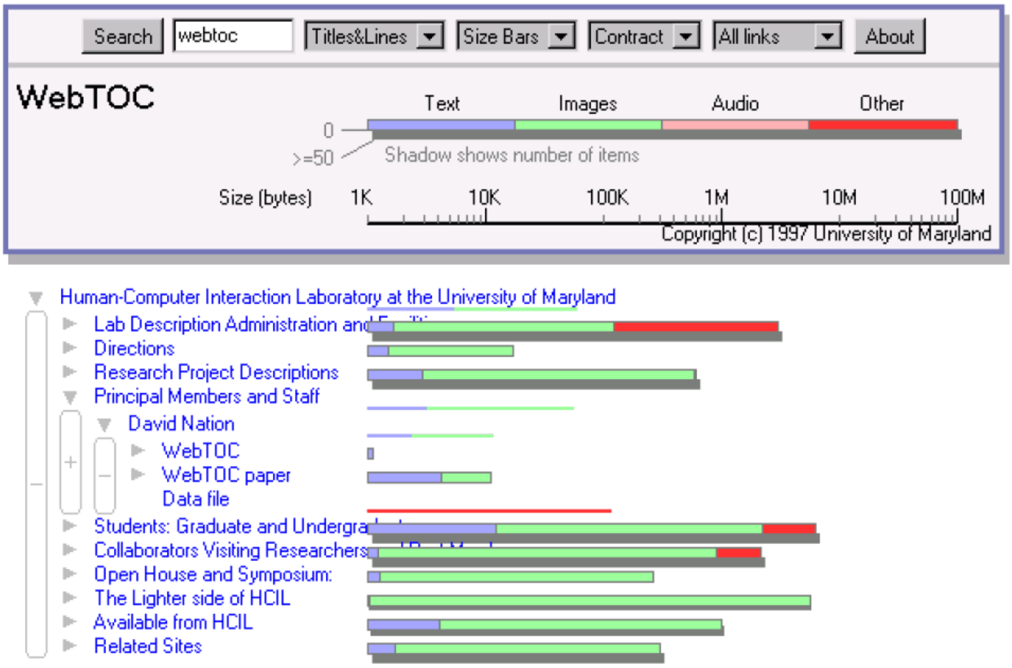


Figure 5.3: A WebTOC table of contents for the University of Maryland's HCI Lab web site.

5.2 Layered Node-Link Tree Browsers

5.2.1 Walker Layout

- Walker [1990], improved by Buchheim et al. [2002].
- Drawing trees of unbounded degree in linear time.
- The root is at the top, children on successive layers beneath.
- The layout progresses bottom-up, allocating the same amount of space to each leaf node. See Figure 5.4.

5.2.2 File System Navigator (FSN)

- SGI, 1992.
- 3d landscape visualisation of file system.
- Files sit atop pedestals, subdirectories recede into the background. See Figure 5.5.
- Featured in Jurassic Park.
- Used in MineSet product to visualise decision trees.
- Software (binaries) available online [Tesler and Strasnick 1992].
- Patented under [Strasnick and Tesler 1996a; Strasnick and Tesler 1996b].

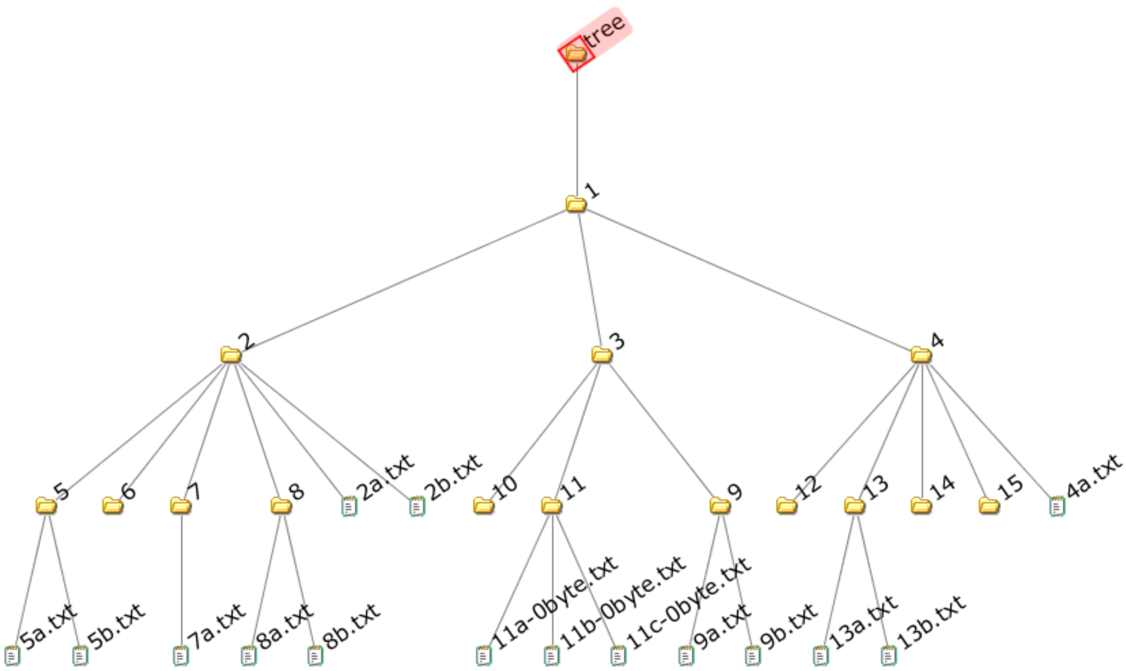


Figure 5.4: The Walker tree browser.

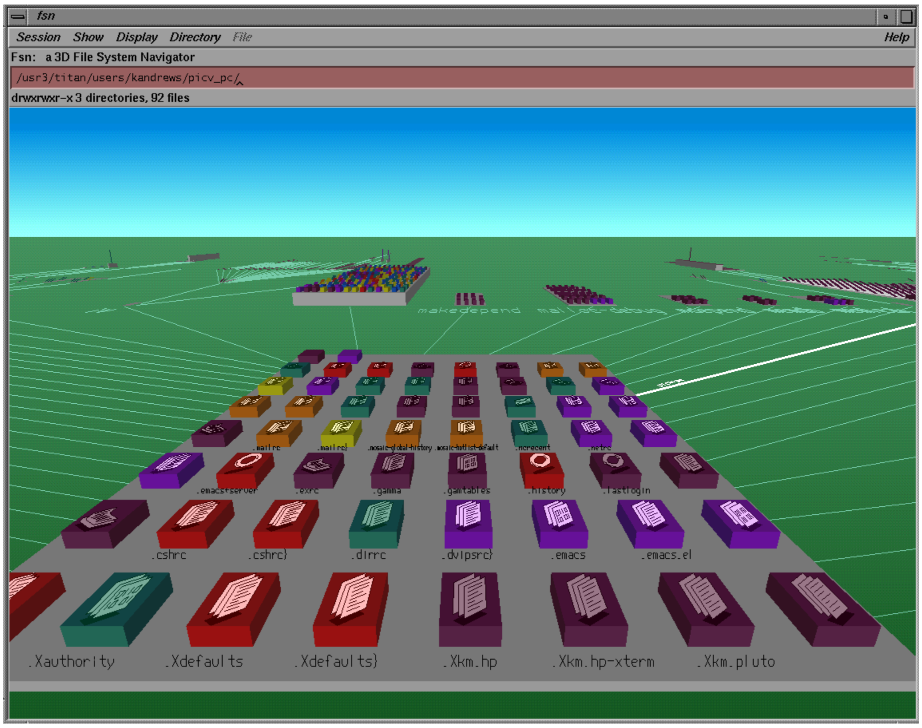


Figure 5.5: FSN landscape visualisation of a file system hierarchy. Files sit atop pedestals, subdirectories recede into the background.

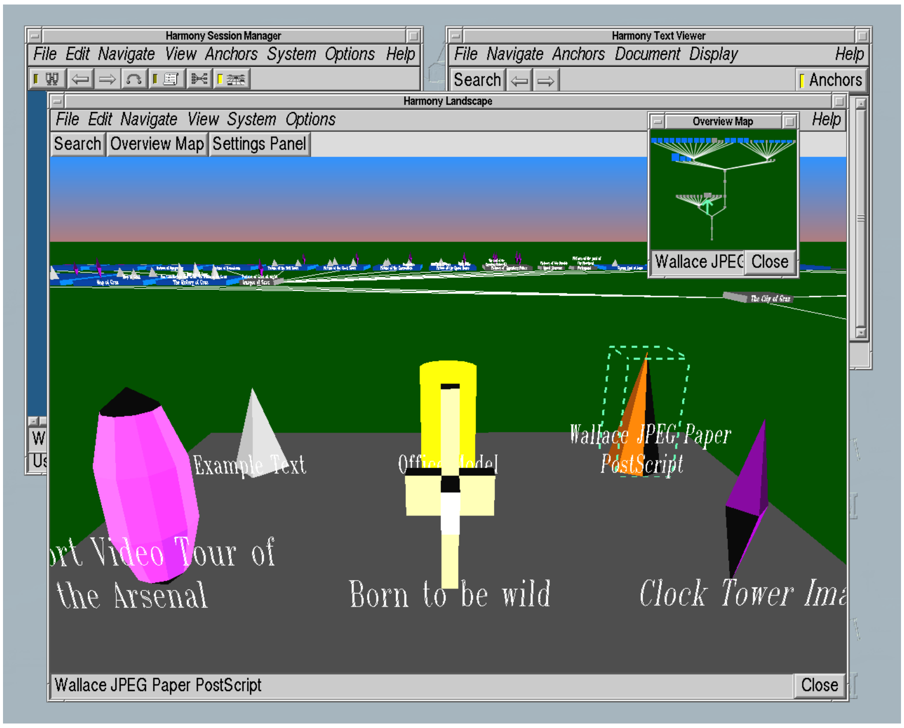


Figure 5.6: The Harmony Information Landscape visualises Hyperwave collection structures.

5.2.3 Harmony Information Landscape

- IICM, 1994–1995.
- 3d landscape visualisation of Hyperwave collection structures. See Figure 5.6.
- Similar to FSN, documents sit atop pedestals, subcollections recede into the background.
- Paper at IEEE InfoVis'95 (reprinted in [Card et al. 1999]), [Andrews 1996].

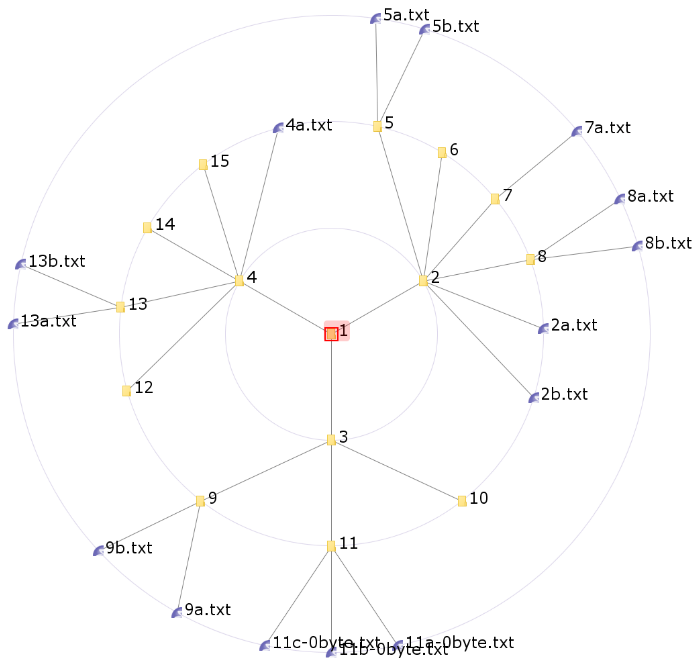


Figure 5.7: A radial tree from HVS.

5.3 Radial Node-Link Tree Browsers

5.3.1 Radial Tree

- Classic tree layout technique.
- The root is in the centre of a circle, surrounded by its descendents on concentric circles based on their depth.
- In fixed-wedge layouts, each branch of the tree is constrained within a wedge of the circle (“annulus wedge”) [di Battista et al. 1999, pages 52–53].
- In flexible-wedge layouts, children are allowed to make use of free space in neighbouring wedges.
- Figure 5.7 shows the radial tree implemented in HVS [Andrews et al. 2007; Fuchs 2015].

5.3.2 Hyperbolic Browser

- Xerox PARC, 1994–1995.
- Focus+context technique, always displaying the entire hierarchy. See Figure 5.8.
- Layout on a hyperbolic plane, which is then mapped to the unit disc. Each child places its children in a wedge of space.
- Developed as a software component by Inxight, acquired by Business Objects, now owned by SAP.
- Papers at UIST’94 and CHI’95 [J. Lamping and R. Rao 1994; J. Lamping et al. 1995].

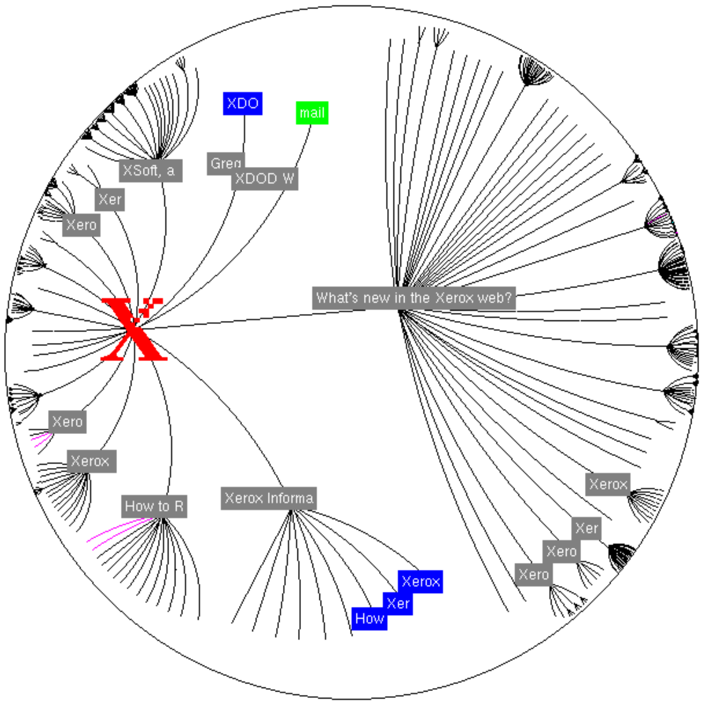


Figure 5.8: The original hyperbolic browser from Xerox. The hyperbolic browser always displays the entire hierarchy. However, subtrees around the edge of the disk become so small they are invisible. [Image used with kind permission of Ramana Rao, Xerox PARC] .

- Video at CHI'96 [J. Lamping and R. Rao 1996]. [Video: `https://youtu.be/8bhq08BQLDs`]
- Patented under [J. O. Lamping and R. B. Rao 1997].
- Won the CHI'97 Great Browse Off!

5.3.3 D3 Hypertree

- Michael Glatzhofer, 2018–2019.
- Open-source implementation of hyperbolic browser in TypeScript using D3.
- Code at `https://github.com/glouwa/d3-hypertree` and `https://github.com/glouwa/d3-hypertree-examples`.
- Examples:
  - Product Taxonomy; `https://keithandrews.com/demos/ivis/hypertree/hypertree-products/`. See Figure 5.9.
  - Hyperbolic Tree of Life; `hyperbolic-tree-of-life.github.io` See Figure 5.10.
  - Several examples on Observable; `https://observablehq.com/@glouwa`.

5.3.4 3D Hyperbolic Browser

- Tamara Munzner, University of Minnesota and Stanford University.
- 3D hyperbolic browser. See Figure 5.11.

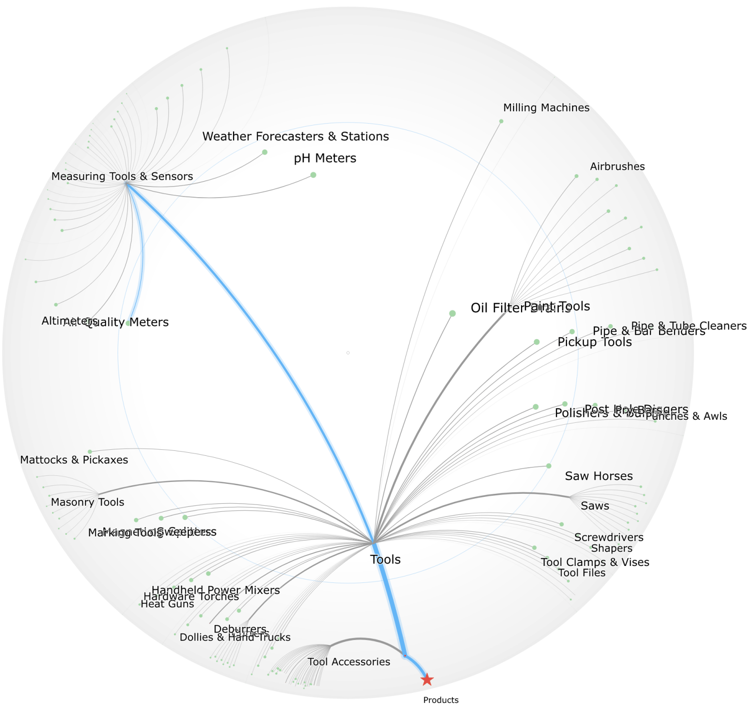


Figure 5.9: D3 Hypertree displaying Google's product taxonomy.

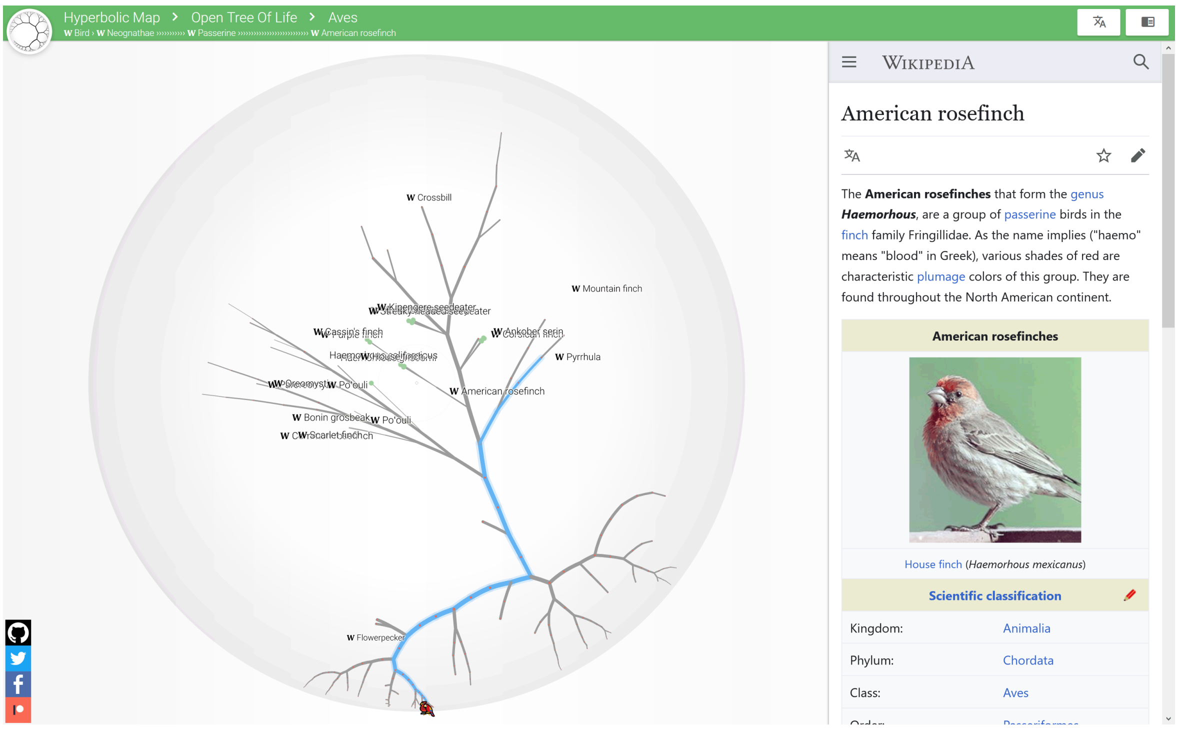


Figure 5.10: The Hypertree of Life is a practical application of D3 Hypertree.

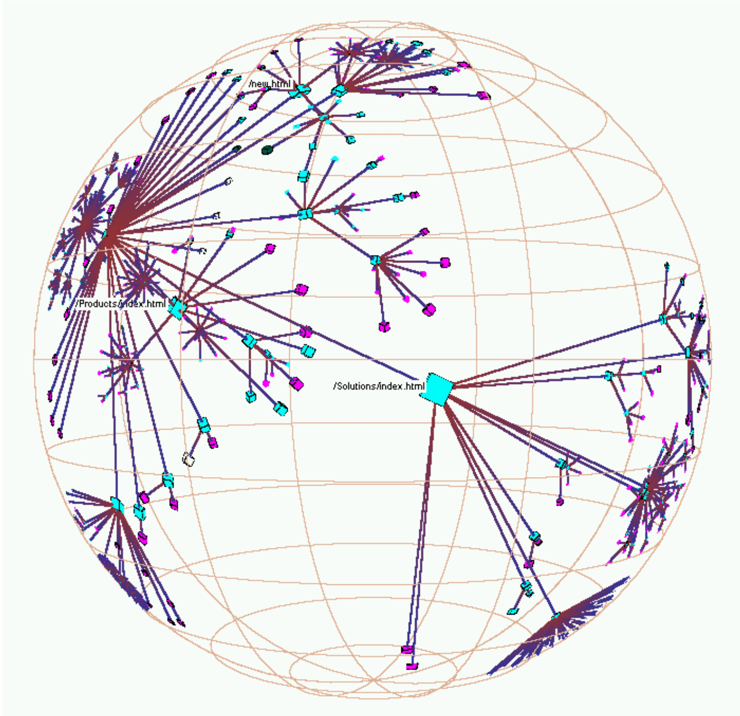


Figure 5.11: The H3 3d hyperbolic browser.

- For web sites, spanning tree is generated and laid out, cross-links are displayed on request.
- Paper at VRML'95 [Munzner and Burchard 1995] and InfoVis '97 [Munzner 1997].

5.3.5 Walrus

- Young Hyun, CAIDA, 2002.
- 3D hyperbolic browser, homegrown implementation of Tamara Munzner's algorithms. See Figure 5.12.
- Paper in BMC Bioinformatics Journal 2004 [Hughes et al. 2004], web site [Hyun 2005].

5.3.6 SInVis Magic Eye View

- Institute of Computer Graphics, University of Rostock, 1999–2001.
- The hierarchy is first laid out in 2d space according to the classic Reingold [Reingold and Tilford 1981] or Walker [Buchheim et al. 2002] algorithm.
- It is then mapped geometrically onto the surface of a hemisphere. See Figure 5.13.
- Smooth animated transitions are possible.
- The effect is similar to a hyperbolic browser, but hyperbolic geometry is not used.
- Masters Thesis (in German) in 1999 [Burger 1999], papers at NPIV'99 [Kreuseler and Schumann 1999] and IEEE InfoVis 2000 [Kreuseler et al. 2000].

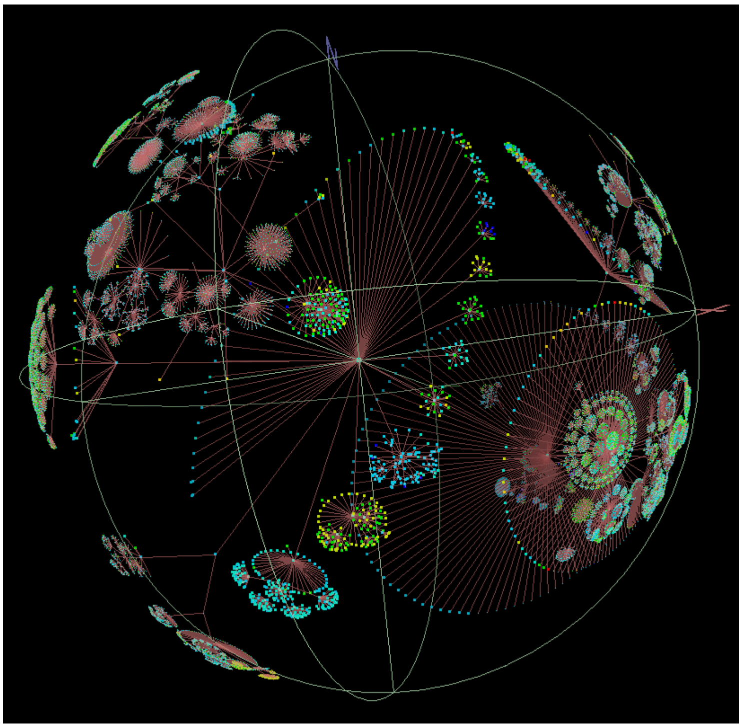


Figure 5.12: The Walrus 3d hyperbolic browser displaying a directory tree. [Image used with kind permission of Young Hyun, CAIDA.]

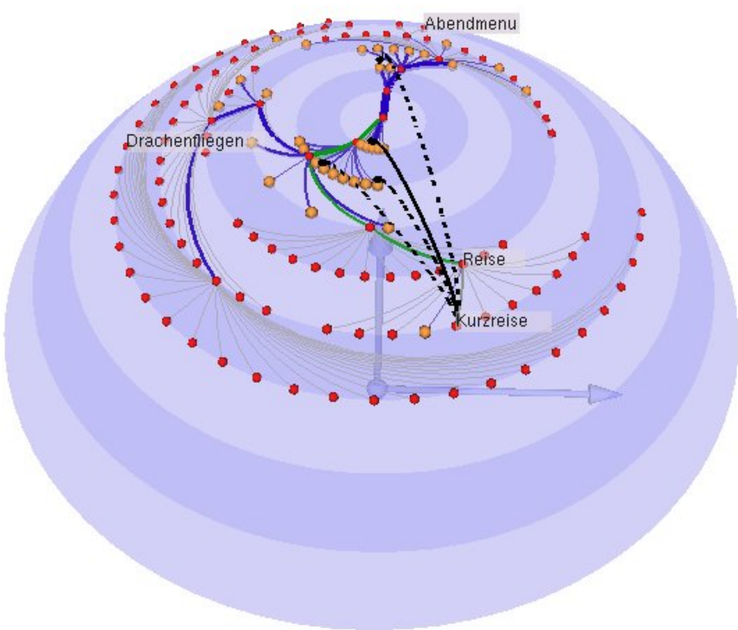


Figure 5.13: The SInVis Magic Eye View. [Image used with kind permission of Matthias Kreuseler, University of Rostock.]

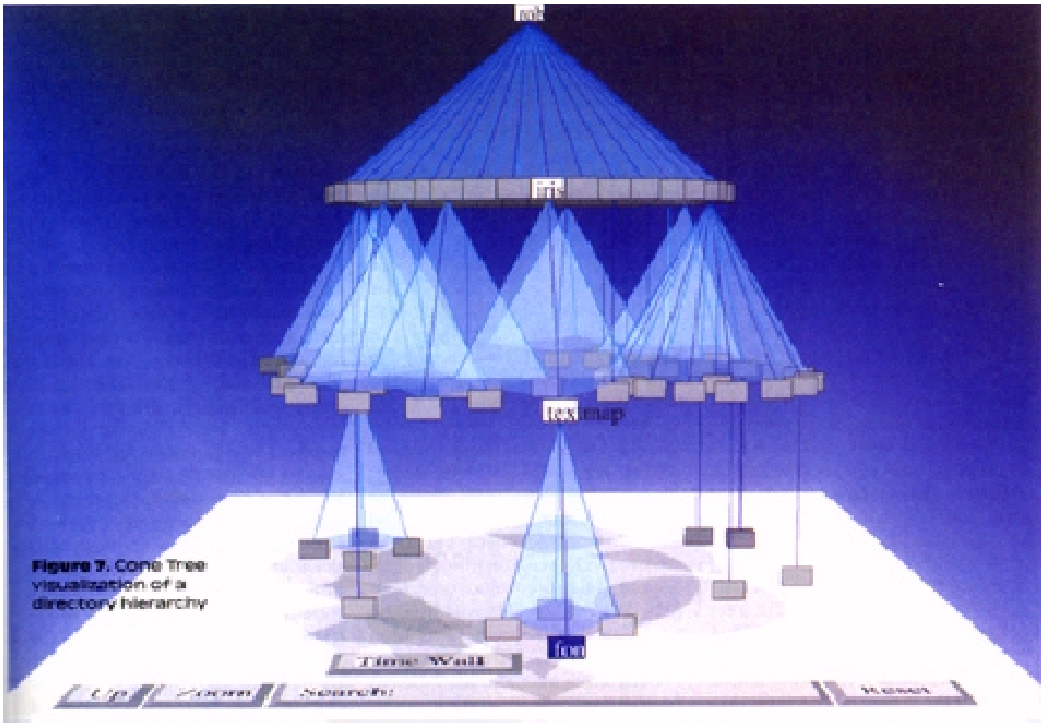


Figure 5.14: The cone tree is a 3d conical representation of a hierarchy. [Copyright © by the Association for Computing Machinery, Inc.]

5.3.7 Cone Tree

- Xerox PARC, 1990.
- 3d conical representation of tree. See Figure 5.14.
- A horizontal layout (cam tree) allows better labeling of nodes.
- CHI'91 paper [Robertson et al. 1991a] and video [Robertson et al. 1991b]. [Video: `https://youtu.be/RbcQT8Oz_yI`]
- Patented under [Robertson et al. 1994a].

5.3.8 Botanical Visualisation

- Eindhoven University of Technology, 2001.
- An abstract tree is converted into a geometric model of branches and leaves and then rendered.
- For better aesthetics, continuing branches are emphasised, long branches are contracted, and leaves are shown as fruit.
- Paper at InfoVis 2001 [Kleiberg et al. 2001]. [Video: `https://youtu.be/mTipHD_MBZk?t=08m35s`]

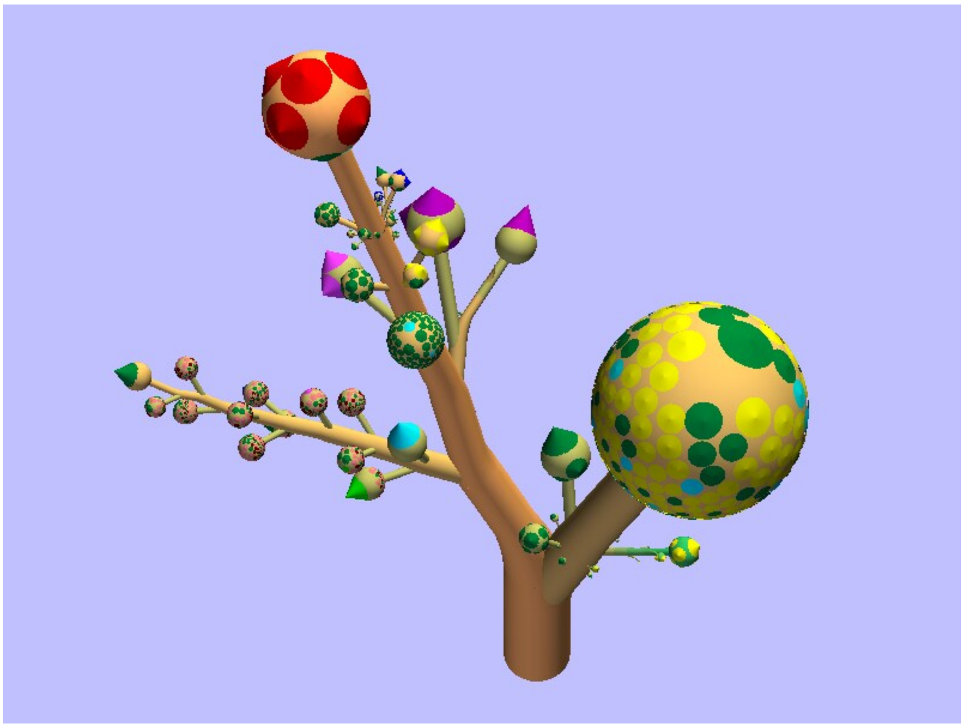


Figure 5.15: Botanical visualisation of a hierarchy. [Image used with kind permission of Jack van Wijk, Eindhoven University of Technology.]

