

Data Visualization, A Survey

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People observe and perceive objects primarily by vision, which allow them to quickly grasp interesting features in daily scenarios. It is desirable to present information such as datasets in an organized fashion so that people could understand. The presentation of datasets could be challenging when the size of the dataset is huge or the elements in the dataset have complex relationships. Therefore, to effectively and efficiently visualize data become a prevalent research direction.

Since the first proposal of data visualization as a research topic, hundreds of powerful visualization techniques and applications have been developed. Each has its own features and rationales. Such a situation stimulates us to investigate and derive the birds eye view over this field, before we attempt to make our own contribution to the research of data visualization.

The rest of this report is organized as follows: Section 1 introduces fundamental concepts, categorized methods, and symbols commonly used in data visualization field. Section 2 introduces notable programming libraries and software applications for data visualization. Section 3 overview important techniques used in visualization. Some lately research progresses with respect to visualization are described in Section 4. We made a summary of prominent data visualization research problems in Section 5.

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1. Introduction to Data Visualization

With the ever-increasing amount of available computing resources, our ability to collect and generate a wide variety of large, complex, high-dimensional datasets continues to grow. High-dimensional datasets show up in numerous fields of study, such as economy, biology, chemistry, political science, astronomy, and physics etc. Their wide availability, increasing size and complexity have led to new challenges and opportunities for their effective visualization. The physical limitations of the display devices and our visual system prevent the direct display and instantaneous recognition of structures with higher dimensions than two or three. In the past decade, a variety of approaches have been introduced to visually convey high-dimensional structural information by utilizing low-dimensional projections or abstractions: from dimension reduction to visual encoding, and from quantitative analysis to interactive exploration. A number of researches have focused on different aspects of data visualization, such as parallel coordinates, quality measures, clutter reduction, visual data mining, and interactive techniques. In the future, data visualization will become a continual hotspot in the fields of science and industry.

1.1. the Definition of Data Visualization

Data visualization, is the scientific study in terms of information display. Display format, is defined as a kind of information recapitulated from raw dataset and involving various attributes and variables attracting our concern.

The basic methodology of data visualization is to interpret each data item within dataset as an element of graph, lots of which form the entire visualization figures, images, or charts. Meanwhile, attributes are exhibited by multi-dimension data. In this way, observing data from different dimension is capable, which facilitates expected further analysis to find out their internal rules.

Critical feature of data visualization can be described as: data visualization and translation tool enables a mapping between source schema and target schema, and they compare different existing mappers on contributions and limitations [2].

Furthermore, Ivan Herman, Guy Melançon, and M. Scott Marshall provide a terse standard to determine the applicability of graph visualization [24]: is there an inherent relation among the data elements to be visualized? If the answer to the question is “no”, than data elements are “unstructured” and the goal of the information visualization system might be to help discover relations among data through visual means. If, however, the answer to the question is “yes”, then the data can be represented by the nodes of a graph, with the edges representing the relations.

1.2. Common Concepts in Data Visualization

In visualization field, there are some common concepts used to describe scenarios in a uniform and convenient way, summarized as follows:

- ① Data Space: a multi-dimension information space constituted by dataset of many multi-attribute elements.
- ② Data Development: quantitative deduction and computation of data employing certain algorithms and tools.
- ③ Data Analysis: utilizing slicing, block, rotation and other operations to analyze multi-dimensional data, which provides multi-angle and multi-side observation of data.
- ④ Data Visualization: the process of translating massive data into graph form, and employ tools in terms of data analysis and development to procure sealed information.

1.3. Data Stream model of Visualization Procedure

Although there have been a great variety of methods proposed to present data with various mechanisms, all of them can be abstracted to a common mode. Systematically speaking, visualizing data goes through the following steps:

- ① First, source data are collected from sense, generation, recording or other applicable methods.
- ② Second, though source data have the biggest chance to reserve the nature of entity, observers may not be able to cognize it by analyzing source data due to obscure representation. As a result, data transformation is required, which promotes source data on validity, integrity, and discrepancy etc. Usual methods of transforming data are coordinate transformation, interpolation, and filtration etc. Taking advantage of these techniques, source data become more suitable for visualization. However, inappropriate transformation can also backfire the influence. Hence, comprehensive awareness of data feature is a critical factor deciding the quality of transformation.
- ③ Third, since transformed data remain abstract and unintuitive, they require an extra mapping process to present data conveniently, i.e. constructing a mapping between transformed data and view elements. By now, a number of mapping techniques have been proposed.
- ④ Through the former three steps, complete view has been generated. Therefore, users can observe it and acquire information they want.