5.4 Layered Space-Filling Tree Browsers

5.4.1 Xdu

- Phil Dykstra, Army Research Laboratory, 1991.
- Utility for the X window system which displays a graphical disk usage for Unix file systems.
- Rectangles are stacked from left to right as the directory tree is descended.
- The vertical space allocated is proportional to size of each subdirectory.
- Software (source) available online [Dykstra 1991].

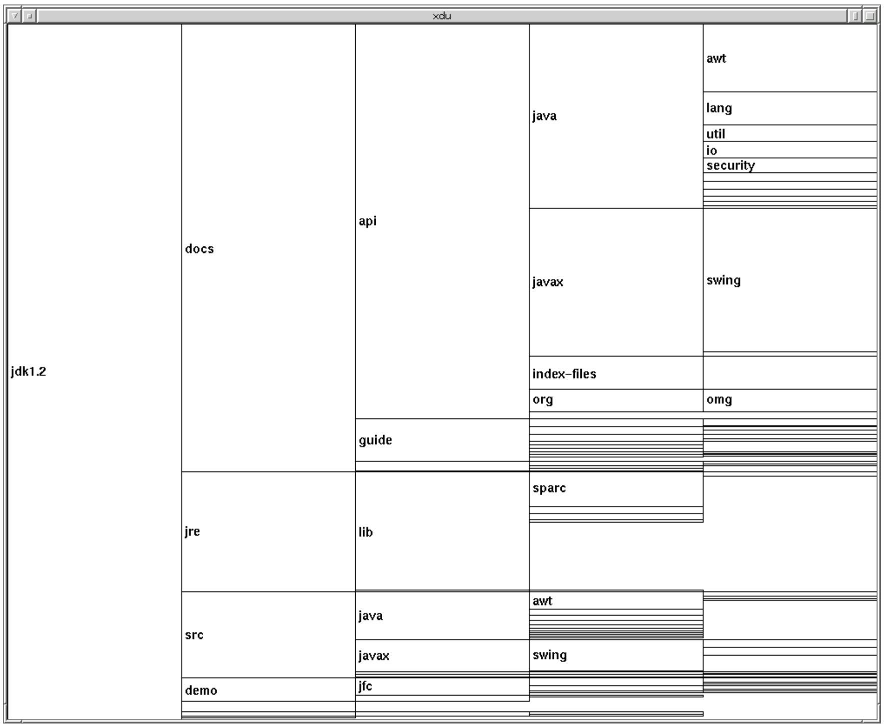


Figure 5.16: An xdu visualisation of the Java JDK 1.2 distribution.

5.5 Radial Space-Filling Tree Browsers

5.5.1 Information Slices

- IICM, 1998–1999.
- The hierarchy is fanned out across one or more semi-circular discs. See Figure 5.17.
- The number of levels displayed on each disc can be changed interactively, 4 or 5 works well.
- The area of each segment is proportional to the total size of its contents.
- Clicking on a directory in the left disc fans out its contents in the right disc, allowing rapid exploration of large hierarchies.
- For very deep hierarchies, clicking on a directory in the right disc causes the left disc to be miniaturised and slide off to the left (to join a stack of miniature discs), and a fresh disc is opened to the right.
- Late Breaking Hot Topic Paper at IEEE InfoVis'98 [Andrews and Heidegger 1998] and IEEE CG&A July/Aug. 1998 [Andrews 1998].

5.5.2 SunBurst

- John Stasko et al, GVU, Georgia Tech, 1999-2000.
- Much more advanced version of InfoSlices. See Figure 5.18.
- Uses full disc and implements fan-out of subtrees.

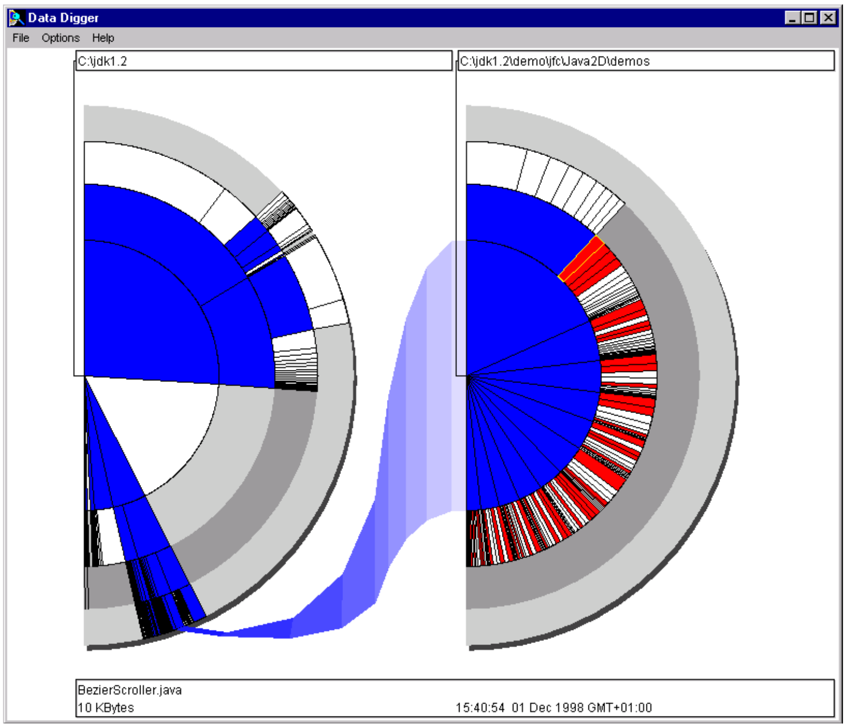


Figure 5.17: An Information Slices visualisation of the JDK 1.2 tree. For deeper hierarchies discs are stacked up in the left margin.

- Papers at IEEE InfoVis 2000 [Stasko and E. Zhang 2000a] and International Journal of Human-Computer Studies [Stasko et al. 2000].
- Video at InfoVis 2000 [Stasko and E. Zhang 2000b]. [Video: `https://youtu.be/YaMmDU6GIpo`]

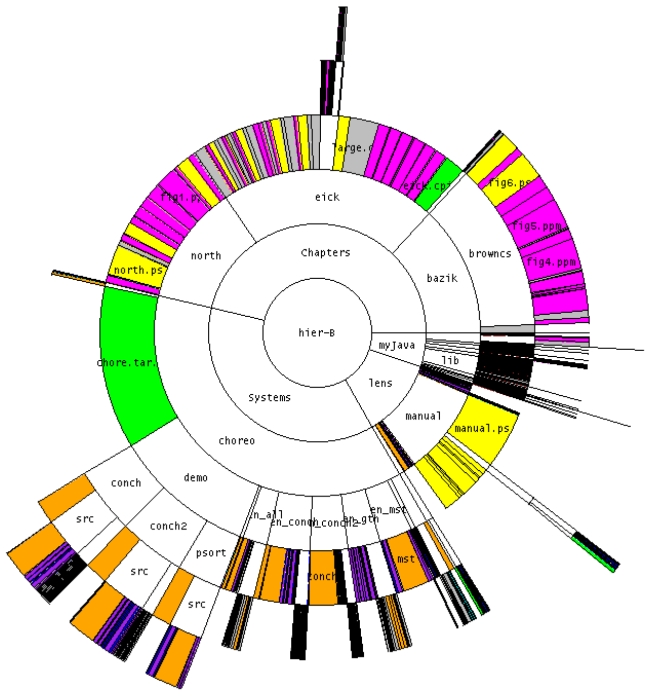


Figure 5.18: The SunBurst directory visualiser. [Image used with kind permission of John Stasko, Georgia Tech.]

5.6 Inclusive Space-Filling Tree Browsers

5.6.1 Tree Maps

- HCIL, University of Maryland, 1991–1993.
- Screen-filling visualisation by alternate vertical and horizontal slicing of available space ("Slice and Dice" treemap layout), as shown in Figure 5.19.
- The size of each rectangle is proportional to its *weight*, typically the total number or size of items within it.
- Child rectangles can be ordered (say alphabetically) within their parent rectangle, but rectangles can degenerate to very narrow strips.
- Visualization'91 paper [Johnson and Shneiderman 1991] and CHI'94 video [Turo 1994].
- Software at `https://cs.umd.edu/hcil/treemap/`.

5.6.2 Market Map

- Martin Wattenberg, SmartMoney, 1999.
- Extension of tree map, avoiding the excessively narrow strips produced by Slice and Dice. See Figure 5.20.
- Uses a heuristic to slice up each rectangle into more evenly proportioned sub-rectangles ("Squarified" treemap layout) by placing the largest child first.

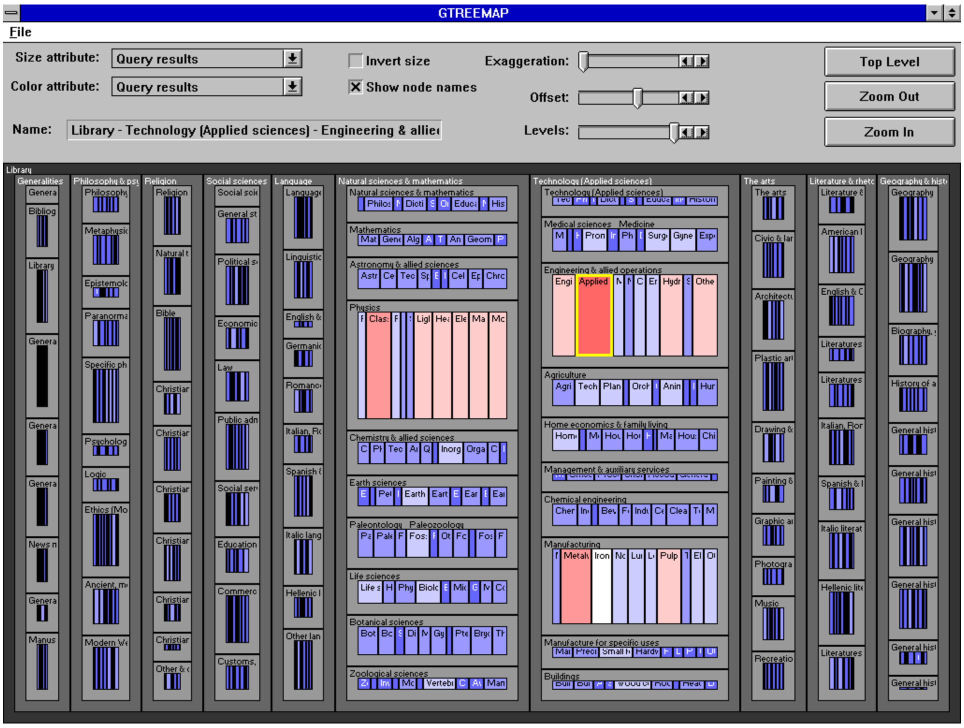


Figure 5.19: A tree map of the Dewey Decimal classification hierarchy widely used in libraries. Copyright ©University of Maryland 1984-1994, all rights reserved.

- Squarified tree maps look better and sub-rectangles are more easily compared in size, but at the cost of no ordering of child rectangles within the parent rectangle.
- CHI 99 late breaking paper [Wattenberg 1999], InfoVis 2001 paper [Shneiderman and Wattenberg 2001].

5.6.3 Cushion Treemaps

- Cushion treemaps: Three-dimensional shading is used to indicate the borders between treemap regions. See Figure 5.21.
- Explicit borders are no longer necessary, freeing up pixels for the data.
- Software package called SequoiaView produces disk usage maps using squarified cushion treemaps [SequoiaView 2005].
- Many clones of SequoiaView have been built for various platforms: KDirStat for Unix/X11 [Hundhammer 2010], WinDirStat for Windows [Seifert and Schneider 2018], and Disc Inventory X for Mac [Derlien 2010].
- InfoVis'99 paper [van Wijk and van de Wetering 1999], VisSym 2000 paper [Bruls et al. 2000]. [Video: `https://youtu.be/mTipHD_MBZk?t=07m09s`]

5.6.4 Information Pyramids

- IICM, 1997–2001.

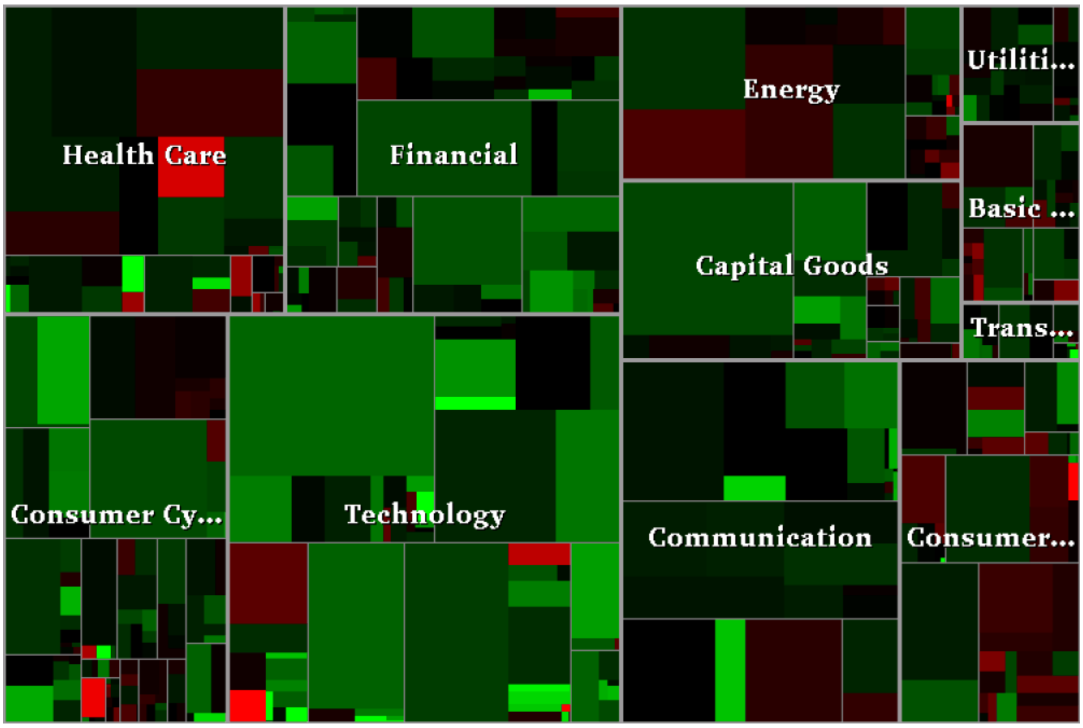


Figure 5.20: A market map of US stocks generated on 17th September 1999.

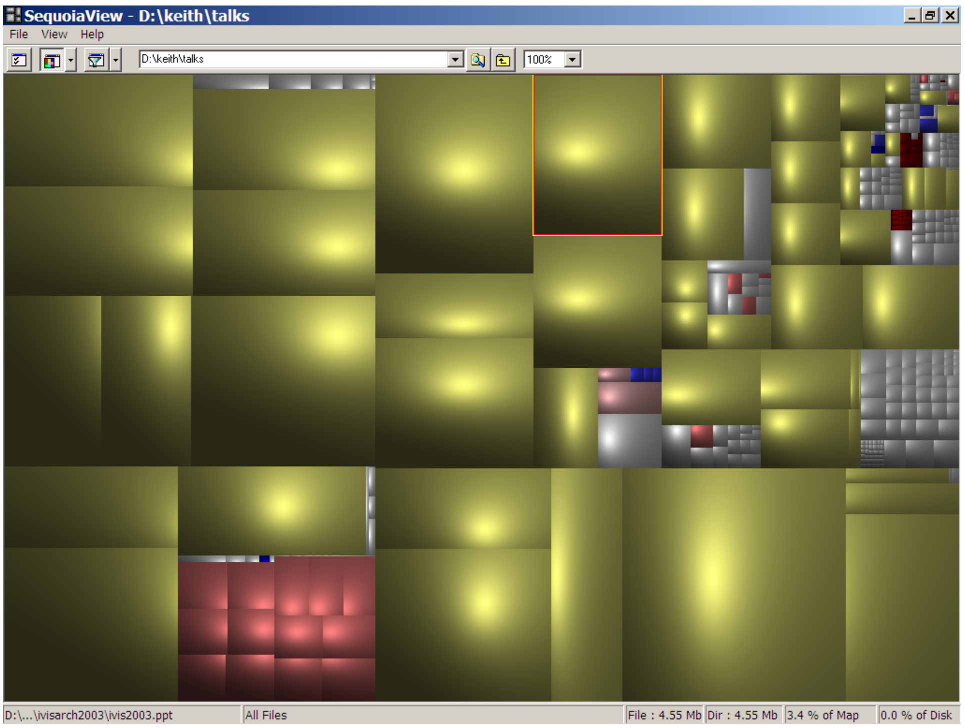


Figure 5.21: SequoiaView produces disk usage maps using squarified cushion treemaps.

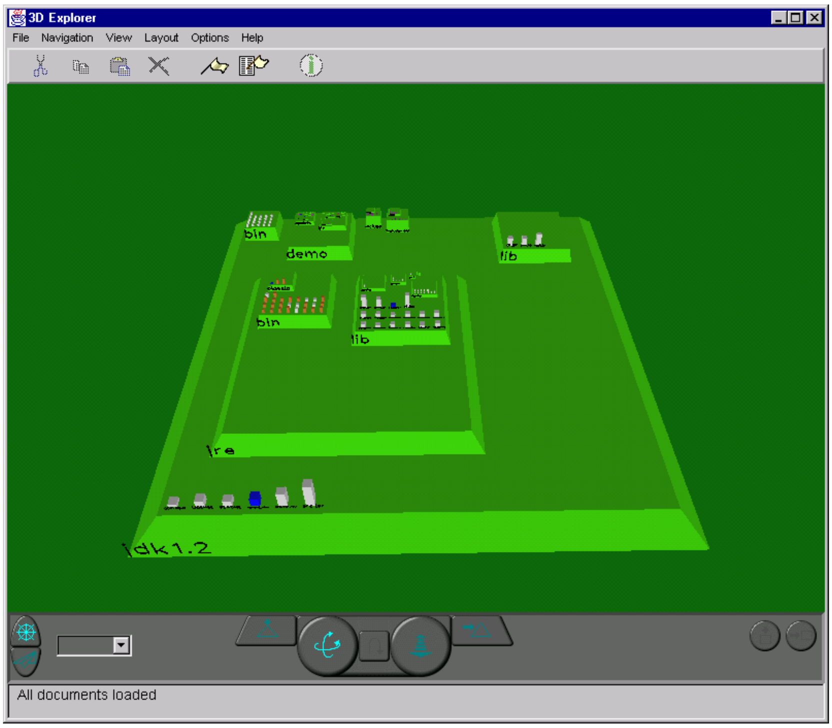


Figure 5.22: An Information Pyramids visualisation of the JDK 1.2 tree. The view from above gives a graphical disk usage. The dashboard provides user navigation. This version uses OpenGL for 3d output.

- A plateau represents the root of the tree. Other, smaller plateaux arranged on top of it represent its subtrees. See Figure 5.22.
- The size of each block is, by default, proportional to the total size of its contents.
- Separate icons are used to represent non-subtree members of a node such as files or documents.
- The overall impression is that of pyramids growing upwards as the hierarchy is descended.
- A redesigned version combines a pyramids display with a Java tree viewer. See Figure 5.23.
- Late Breaking Hot Topics Proc., IEEE Visualization'97 [Andrews et al. 1997] and IEEE CG&A July/Aug. 1998 [Andrews 1998], IV'02 [Andrews 2002a].

5.6.5 InfoSky Cobweb Browser

- First example of recursive Voronoi subdivision for hierarchy visualisation.
- Each parent polygon is subdivided into Voronoi polygons, one for each child, whose area is proportional to its size. See Figures 5.24 and 5.25.
- Paper in journal [Andrews et al. 2002] and at InfoVis 2004 [Granitzer et al. 2004]. [Video: `https://youtu.be/fnyKj8r0CN4?t=06m45s`]

5.6.6 Voronoi Treemap

- Three years after InfoSky Cobweb.

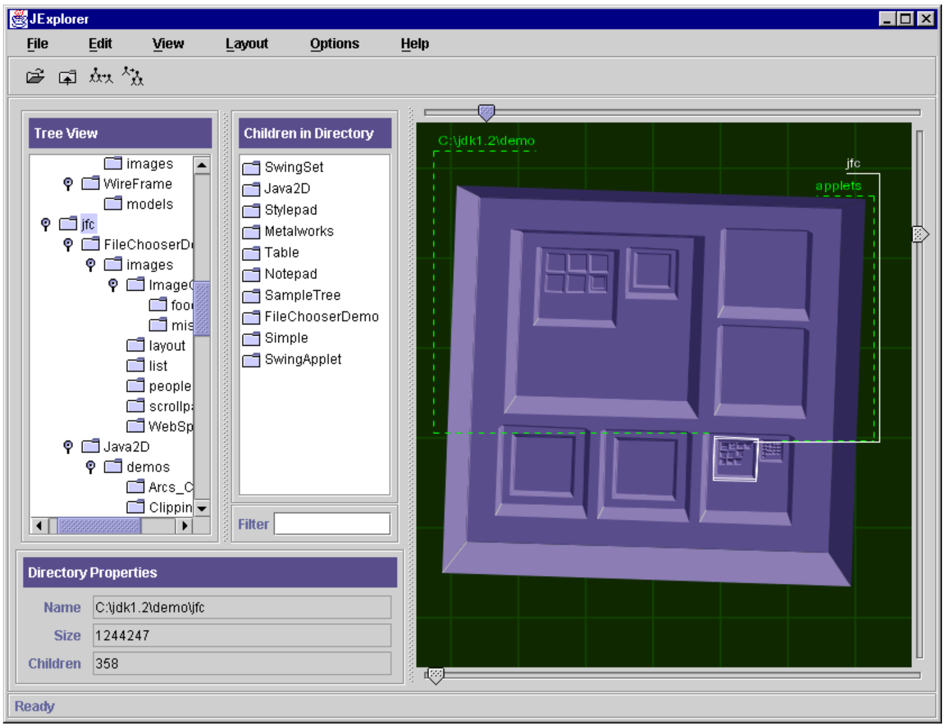


Figure 5.23: The JExplorer combines a Java tree viewer with a synchronised Information Pyramids display.

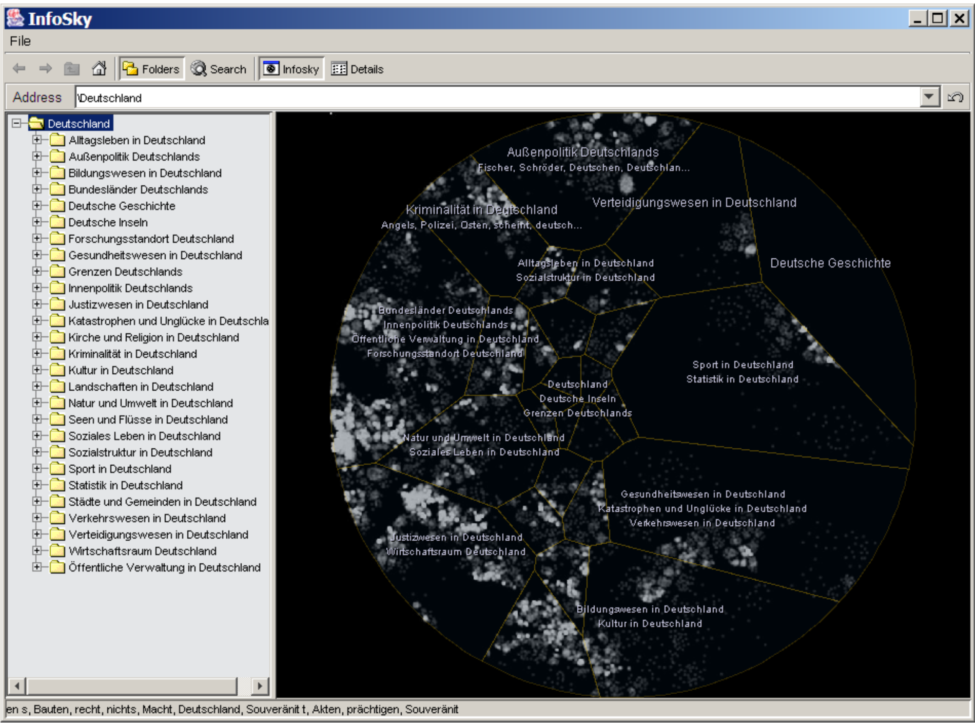


Figure 5.24: The InfoSky Cobweb hierarchy browser.

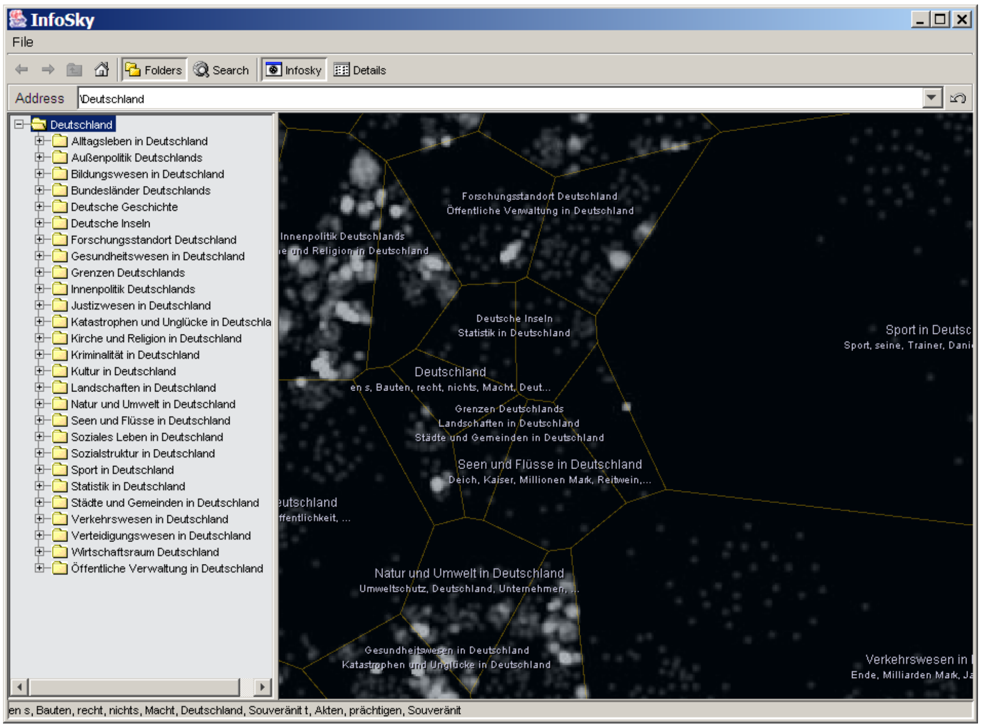


Figure 5.25: The InfoSky Cobweb hierarchy browser, zoomed in for a closer look.

- Also uses space-filling, recursive voronoi subdivision to allocate available space to child polygons. See Figure 5.26.
- Papers at SoftVis 2005 [Balzer et al. 2005] and InfoVis 2005 [Balzer and Deussen 2005a].
- Video at [Balzer and Deussen 2005b]. [Video: `https://youtu.be/3Qd56UBDKQE`]

5.6.7 VoroTree

- Open-source implementation of Voronoi Treemap in TypeScript by Chris Oser [Oser 2022]. See Figure 5.27.
- Live demo application at `https://somestudentcoder.github.io/vorotree/`.
- Code for demo application at `https://github.com/somestudentcoder/vorotree`.
- Code for library at `https://github.com/somestudentcoder/vorolib`.

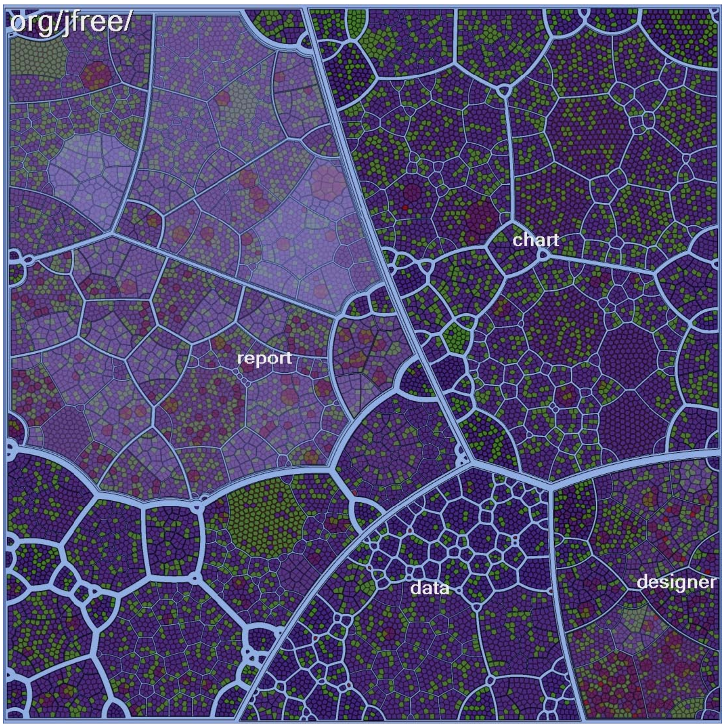


Figure 5.26: The Voronoi Treemap also uses recursive voronoi subdivision. [Image extracted from [Balzer et al. 2005], Copyright © by the Association for Computing Machinery, Inc..]

Figure 5.27: The VoroTree demo application displaying part of Google's product taxonomy.

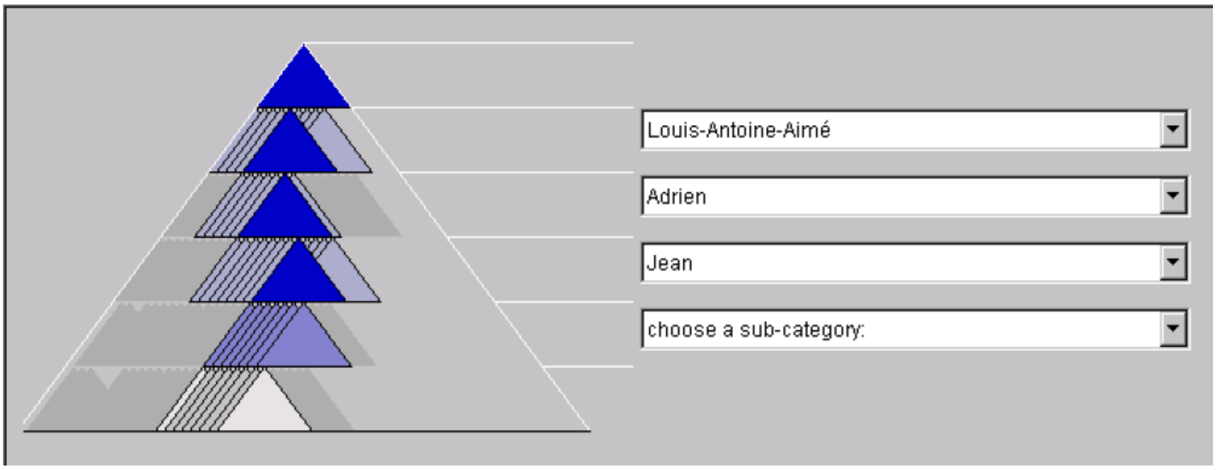


Figure 5.28: Cheops uses stacked triangles to compactly display a hierarchy.

5.7 Overlapping Space-Filling Tree Browsers

5.7.1 Cheops

- Centre du recherche Informatique de Montréal, 1996.
- Compact 2d representation of a hierarchy by overlaying (squashing together) children to save on screen space. See Figure 5.28.
- Paper at Visualization'96 [Beaudoin et al. 1996].
- Software (Java classes) at CRIM [2002].

5.7.2 BeamTree

- Directories are in blue, files in other colours.
- The root beam is in the background, other beams are laid on top.
- See Figures 5.29 and 5.30.
- InfoVis 2002 paper [van Ham and van Wijk 2002].

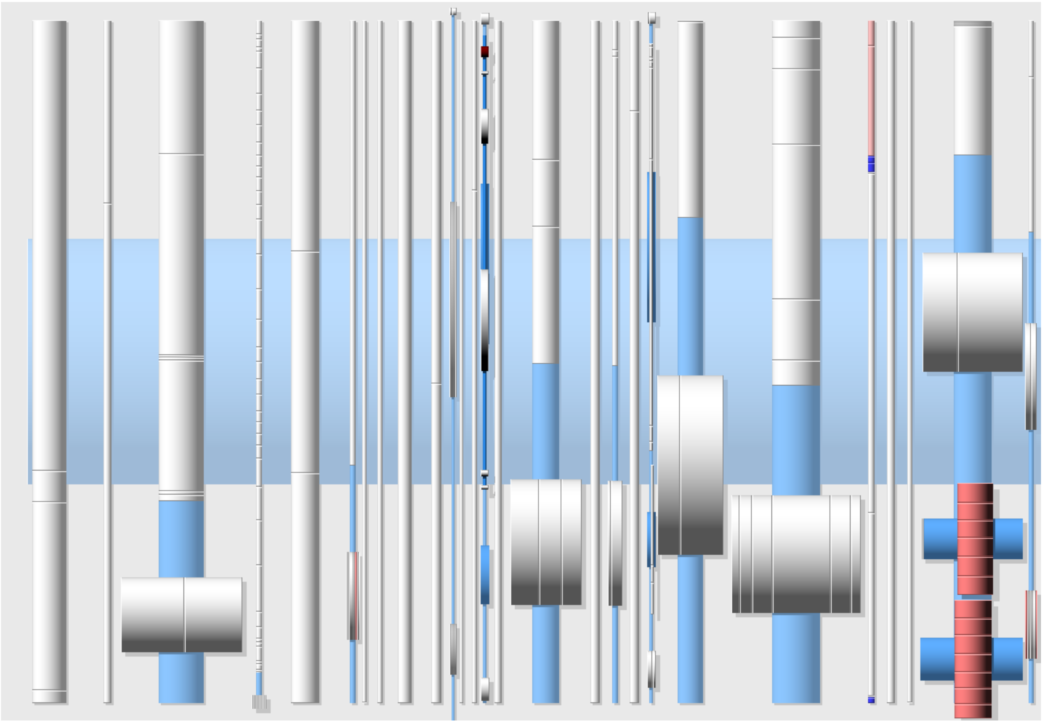


Figure 5.29: BeamTrees are a variation on treemaps using overlapping beams. Directories are coloured blue, files are other colours. The root directory is at the back, other directories are overlaid upon it.

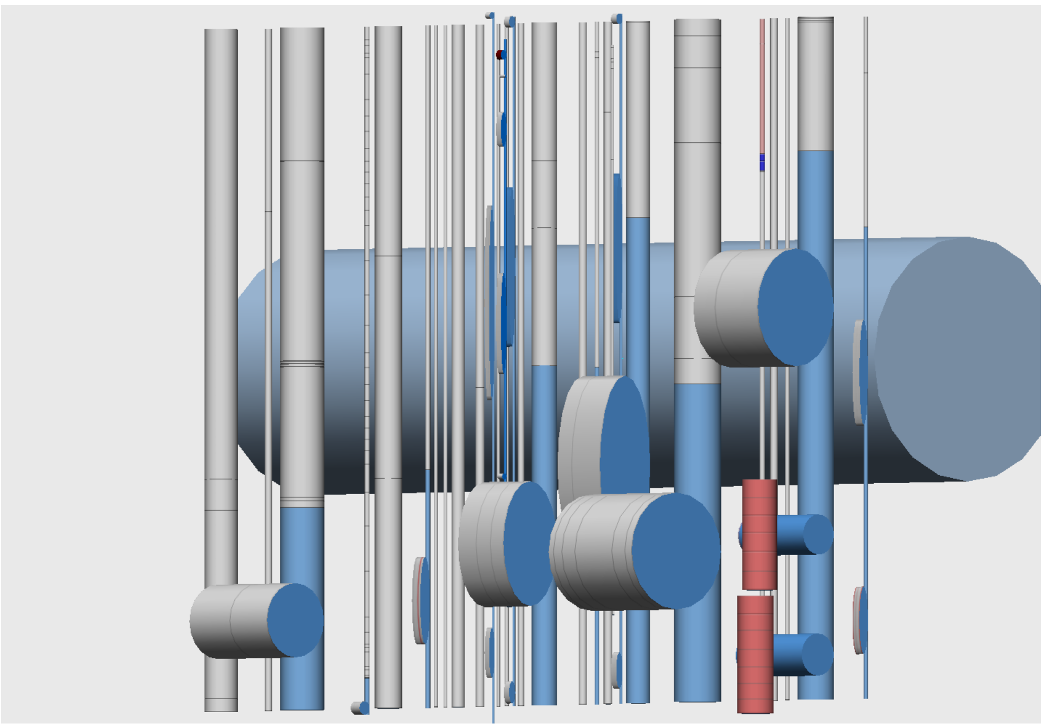


Figure 5.30: The directory structure is only really recognisable when a 3D rendering is used.

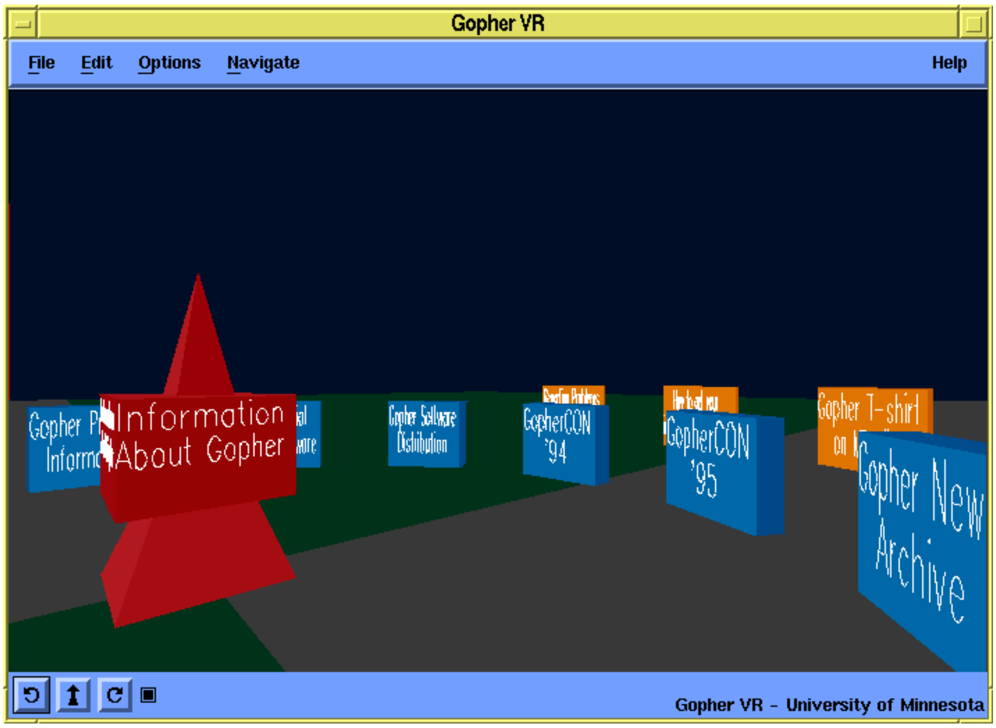


Figure 5.31: GopherVR visualises one level of a Gopher hierarchy at a time. The central pyramid bears the name of the current level, clicking on it returns the user to the next higher level.

5.8 Single-Level Tree Browsers

5.8.1 GopherVR

- University of Minnesota, 1995.
- 3d landscape visualisation of *individual* levels of a Gopher hierarchy. Members of a collection are arranged in a stonehenge-like circle.
- Spiral visualisation of Gopher search result sets, spiraling out from centre with decreasing relevance.
- Possibility to hand-place items, for example grouping related items.
- Cute physical simulation of shaking when landing, can jump up and look around.
- Papers [McCahill and Erickson 1995; Iacovou and McCahill 1995]. [Video: `https://youtu.be/mljHFaNHzhc`]

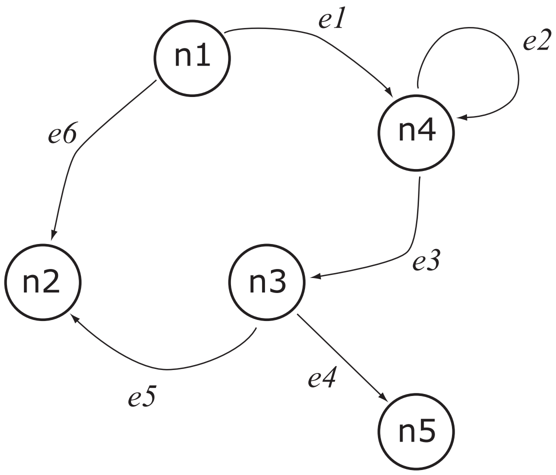
Chapter 6

Visualising Networks and Graphs

6.1 Adjacency Matrix

An *adjacency matrix* explicitly tabulates links between nodes.

- Also sometimes called a *connectivity matrix* and a *design structure matrix* (DSM).
- For a graph with N nodes, an $N \times N$ matrix is used to indicate where edges occur.
- Figure 6.1 shows an example for a graph with five nodes and six edges.



To

From	n1	n2	n3	n4	n5
n1		*e6*		*e1*	
n2					
n3		*e5*			*e4*
n4			*e3*	*e2*	
n5					

Figure 6.1: A graph with five nodes and six directed edges. The drawing on the left is hand-drawn. The representation on the right shows the same graph in the form of an adjacency matrix.

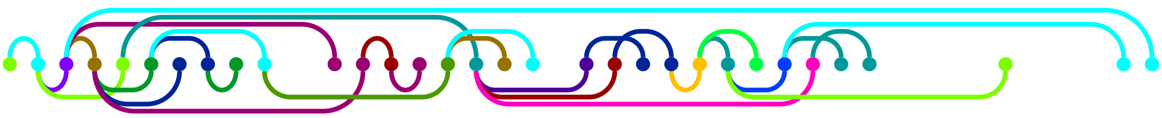


Figure 6.2: ThreadVis implements the Thread Arcs visualisation as an add-on for Thunderbird. Here is a thread from the `alt.gesellschaft.recht` newsgroup containing 32 messages.

6.2 Predetermined Position

The nodes of a graph are laid out in predetermined positions (linear, circular, grid, geographical) and the edges are routed and encoded in various ways.

6.2.1 Linear

Thread Arcs

- Thread Arcs were developed to visualise threads of conversation between email or newsgroup messages [Kerr 2003].
- ThreadVis is an implementation of Thread Arcs for the Thunderbird news and email client [Hubmann-Haidvogel 2008]. See Figure 6.2. `http://threadvis.mozdev.org/`

6.2.2 Circular

Also called ring-based layouts or chord diagrams.

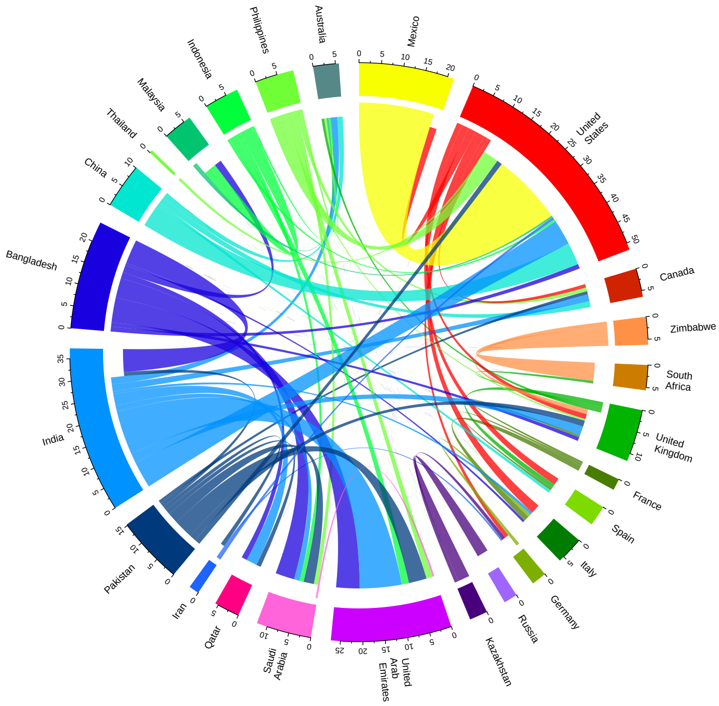


Figure 6.3: A circular plot of migration flows between the world's top 25 sending and receiving countries between 2005 and 2010. A large gap at the outer segment indicates destination, a small gap indicates origin. The tick marks show the numbers of migrants in millions [Image created by Keith Andrews using data and R code kindly provided by G. Abel [2014]] .

Migration Flows

- Guy Abel and Nikola Sander, at Vienna Institute of Demography, produce circular plots of migration data [G. J. Abel and Sander 2014; G. Abel 2014].
- Figure 6.3 shows a circular plot of migration flows between the world's top 25 sending and receiving countries between 2005 and 2010.

Flare Dependency Graph

- The Flare Dependency Graph is a circular layout showing dependencies among classes within the Flare library [Heer 2010].
- Each class is placed around the edge of a circle. The exact radius indicates the depth of the class in the package structure tree.
- A link indicates that a class imports another.
- Edges are "bundled" together for greater clarity.
- See Figure 6.4.

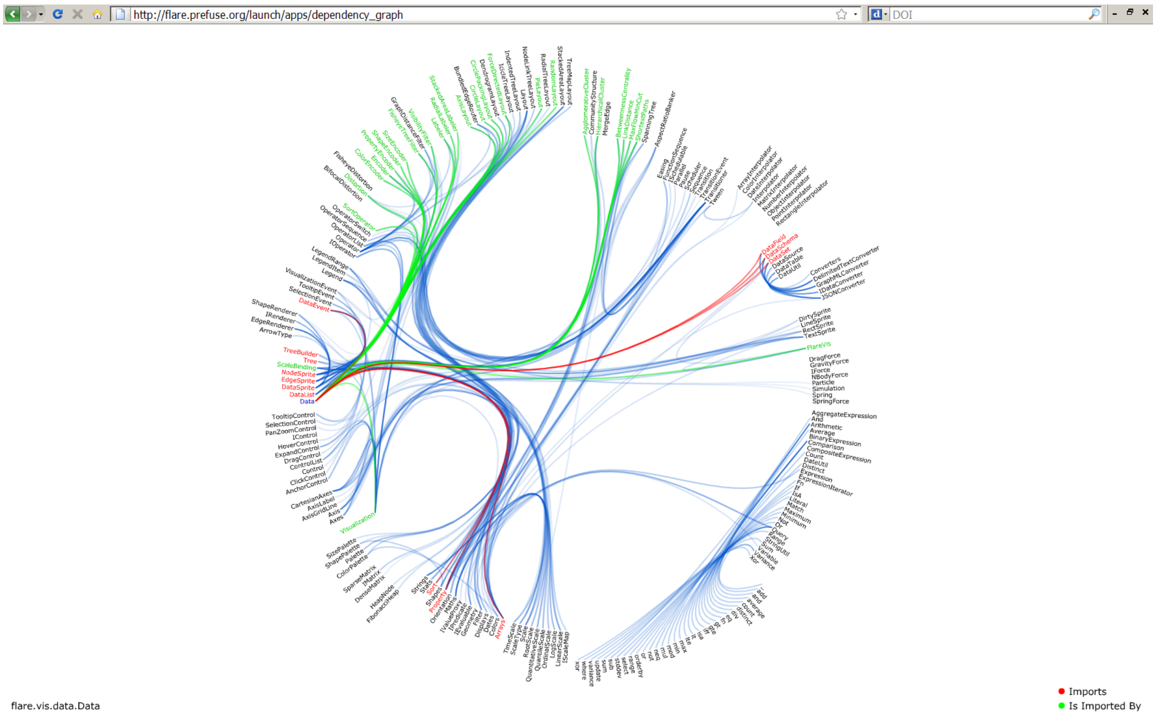


Figure 6.4: The Flare Dependency Graph is a circular layout showing the dependencies between classes in the Flare library. Here the class Data has been selected.

6.2.3 Grid-Based

Intermedia Global Map

- Intermedia was a network hypermedia system developed for Apple computers in the 1980s. [Haan et al. 1992; Yankelovich et al. 1988].
- Hypermedia nodes (documents) are placed on a regular grid and links are drawn between them.
- See Figure 6.5.

6.2.4 Geography-Based

Flow Maps

- Historical flow maps created by Charles Minard.
- Layout algorithm described by Doantam Phan et al in InfoVis 2005 paper [Phan et al. 2005].
- See Figure 6.6 shows migration to California using US Census data from 2000.

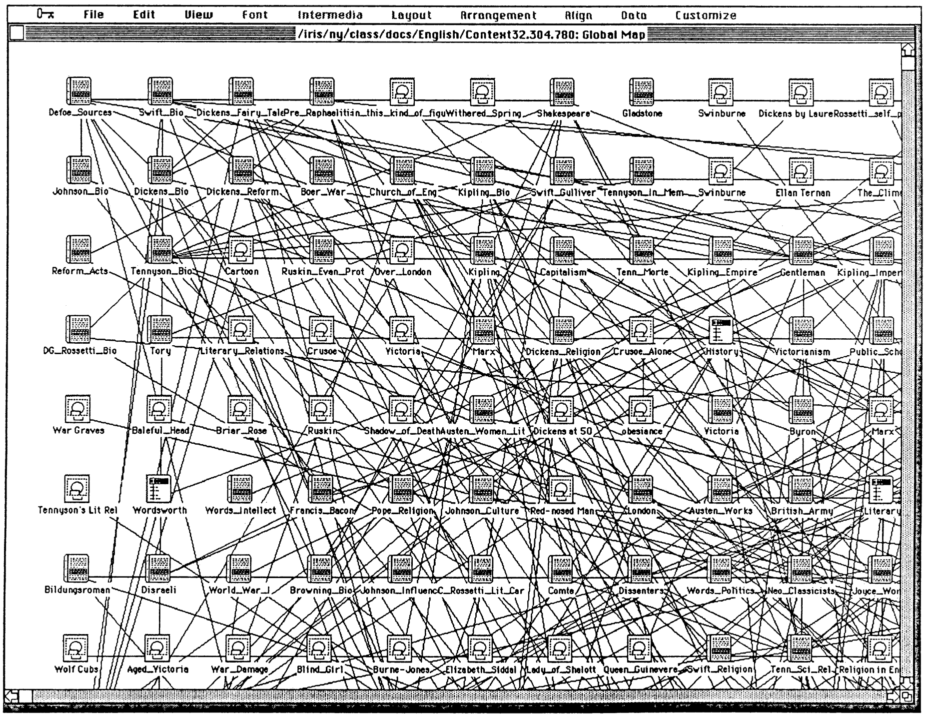


Figure 6.5: The Intermedia Global Map. Hypermedia nodes (documents) are placed on a regular grid and links are drawn between them. [Image extracted from Conklin [1987]. Copyright ©1987 IEEE. Used with permission.]

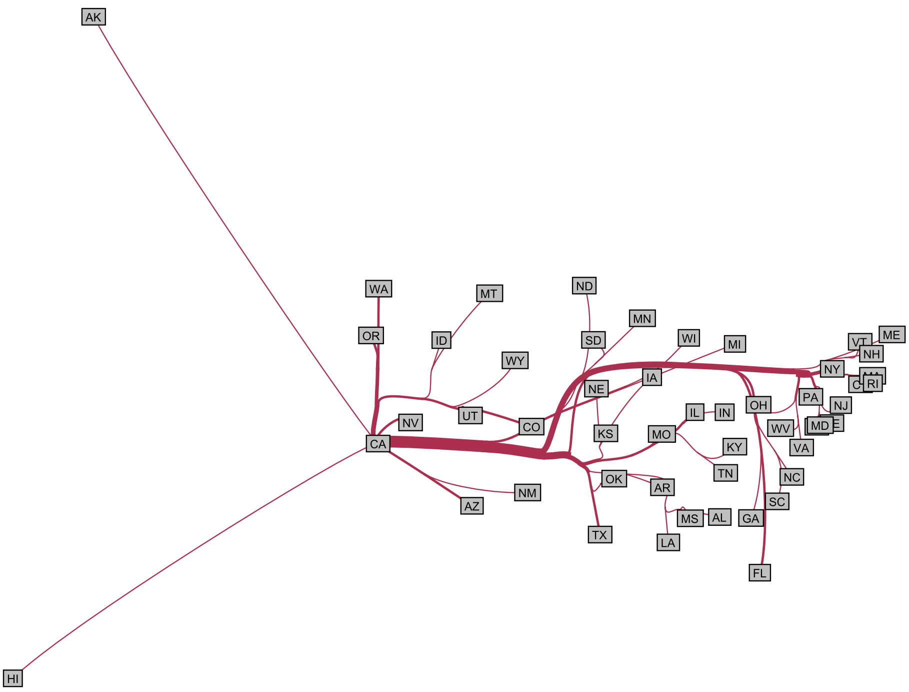


Figure 6.6: A flow map showing migration to California from other US states, using data from the US Census 2000. [Image created by Keith Andrews using the software available from Phan et al. [2006]] .

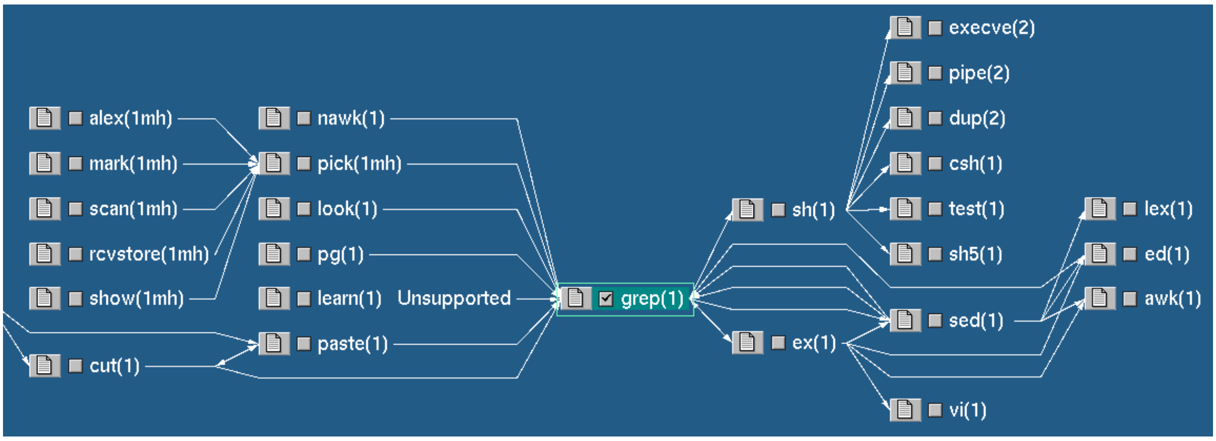


Figure 6.7: The Harmony Local Map uses graph drawing algorithms to lay out a map of the link environment of hypermedia documents. In this example, Unix manual pages one and two links away from the grep manual page are visualised.

6.3 Layered Graph Drawing

Layered Graph Drawing, also called Sugiyama layout. User for (acyclic) directed graphs.

Three main steps:

1. Layering
2. Crossing reduction
3. X-coordinate assignment

Ideal for directed graphs: directionality is reflected in the layering (flow from top to bottom, or left to right).

6.3.1 Harmony Local Map

- IICM, 1993-1994.
- Graph layout for nodes and links of a hypermedia network.
- Modified version of Eades and Sugiyama's [Eades and Sugiyama 1990] graph layout algorithm [di Battista et al. 1999].
- Description in Chapter 8 of [Andrews 1996].

Harmony Local Map 3D

- IICM, 1995.
- Links in vertical plane superimposed atop information landscape. See Figure 6.8.
- Description in Chapter 8 of [Andrews 1996].

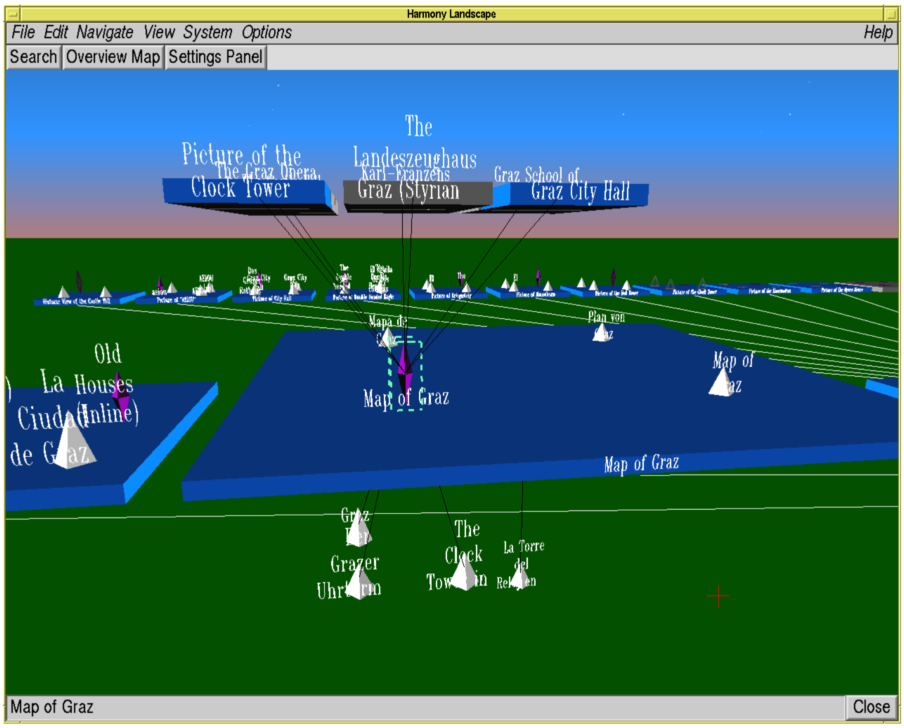


Figure 6.8: The Harmony Local Map 3D display hierarchical structure on the horizontal plane and superimposes hyperlink connections in the vertical plane.

6.4 Force-Based Layouts

6.4.1 SemNet

- Fairchild, Poltrock, Furnas, MCC, 1988.
- The first 3d information visualisation.
- 3d spatial layout of a semantic network. See Figure 6.9.
- Article [K. M. Fairchild et al. 1988].
- Video at CHI '87 [K. Fairchild 1987]. [Video: `https://youtu.be/wAu75r77Qko?t=03m00s`]
- Patented under [Wexelblat and K. M. Fairchild 1991].

6.4.2 HyperSpace (Narcissus)

- University of Birmingham, 1995.
- Self-organising structure based forces and springs. See Figure 6.10.
- The number of links between documents provides the attractive force.
- Narcissus [Hendley et al. 1995], later renamed HyperSpace [Wood et al. 1995].

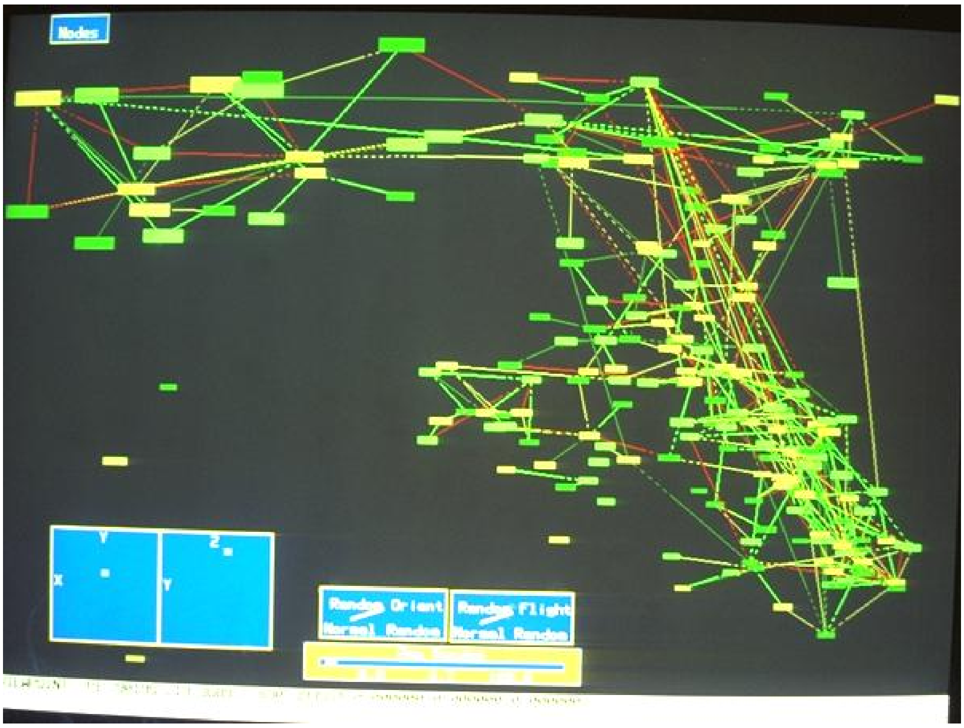


Figure 6.9: SemNet visualised a semantic network in 3d. [Image used with kind permission of Kim Fairchild.]

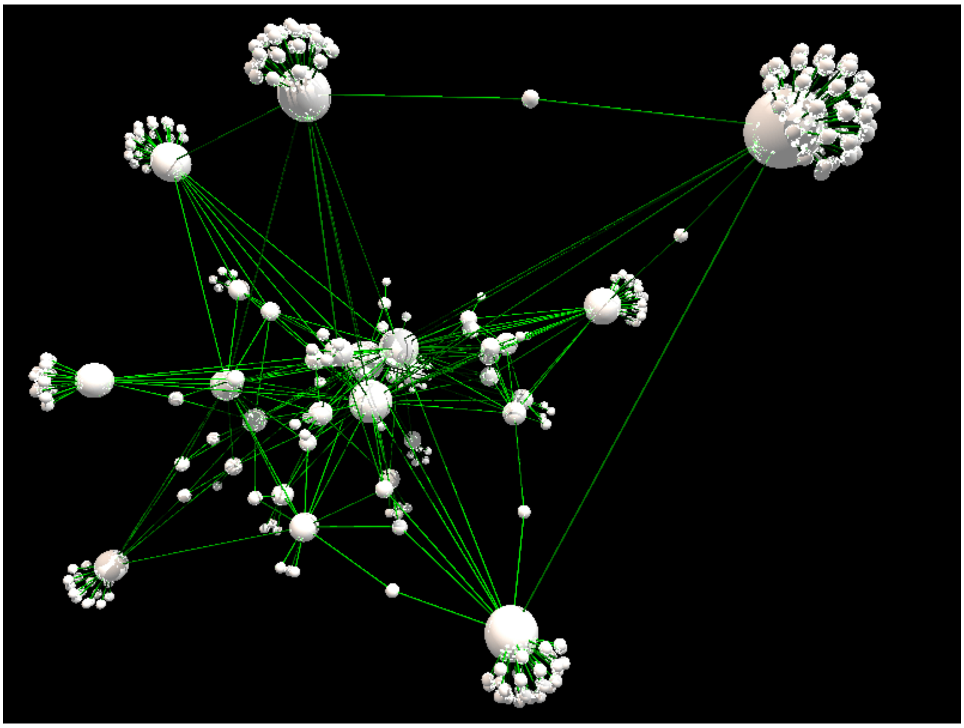


Figure 6.10: HyperSpace showing the structure of a website. White spheres represent web pages. Green lines represent links between pages. The size of a sphere is proportional to the total number of incoming and outgoing links. [Image used with kind permission of Andy Wood.]

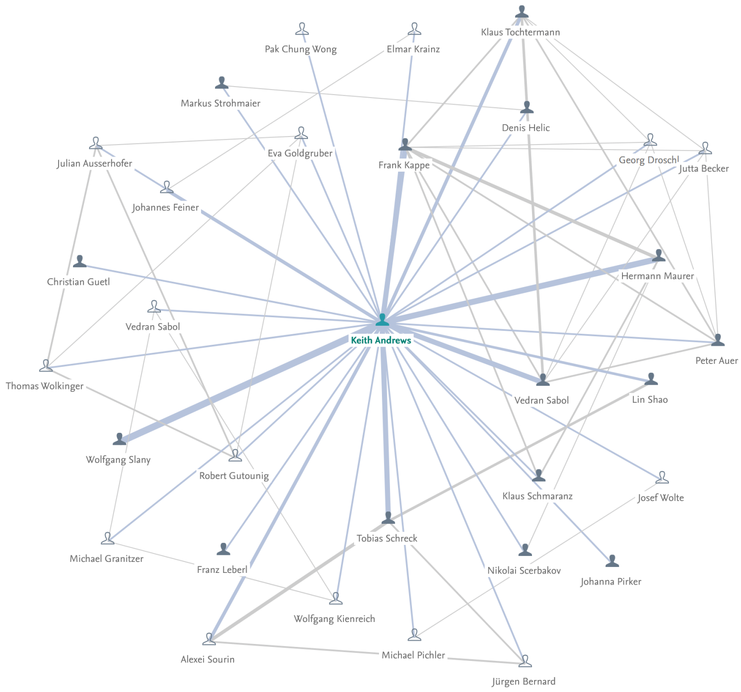


Figure 6.11: The co-authorship network for Keith Andrews from 1991 to 2020, as generated by Pure. A minimum level of collaboration of two papers has been set.

6.4.3 Co-Authorship Network from Pure

- A co-authorship network reflects academic collaboration.
- The co-authorship network for Keith Andrews from 1991 to 2020, as generated by Pure using force-directed placement, is shown in Figure 6.11.
- It is accessible online here: `https://graz.pure.elsevier.com/en/persons/keith-andrews`.

6.4.4 Friendship Network from Vizster

- Vizster was a visualisation tool for Friendster, an early social network.
- It uses force-directed placement to lay out a friendship network, and could also identify communities, as shown in Figure 6.12.
- Paper at InfoVis 2005 [Heer and Boyd 2005b].

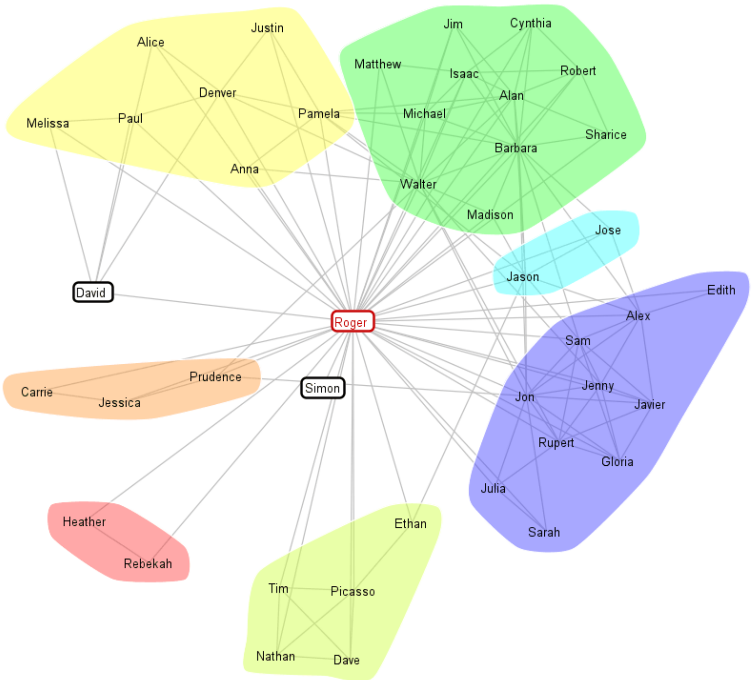


Figure 6.12: Vizster shows friendship networks from Friendster. It can also identify communities. [Image created by Keith Andrews, using the Vizster software and demo dataset [Heer and Boyd 2005a].]

Chapter 7

Visualising Multidimensional Metadata

> *" Getting information from a table is like extracting sunlight from a cucumber. "*
>
> [Arthur and Henry Farquhar, Economic and Industrial Delusions, Putnam, New York, 1891.]

7.1 Interactive Tables

7.1.1 Table Lens

- Xerox PARC, 1994.
- Focus + context technique for large tables.
- Rows and columns are squeezed down to pixel and subpixel sizes. See Figure 7.1.
- CHI'94 paper [R. Rao and Card 1994] and CHI'95 video [R. Rao and Card 1995]. [Video: `https://youtu.be/ZDY9YCYv7z8?t=49s`]
- US Patent 5632009 [R. B. Rao and Card 1997].

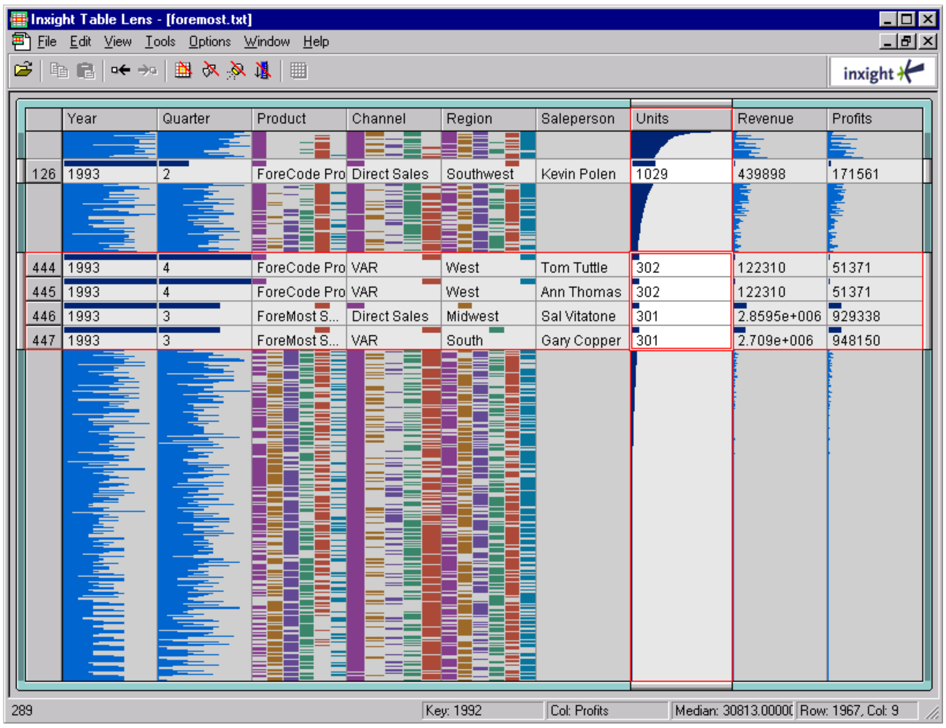


Figure 7.1: The Table Lens represents rows of a table as rows of pixels. The user can focus and stretch out rows or columns to see the data, whilst maintaining surrounding context. [Screenshot made by Keith Andrews using the Inxight Eureka 30-day free trial.]

7.2 Interactive Scatterplots

7.2.1 FilmFinder

- HCIL, University of Maryland, 1991-1993.
- Sliders and controls directly manipulate an on-screen scatterplot.
- The scatterplot is called a “starfield display”.
- CHI’92 paper [Ahlberg et al. 1992] and video [Shneiderman et al. 1992], CHI’94 paper [Ahlberg and Shneiderman 1994b] and video [Ahlberg and Shneiderman 1994a]. [Video: `https://youtu.be/usLM4ncvhjk?t=04m33s`]
- Commercialised as part of the Spotfire toolkit [Spotfire 2000].

7.2.2 Envision

- Virginia Tech, 1993–1997.
- Direct manipulation of search result sets by mapping document attributes along two axes.
- SIGIR’96 paper [Nowell et al. 1996] and CHI’97 online abstracts [Nowell et al. 1997].

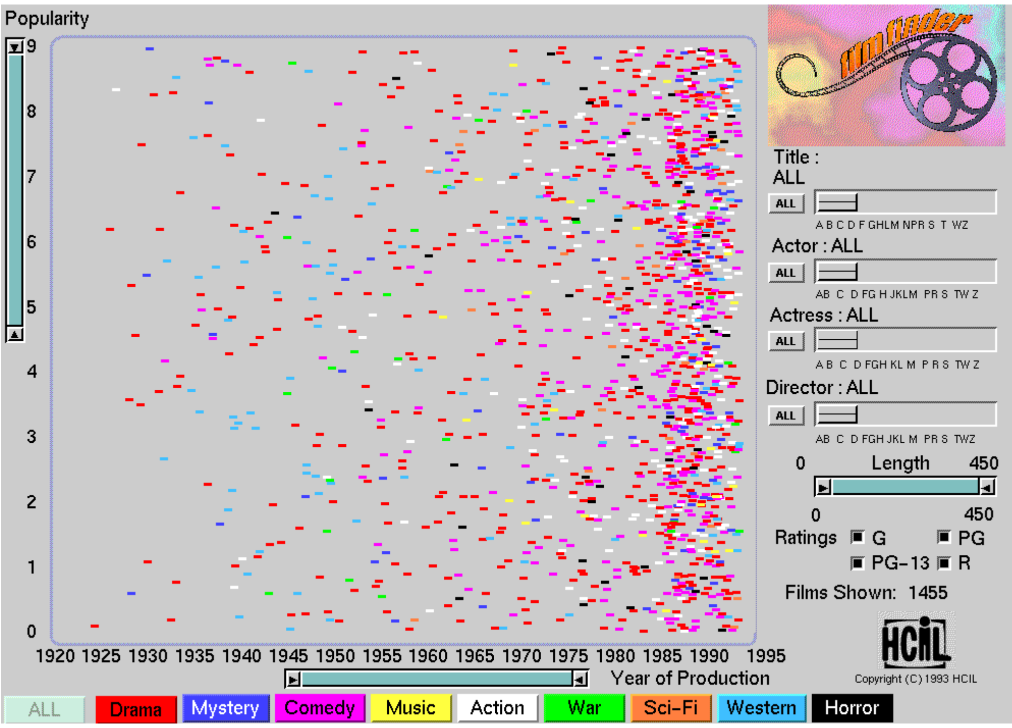


Figure 7.2: The FilmFinder, a starfield display combined with dynamic queries for rapid filtering. [Copyright ©University of Maryland 1984-1994.]

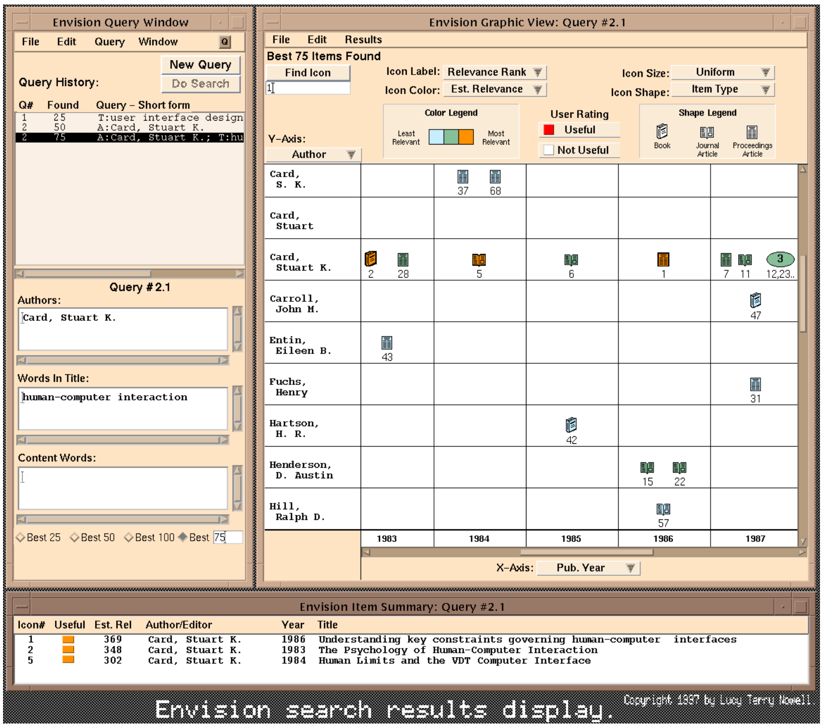


Figure 7.3: Envision visualises a set of search results, by mapping document attributes along two axes. Where too many documents would occupy a cell, an ellipse is used as a container object. Another problem is where to place documents matching multiple categories. [Copyright © by the Association for Computing Machinery, Inc.]

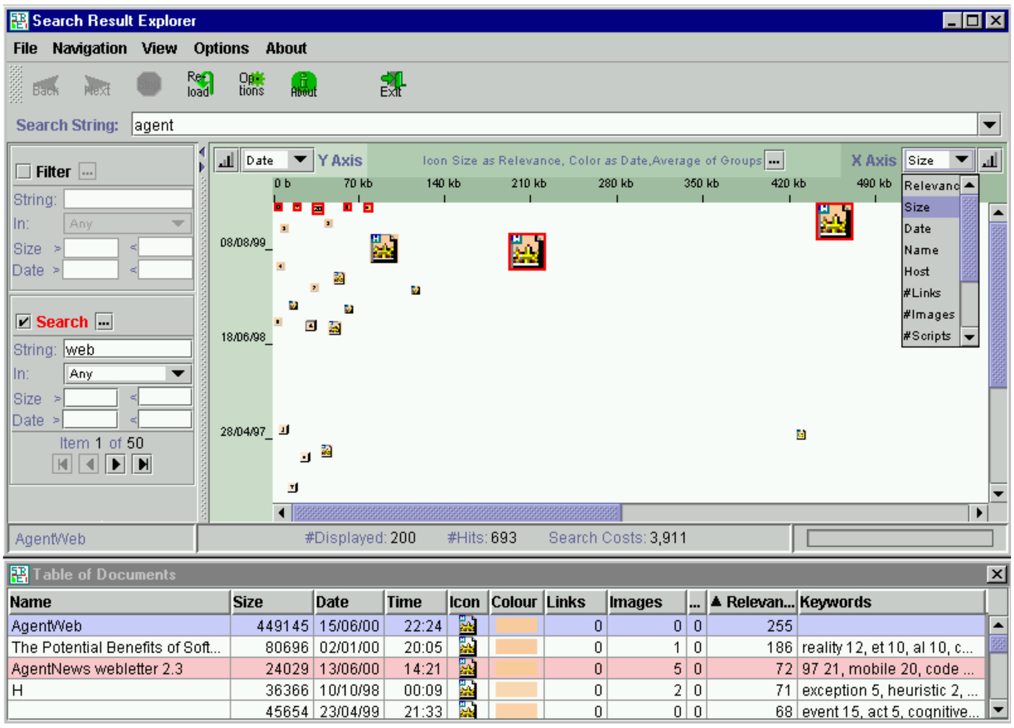


Figure 7.4: Search Result Explorer.

7.2.3 Search Result Explorer

- IICM, 1999.
- Similar to Envision, Java implementation for the xFIND search engine.
- Paper at UIDIS 2001 [Andrews et al. 2001].

7.3 Multidimensional Glyphs

Chernoff Faces

- Invented by Herman Chernoff in 1973 [Chernoff 1973].
- Dimensions (variables) are mapped to characteristics of cartoon-like human faces, such as the curvature of the mouth and the slant of the eyes.
- Figure 7.5 shows Chernoff faces for R's built-in mtcars dataset.

Name	*mpg*	*cyl*	*disp*	*hp*	*drat*	*wt*	*qsec*	*vs*	*am*	*gear*	*carb*
Mazda RX4	21.0	6	160.0	110	3.90	2.620	16.46	0	1	4	4
Mazda RX4 Wag	21.0	6	160.0	110	3.90	2.875	17.02	0	1	4	4
Datsun 710	22.8	4	108.0	93	3.85	2.320	18.61	1	1	4	1
Hornet 4 Drive	21.4	6	258.0	110	3.08	3.215	19.44	1	0	3	1
Hornet Sportabout	18.7	8	360.0	175	3.15	3.440	17.02	0	0	3	2
Valiant	18.1	6	225.0	105	2.76	3.460	20.22	1	0	3	1
Duster 360	14.3	8	360.0	245	3.21	3.570	15.84	0	0	3	4
Merc 240D	24.4	4	146.7	62	3.69	3.190	20.00	1	0	4	2
Merc 230	22.8	4	140.8	95	3.92	3.150	22.90	1	0	4	2
Merc 280	19.2	6	167.6	123	3.92	3.440	18.30	1	0	4	4
Merc 280C	17.8	6	167.6	123	3.92	3.440	18.90	1	0	4	4
Merc 450SE	16.4	8	275.8	180	3.07	4.070	17.40	0	0	3	3
Merc 450SL	17.3	8	275.8	180	3.07	3.730	17.60	0	0	3	3
Merc 450SLC	15.2	8	275.8	180	3.07	3.780	18.00	0	0	3	3
Cadillac Fleetwood	10.4	8	472.0	205	2.93	5.250	17.98	0	0	3	4
Lincoln Continental	10.4	8	460.0	215	3.00	5.424	17.82	0	0	3	4
Chrysler Imperial	14.7	8	440.0	230	3.23	5.345	17.42	0	0	3	4
Fiat 128	32.4	4	78.7	66	4.08	2.200	19.47	1	1	4	1
Honda Civic	30.4	4	75.7	52	4.93	1.615	18.52	1	1	4	2
Toyota Corolla	33.9	4	71.1	65	4.22	1.835	19.90	1	1	4	1
Toyota Corona	21.5	4	120.1	97	3.70	2.465	20.01	1	0	3	1
Dodge Challenger	15.5	8	318.0	150	2.76	3.520	16.87	0	0	3	2
AMC Javelin	15.2	8	304.0	150	3.15	3.435	17.30	0	0	3	2
Camaro Z28	13.3	8	350.0	245	3.73	3.840	15.41	0	0	3	4
Pontiac Firebird	19.2	8	400.0	175	3.08	3.845	17.05	0	0	3	2
Fiat X1-9	27.3	4	79.0	66	4.08	1.935	18.90	1	1	4	1
Porsche 914-2	26.0	4	120.3	91	4.43	2.140	16.70	0	1	5	2
Lotus Europa	30.4	4	95.1	113	3.77	1.513	16.90	1	1	5	2
Ford Pantera L	15.8	8	351.0	264	4.22	3.170	14.50	0	1	5	4
Ferrari Dino	19.7	6	145.0	175	3.62	2.770	15.50	0	1	5	6
Maserati Bora	15.0	8	301.0	335	3.54	3.570	14.60	0	1	5	8
Volvo 142E	21.4	4	121.0	109	4.11	2.780	18.60	1	1	4	2

Table 7.1: R's mtcars dataset.

Variable	*Characteristic*
mpg	height of face
cyl	width of face
disp	structure of face
hp	height of mouth
drat	width of mouth
wt	smiling
qsec	height of eyes
vs	width of eyes
am	height of hair
gear	width of hair
carb	style of hair
mpg	height of nose
cyl	width of nose
disp	width of ear
hp	height of ear

Table 7.2: The mapping of variables in the mtcars dataset to facial characteristics.

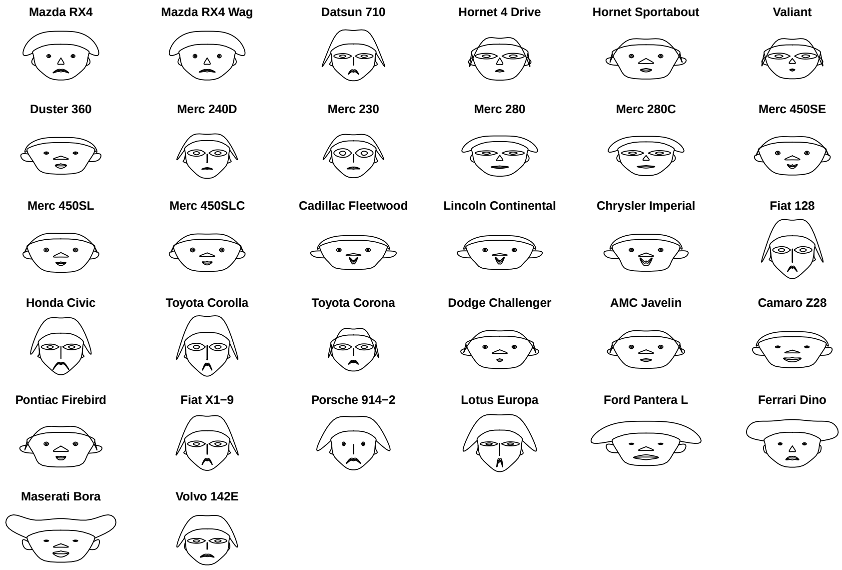


Figure 7.5: Chernoff faces for R's built-in mtcars dataset.

7.4 Parallel Coordinates

Parallel Coordinates Plot

- Equidistant parallel vertical lines represent the axes of a multidimensional space.
- One vertical line for each dimension.
- Each object is plotted as a polyline defined by values along each dimension.
- Objects which are very similar will have polylines which follow each other.
- Figure 7.6 shows plot of 11 data points (students) on six dimensions (FirstName, Quiz1, Quiz2, Homework1, Homework2, Final).
- Figure 7.7 shows InfoScope [Brodbeck and Girardin 2003; Girardin and Brodbeck 2001; MacroFocus 2015], which combines a parallel coordinates view with a geographic map and a similarity map for exploration of multidimensional data about 73 cities. [Video: `https://youtu.be/fnyKj8r0CN4?t=03m27s`]

History of Parallel Coordinates

- The first known use was by Henry Gannett in 1883 [Hewes and Gannett 1883, Plate 151] used to visualise 10 attributes for each the (then 47) states of the USA. [It is shown in Figure 3.11.]
- Maurice d'Ocagne discussed the theoretical foundations of parallel coordinates in his book in 1885 [d'Ocagne 1885].
- The technique was independently re-invented by Alfred Inselberg in 1959 [Inselberg 2004]

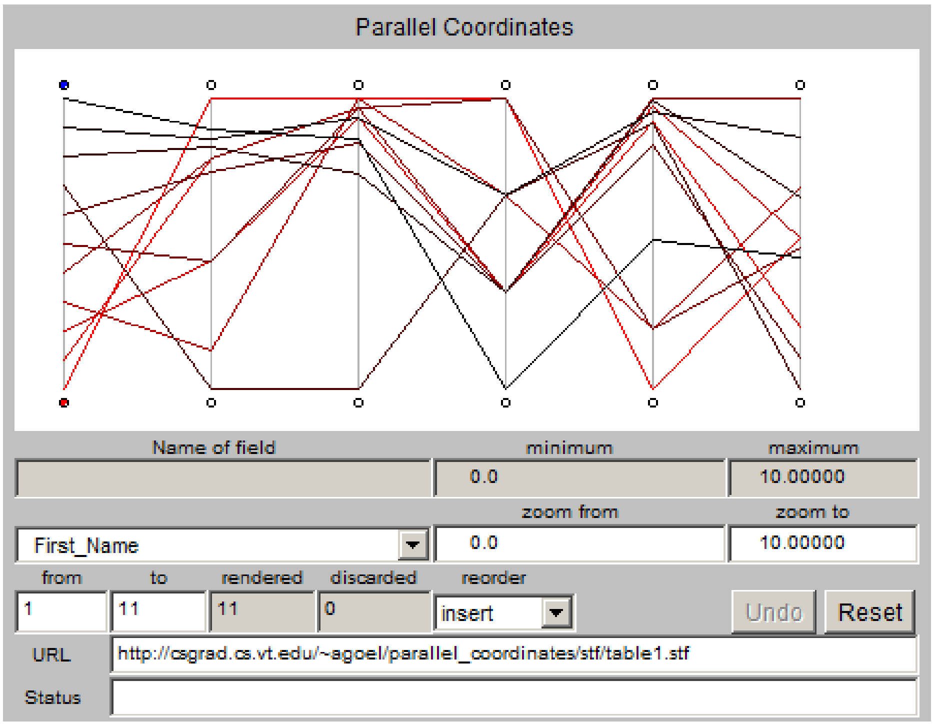


Figure 7.6: Parallel Coordinates. The six vertical lines represent (from left to right) the name and marks of students in five exams. The eleven polylines represent the data from eleven students. Polylines which mirror one another closely from vertical lines 2 to 6 indicate students achieving very similar marks.

- Inselberg published a comprehensive overview paper in the journal The Visual Computer in 1985 [Inselberg 1985] and has published widely on parallel coordinates since.
- Inselberg published his definitive book on the subject in 2009 [Inselberg 2009].

  [Alfred Inselberg passed away on 30 Dec 2019.]

References

++ Alfred Inselberg; *Parallel Coordinates: Visual Multidimensional Geometry and Its Applications*; Springer, 08 Oct 2009. ISBN 0470856181 (com, uk) [Inselberg 2009]

++ Fletcher W. Hewes and Henry Gannett; *Scribner's Statistical Atlas of the United States*; Charles Scribner's Sons, Broadway, New York, 1883. [Hewes and Gannett 1883]

++ Maurice d'Ocagne; *Coordonnées Parallèles et Axiales*; Gauthier-Villars, Paris, 1885. [d'Ocagne 1885]

InfoScope

- InfoScope combines a parallel coordinates view with a geographic map and a similarity map [Brodbeck and Girardin 2003; Girardin and Brodbeck 2001; MacroFocus 2015], as shown in Figure 7.7.
- The dataset is garnered from the UBS Prices and Earnings Survey 2012, and contains various indices such as Net Purchasing Power, Net Wages, Working Time (hours per year), and Vacation (paid working days per year) for 73 cities.
- Video clip of live demo: [Video: `https://youtu.be/fnyKj8r0CN4?t=03m27s`]

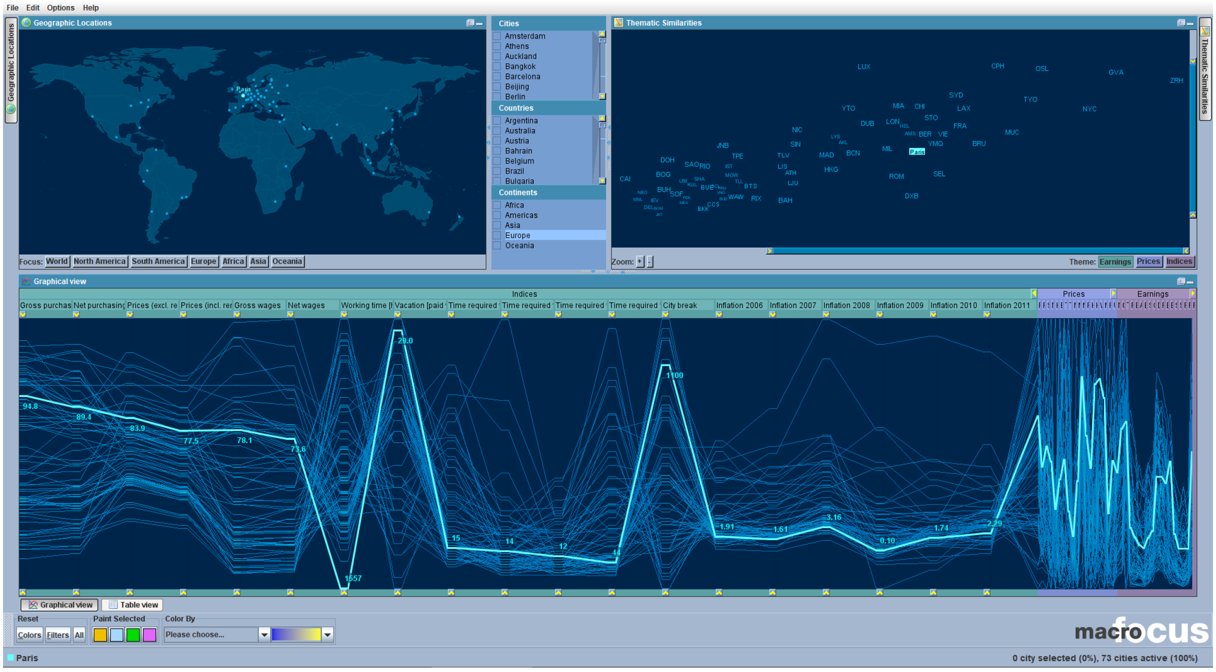


Figure 7.7: InfoScope [Brodbeck and Girardin 2003] allows users to explore multidimensional data from 73 cities, garnered from the UBS Prices and Earnings Survey 2012. The parallel coordinates view at the bottom is complemented with geographic map and a similarity map. [Screenshot made by Keith Andrews with the InfoScope software [MacroFocus 2015].]

AVL SimBook

- SimBook is a visualisation tool for multidimensional race car simulation data used by AVL Racing to optimise Formula 1 race car performance [Osmić 2015; Andrews et al. 2015], as shown in Figure 7.8.
- A small number of output parameters are calculated from hundreds of configurations (records) of hundreds of input parameters.
- A typical goal is to find a configuration which optimises (minimises) lap time.

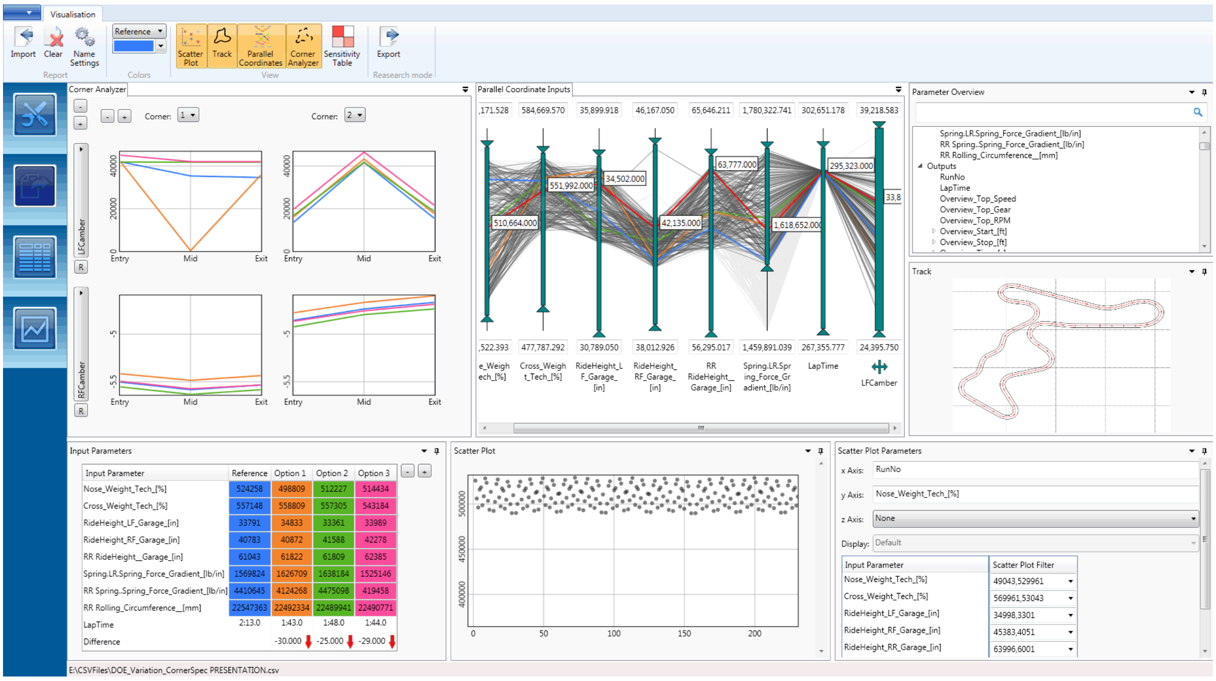


Figure 7.8: SimBook [Osmić 2015] is used to explore simulation results. [Screenshot made by Majda Osmić and used with permission.]

7.5 Star Plot

- Also known as star chart, radar chart, spider plot, wheel chart, and polar chart.
- Dimensions are laid out radially.
- Each record is represented as an irregular polygon.
- The visual image is highly dependent on the chosen ordering of dimensions.
- Sometimes lines are drawn on top of one another (occlusion).

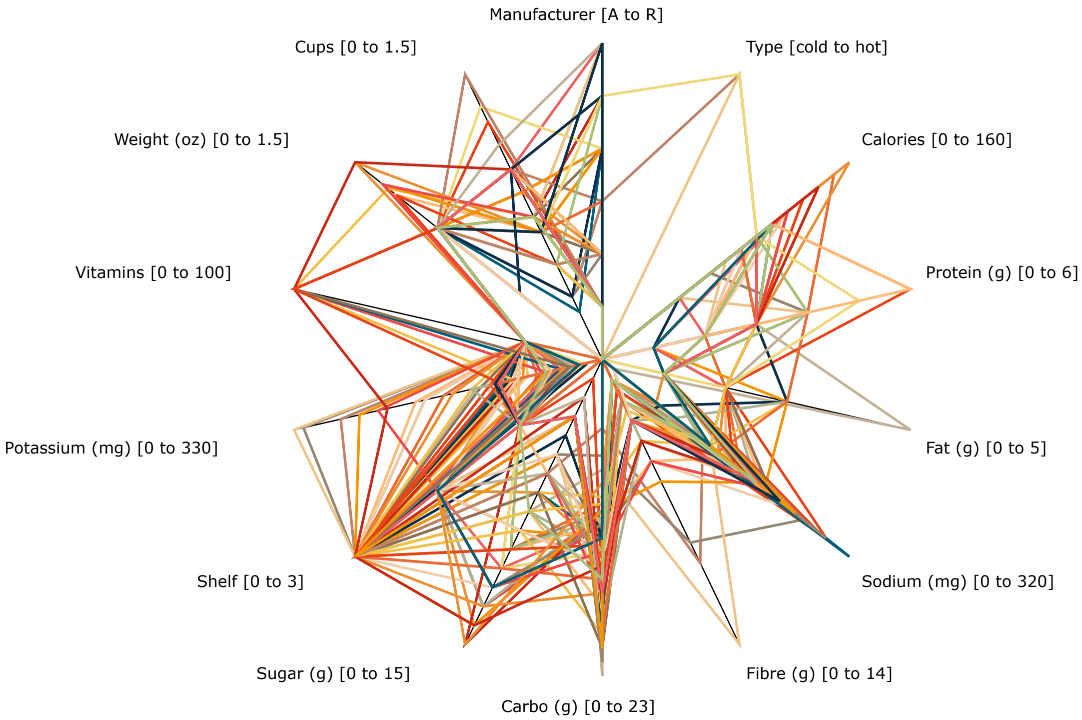


Figure 7.9: A star plot of the classic cereals dataset. [Image created by Keith Andrews using Liquid Diagrams.]

7.6 Interactive Attraction

7.6.1 Dust and Magnet

- Ji Soo Yi, John Stasko, et al, Georgia Tech, 2005.
- Metaphor of dust particles attracted to magnets, as shown in Figure 7.10.
- Magnets can be added and removed, and their strength increased or decreased.
- Paper in IV journal 2005 [Yi et al. 2005b].
- Video from 2005 [Yi et al. 2005a]. [Video: `https://youtu.be/wLXwL38xek0?t=28s`]
- More recently re-implemented for touch interface. [Video: `https://www.cc.gatech.edu/gvu/ii/dnm/dustnmagnet-16Hub.mp4`]

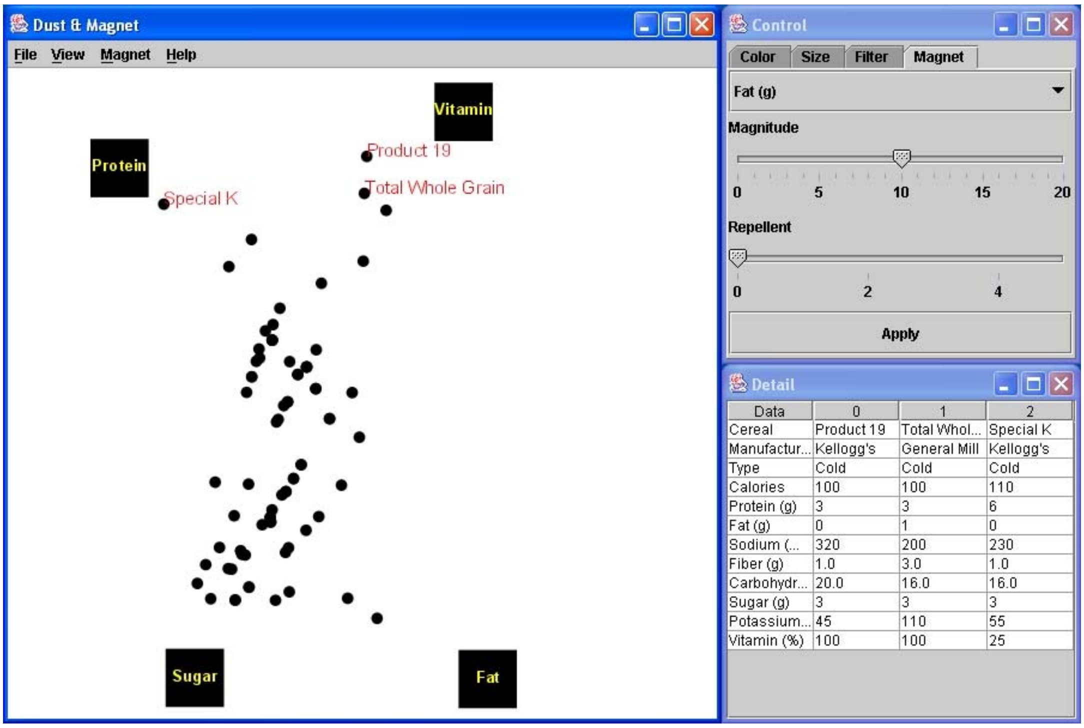


Figure 7.10: Dust and Magnet. Small circles (dust) represent items, square blocks (magnets) represent dimensions (variables). A higher value along a dimension causes an item to be attracted more strongly. [Image used with kind permission of Ji Soo Yi.]

7.7 Interactive Histograms

7.7.1 Attribute Explorer

- Imperial College, 1993.
- Direct manipulation of coupled views of histograms, as shown in Figure 7.11.
- Each attribute is assigned to a scale with histograms showing the population spread.
- If there are few enough items, individual icons are shown.
- Sliders are provided for continuous attributes (e.g. price) and buttons for discrete attributes (e.g. type of house).
- The effect of one attribute on the others can be explored by selecting values of interest on one scale and viewing where those items appear on the other attribute scales.
- CHI'94 video [Tweedie et al. 1994]. [Video: `https://open-video.org/details.php?videoid=8162`]
- Figure 7.12 shows a more recent implementation of an Attribute Explorer in JavaScript.

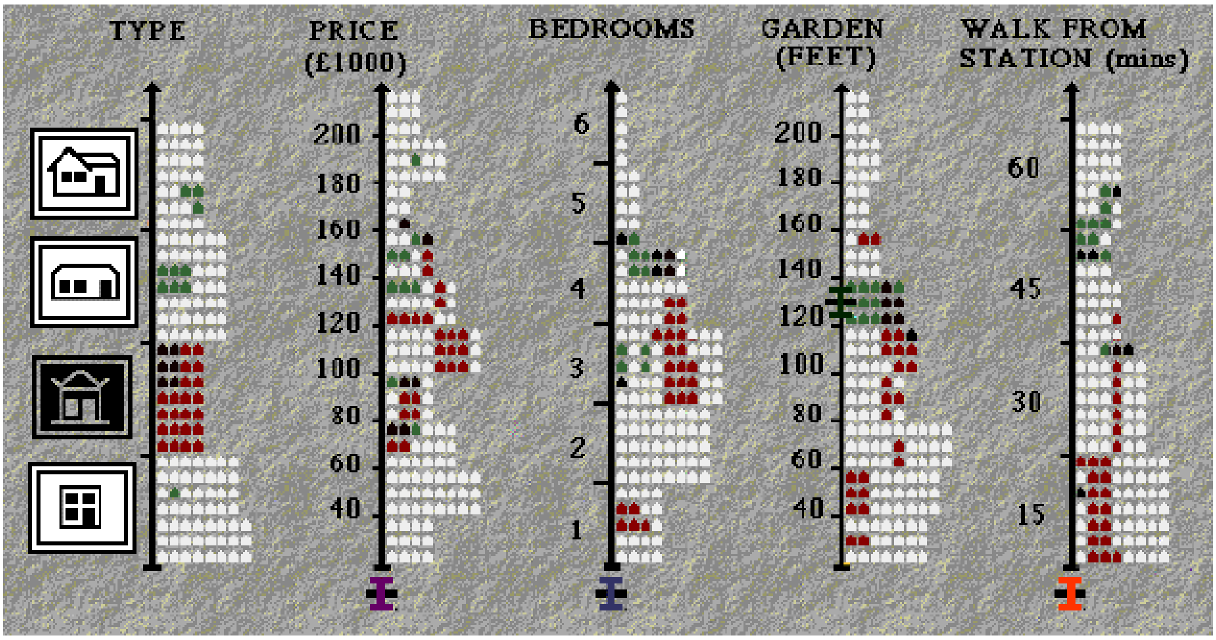


Figure 7.11: The Attribute Explorer. Terraced houses have been selected (red) together with a garden length of 120–140 feet (green). Houses fulfilling both criteria are shown in black. [Copyright © by the Association for Computing Machinery, Inc.]

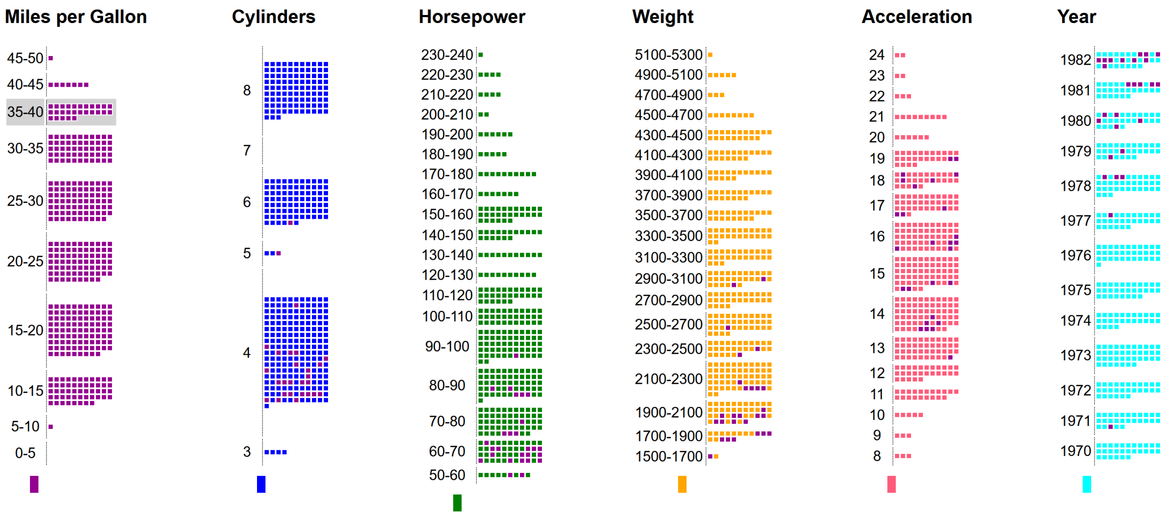


Figure 7.12: A more recent implementation in JavaScript of an Attribute Explorer showing the classic cars dataset. Cars in the Miles per Gallon range of 35–40 have been selected. It is easy to see how these cars are distributed across the other dimensions. Clicking a single car icon highlights its position in the other dimensions. [Screenshot made by Keith Andrews.]

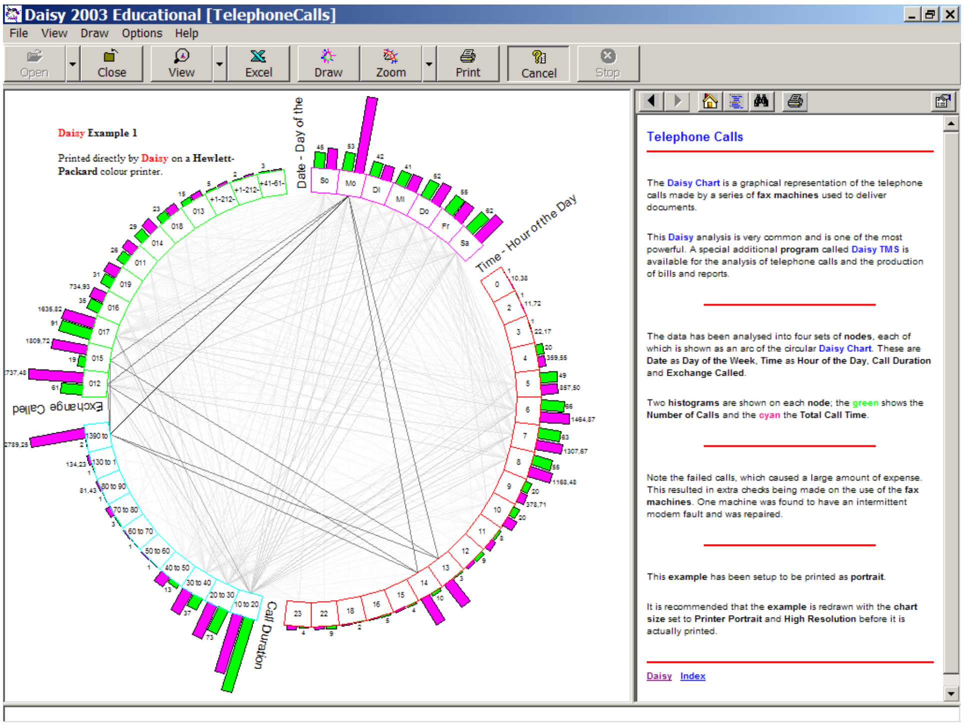


Figure 7.13: The Daisy Chart maps attributes and ranges of their values to positions on the circumference of a circle. Here, four attributes (Day of the Week, Hour of the Day, Call Duration, and Exchange) are given space on the perimeter. Each item (phone call) is represented by a polygon touching each attribute once. In each mini-histogram, green indicates the number of calls, and cyan the total call time.

7.8 Circular Histograms

Daisy Chart

- Daisy Analysis, UK, 2003 [Daisy 2003].
- Attributes and (ranges of) their values are arranged around the perimeter of a circle. A polygon of connecting lines represents an individual item. See Figure 7.13.

Chapter 8

Visualising Text and Object Collections (Feature Spaces)

References

++ Borg and Groenen; *Modern Multidimensional Scaling*; Second Edition, Springer, 2005. ISBN 0387251502 (com, uk) [Borg and Groenen 2005]

◦ Cox and Cox; *Multidimensional Scaling*; Second Edition, Chapman & Hall, 2000. ISBN 1584880945 (com, uk) [T. F. Cox and M. A. A. Cox 2000]

8.1 Distance-Based Projection

Distance Calculation

Calculate the similarity (or dissimilarity) between every pair of objects in nD.

Techniques include:

- Vector space model and distance metric (such as scalar product).
- Normalised compression distance based on Kolmogorov complexity (NCD) [Telles et al. 2007].
- Distances are often normalised to values between 0 and 1.
- Results in a symmetric matrix of distance values.

Multidimensional Projection

- Each object is represented by a vector in nD space.
- Objects are mapped directly to positions in 1D, 2D, or 3D space.
- Preserving (as far as possible) the distance relationships from the high-dimensional space in the target space.
- Typically by minimising a stress function.

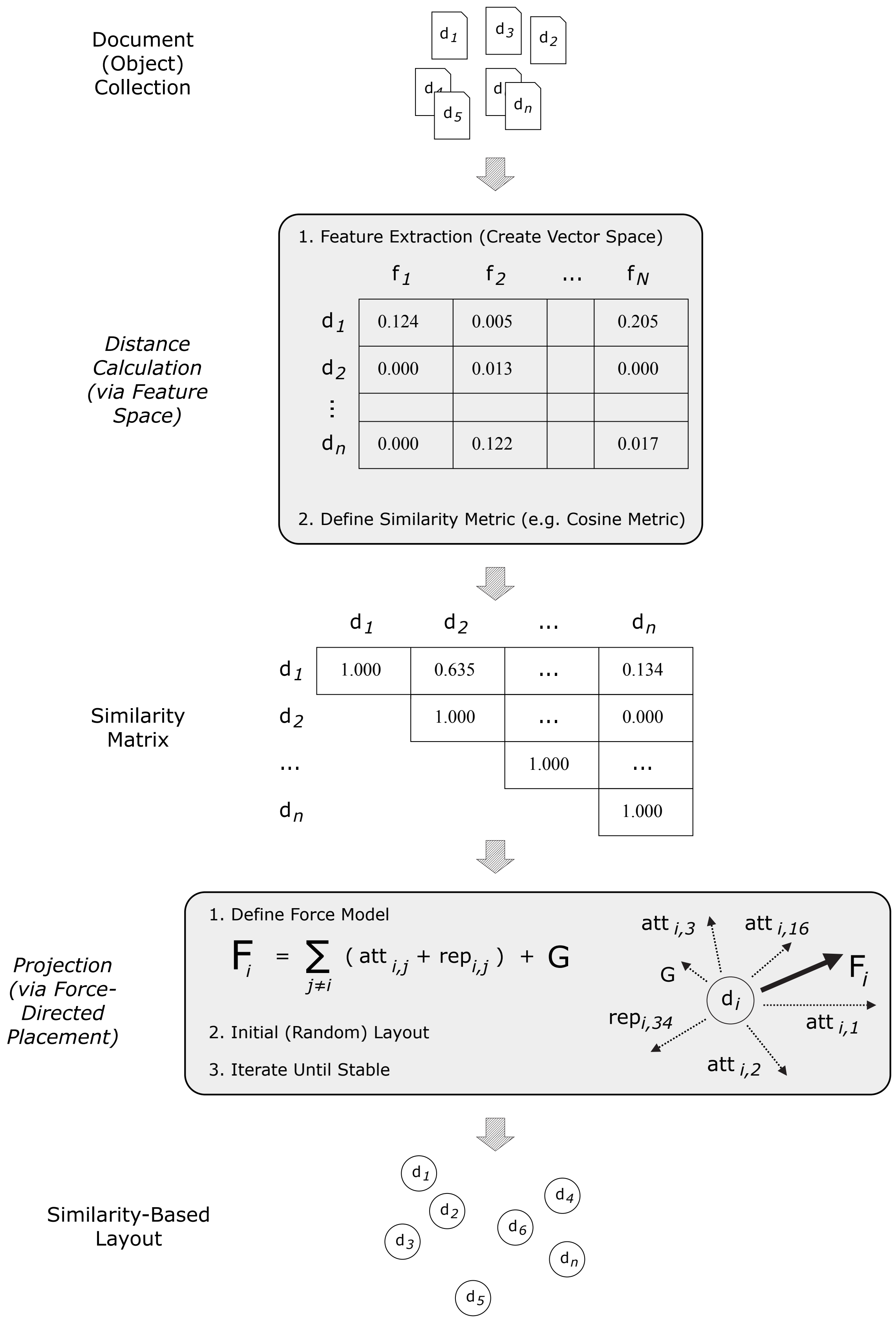


Figure 8.1: The visualisation pipeline for distance-based projection. Here, the vector space model has been chosen as the distance calculation algorithm and force-directed placement has been chosen as the projection algorithm.

8.1.1 Linear Projection

- Input is nD vector space.
- Can be directly calculated (no need for iterative process).
- Each embedding axis is a linear combination of the original axes.
- Creates meaningful axes which can be interpreted (given a “name”).
- Straightforward mapping of new objects.
- Low computational complexity.

Linear Projection Techniques

- Principal Component Analysis (PCA):
  - Covariance matrix is decomposed into m eigenvectors, the first p with largest eigenvalues are chosen.
  - The first principal component accounts for as much of the variability in the data as possible.
  - Each succeeding component accounts for as much of the remaining variability as possible.
  - For a mapping to 2D, choose the first 2 principle components.

8.1.2 Non-Linear Projection

- Input is set (triangular matrix) of pairwise similarities (or dissimilarities).
- Similarity matrix can, of course, be calculated from an nD vector space.
- Usually needs an iterative process (cannot be directly calculated).
- Optimise a cost (stress) function.
- Change in objects means need to run a few more iterations (incremental layout).
- Can handle non-linear structures.
- New axes cannot be interpreted (given a “name”).

Non-Linear Projection Techniques

- Multi-Dimensional Scaling (MDS)
  - Majorisation: iterative nonlinear optimisation based on steepest descent towards a (local) minimum.
- Force-directed placement (FDP): Iterative solution of a force model.
- Fastmap [Faloutsos and Lin 1995].
- Nearest Neighbor Projection (NNP) [Tejada et al. 2003].
- Least Squares Projection (LSP) [Paulovich et al. 2008].
- SNE Stochastic Neighbor Embedding.

- t-SNE [van der Maaten and Hinton 2008; Wattenberg et al. 2016]. Stochastic Neighbor Embedding with a t-distribution.
- UMAP [McInnes et al. 2018]. Uniform Manifold Approximation and Projection.

8.2 Force-Directed Placement (FDP)

- Invented in 1984 by Peter Eades [Eades 1984]: spring model, forces move the system to a minimal energy state. Brute force, $O(n^3)$.
- Improved and named *force-directed placement* in 1991 by Fruchtermann and Reingold [Fruchtermann and Reingold 1991]. Forces are computed only to nearby objects (within a certain radius). Attempts to achieve uniform edge length.
- Series of improvements by Chalmers: 1992 $O(n^2\sqrt{n})$ [Chalmers and Chitson 1992], 1996 $O(n^2)$ [Chalmers 1996a], 2003 $O(n^{\frac{5}{4}})$ [Morrison et al. 2003].
- Jourdan and Melancon, MultiscaleMDS, in 2004 $O(n \log n)$ [Jourdan and Melancon 2004].
- Brandes and Pich; PivotMDS, in 2006 $O(n)$ through sampling and approximation [Brandes and Pich 2006].
- Ingram, Munzner, and Olano; Glimmer, in 2009 theoretically $O(n^2)$, but massively parallel [Ingram et al. 2009].

8.3 Example Systems

8.3.1 Bead

- Matthew Chalmers (EuroPARC, Ubilab), 1992 [Chalmers and Chitson 1992; Chalmers 1993; Chalmers 1996b].
- Vector space model and force-directed placement.
- Produces a 3d point cloud.

8.3.2 SPIRE

- Pacific Northwest National Labs, 1995 [Wise et al. 1995; Wise 1999].
- Build vector space model from text (or other document) corpus.
- Anchored Least Stress (ALS): first project small subset of objects using PCA (first two principle components), then interpolate remaining objects.
- Results in 2d Galaxy View.
- From Galaxy View aggregate of keywords in height dimension to form Themescape. See Figure 8.3.
- Paper in ISKO [Hetzler et al. 1998], technical details paper in JASIS [Wise et al. 1995], good overview at I-Know '01 [Thomas et al. 2001].

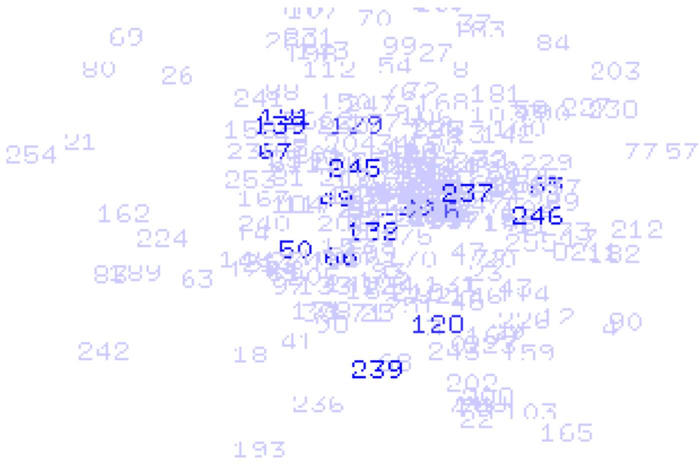


Figure 8.2: Part of the Bead visualisation of 301 entries from the HCI Bibliography. The objects represent articles from the field of HCI. Documents containing similar keywords are placed near each other in the 3d point cloud. A search has been done on the keywords "information retrieval" and the results are highlighted. [Copyright © by the Association for Computing Machinery, Inc.]

- Video at InfoVis 2004 Contest `http://www.cs.umd.edu/hcil/InfovisRepository/contest-2004/`
- Tutorial video `https://youtu.be/YONTBZaxz8g`.

8.3.3 VxInsight

- Sandia National Labs, 1998 [Davidson et al. 1998].
- VxOrd: force-directed placement.
- Accepts list of pre-computed similarities.
- Nodes are moved to minimise an energy function.

8.3.4 VisIslands

- IICM, 2001 [Andrews et al. 2001].
- First (as far as we know) interactive FDP (a few seconds).
- Build vector space from objects in search result set.
- Initially cluster objects using fast algorithm.
- Position cluster centroids using FDP.
- Place other cluster members around centroid, then run a few iterations of FDP.

8.3.5 InfoSky

- IICM + Know-Center + Hyperwave, 2002 [Andrews et al. 2002].
- InfoSky assumes objects are pre-placed within a hierarchy.

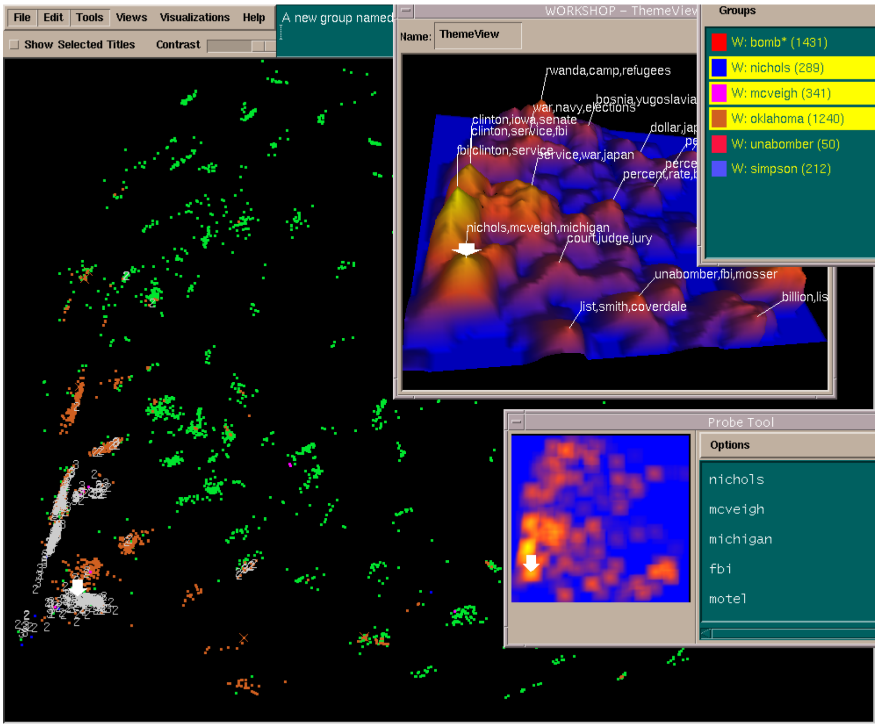


Figure 8.3: SPIRE showing the Galaxy View (below), Themescape (upper right) and Probe Tool. [Image used with kind permission of Pacific Northwest National Laboratory.]

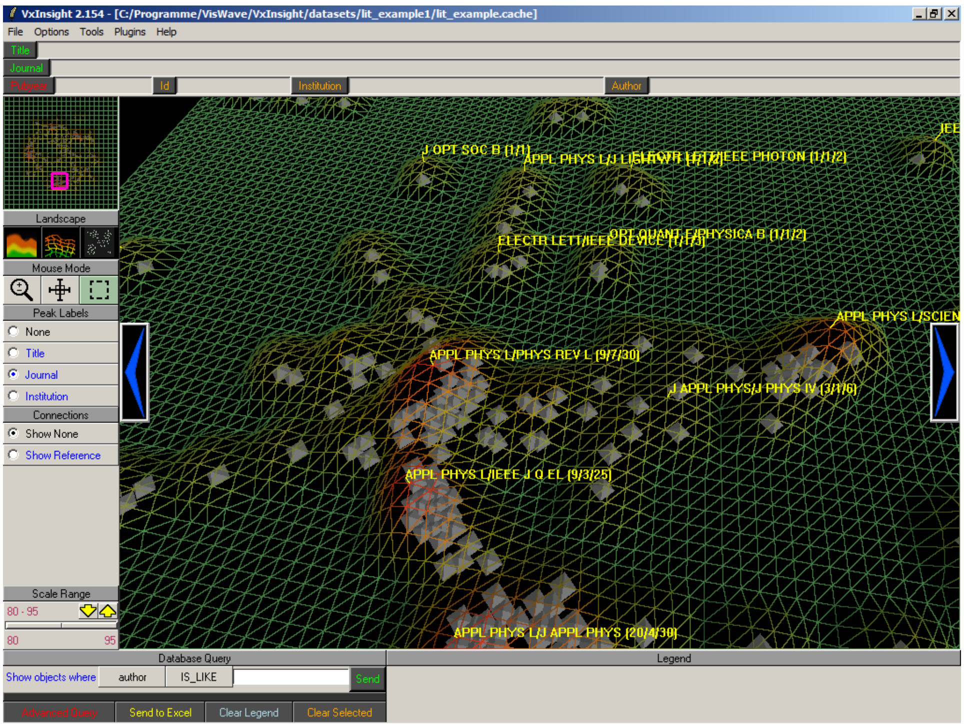


Figure 8.4: VxInsight showing some of 1,231 bibliographic records extracted from the physical sciences portion of the Science Citation Index Expanded. The layout uses similarities based on direct and cocitation links between articles. [Thanks to Brian Wylie, Sandia National Laboratories, for providing a demo version of VxInsight.]

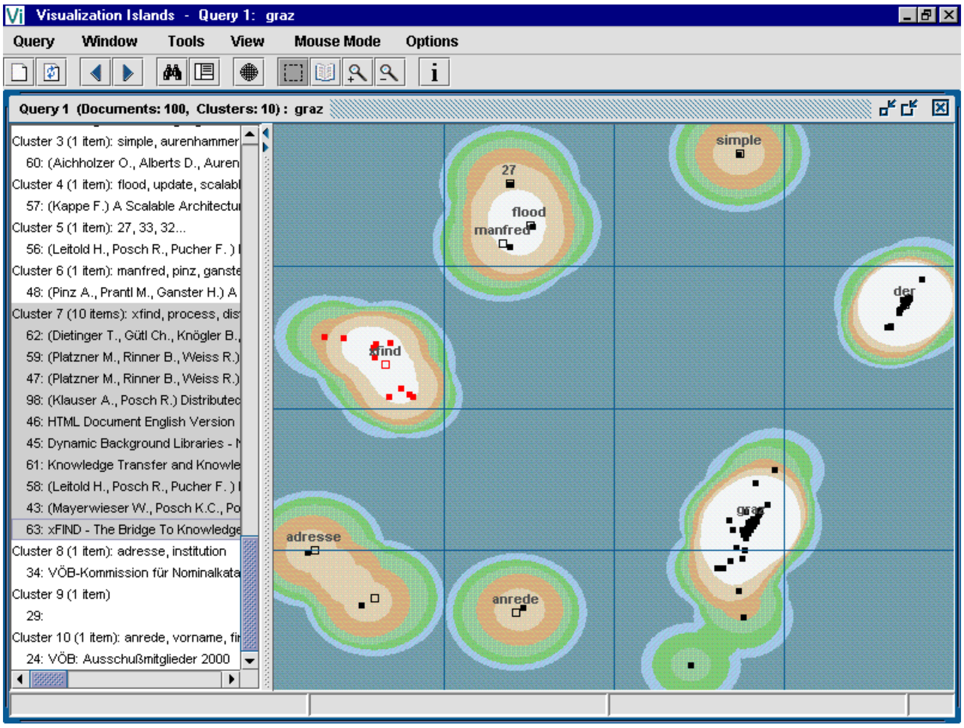


Figure 8.5: VisIslands forms visual clusters of search result sets.

- Force-directed placement is not done globally, but recursively at each level of the hierarchy (only for the nodes at that level).
- First system to use recursive Voronoi subdivision of a hierarchy (now known as Voronoi Treemaps).

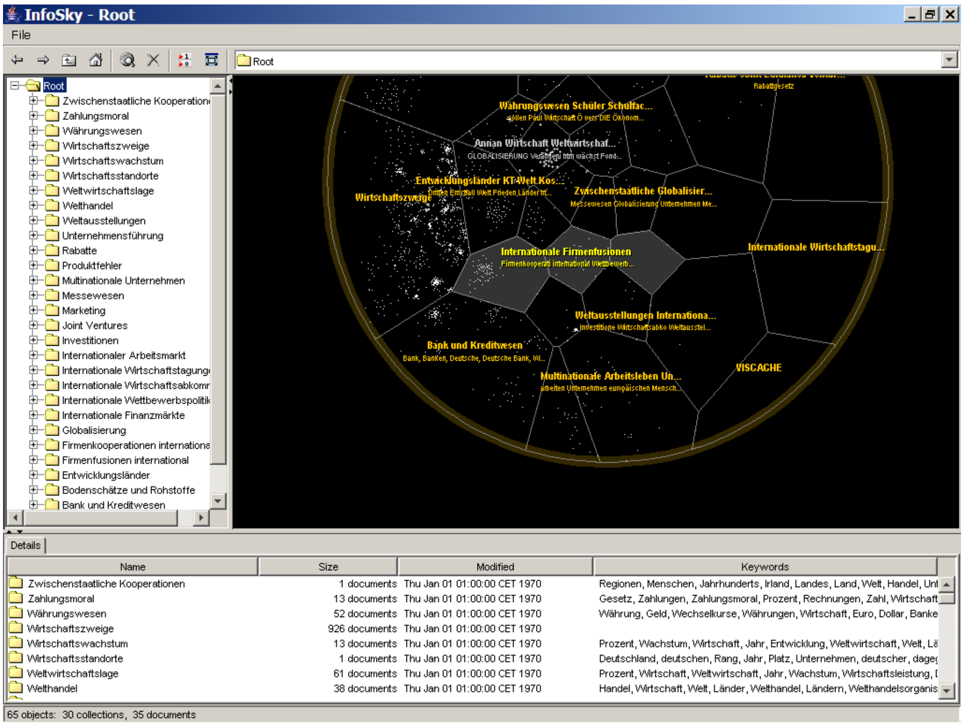


Figure 8.6: InfoSky showing a collection of newspaper articles from the German newspaper Süddeutsche Zeitung. The articles have previously been manually placed within a topical hierarchy by the newspaper editors.

8.4 Self-Organizing Maps (SOM)

- Self-organizing map (SOM) invented by Kohonen [2000].
- Based on neural networks.
- The map consists of a regular grid of cells ("neurons").
- The cells may be rectangular (like a shelf of post boxes), hexagonal (like a wine rack), or other regular shapes.
- A feature vector (descriptor) describes each cell.
- Each object is represented by a feature vector.
- Cell descriptors are usually initialised using a training set.
- An object is assigned to its closest cell. The feature vectors of that cell and neighbouring cells are then updated to reflect the new object.

8.4.1 SOMLib

- Based on a variant of the SOM algorithm [Rauber and Merkl 1999].

8.4.2 WEBSOM

- Self-organizing map (SOM) algorithm [Kohonen 2000].

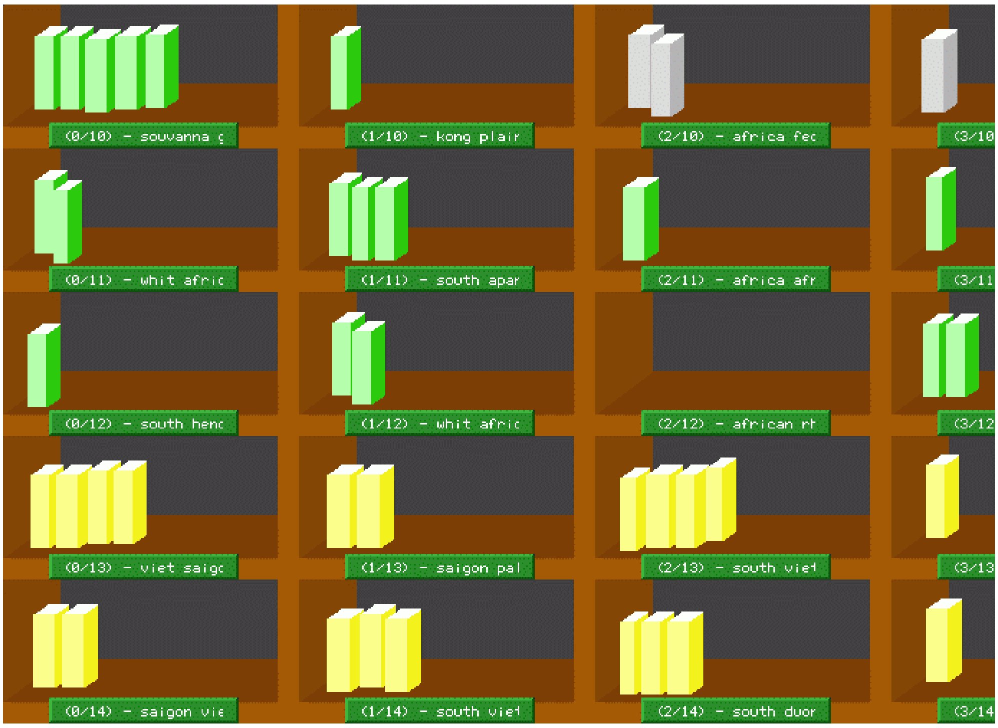


Figure 8.7: The SOMLib system with the libViewer interface. Documents are assigned to sections of a bookshelf (or post boxes) according to their content. [Image used with kind permission of Andreas Rauber.]

- Papers in IEEE Transactions on Neural Networks [Kohonen et al. 2000] and Information Sciences [Lagus et al. 2004]

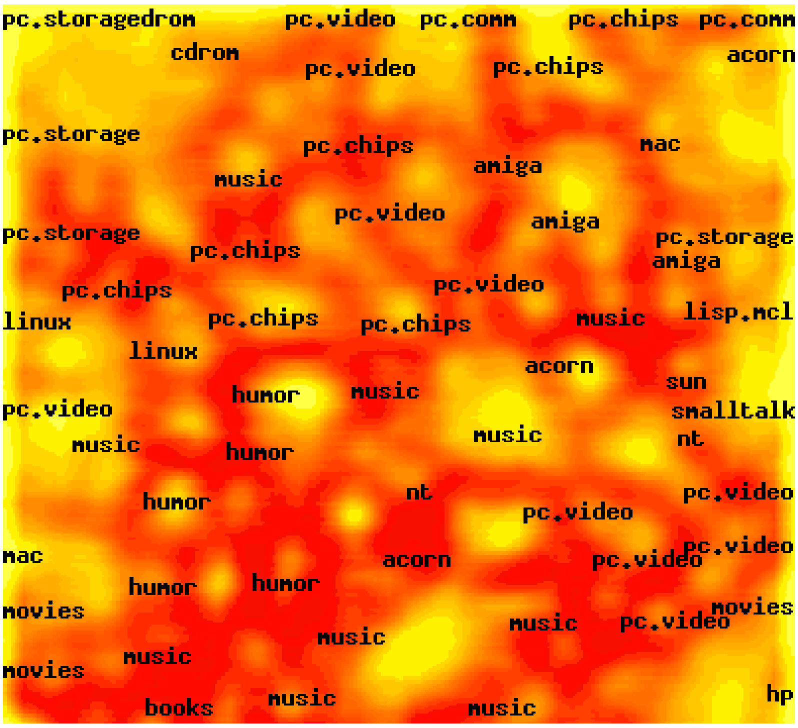


Figure 8.8: WEBSOM.

Chapter 9

Other Kinds of Visualisation

9.1 Visualising Query Spaces

9.1.1 InfoCrystal

- Anselm Spoerri, MIT, 1993.
- Builds upon the idea of a Venn diagram to indicate which sets of items match each permutation of a boolean query, as shown in Figure 9.1.
- n boolean query terms are placed at the corners of an n-sided regular polygon.
- Icons representing items matching each permutation of a boolean query are positioned within the polygon.
- Figure 9.2 shows an InfoCrystal with four query terms.
- Papers at Vis'93 [Spoerri 1993a], CIKM'93 [Spoerri 1993b], and VL'93 [Spoerri 1993c], as well as PhD thesis [Spoerri 1995].

9.1.2 MetaCrystal

- Application of InfoCrystal idea to search results from multiple search engines [Spoerri 2004a; Spoerri 2004b].
- See Figure 9.3.

9.1.3 LyberWorld

- Matthias Hemmje, GMD-IPSI, 1993.
- LyberWorld's Navigation Cone helps an analyst to progressively narrow down a result set of matching documents.
- Terms and documents are selected at alternate levels within a cone tree. [Video: `https://youtu.be/uGBW7uPKyCM?t=02m03s`]

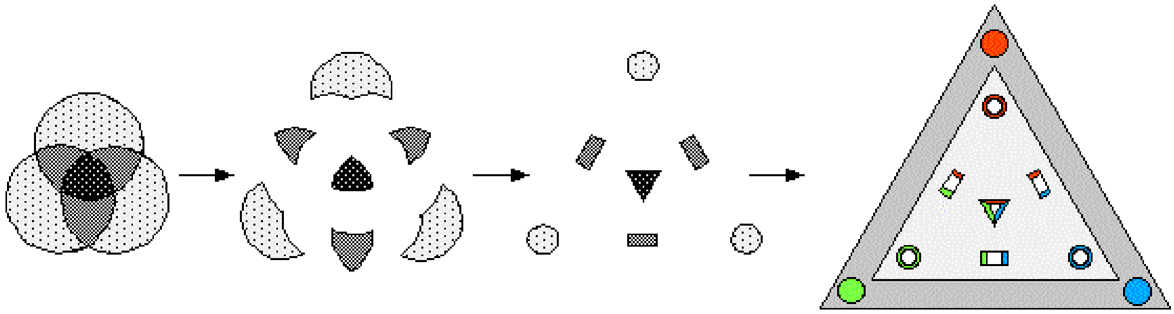


Figure 9.1: InfoCrystal builds upon the idea of a Venn diagram to indicate which sets of items match each permutation of a boolean query. [Image used with kind permission of Anselm Spoerri.]

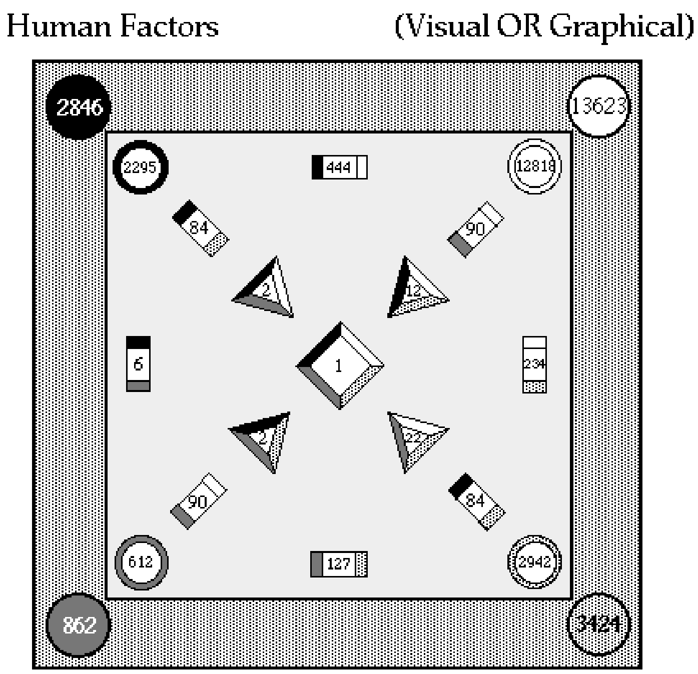


Figure 9.2: InfoCrystal with four query terms. The numbers indicate how many document match the corresponding boolean query. [Image used with kind permission of Anselm Spoerri.]

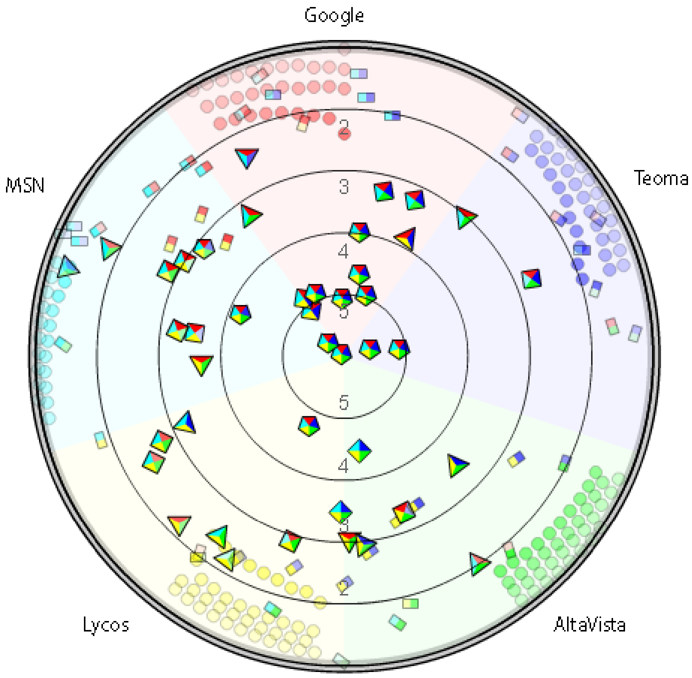


Figure 9.3: MetaCrystal combines the results from multiple search engines in response to the same query. [Image used with kind permission of Anselm Spoerri.]

- LyberWorld's Relevance Sphere allows the analyst to place search terms around the outside of a sphere and documents inside the sphere are attracted to them (similar to Dust and Magnets). [Video: `https://youtu.be/uGBW7uPKyCM?t=05m30s`]
- Paper at SIGIR'94 [Hemmje et al. 1994], video at CHI'95 [Hemmje 1995]. [Video: `https://youtu.be/uGBW7uPKyCM`]

9.2 Internal Document Visualisation (Content Analysis)

9.2.1 TileBars

- Marti Hearst, Berkeley 1993-94, Xerox PARC, 1994–95.
- Visualisation of distribution of search terms within matching documents in a search result list.
- The structure of longer text documents is analysed, and the document is broken down into topical units.
- Each topical unit is a contiguous block of say a few paragraphs discussing the same themes.
- For each search term, a row of tiles indicates how frequently that term occurs in each topical unit (dark = very frequent). See Figure 9.4.
- Paper at CHI'95 [Hearst 1995], video at CHI'96 [Hearst and Pedersen 1996].

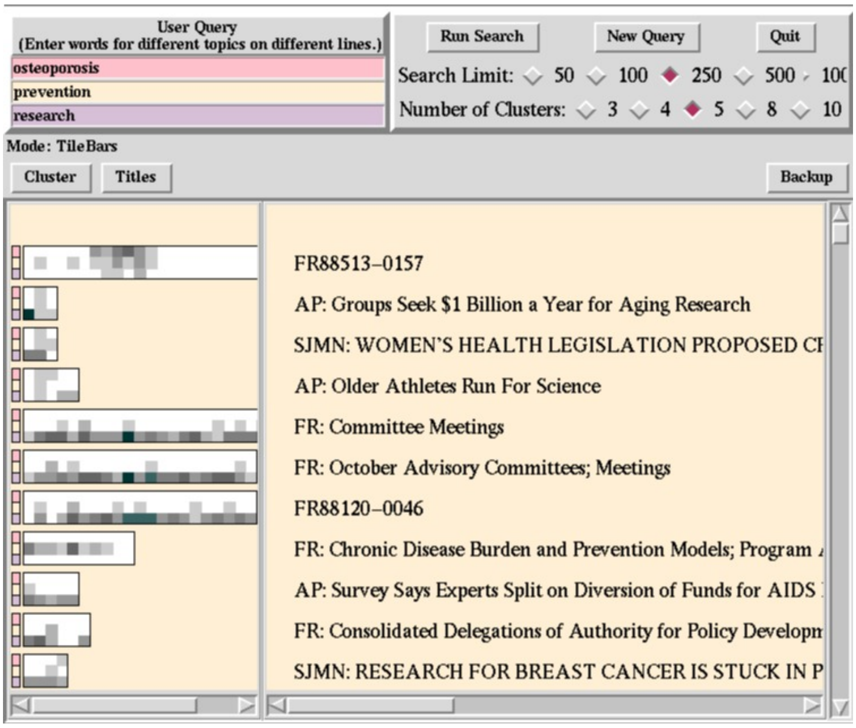


Figure 9.4: TileBars visualisation of the distribution of three search terms "osteoporosis", "prevention", and "research" within matching documents. The top-ranked document has some disussion of all three terms in the middle of the document. The fifth, sixth, and seventh matching documents all discuss research but have no mention of osteoporosis. [Image used with kind permission of Marti Hearst.]

Bibliography

Abel, Guy [2014]. *Circular Migration Flow Plots in R*. 28 Mar 2014. https://gjabel.wordpress.com/2014/03/28/circular-migration-flow-plots-in-r/ (cited on page 79).

Abel, Guy J. and Nikola Sander [2014]. *Quantifying Global International Migration Flows*. Science 343.6178 (28 Mar 2014), pages 1520–1522. ISSN 0036-8075. doi:10.1126/science.1248676 (cited on page 79).

Afzal, Muhammad Tanvir, Atif Latif, Anwar Us Saeed, Philipp Sturm, Salman Aslam, Keith Andrews, Klaus Tochtermann, and Hermann Maurer [2009]. *Discovery and Visualization of Expertise in a Scientific Community*. Proc. 7th International Conference on Frontiers of Information Technology (FIT'09) (Abbottabad, Pakistan). ACM, Dec 2009, 43:1–43:6. ISBN 1605586420 (com, uk). doi:10.1145/1838002.1838051 (cited on page 49).

Ahlberg, Christopher and Ben Shneiderman [1994a]. *Visual Information Seeking using the FilmFinder*. CHI'94 Video Program. ACM. Apr 1994 (cited on page 88).

Ahlberg, Christopher and Ben Shneiderman [1994b]. *Visual Information Seeking: Tight Coupling of Dynamic Query Filters with Starfield Displays*. Proc. CHI'94 (Boston, Massachusetts, USA). ACM. Apr 1994, pages 313–317. doi:10.1145/259963.260390. http://citeseer.ist.psu.edu/ahlberg94visual.html (cited on page 88).

Ahlberg, Christopher, Christopher Williams, and Ben Shneiderman [1992]. *Dynamic Queries for Information Exploration: An Implementation and Evaluation*. Proc. CHI'92 (Monterey, California, USA). ACM. May 1992, pages 619–626. doi:10.1145/142750.143054 (cited on page 88).

Aisch, Gregor [2011]. *How To Avoid Equidistant HSV Colors*. 13 Dec 2011. https://vis4.net/blog/2011/12/avoid-equidistant-hsv-colors/ (cited on page 30).

Andrews, Keith [1996]. *Browsing, Building, and Beholding Cyberspace: New Approaches to the Navigation, Construction, and Visualisation of Hypermedia on the Internet*. PhD Thesis. Graz University of Technology, Austria, 10 Sep 1996. https://ftp.isds.tugraz.at/pub/keith/phd/andrews-1996-phd.pdf (cited on pages ix, 52, 56, 82).

Andrews, Keith [1998]. *Visualizing Rich, Structured Hypermedia*. IEEE Computer Graphics and Applications 18.4 (Jul 1998), pages 40–42. doi:10.1109/38.689661 (cited on pages 64, 69).

Andrews, Keith [2002a]. *Visual Exploration of Large Hierarchies with Information Pyramids*. Proc. Sixth International Conference on Information Visualisation (IV'02) (London, England). IEEE Computer Society Press, Jul 2002, pages 793–798. doi:10.1109/IV.2002.1028871 (cited on page 69).

Andrews, Keith [2002b]. *Visualising Information Structures: Aspects of Information Visualisation*. Professorial Thesis, Graz University of Technology, Austria. 13 Nov 2002. https://ftp.isds.tugraz.at/pub/keith/habil/visinfo.pdf (cited on page ix).

Andrews, Keith [2015]. *Illuminating Data Through Visualisation*. TEDxGraz 2015 Talk (Graz, Austria). TEDxGraz. 06 Nov 2015. https://youtu.be/fnyKj8r0CN4 (cited on page 2).

Andrews, Keith, Christian Gütl, Josef Moser, Vedran Sabol, and Wilfried Lackner [2001]. *Search Result Visualisation with xFIND*. Proc. 2nd International Workshop on User Interfaces to Data Intensive Systems (UIDIS 2001) (Zurich, Switzerland). IEEE Computer Society Press, May 2001, pages 50–58. doi:10.1109/UIDIS.2001.929925 (cited on pages 90, 105).

Andrews, Keith and Helmut Heidegger [1998]. *Information Slices: Visualising and Exploring Large Hierarchies using Cascading, Semi-Circular Discs*. Late Breaking Hot Topic Paper, IEEE Symposium on Information Visualization (InfoVis'98) (Research Triangle Park, North Carolina, USA). Oct 1998, pages 9–12. https://ftp.isds.tugraz.at/pub/papers/ivis98.pdf (cited on page 64).

Andrews, Keith, Wolfgang Kienreich, Vedran Sabol, Jutta Becker, Georg Droschl, Frank Kappe, Michael Granitzer, Peter Auer, and Klaus Tochtermann [2002]. *The InfoSky Visual Explorer: Exploiting Hierarchical Structure and Document Similarities*. Information Visualization 1.3/4 (Dec 2002), pages 166–181. doi:10.1057/palgrave.ivs.9500023 (cited on pages 69, 105).

Andrews, Keith and Martin Lessacher [2010]. *Liquid Diagrams: Information Visualisation Gadgets*. Proc. 14th International Conference on Information Visualisation (IV'10) (London, UK). IEEE Computer Society Press, 26 Jul 2010, pages 104–109. doi:10.1109/IV.2010.100. https://ftp.isds.tugraz.at/pub/papers/andrews-iv2010-ld.pdf (cited on pages 12–13).

Andrews, Keith, Majda Osmić, and Gerhard Schagerl [2015]. *Aggregated Parallel Coordinates: Integrating Hierarchical Dimensions into Parallel Coordinates Visualisations*. Proc. 15th International Conference on Knowledge Technologies and Data-Driven Business (I-Know 2015) (Graz, Austria). Best Poster Award. 21 Oct 2015, 37:1–37:4. doi:10.1145/2809563.2809588. https://ftp.isds.tugraz.at/pub/papers/andrews-iknow2015-apc.pdf (cited on page 94).

Andrews, Keith, Werner Putz, and Alexander Nussbaumer [2007]. *The Hierarchical Visualisation System (HVS)*. Proc. 11th International Conference on Information Visualisation (IV'07) (Zurich, Switzerland). IEEE Computer Society Press, 02 Jul 2007, pages 257–262. doi:10.1109/IV.2007.112. https://ftp.isds.tugraz.at/pub/papers/andrews-iv2007-hvs.pdf (cited on page 57).

Andrews, Keith, Josef Wolte, and Michael Pichler [1997]. *Information Pyramids: A New Approach to Visualising Large Hierarchies*. IEEE Visualization'97, Late Breaking Hot Topics Proc. (Phoenix, Arizona, USA). Oct 1997, pages 49–52. https://ftp.isds.tugraz.at/pub/papers/vis97.pdf (cited on page 69).

Anscombe, Francis J. [1973]. *Graphs in Statistical Analysis*. The American Statistician 27.1 (Feb 1973), pages 17–21. doi:10.1080/00031305.1973.10478966. http://www.sjsu.edu/faculty/gerstman/StatPrimer/anscombe1973.pdf (cited on page 9).

Apperley, Mark D., Ioannis V. Tzavaras, and Robert Spence [1982]. *A Bifocal Display Technique for Data Presentation*. Proc. Eurographics 1982 (Minneapolis, Minnesota, USA). Edited by D. S. Greenaway and E. A. Warman. Eurographics Association. 1982, pages 27–43. doi:10.2312/eg.19821002 (cited on page 45).

Bacon, Francis [1620]. *The New Organon: Or True Directions Concerning the Interpretation of Nature*. 1620. http://www.constitution.org/bacon/nov_org.htm (cited on page 32).

Ball, Thomas A. and Stephen G. Eick [1996]. *Software Visualization in the Large*. IEEE Computer 29.4 (Apr 1996), pages 33–43. ISSN 0018-9162. doi:10.1109/2.488299 (cited on page 47).

Balzer, Michael and Oliver Deussen [2005a]. *Voronoi Treemaps*. Proc. IEEE Symposium on Information Visualization (InfoVis 2005) (Minneapolis, Minnesota, USA). IEEE Computer Society. Oct 2005, pages 49–56. doi:10.1109/INFOVIS.2005.40. http://graphics.uni-konstanz.de/publikationen/Balzer2005VoronoiTreemaps/Balzer2005VoronoiTreemaps.pdf (cited on page 71).

Balzer, Michael and Oliver Deussen [2005b]. *Voronoi Treemaps*. 2005. http://ub.uni-konstanz.de/kops/volltexte/2007/2726/avi/Voronoi_Treemaps.avi (cited on page 71).

Balzer, Michael, Oliver Deussen, and Claus Lewerentz [2005]. *Voronoi Treemaps for the Visualization of Software Metrics*. Proc. ACM Symposium on Software Visualization (SoftVis 2005). IEEE Computer Society. St. Louis, Missouri, USA, May 2005, pages 165–172. doi:10.1145/1056018.1056041. http://www.ub.uni-konstanz.de/kops/volltexte/2007/2417/pdf/Voronoi_Treemaps_for_the_Visualization_of_Software_Metrics_2005.pdf (cited on pages 71–72).

Bazerman, Max H. and Ann E. Tenbrunsel [2016]. *Blind Spots, Chpater 5, Neisser*. 08 Mar 2016. http://people.hbs.edu/mbazerman/blindspots-ethics/neisser.html (cited on page 20).

Beaudoin, Luc, Marc-Antoine Parent, and Loius C. Vroomen [1996]. *Cheops: A Compact Explorer for Complex Hierarchies*. Proc. 7th IEEE Visualization Conference (Vis 1996) (San Francisco, California, USA). IEEE Computer Society. Oct 1996, pages 87–92. doi:10.1109/VISUAL.1996.567745. http://pages.infinit.net/lbeaudoi/cheops.html (cited on page 73).

Bertin, Jacques [1999]. *Sémiologie graphique: Les diagrammes – Les réseaux – Les cartes*. Editions de l'Ecole des Hautes Etudes en Sciences, 31 Jan 1999. 431 pages. ISBN 2713212774 (com, uk) (cited on page 31).

Bertin, Jacques [2010]. *Semiology of Graphics: Diagrams, Networks, Maps*. ESRI Press, Nov 2010. 436 pages. ISBN 1589482611 (com, uk) (cited on page 31).

Visualization of Categorical Data [1998]. Academic Press, 1998. ISBN 0122990455 (com, uk) (cited on page 4).

Borg, Ingwer and Patrick J. F. Groenen [2005]. *Modern Multidimensional Scaling*. 2nd Edition. Springer, Aug 2005. ISBN 0387251502 (com, uk) (cited on page 101).

Bradley, Steven [2011]. *What Designers Should Know About Visual Perception and Memory*. Blog article. 07 Mar 2011. http://www.vanseodesign.com/web-design/visual-perception-memory/ (cited on page 20).

Brandes, Ulrik and Christian Pich [2006]. *Eigensolver Methods for Progressive Multidimensional Scaling of Large Data*. Proc. International Symposium on Graph Drawing (GD 2006). Springer LNCS 4372. Karlsruhe, Germany, 2006, pages 42–53. doi:10.1007/978-3-540-70904-6_6 (cited on page 104).

Brodbeck, Dominique and Luc Girardin [2003]. *Using Multiple Coordinated Views to Analyze Geo-Referenced High-Dimensional Datasets*. Proc. International Conference on Coordinated and Multiple Views in Exploratory Visualization (CMV 2003). Jul 2003, pages 104–111. doi:10.1109/CMV.2003.1215008. http://download.macrofocus.com/publications/cmv2003.pdf (cited on pages 92–94).

Brody, Howard, Michael Russell Rip, Peter Vinten-Johansen, Nigel Paneth, and Stephen Rachman [2000]. *Map-Making and Myth-Making in Broad Street: The London Cholera Epidemic, 1854*. The Lancet 356.9223 (01 Jul 2000), pages 64–68. doi:10.1016/S0140-6736(00)02442-9). http://www.casa.ucl.ac.uk/martin/msc_gis/map_making_myth_making.pdf (cited on page 35).

Bruce, Vicki, Patrick R. Green, and Mark A. Georgeson [2003]. *Visual Perception: Physiology, Psychology, and Ecology*. 4th Edition. Psychology Press, Sep 2003. ISBN 1841692379 (com, uk) (cited on page 19).

Bruls, Mark, Kees Huizing, and Jarke J. van Wijk [2000]. *Squarified Treemaps*. Proc. Joint Eurographics and IEEE TCVG Symposium on Visualization (VisSym 2000) (Amsterdam, The Netherlands). Spinger LNCS. Oct 2000, pages 33–42. http://www.win.tue.nl/~vanwijk/stm.pdf (cited on page 67).

Buchheim, Christoph, Michael Jünger, and Sebastian Leipert [2002]. *Improving Walker's Algorithm to Run in Linear Time*. Proc. 10th International Symposium on Graph Drawing (GD 2002) (Irvine,

California, USA). Springer LNCS 2528. Aug 2002, pages 344–353. http://www.springerlink.com/content/u73fyc4tlxp3uwt8 (cited on pages 54, 60).

Burger, Thomas [1999]. *Magic Eye View: Eine neue Fokus + Kontext Technik zur Darstellung von Graphen*. In German. Institute of Computer Graphics: University of Rostock, Apr 1999. http://wwwicg.informatik.uni-rostock.de/Diplomarbeiten/1999/Thomas_Buerger/ (cited on page 60).

Cairo, Alberto [2012]. *The Functional Art*. New Riders, 01 Sep 2012. 384 pages. ISBN 0321834739 (com, uk) (cited on page 2).

Cairo, Alberto [2014]. *Graphics Lies, Misleading Visuals*. In: *New Challenges for Data Design*. Edited by David Bihanic. Springer, 27 Dec 2014. Chapter 5, pages 103–116. ISBN 1447165950 (com, uk). doi:10.1007/978-1-4471-6596-5. http://infovis.fh-potsdam.de/readings/Cairo2015.pdf (cited on page 10).

Cairo, Alberto [2016]. *The Truthful Art*. New Riders, 28 Feb 2016. 400 pages. ISBN 0321934075 (com, uk) (cited on page 2).

Cairo, Alberto [2019]. *How Charts Lie*. W. W. Norton, 15 Oct 2019. 256 pages. ISBN 1324001569 (com, uk) (cited on page 10).

Card, Stuart K., Jock D. Mackinlay, and Ben Shneiderman, editors [1999]. *Readings in Information Visualization: Using Vision to Think*. Morgan Kaufmann, 02 Feb 1999. 712 pages. ISBN 1558605339 (com, uk) (cited on pages 2, 13–14, 56).

Chabris, Christopher F. and Daniel J. Simons [2011a]. *The Invisible Gorilla*. 05 Aug 2011. http://theinvisiblegorilla.com/ (cited on page 20).

Chabris, Christopher F. and Daniel J. Simons [2011b]. *The Invisible Gorilla: And Other Ways Our Intuition Deceives Us*. HarperCollins, 03 Jan 2011. 320 pages. ISBN 000731731X (com, uk) (cited on pages 19–20).

Chalmers, Matthew [1993]. *Using a Landscape Metaphor to Represent a Corpus of Documents*. Spatial Information Theory, Proc. COSIT'93. Springer LNCS 716. Boston, Massachusetts, USA, Sep 1993, pages 377–390. doi:10.1007/3-540-57207-4_25. http://www.dcs.gla.ac.uk/~matthew/papers/ecsit93.pdf (cited on page 104).

Chalmers, Matthew [1996a]. *A Linear Iteration Time Layout Algorithm for Visualising High-Dimensional Data*. Proc. Visualization'96. IEEE Computer Society. San Francisco, California, USA, Oct 1996, pages 127–132. doi:10.1109/VISUAL.1996.567787. http://www.dcs.gla.ac.uk/~matthew/papers/vis96.pdf (cited on page 104).

Chalmers, Matthew [1996b]. *Adding Imageability Features to Information Displays*. Proc. 9th Annual ACM Symposium on User Interface Software and Technology (UIST'96). ACM. Seattle, Washington, USA, Nov 1996, pages 33–39. doi:10.1145/237091.237096. http://www.dcs.gla.ac.uk/~matthew/papers/uist96.pdf (cited on page 104).

Chalmers, Matthew and Paul Chitson [1992]. *Bead: Explorations in Information Visualization*. Proc. SIGIR '92. ACM. Copenhagen, Denmark, Sep 1992, pages 330–337. doi:10.1145/133160.133215. http://www.dcs.gla.ac.uk/~matthew/papers/sigir92.pdf (cited on page 104).

Chegini, Mohammad, Jürgen Bernard, Philip Berger, Alexei Sourin, Keith Andrews, and Tobias Schreck [2019]. *Interactive Labelling of a Multivariate Dataset for Supervised Machine Learning Using Linked Visualisations, Clustering, and Active Learning*. Visual Informatics 3.1 (23 Apr 2019), pages 9–17. ISSN 2468-502X. doi:10.1016/j.visinf.2019.03.002. https://ftp.isds.tugraz.at/pub/papers/chegini-pvast2019-ix-labelling.pdf (cited on page 17).

Chen, Chaomei [1999]. *Information Visualisation and Virtual Environments*. Springer, Jun 1999. 256 pages. ISBN 1852331364 (com, uk) (cited on page 3).

Chernoff, Herman [1973]. *The Use of Faces to Represent Points in K-Dimensional Space Graphically*. Journal of the American Statistical Association 68.342 (Jun 1973), pages 361–368. ISSN 0162-1459. doi:10.1080/01621459.1973.10482434. http://jstor.org/stable/2284077 (cited on page 90).

Conklin, Jeff [1987]. *Hypertext: An Introduction and Survey*. IEEE Computer 20.9 (Sep 1987), pages 17–41. doi:10.1109/MC.1987.1663693 (cited on page 81).

Cox, Trevor F. and Michael A. A. Cox [2000]. *Multidimensional Scaling*. 2nd Edition. Chapman & Hall, Sep 2000. ISBN 1584880945 (com, uk) (cited on page 101).

CRIM [2002]. *CRIM's Hierarchical Engine for OPen Search*. 2002. https://web.archive.org/web/19980207143036/http://www.crim.ca/hci/cheops/ (cited on page 73).

d'Ocagne, Maurice [1885]. *Coordonnées Parallèles et Axiales: Méthode de transformation géométrique et procédé nouveau de calcul graphique déduits de la considération des coordonnées parallèlles.* Gauthier-Villars, 1885. 93 pages. https://archive.org/details/coordonnesparal00ocaggoog (cited on pages 92–93).

Daisy [2003]. *Daisy Chart*. 2003. https://daisy.co.uk/daisy.html (cited on page 99).

Davidson, George S., Bruce Hendrickson, David K. Johnson, Charles E. Meyers, and Brian N. Wylie [1998]. *Knowledge Mining with VxInsight: Discovery Through Interaction*. Journal of Intelligent Information Systems 11.3 (Nov 1998), pages 259–285. doi:10.1023/A:1008690008856. http://www.cs.sandia.gov/projects/VxInsight/pubs/jiis98_prepub.pdf (cited on page 105).

Del Bimbo, Alberto [1999]. *Visual Information Retrieval*. Morgan Kaufmann, Jun 1999. ISBN 1558606246 (com, uk) (cited on page 4).

Derlien, Tjark [2010]. *Disc Inventory X*. 2010. http://derlien.com/ (cited on page 67).

Di Battista, Giuseppe, Peter Eades, Roberto Tamassia, and Ioannis G. Tollis [1999]. *Graph Drawing: Algorithms for the Visualization of Graphs*. Prentice Hall, 1999. ISBN 0133016153 (com, uk) (cited on pages 57, 82).

Diderot, Denis and Jean le Rond d'Alembert [1751a]. *Encyclopédie, ou dictionnaire raisonné des sciences, des arts et des métiers*. 1751. http://en.wikipedia.org/wiki/Encyclopedie (cited on page 32).

Diderot, Denis and Jean le Rond d'Alembert [1751b]. *Figurative System of Human Knowledge*. 1751. http://en.wikipedia.org/wiki/Figurative_system_of_human_knowledge (cited on page 32).

Diderot, Denis and Jean le Rond d'Alembert [1751c]. *Figurative System of Human Knowledge*. Wikimedia Commons. 1751. http://en.wikipedia.org/wiki/Image:ENC_SYSTEME_FIGURE.jpeg (cited on page 32).

Dodge, Martin and Rob Kitchin [2000]. *Mapping Cyberspace*. Routledge, 27 Oct 2000. 272 pages. ISBN 0415198844 (com, uk) (cited on page 3).

Dykstra, Phillip [1991]. *XDU*. WareOnEarth. 1991. https://web.archive.org/web/20090310190801/http://sd.wareonearth.com/~phil/xdu/ (cited on page 63).

Eades, Peter [1984]. *A Heuristic for Graph Drawing*. Congressus Numerantium 42 (1984), pages 149–160. http://www.cs.usyd.edu.au/~peter/old_spring_paper.pdf (cited on page 104).

Eades, Peter and Kozo Sugiyama [1990]. *How to Draw a Directed Graph*. Journal of Information Processing 13.4 (1990), pages 424–437 (cited on page 82).

Eick, Stephen G. [1997]. *Information display apparatus and methods*. US Patent 5644692. Filed 6th Dec. 1991, issued 1st July 1997. Lucent Technologies, Jul 1997 (cited on page 47).

Eick, Stephen G., Joseph L. Steffen, and Eric E. Sumner Jr. [1992]. *Seesoft – A Tool for Visualizing Line Oriented Software Statistics*. IEEE Transactions on Software Engineering 18.11 (Nov 1992),

pages 957–968. ISSN 0098-5589. doi:10.1109/32.177365. http://www.cs.kent.edu/~jmaletic/softvis/papers/eick1992.pdf (cited on page 47).

Fairchild, Kim [1987]. *SemNet 2.1*. CHI+GI 1987 Video Program. ACM. 1987. https://youtu.be/wAu75r77Qko (cited on page 83).

Fairchild, Kim Michael, Steven E. Poltrock, and George W. Furnas [1988]. *SemNet: Three-Dimensional Representations of Large Knowledge Bases*. In: *Cognitive Science and its Applications for Human-Computer Interaction*. Edited by Raymonde Guindon. Hillsdale, New Jersey: Lawrence Erlbaum, 1988, pages 201–233 (cited on page 83).

Faloutsos, Christos and King-Ip Lin [1995]. *FastMap: A Fast Algorithm for Indexing, Data-Mining and Visualization of Traditional and Multimedia Datasets*. Proc. International Conference on Management of Data (SIGMOD '95). ACM. San Jose, California, USA, May 1995, pages 163–174. doi:10.1145/223784.223812. http://www.cs.cmu.edu/~christos/PUBLICATIONS.OLDER/sigmod95.pdf (cited on page 103).

Fekete, Jean-Daniel and Catherine Plaisant [1999]. *Excentric Labeling: Dynamic Neighborhood Labeling for Data Visualization*. Proc. SIGCHI Conference on Human Factors in Computing Systems (CHI'99) (Pittsburgh, Pennsylvania, USA). ACM. May 1999, pages 512–519. doi:10.1145/302979.303148. http://hcil2.cs.umd.edu/trs/98-09/98-09.pdf (cited on page 15).

Fertig, Scott, Eric Freeman, and David Gelernter [1996]. *Lifestreams: An Alternative to the Desktop Metaphor*. CHI'96 Video Program. ACM. 13 Apr 1996. https://open-video.org/details.php?videoid=5023 (cited on page 48).

Few, Stephen [2004]. *Tapping the Power of Visual Perception*. Blog article. 04 Sep 2004. http://www.perceptualedge.com/articles/ie/visual_perception.pdf (cited on page 20).

Few, Stephen [2008]. *Now You See It*. Tableau Customer Conference 2008 (TCC08) (Seattle, Washington, USA). Tableau. 22 Jul 2008. http://mkt.tableau.com/downloads/TCC08-Keynote-Stephen-Few.pdf (cited on page 7).

Few, Stephen [2012]. *Show Me the Numbers: Designing Tables and Graphs to Enlighten*. 2nd Edition. Analytics Press, 01 Jun 2012. 371 pages. ISBN 0970601972 (com, uk) (cited on page 2).

Few, Stephen [2013]. *Information Dashboard Design: Displaying Data for At-A-Glance Monitoring*. 2nd Edition. Analytics Press, 15 Aug 2013. 260 pages. ISBN 1938377001 (com, uk) (cited on pages 3, 19).

Few, Stephen [2014]. *Data Visualization for Human Perception*. In: *The Encyclopedia of Human-Computer Interaction*. Edited by Mads Soegaard and Rikke Friis Dam. 2nd Edition. The Interaction Design Foundation, 2014. Chapter 35. https://interaction-design.org/encyclopedia/data_visualization_for_human_perception.html (cited on page 20).

Few, Stephen [2021]. *Now You See It: An Introduction to Visual Data Sensemaking*. 2nd Edition. Analytics Press, 15 Apr 2021. 301 pages. ISBN 1938377125 (com, uk) (cited on page 3).

Fisher, Danyel and Miriah Meyer [2018]. *Making Data Visual: A Practical Guide to Using Visualization for Insight*. O'Reilly, 12 Jan 2018. 168 pages. ISBN 1491928468 (com, uk) (cited on page 3).

Freeman, Eric and Scott Fertig [1995]. *Lifestreams: Organizing Your Electronic Life*. AAAI Fall Symposium 1995. AAAI, Nov 1995. http://www.aaai.org/Papers/Symposia/Fall/1995/FS-95-03/FS95-03-007.pdf (cited on page 48).

Frerichs, Ralph R. [2009]. *John Snow - A Historical Giant in Epidemiology*. Mar 2009. http://www.ph.ucla.edu/epi/snow.html (cited on page 35).

Friendly, Michael and Howard Wainer [2021]. *A History of Data Visualization and Graphic Communication*. Harvard University Press, 08 Jun 2021. 320 pages. ISBN 0674975235 (com, uk). https://friendly.github.io/HistDataVis/ (cited on page 31).

Fruchtermann, Thomas M. J. and Edward M. Reingold [1991]. *Graph Drawing by Force-Directed Placement*. Software: Practice and Experience 21.11 (1991), pages 1129–1164. doi:10.1002/spe.4380211102 (cited on page 104).

Fuchs, Matthias [2015]. *Extending the Hierarchical Visualisation System (HVS) with a Radial Tree Visualisation and SKOS Import Functionality*. Bachelor's Thesis. Graz University of Technology, Austria, 24 Apr 2015. https://ftp.isds.tugraz.at/pub/theses/mfuchs-2015-bsc.pdf (cited on page 57).

Furnas, George W. [1981]. *The Fisheye View: A New Look at Structured Files*. Technical Memorandum 81-11221-9. Bell Labs, Oct 1981. http://www.si.umich.edu/~furnas/Papers/FisheyeOriginalTM.pdf (cited on page 15).

Furnas, George W. [1986]. *Generalized Fisheye Views*. Proc. CHI'86 (Boston, Massachusetts, USA). ACM. Apr 1986, pages 16–23. doi:10.1145/22627.22342 (cited on page 15).

Geroimenko, Vladimir and Chaomei Chen, editors [2005]. *Visualising the Semantic Web: XML-based Internet and Information Visualization*. 2nd Edition. Springer Verlag, 2005. ISBN 1852339764 (com, uk) (cited on page 3).

Girardin, Luc and Dominique Brodbeck [2001]. *Interactive Visualization of Prices and Earnings Around the Globe*. IEEE Symposium on Information Visualization (InfoVis 2001) (San Diego, California, USA). IEEE, 21 Oct 2001. http://download.macrofocus.com/publications/infovis2001.pdf (cited on pages 92–93).

Granitzer, Michael, Wolfgang Kienreich, Vedran Sabol, Keith Andrews, and Werner Klieber [2004]. *Evaluating a System for Interactive Exploration of Large, Hierarchically Structured Document Repositories*. Proc. IEEE Symposium on Information Visualization (InfoVis 2004) (Austin, Texas, USA). Oct 2004, pages 127–134. doi:10.1109/INFOVIS.2004.19 (cited on page 69).

Gregory, Richard [1997]. *Eye and Brain: The Psychology of Seeing*. 5th Edition. Princeton University Press, Dec 1997. ISBN 0691048371 (com, uk) (cited on page 19).

Haan, Bernard J., Paul Kahn, Victor A. Riley, James H. Coombs, and Norman K. Meyrowitz [1992]. *IRIS Hypermedia Services*. Communications of the ACM 35.1 (Jan 1992), pages 36–51. doi:10.1145/129617.129618 (cited on page 80).

Harris, Robert L. [2000]. *Information Graphics: A Comprehensive Illustrated Reference*. Oxford University Press, Feb 2000. 448 pages. ISBN 0195135326 (com, uk) (cited on page 3).

Healey, Christopher [2009]. *Perception in Visualization*. 11 May 2009. https://web.archive.org/web/20100123045959/https://csc.ncsu.edu/faculty/healey/PP/ (cited on page 19).

Healey, Christopher G. and James T. Enns [2012]. *Attention and Visual Memory in Visualization and Computer Graphics*. IEEE Transactions on Visualization and Computer Graphics 18.7 (Jul 2012), pages 1170–1188. ISSN 1077-2626. doi:10.1109/TVCG.2011.127. https://www.csc2.ncsu.edu/faculty/healey/download/tvcg.12a.pdf (cited on page 19).

Hearst, Marti A. [1995]. *TileBars: Visualization of Term Distribution Information in Full Text Information Access*. Proc. SIGCHI Conference on Human Factors in Computing Systems (CHI'95) (Denver, Colorado, USA). ACM. May 1995, pages 59–66. doi:10.1145/223904.223912. http://people.ischool.berkeley.edu/~hearst/papers/chi95.pdf (cited on page 113).

Hearst, Marti A. and Jan O. Pedersen [1996]. *Visualizing Information Retrieval Results: A Demonstration of the TileBars Interface*. CHI'96 Video Program (Vancouver, Canada). ACM. Apr 1996, pages 394–395. doi:10.1145/257089.257392 (cited on page 113).

Heer, Jeffrey [2010]. *Flare Dependency Graph*. Nov 2010. http://flare.prefuse.org/apps/dependency_graph (cited on page 79).

Heer, Jeffrey and Danah Boyd [2005a]. *Vizster*. 2005. http://vis.stanford.edu/jheer/projects/vizster/ (cited on page 86).

Heer, Jeffrey and Danah Boyd [2005b]. *Vizster: Visualizing Online Social Networks*. Proc. IEEE Symposium on Information Visualization (InfoVis 2005). IEEE Computer Society. Seattle, Washington, USA, 23 Oct 2005, pages 32–39. doi:10.1109/INFOVIS.2005.39. https://danah.org/papers/InfoViz2005.pdf (cited on page 85).

Hemmje, Matthias [1995]. *LyberWorld: A 3D Graphical User Interface for Fulltext Retrieval*. CHI'95 Video Program. ACM. May 1995. doi:10.1145/223355.223759 (cited on page 113).

Hemmje, Matthias, Clemens Kunkel, and Alexander Willet [1994]. *LyberWorld - A Visualization User Interface Supporting Fulltext Retrieval*. Proc. 17th Annual International ACM SIGIR Conference on Research and Development in Information Retrieval (SIGIR'94) (Dublin, Ireland). ACM. Jul 1994, pages 249–259. doi:10.1007/978-1-4471-2099-5_26. http://portal.acm.org/citation.cfm?id=188563 (cited on page 113).

Hendley, Bob J., Nick S. Drew, Andrew M. Wood, and Russell Beale [1995]. *Narcissus: Visualising Information*. Proc. IEEE Symposium on Information Visualization (InfoVis'95) (Atlanta, Georgia, USA). IEEE Computer Society. Oct 1995, pages 90–96. doi:10.1109/INFVIS.1995.528691 (cited on page 83).

Henig, Robin Marantz [1996]. *The People's Health: A Memoir of Public Health and its Evolution at Harvard*. Joseph Henry Press, 1996. ISBN 0309054923 (com, uk) (cited on page 35).

Henry, Nathalie [2008]. *Exploring Social Networks with Matrix-based Representations*. PhD Dissertation. Universite Paris Sud, Oct 2008. http://research.microsoft.com/en-us/um/people/nath/docs/Henry_thesis_oct08.pdf (cited on page 42).

Hetzler, Beth, W. Michelle Harris, Susan Havre, and Paul Whitney [1998]. *Visualizing the Full Spectrum of Document Relationships*. Proc. Fifth International ISKO Conference (Lille, France). ERGON Verlag. Aug 1998, pages 168–175. http://www.pnl.gov/infoviz/isko.pdf (cited on page 104).

Hewes, Fletcher Willis and Henry Gannett [1883]. *Scribner's Statistical Atlas of the United States*. 743–745 Broadway, New York, NY, USA: Charles Scribner's Sons, 1883. http://davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~32803~1152181 (cited on pages 40, 92–93).

Holten, Danny [2006]. *Hierarchical Edge Bundles: Visualization of Adjacency Relations in Hierarchical Data*. IEEE Transactions on Visualization and Computer Graphics (TVCG) 12.5 (Sep 2006): *Proc. IEEE Symposium on Information Visualization (InfoVis 2006)*, pages 741–748. ISSN 1077-2626. doi:10.1109/TVCG.2006.147. http://www.win.tue.nl/~dholten/papers/bundles_infovis.pdf (cited on page 15).

Holtz, Yan [2017]. *#309 Intro to Hierarchical Edge Bundling*. The R Graph Gallery. 2017. https://r-graph-gallery.com/309-intro-to-hierarchical-edge-bundling/ (cited on page 16).

Hubmann-Haidvogel, Alexander C. [2008]. *ThreadVis for Thunderbird: A Thread Visualisation Extension for the Mozilla Thunderbird Email Client*. Master's Thesis. Graz University of Technology, Austria, 02 Sep 2008. 167 pages. https://ftp.isds.tugraz.at/pub/theses/ahubmann.pdf (cited on page 78).

Huff, Darrell [1993]. *How to Lie with Statistics*. Reissue. W. W. Norton, 17 Oct 1993. 144 pages. ISBN 0393310728 (com, uk) (cited on page 11).

Hughes, Timothy, Young Hyun, and David A. Liberles [2004]. *Visualising very large phylogenetic trees in three dimensional hyperbolic space*. BMC Bioinformatics Journal 5.48 (Apr 2004). doi:10.1186/1471-2105-5-48. http://www.caida.org/outreach/papers/2004/bioinformatics/ (cited on page 60).

Hundhammer, Stefan [2010]. *KDirStat*. 2010. http://kdirstat.sourceforge.net/ (cited on page 67).

Hyun, Young [2005]. *Walrus*. 2005. https://caida.org/tools/visualization/walrus/ (cited on page 60).

Iacovou, Neophytos and Mark P. McCahill [1995]. *GODOT: GopherVR Organized Directories of Titles*. Proc. CIKM '95 Workshop on New Paradigms in Information Visualization and Manipulation. ACM. Baltimore, Maryland, USA, Dec 1995. http://www.cs.umbc.edu/conferences/cikm/1995/npiv/iacovou/paper.ps (cited on page 75).

Iliinsky, Noah [2012]. *Data Visualizations Done Wrong*. ORDcamp 2012 Ignite Talk (Chicago, Illinois, USA). 21 Jan 2012. https://youtu.be/lb7JaPIeEE4 (cited on page 13).

Ingram, Stephen, Tamara Munzner, and Marc Olano [2009]. *Glimmer: Multilevel MDS on the GPU*. IEEE Transactions on Visualization and Computer Graphics (TVCG) 15.2 (Mar 2009), pages 249–261. ISSN 1077-2626. doi:10.1109/TVCG.2008.85 (cited on page 104).

Inselberg, Alfred [1985]. *The Plane with Parallel Coordinates*. The Visual Computer 1.2 (Dec 1985), pages 69–91. ISSN 1432-2315. doi:10.1007/BF01898350 (cited on page 93).

Inselberg, Alfred [2004]. *Parallel Coordinates – How It Happened*. web site. 2004. http://www.cs.tau.ac.il/~aiisreal/ (cited on page 92).

Inselberg, Alfred [2009]. *Parallel Coordinates: Visual Multidimensional Geometry and Its Applications*. Springer, 08 Oct 2009. 554 pages. ISBN 0387215077 (com, uk) (cited on page 93).

Jobs, Steve [2008]. *Keynote Speech*. Macworld 2008 (San Francisco, California, USA). 15 Jan 2008. https://youtu.be/i9XU6wk_mWY (cited on page 11).

Johnson, Brian and Ben Shneiderman [1991]. *Tree-Maps: A Space-Filling Approach to the Visualization of Hierarchical Information Structures*. Proc. IEEE Visualization '91 (San Diego, California, USA). IEEE Computer Society. Oct 1991, pages 284–291. doi:10.1109/VISUAL.1991.175815. http://www.cs.umd.edu/hcil/treemaps/ (cited on page 66).

Jourdan, Fabien and Guy Melancon [2004]. *Multiscale Hybrid MDS*. Proc. Eighth International Conference on Information Visualisation (IV'04). IEEE. London, UK, Jul 2004, pages 388–393. doi:10.1109/IV.2004.1320173 (cited on page 104).

Jürgensmann, Susanne and Hans-Jörg Schulz [2010]. *A Visual Survey of Tree Visualization*. Best poster at InfoVis 2010. 27 Oct 2010. http://vcg.informatik.uni-rostock.de/~hs162/treeposter/oldposter/poster.html (cited on page 51).

Kerr, Bernard [2003]. *Thread Arcs: An Email Thread Visualization*. Proc. IEEE Symposium on Information Visualization (InfoVis 2003). IEEE Computer Society. Seattle, Washington, USA, 19 Oct 2003, pages 211–218. doi:10.1109/INFVIS.2003.1249028 (cited on page 78).

Kirk, Andy [2019]. *Data Visualisation*. 2nd Edition. Sage Publications, 08 Jul 2019. 328 pages. ISBN 1526468921 (com, uk) (cited on page 3).

Kleiberg, Ernst, Huub van de Wetering, and Jack van Wijk [2001]. *Botanical Visualization of Huge Hierarchies*. Proc. IEEE Symposium on Information Visualization (InfoVis 2001). IEEE Computer Society. San Diego, California, USA, Oct 2001, pages 87–94. doi:10.1109/INFVIS.2001.963285. http://www.win.tue.nl/~vanwijk/botatree.pdf (cited on page 62).

Kohonen, Teuvo [2000]. *Self-Organizing Maps*. 3rd Edition. Springer, Dec 2000. ISBN 3540679219 (com, uk) (cited on pages 4, 108).

Kohonen, Teuvo, Samuel Kaski, Krista Lagus, Jarkko Salojärvi, Jukka Honkela, Vesa Paatero, and Antti Saarela [2000]. *Self Organization of a Massive Document Collection*. IEEE Transactions on Neural Networks 11.3 (May 2000), pages 574–585. doi:10.1109/72.846729 (cited on page 109).

Kosara, Robert [2011]. *Anscombe's Quartet*. 13 Feb 2011. http://eagereyes.org/criticism/anscombes-quartet (cited on page 9).

Kreuseler, Matthias, Norma Lopez, and Heidrun Schuhmann [2000]. *A Scalable Framework for Information Visualization*. Proc. IEEE Symposium on Information Visualization (InfoVis 2000) (Salt Lake City, Utah, USA). IEEE Computer Society. Oct 2000, pages 27–36. doi:10.1109/INFVIS.2000.885088. http://www.informatik.uni-rostock.de/~mkreusel/SInVis/infovis.html (cited on page 60).

Kreuseler, Matthias and Heidrun Schumann [1999]. *Information Visualization using a New Focus+Context Technique in Combination with Dynamic Clustering of Information Space*. Proceedings of the 1999 Workshop on New Paradigms in Information Visualization and Manipulation (NPIV'99) (Kansas City, Missouri, USA). 1999, pages 1–5. doi:10.1145/331770.331772 (cited on page 60).

Kruja, Eriola, Joe Marks, Ann Blair, and Richard Waters [2002]. *A Short Note on the History of Graph Drawing*. Proc. International Symposium on Graph Drawing (GD 2002) (Vienna, Austria). Springer LNCS 2265. 2002, pages 272–286. doi:10.1007/3-540-45848-4_22. http://merl.com/publications/docs/TR2001-49.pdf (cited on page 31).

Lagus, Krista, Samuel Kaski, and Teuvo Kohonen [2004]. *Mining Massive Document Collections by the WEBSOM Method*. Information Sciences 163.1–3 (Jun 2004), pages 135–156. doi:10.1016/j.ins.2003.03.017 (cited on page 109).

Lamping, John and Ramana Rao [1994]. *Laying Out and Visualizing Large Trees Using a Hyperbolic Space*. Proc. 7th ACM Symposium on User Interface Software and Technology (UIST '94) (Marina del Rey, California, USA). ACM. Nov 1994, pages 13–14. doi:10.1145/192426.192430 (cited on page 57).

Lamping, John and Ramana Rao [1996]. *Visualizing Large Trees Using the Hyperbolic Browser*. CHI'96 Video Program. ACM. 13 Apr 1996. doi:10.1145/257089.257389. https://youtu.be/8bhq08BQLDs (cited on page 58).

Lamping, John, Ramana Rao, and Peter Pirolli [1995]. *A Focus+Context Technique Based on Hyperbolic Geometry for Visualizing Large Hierarchies*. Proc. ACM Conference on Human Factors in Computing Systems (CHI '95) (Denver, Colorado, USA). ACM. May 1995, pages 401–408. doi:10.1145/223904.223956. http://idav.ucdavis.edu/~asharf/shrek/Projects/HypBrowser/startree-chi95.pdf (cited on page 57).

Lamping, John O. and Ramana B. Rao [1997]. *Displaying Node-Link Structure with Region of Greater Spacings and Peripheral Branches*. US Patent 5619632. Filed 14th Sept. 1994, issued 8th April 1997. Xerox Corporation, Apr 1997 (cited on page 58).

Lhuillier, Antoine, Christophe Hurter, and Alexandru C. Telea [2017]. *State of the Art in Edge and Trail Bundling Techniques*. Computer Graphics Forum 36.3 (2017), pages 619–645. doi:10.1111/cgf.13213. http://www.cs.rug.nl/~alext/PAPERS/EuroVis17/star.pdf (cited on page 15).

Lima, Manuel [2014]. *The Book of Trees*. Princeton Architectural Press, 08 Apr 2014. ISBN 1616892188 (com, uk) (cited on pages 31, 51).

Mackinlay, Jock D. [1988]. *Applying a Theory of Graphical Perception to the Graphic Design of User Interfaces*. Proc. ACM Symposium on User Interface Software and Technology (UIST 1988) (Alberta, Canada). 17 Oct 1988, pages 179–189. doi:10.1145/62402.62431 (cited on page 29).

Mackinlay, Jock D., George G. Robertson, and Stuart K. Card [1991]. *The Perspective Wall: Detail and Context Smoothly Integrated*. Proc. CHI'91 (New Orleans, Louisiana, USA). ACM. May 1991, pages 173–179. doi:10.1145/108844.108870 (cited on page 46).

MacroFocus [2015]. *InfoScope*. 19 Aug 2015. http://macrofocus.com/installers/infoscope/ (cited on pages 92–94).

Malamed, Connie [2009]. *Visual Language for Designers: Principles for Creating Graphics That People Understand*. Rockport Publishers, 01 Jun 2009. ISBN 1592537413 (com, uk) (cited on page 19).

Marey, Entienne Jules [1878]. *La Méthode Graphique dans les Sciences Expérimentales*. 1st Edition. Paris, 1878 (cited on page 41).

Marey, Entienne Jules [1885]. *La Méthode Graphique dans les Sciences Expérimentales*. 2nd Edition. Paris: A. Lahure, 1885 (cited on page 41).

McCahill, Mark P. and Thomas Erickson [1994]. *A Preliminary Design for a 3-D Spatial User Interface for Internet Gopher*. Longer draft of ED-MEDIA'95 paper. 1994. http://pliant.org/personal/Tom_Erickson/GopherVR.html (cited on page 49).

McCahill, Mark P. and Thomas Erickson [1995]. *Design for a 3D Spatial User Interface for Internet Gopher*. Proc. World Conference on Educational Multimedia and Hypermedia (ED-MEDIA 95). AACE. Graz, Austria, Jun 1995, pages 39–44. http://www.pliant.org/personal/Tom_Erickson/GopherVR.html (cited on page 75).

McCandless, David [2010]. *The Beauty of Data Visualization*. TED Global 2006 Talk (Oxford, UK). TED. 14 Jul 2010. https://ted.com/talks/david_mccandless_the_beauty_of_data_visualization (cited on pages 18, 20).

McInnes, Leland, John Healy, and James Melville [2018]. *UMAP: Uniform Manifold Approximation and Projection for Dimension Reduction*. arXiv, 09 Feb 2018. doi:10.48550/arXiv.1802.03426. https://github.com/lmcinnes/umap (cited on page 104).

Meirelles, Isabel [2013]. *Design for Information*. Rockport, 01 Oct 2013. 224 pages. ISBN 1592538061 (com, uk) (cited on page 31).

Morrison, Alistair, Greg Ross, and Matthew Chalmers [2003]. *Fast Multidimensional Scaling through Sampling, Springs and Interpolation*. Information Visualization 2.1 (Mar 2003), pages 68–77. ISSN 1473-8716. doi:10.1057/palgrave.ivs.9500040 (cited on page 104).

Munzner, Tamara [1997]. *H3: Laying Out Large Directed Graphs in 3D Hyperbolic Space*. Proc. IEEE Symposium on Information Visualization (InfoVis'97) (Phoenix, Arizona, USA). IEEE Computer Society. Oct 1997, pages 2–10. doi:10.1109/INFVIS.1997.636718. http://graphics.stanford.edu/papers/h3/ (cited on page 60).

Munzner, Tamara [2014]. *Visualization Analysis and Design*. CRC Press, 26 Nov 2014. 428 pages. ISBN 1466508914 (com, uk). https://cs.ubc.ca/~tmm/vadbook/ (cited on page 2).

Munzner, Tamara [2021]. *Visualization Analysis and Design*. Course at UBC. Oct 2021. https://cs.ubc.ca/~tmm/vadbook/#videos (cited on page 18).

Munzner, Tamara and Paul Burchard [1995]. *Visualizing the Structure of the World Wide Web in 3D Hyperbolic Space*. Proc. 1995 Symposium on the Virtual Reality Modeling Language (VRML'95) (San Diego, California, USA). ACM Press, Dec 1995, pages 33–38. ISBN 0897918185 (com, uk). doi:10.1145/217306.217311. http://graphics.stanford.edu/papers/webviz/webviz.72dpi.pdf (cited on page 60).

Nation, David A. [1998]. *WebTOC: A Tool to Visualize and Quantify Web Sites Using a Hierarchical Table of Contents Browser*. CHI'98 Video Program. ACM. Apr 1998 (cited on page 53).

Nation, David A., Catherine Plaisant, Gary Marchionini, and Anita Komlodi [1997]. *Visualizing websites using a hierarchical table of contents browser: WebTOC*. Proc. 3rd Conference on Human Factors and the Web (Denver, Colorado, USA). US WEST. Jun 1997. ftp://ftp.cs.umd.edu/pub/hcil/Demos/WebTOC/Paper/WebTOC.html (cited on page 53).

Neisser, Ulric [1979]. *The Concept of Intelligence*. Intelligence 3.3 (Jul 1979), pages 217–227. ISSN 0160-2896. doi:10.1016/0160-2896(79)90018-7 (cited on page 20).

Notopoulos, Katie [2014]. *13 Graphs That Are Clearly Lying*. 03 Oct 2014. https://buzzfeed.com/katienotopoulos/graphs-that-lied-to-us (cited on page 10).

Nowell, Lucy Terry, Robert K. France, and Deborah Hix [1997]. *Exploring Search Results with Envision*. CHI'97 Demonstration (Extended Abstracts) (Atlanta, Georgia, USA). ACM. Mar 1997, pages 14–15. doi:10.1145/1120212.1120223. http://www.acm.org/sigchi/chi97/proceedings/demo/ltn1.htm (cited on page 88).

Nowell, Lucy Terry, Robert K. France, Deborah Hix, Lenwood S. Heath, and Edward A. Fox [1996]. *Visualizing Search Results: Some Alternatives to Query-Document Similarity*. Proc. SIGIR'96 (Zurich, Switzerland). ACM. Aug 1996, pages 67–75. doi:10.1145/243199.243214 (cited on page 88).

Nussbaumer Knaflic, Cole [2015]. *Storytelling with Data*. Wiley, 02 Nov 2015. 288 pages. ISBN 1119002257 (com, uk) (cited on page 3).

Okabe, Atsuyuki, Barry Boots, Kokichi Sugihara, and Sung Nok Chiu [2000]. *Spatial Tesselations: Concepts and Applications of Voronoi Diagrams*. 2nd Edition. Wiley, 26 May 2000. 696 pages. ISBN 0471986356 (com, uk) (cited on page 4).

Oser, Christopher [2022]. *Responsive Voronoi Treemaps with VoroTree and VoroLib*. Master's Thesis. Graz University of Technology, Austria, 23 Feb 2022. 105 pages. https://ftp.isds.tugraz.at/pub/theses/coser-2022-msc.pdf (cited on page 71).

Osmić, Majda [2015]. *Aggregated Parallel Coordinates: Multi-Dimensional Information Visualisation in Race Car Engineering*. Master's Thesis. Graz University of Technology, Austria, 21 May 2015. 151 pages. https://ftp.isds.tugraz.at/pub/theses/mosmic-2015-msc.pdf (cited on pages 94–95).

Paulovich, Fernando V., Luis G. Nonato, Rosane Minghim, and Haim Levkowitz [2008]. *Least Square Projection: A Fast High-Precision Multidimensional Projection Technique and Its Application to Document Mapping*. IEEE Transactions on Visualization and Computer Graphics 14.3 (May 2008), pages 564–575. ISSN 1077-2626. doi:10.1109/TVCG.2007.70443. http://www.lcad.icmc.usp.br/~nonato/pubs/lsp.pdf (cited on page 103).

Phan, Doantam, Ling Xiao, and Ron Yeh [2006]. *Flow Map Layout Code*. Oct 2006. http://graphics.stanford.edu/~dphan/code/flowmap/ (cited on page 81).

Phan, Doantam, Ling Xiao, Ron Yeh, Pat Hanrahan, and Terry Winograd [2005]. *Flow Map Layout*. Proc. IEEE Symposium on Information Visualization (InfoVis 2005). IEEE Computer Society. Minneapolis, Minnesota, USA, Oct 2005, pages 219–224. ISBN 078039464X (com, uk). doi:10.1109/INFOVIS.2005.13. http://graphics.stanford.edu/papers/flow_map_layout/flow_map_layout.pdf (cited on page 80).

Pietsch, Theodore W. [2013]. *Trees of Life: A Visual History of Evolution*. Johns Hopkins University Press, 02 May 2013. ISBN 1421411857 (com, uk) (cited on page 31).

Playfair, William [1801a]. *The Commercial and Political Atlas*. 3rd Edition. Reprinted in 2005. London: Wallis, 1801. ISBN 0521855543 (com, uk) (cited on page 33).

Playfair, William [1801b]. *The Statistical Breviary*. London: Wallis, 1801 (cited on page 33).

Rao, Ramana and Stuart K. Card [1994]. *The Table Lens: Merging Graphical and Symbolic Representations in an Interactive Focus+Context Visualization for Tabular Information*. Proc. CHI'94 (Boston, Massachusetts, USA). ACM. Apr 1994, pages 318–322. doi:10.1145/191666.191776 (cited on page 87).

Rao, Ramana and Stuart K. Card [1995]. *Exploring Large Tables with the Table Lens*. CHI'95 Video Program. ACM. May 1995. doi:10.1145/223355.223745. http://www.open-video.org/details.php?videoid=8304 (cited on page 87).

Rao, Ramana B. and Stuart K. Card [1997]. *Method and system for producing a table image showing indirect data representation*. US Patent 5632009. Filed 17th Sept. 1993, issued 20th May 1997. Xerox Corporation, May 1997 (cited on page 87).

Rauber, Andreas and Dieter Merkl [1999]. *The SOMLib Digital Library System*. Proc. 3rd European Conference on Research and Advanced Technology for Digital Libraries (ECDL'99). Springer LNCS 1696. Paris, France, Sep 1999, pages 323–342. doi:10.1007/3-540-48155-9_21 (cited on page 108).

Reingold, Edward M. and John S. Tilford [1981]. *Tidier Drawing of Trees*. IEEE Transactions on Software Engineering 7.2 (1981), pages 223–228 (cited on page 60).

Rendgen, Sandra [2019]. *History of Information Graphics*. Taschen, 08 May 2019. 462 pages. ISBN 3836567679 (com, uk) (cited on page 31).

Robertson, George G., Jock Mackinlay, and Stuart K. Card [1994a]. *Display of Hierarchical Three-Dimensional Structures with Rotating Substructures*. US Patent 5295243. Filed 29th Dec. 1989, issued 15th March 1994. Xerox Corporation, Mar 1994 (cited on page 62).

Robertson, George G., Jock Mackinlay, and Stuart K. Card [1994b]. *Operating a Processor to Display Stretched Continuation of a Workspace*. US Patent 5339390. Filed 5th March 1990, issued 16th Aug. 1994. Xerox Corporation, Aug 1994 (cited on page 46).

Robertson, George G., Jock D. Mackinlay, and Stuart K. Card [1991a]. *Cone Trees: Animated 3D Visualizations of Hierarchical Information*. Proc. SIGCHI Conference on Human Factors in Computing Systems (CHI'91) (New Orleans, Louisiana, USA). ACM. May 1991, pages 189–194. doi:10.1145/108844.108883 (cited on pages 14, 62).

Robertson, George G., Jock D. Mackinlay, and Stuart K. Card [1991b]. *Information Visualization Using 3D Interactive Animation*. CHI'91 Video Proceedings. SIGGRAPH Video Review Issue 63. ACM. Apr 1991. doi:10.1145/108844.109003 (cited on pages 46, 62).

Rosling, Hans [2006]. *The Best Stats You've Ever Seen*. TED 2006 Talk (Monterey, California, USA). TED. 22 Feb 2006. `https://ted.com/talks/hans_rosling_the_best_stats_you_ve_ever_seen` (cited on page 7).

Rosling, Hans [2009]. *Let My Dataset Change Your Mindset*. TED@State 2008 Talk (Washington, DC, USA). TED. 03 Jun 2009. `https://ted.com/talks/hans_rosling_let_my_dataset_change_your_mindset` (cited on page 1).

Schofield, Jack [2008]. *Lies, Damn Lies, and Steve Jobs Keynotes*. The Guardian (21 Jan 2008). `http://www.guardian.co.uk/technology/blog/2008/jan/21/liesdamnliesandstevejobs` (cited on page 11).

Schulz, Hans-Jörg [2011]. *treevis.net: A Tree Visualization Reference*. IEEE Computer Graphics and Applications 31.6 (20 Oct 2011), pages 11–15. ISSN 0272-1716. doi:10.1109/MCG.2011.103 (cited on page 51).

Schulz, Hans-Jörg, Steffen Hadlak, and Heidrun Schumann [2011]. *The Design Space of Implicit Hierarchy Visualization: A Survey*. IEEE Transactions on Visualization and Computer Graphics 17.4 (Apr 2011), pages 393–411. ISSN 1077-2626. doi:10.1109/TVCG.2010.79 (cited on page 51).

Seifert, Bernhard and Oliver Schneider [2018]. *WinDirStat*. 12 Nov 2018. `https://windirstat.net/` (cited on page 67).

SequoiaView [2005]. *SequoiaView*. 2005. `http://www.win.tue.nl/sequoiaview/` (cited on page 67).

Sheps, Arthur [1999]. *Joseph Priestley's Time Charts: The Use and Teaching of History by Rational Dissent in late Eighteenth-Century England*. Lumen 18 (1999), pages 135–154. doi:10.7202/1012372ar. `http://erudit.org/revue/lumen/1999/v18/n/1012372ar.pdf` (cited on page 32).

Shneiderman, Ben [1996]. *The Eyes Have It: A Task by Data Type Taxonomy for Information Visualizations*. Proc. 1996 IEEE Symposium on Visual Languages (VL'96) (Boulder, Colorado). IEEE Computer Society. Sep 1996, pages 336–343. doi:10.1109/VL.1996.545307. http://citeseer.ist.psu.edu/shneiderman96eyes.html (cited on page 14).

Shneiderman, Ben and Martin Wattenberg [2001]. *Ordered Treemap Layouts*. Proc. IEEE Symposium on Information Visualization (InfoVis 2001). IEEE Computer Society. San Diego, California, USA, Oct 2001, pages 73–78. doi:10.1109/INFVIS.2001.963283 (cited on page 67).

Shneiderman, Ben, Christopher Williams, and Christopher Ahlberg [1992]. *Dynamic Queries: Database Searching by Direct Manipulation*. CHI'92 Technical Video Program. ACM. May 1992 (cited on page 88).

Simons, Daniel J. and Christopher F. Chabris [1999a]. *Gorillas in our Midst: Sustained Inattentional Blindness for Dynamic Events*. Perception 28.9 (1999), pages 1059–1074. ISSN 0301-0066. doi:10.1068/p281059. http://chabris.com/Simons1999.pdf (cited on page 20).

Simons, Daniel J. and Christopher F. Chabris [1999b]. *Selective Attention Test*. 1999. https://youtube.com/watch?v=vJG698U2Mvo (cited on page 20).

Simons, Daniel J. and Daniel T. Levin [1998a]. *Failure to Detect Changes to People During a Real-World Interaction*. Psychonomic Bulletin & Review 5.4 (08 Jan 1998), pages 644–649. ISSN 1531-5320. doi:10.3758/BF03208840. http://psych.unl.edu/mdodd/Psy498/simonslevin.pdf (cited on page 20).

Simons, Daniel J. and Daniel T. Levin [1998b]. *The Door Study*. 1998. https://vimeo.com/81039224 (cited on page 20).

Small, Hugh [1998]. *Florence Nightingale's Statistical Diagrams*. Proc. Stats. & Lamps Research Conference. Florence Nightingale Museum. St. Thomas' Hospital, London, UK, Mar 1998. http://www.florence-nightingale.co.uk/small.htm (cited on pages 36, 38).

Smith, Andy and Dave Clark [2001]. *Building a Customized Tree View*. IBM developerWorks Tutorial. Free registration required. Jan 2001. http://www.ibm.com/developerworks/edu/j-dw-javatree-i.html (cited on page 52).

Spence, Robert [2014]. *Information Visualization: An Introduction*. 3rd Edition. Springer, 14 Dec 2014. 321 pages. ISBN 3319073400 (com, uk). doi:10.1007/978-3-319-07341-5 (cited on page 2).

Spence, Robert and Mark D. Apperley [2018]. *Bifocal Display*. In: *The Encyclopedia of Human-Computer Interaction*. Edited by Mads Soegaard and Rikke Friis Dam. 2nd Edition. Interaction Design Foundation, 15 Mar 2018. Chapter 7. https://interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/bifocal-display (cited on page 45).

Spoerri, Anselm [1993a]. *InfoCrystal: A Visual Tool for Information Retrieval*. Proc. 4th Conference on Visualization (Vis'93) (San Jose, California, USA). IEEE Computer Society. Oct 1993, pages 150–157. doi:10.1109/VISUAL.1993.398863 (cited on page 111).

Spoerri, Anselm [1993b]. *InfoCrystal: A Visual Tool for Information Retrieval Management*. Proc. 2nd International Conference on Information and Knowledge Management (CIKM'93) (Washington, D.C., USA). ACM. Nov 1993, pages 11–20. doi:10.1145/170088.170095 (cited on page 111).

Spoerri, Anselm [1993c]. *Visual Tools for Information Retrieval*. Proc. 1993 IEEE Symposium on Visual Languages (VL'93) (Bergen, Norway). IEEE Computer Society. Aug 1993, pages 160–168. doi:10.1109/VL.1993.269592 (cited on page 111).

Spoerri, Anselm [1995]. *InfoCrystal: A Visual Tool for Information Retrieval*. PhD Dissertation. Department of Civil and Environmental Engineering: Massachusetts Institute of Technology, 20 Jan 1995. http://dspace.mit.edu/handle/1721.1/36946 (cited on page 111).

Spoerri, Anselm [2004a]. *Coordinated Views and Tight Coupling to Support Meta Searching*. Proc. 2nd International Conference on Coordinated & Multiple Views in Exploratory Visualization (CMV 2004) (London, UK). IEEE. 13 Jul 2004, pages 39–48. doi:10.1109/CMV.2004.1319525 (cited on page 111).

Spoerri, Anselm [2004b]. *MetaCrystal: Visual Interface for Meta Searching*. Conference on Human Factors in Computing Systems (CHI 2004) (Vienna, Austria). 24 Apr 2004, pages 1558–1558. doi:10.1145/985921.986134. http://aspoerri.comminfo.rutgers.edu/Publications/CHI2004publicPoster.pdf (cited on page 111).

Spotfire [2000]. *Spotfire*. 2000. http://www.spotfire.com/ (cited on page 88).

Stasko, John T., Richard Catrambone, Mark Guzdial, and Kevin McDonald [2000]. *An Evaluation of Space-Filling Information Visualizations for Depicting Hierarchical Structures*. International Journal of Human-Computer Studies 53.5 (Nov 2000), pages 663–694. doi:10.1006/ijhc.2000.0420. http://www.cc.gatech.edu/~john.stasko/papers/ijhcs00.pdf (cited on page 65).

Stasko, John T. and Eugene Zhang [2000a]. *Focus+Context Display and Navigation Techniques for Enhancing Radial, Space-Filling Hierarchy Visualizations*. Proc. IEEE Symposium on Information Visualization (InfoVis 2000) (Salt Lake City, Utah, USA). IEEE Computer Society. Oct 2000, pages 57–65. doi:10.1109/INFVIS.2000.885091. http://www.cc.gatech.edu/gvu/ii/sunburst/ (cited on page 65).

Stasko, John T. and Eugene Zhang [2000b]. *Focus+Context Display and Navigation Techniques for Enhancing Radial, Space-Filling Hierarchy Visualizations*. IEEE Symposium on Information Visualization (InfoVis 2000) CD-ROM (Salt Lake City, Utah). IEEE Computer Society. Oct 2000. http://www.cc.gatech.edu/gvu/ii/sunburst/sunburst1.mpg (cited on page 65).

Steele, Julie and Noah Iliinsky, editors [2010]. O'Reilly, 21 Jun 2010. 416 pages. ISBN 1449379869 (com, uk) (cited on page 3).

Steffen, Joseph L. and Stephen G. Eick [1993]. *High Interaction Data Visualization – Using SeeSoft to Visualize Program Change History*. InterCHI'93 Technical Video Program. ACM. Apr 1993. http://open-video.org/details.php?videoid=8144 (cited on page 47).

Steinberg, Steve G. [1997]. *Lifestreams*. Wired 5.2 (Feb 1997), pages 148–208. http://wwww.wired.com/wired/5.02/features/fflifestreams.html (cited on page 48).

Strasnick, Steven L. and Joel D. Tesler [1996a]. *Method and Apparatus for Displaying Data within a Three-Dimensional Information Landscape*. US Patent 5528735. Filed 23rd March 1993, issued 18th June 1996. Silicon Graphics, Inc., Jun 1996 (cited on page 54).

Strasnick, Steven L. and Joel D. Tesler [1996b]. *Method and Apparatus for Navigation within Three-Dimensional Information Landscape*. US Patent 5555354. Filed 23rd March 1993, issued 10th Sept. 1996. Silicon Graphics, Inc., Sep 1996 (cited on page 54).

Tejada, Eduardo, Rosane Minghim, and Luis Gustavo Nonato [2003]. *On Improved Projection Techniques to Support Visual Exploration of Multi-Dimensional Data Sets*. Information Visualization 2.4 (Dec 2003), pages 218–231. ISSN 1473-8716. doi:10.1057/palgrave.ivs.9500054 (cited on page 103).

Telles, Guilherme P., Rosane Minghim, and Fernando V. Paulovich [2007]. *Normalized Compression Distance for Visual Analysis of Document Collections*. Computers & Graphics 31.3 (Jun 2007), pages 327–337. ISSN 0097-8493. doi:10.1016/j.cag.2007.01.024 (cited on page 101).

Tesler, Joel D. and Steven L. Strasnick [1992]. *FSN: The 3D File System Navigator*. Silicon Graphics, Inc. 1992. ftp://ftp.sgi.com/sgi/fsn (cited on page 54).

Thomas, Jim, Paula Cowley, Olga Kuchar, Lucy Nowell, Judi Thomson, and Pak Chung Wong [2001]. *Discovering Knowledge Through Visual Analysis*. Journal of Universal Computer Science 7.6 (Jun

2001), pages 517–529. http://www.jucs.org/jucs_7_6/discovering_knowledge_through_visual (cited on page 104).

Tominski, Christian and Heidrun Schuhmann [2020]. *Interactive Visual Data Analysis*. CRC Press, 30 Apr 2020. 346 pages. ISBN 0367898756 (com, uk) (cited on page 2).

Tufte, Edward R. [1990]. *Envisioning Information*. Graphics Press, 1990. ISBN 0961392118 (com, uk) (cited on page 3).

Tufte, Edward R. [1997]. *Visual Explanations: Images and Quantities, Evidence and Narrative*. Graphics Press, 1997. ISBN 0961392126 (com, uk) (cited on pages 3, 35).

Tufte, Edward R. [2001]. *The Visual Display of Quantitative Information*. 2nd Edition. Graphics Press, Jan 2001. 200 pages. ISBN 0961392142 (com, uk) (cited on pages 3, 15).

Tufte, Edward R. [2006]. *Beautiful Evidence*. Graphics Press, 01 Jul 2006. 213 pages. ISBN 0961392177 (com, uk) (cited on page 3).

Tufte, Edward R. [2020]. *Seeing with Fresh Eyes: Meaning, Space, Data, Truth*. Graphics Press, 30 Nov 2020. 176 pages. ISBN 1930824009 (com, uk) (cited on page 3).

Turo, David [1994]. *Hierarchical Visualization with Treemaps: Making Sense of Pro Basketball Data*. CHI'94 Video Program. ACM. Apr 1994 (cited on page 66).

Tweedie, Lisa, Bob Spence, David Williams, and Ravinder Bhogal [1994]. *The Attribute Explorer*. CHI'94 Video Program. ACM. Apr 1994. doi:10.1145/259963.260433. https://open-video.org/details.php?videoid=8162 (cited on page 97).

Usama Fayyad Georges Grinstein, Andreas Wierse [2001]. *Information Visualization in Data Mining and Knowledge Discovery*. Morgan Kaufmann, 03 Sep 2001. 407 pages. ISBN 1558606890 (com, uk) (cited on page 3).

Van der Maaten, Laurens and Geoffrey Hinton [2008]. *Visualizing Data using t-SNE*. Journal of Machine Learning Research 9.86 (2008), pages 2579–2605. ISSN 1533-7928. https://jmlr.org/papers/v9/vandermaaten08a.html (cited on page 104).

Van Ham, Frank and Jarke J. van Wijk [2002]. *Beamtrees: Compact Visualization of Large Hierarchies*. Proc. IEEE Symposium on Information Visualization (InfoVis 2002) (Boston, Massachusetts, USA). IEEE Computer Society. Oct 2002, pages 93–100. doi:10.1109/INFVIS.2002.1173153. http://www.win.tue.nl/~fvham/beamtrees/ (cited on page 73).

Van Wijk, Jarke J. and Huub van de Wetering [1999]. *Cushion Treemaps: Visualization of Hierarchical Information*. Proc. IEEE Symposium on Information Visualization (InfoVis'99). IEEE Computer Society. San Francisco, California, USA, Oct 1999, pages 73–78. doi:10.1109/INFVIS.1999.801860. http://www.win.tue.nl/~vanwijk/ctm.pdf (cited on page 67).

Vogel, Edward K., Geoffrey F. Woodman, and Steven J. Luck [2001]. *Storage of Features, Conjunctions, and Objects in Visual Working Memory*. Journal of Experimental Psychology: Human Perception and Performance 27.1 (Feb 2001), pages 92–114. ISSN 0096-1523. doi:10.1037/0096-1523.27.1.92. http://www.psy.vanderbilt.edu/faculty/woodman/papers/VogelWoodmanLuck01.pdf (cited on page 21).

Wainer, Howard, Polina Harik, and John Neter [2013]. *Stigler's Law of Eponymy and Marey's Train Schedule*. CHANCE 26.1 (06 Feb 2013), pages 53–56. doi:doi:10.1080/09332480.2013.772394. https://www.researchgate.net/publication/286085953_Visual_Revelations_Stigler's_Law_of_Eponymy_and_Marey's_Train_Schedule_Did_Serjev_Do_It_Before_Ibry_and_What_About_Jules_Petiet (cited on page 41).

Walker II, John Q. [1990]. *A Node-Positioning Algorithm for General Trees*. Software: Practice and Experience 20.7 (Jul 1990), pages 685–705. doi:10.1002/spe.4380200705. https://www.cs.unc.edu/techreports/89-034.pdf (cited on page 54).

Wandell, Brian [1995]. *Foundations of Vision*. Sinauer Associates, May 1995. ISBN 0878938532 (com, uk) (cited on page 19).

Ward, Matthew, Georges Grinstein, and Daniel Keim [2015]. *Interactive Data Visualization: Foundations, Techniques, and Applications*. 2nd Edition. CRC Press, 29 May 2015. 578 pages. ISBN 1482257378 (com, uk) (cited on page 2).

Ware, Colin [2020]. *Information Visualization: Perception for Design*. 4th Edition. Morgan Kaufmann, 11 Mar 2020. 560 pages. ISBN 0128128755 (com, uk) (cited on pages 2, 19).

Ware, Colin [2021]. *Visual Thinking for Information Design*. 2nd Edition. Morgan Kaufmann, 14 Jul 2021. 224 pages. ISBN 0128235675 (com, uk) (cited on pages 2, 19).

Wattenberg, Martin [1999]. *Visualizing the Stock Market*. CHI 99 Extended Abstracts (Pittsburgh, Philadelphia). ACM. May 1999, pages 188–189. http://bewitched.com/marketmap.html (cited on page 67).

Wattenberg, Martin, Fernanda Viégas, and Ian Johnson [2016]. *How to Use t-SNE Effectively*. Distill (13 Oct 2016). ISSN 2476-0757. doi:10.23915/distill.00002. https://distill.pub/2016/misread-tsne/ (cited on page 104).

Welz, Michael [1999]. *The Java Pyramids Explorer: A Portable, Graphical Hierarchy Browser*. Master's Thesis. Graz University of Technology, Austria, 20 Sep 1999. http://ftp.iicm.tugraz.at/pub/theses/mwelz.pdf (cited on page 15).

Wexelblat, Alan D. and Kim M. Fairchild [1991]. *Method and system for generating dynamic, interactive visual representations of information structures within a computer*. US Patent 5021976. Filed 14th Nov. 1988, issued 4th June 1991. Microelectronics and Computer Technology Corporation (MCC), Jun 1991 (cited on page 83).

Wikipedia [2013]. *Anscombe's Quartet*. 06 Mar 2013. http://en.wikipedia.org/wiki/Anscombe's_quartet (cited on page 9).

Wise, James A. [1999]. *The Ecological Approach to Text Visualization*. Journal of the American Society for Information Science 50.13 (Nov 1999), pages 1224–1233. doi:10.1002/(SICI)1097-4571(1999)50:13<1224::AID-ASI8>3.0.CO;2-4. http://www.geog.ucsb.edu/~sara/teaching/geo234_02/papers/wise.pdf (cited on page 104).

Wise, James A., James J. Thomas, Kelly Pennock, David Lantrip, Marc Pottier, Anne Schur, and Vern Crow [1995]. *Visualizing the Non-Visual: Spatial Analysis and Interaction with Information from Text Documents*. Proc. IEEE Symposium on Information Visualization (InfoVis'95) (Atlanta, Georgia, USA). IEEE Computer Society. Oct 1995, pages 51–58. ISBN 0818672013 (com, uk). doi:10.1109/INFVIS.1995.528686 (cited on page 104).

Wiseman, Richard [2008]. *Red Card Trick*. Discovery, Human Body: Pushing the Limits, Sight. 2008. https://youtu.be/5HkGSrY1N9Y (cited on page 20).

Wood, Andrew M., Nick S. Drew, Russell Beale, and Bob J. Hendley [1995]. *HyperSpace: Web Browsing with Visualisation*. Proc. WWW3 (Darmstadt, Germany). Apr 1995, pages 21–25. https://web.archive.org/web/20021224194556/http://www.igd.fhg.de/archive/1995_www95/proceedings/posters/35/index.html (cited on page 83).

WTF [2017]. *WTF Visualizations*. 08 Mar 2017. http://viz.wtf/ (cited on page 10).

Wurman, Richard Saul [1997]. *Information Architects*. Watson-Guptill, 15 Sep 1997. 235 pages. ISBN 1888001380 (com, uk) (cited on page 4).

Yankelovich, Nicole, Bernard J. Haan, Norman K. Meyrowitz, and Steven M. Drucker [1988]. *Intermedia: The Concept and the Construction of a Seamless Information Environment*. IEEE Computer 21.1 (Jan 1988), pages 81–96. doi:10.1109/2.222120 (cited on page 80).

Yau, Nathan [2017]. *How to Spot Visualization Lies*. 09 Feb 2017. `https://flowingdata.com/2017/02/09/how-to-spot-visualization-lies/` (cited on page 10).

Yi, Ji Soo, Rachel Melton, John Stasko, and Julie Jacko [2005a]. *Dust & Magnet: Interactive Visualization for Everyday Data*. Information Interfaces Group, Georgia Tech. 2005. `https://youtu.be/wLXwL38xek0` (cited on page 96).

Yi, Ji Soo, Rachel Melton, John Stasko, and Julie Jacko [2005b]. *Dust & Magnet: Multivariate Information Visualization using a Magnet Metaphor*. Information Visualization 4.4 (01 Dec 2005), pages 239–256. doi:10.1057/palgrave.ivs.9500099. `http://cc.gatech.edu/~stasko/papers/iv05-dnm.pdf` (cited on page 96).

Zer-Aviv, Mushon [2014]. *Disinformation Visualization: How to Lie with DataVis*. 31 Jan 2014. `https://visualisingadvocacy.org/blog/disinformation-visualization-how-lie-datavis` (cited on page 10).

Zhang, Jin-Ting [2007]. *Visualization for Information Retrieval*. Springer, 16 Nov 2007. 312 pages. ISBN 3540751475 (com, uk) (cited on page 3).