The aforementioned procedure to visualize data can be felicitously expressed as a flow chart, namely data stream model. Fig. 1 provides an example of the model. Furthermore, it demonstrates that user reciprocity is accessible in each step.

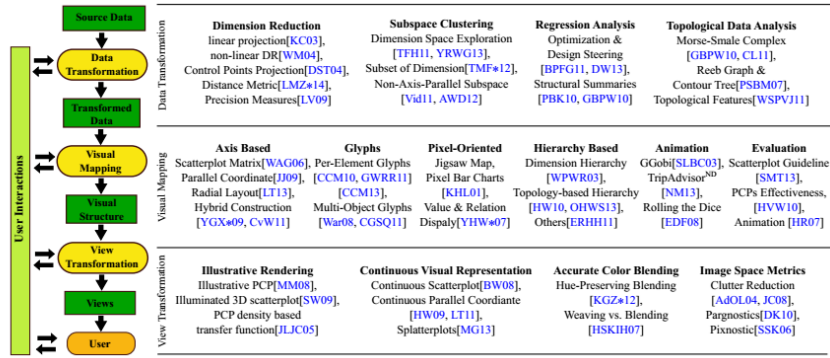


Figure 1: Categorization based on transformation steps within the information visualization pipeline, with customized action-driven subcategories [26].

1.4. the Categories of Data Visualization Techniques

Since data visualization involves techniques and tools in many fields, such as computer graphics, data mining, computer visualization etc, approaches to visualize data can be categorized according to different criterions.

As per Kenneth I. Joy's classification [23], a data visualization method belongs to one of the following type:

- ① Compression and simplification – Reduce the size of the information stream by utilizing data compression methods or by simplifying the data to remove redundant or superfluous items.
- ② Multiresolution methods – Design multiresolution hierarchies to represent the information at varying resolutions, allowing the user (or the application) to dictate the resolution displayed.
- ③ Memory external methods – Create innovative methods that store the data externally and develop methods that access relevant data subject to the interactivity required by the user.
- ④ Abstraction – Create new visual metaphors that display data in new ways.

While Keim and Kriegel [4] [5] divided visual data exploration techniques for multidimensional multivariate data into six classes, namely geometric, icon-based, pixel-oriented, hierarchical, graph-based and hybrid techniques.

Furthermore, Winnie Wing-Yi Chan refers this taxonomy and tailors it to multivariate data visualization techniques, which are classified into four broad categories according to the overall approaches taken to generate resulting visualizations [27]: Geometric projection, pixel-oriented techniques, hierarchical display and iconography.

1.4.1. Geometric Projection Techniques

Geometric projection techniques refer to presenting dataset with modern mathematic methods with respect to geometric brushwork or geometric projection. It is the most prevalent and well-known kind of visualization techniques in the world. In the following, some typical techniques using geometric projection are introduced:

- ① Scatterplot Matrix: A method to project data items according to any two attributes served as x-y axes of the Cartesian coordinates and hence generate a 2D graph. Array all the 2D scatterplot graphs as per the certain order of attributes, a matrix is derived, i.e. so-called scatterplot matrix.

Scatterplot matrix is suitable to reflect patterns between two attributes, besides that, this method is simple for us to perform. Its biggest issue [6], however, is the shortcoming in observing correlations among higher dimensions than two. Fortunately the technique of brushing [28] can be applied to address the above problem. Brushing aims interpretation by highlighting a particular n-dimensional subspace in the visualization [29], that is, the respective points of interested are colored or highlighted in each scatterplot in the matrix. Fig. 1 gives an instance of scatterplot matrix. In Fig. 1, automobiles are color-coded by the number of cylinders. Manufacturers can analyze the performance of the cars based on the number of cylinders for improvements, while customers can decide how many cylinders they need in order to suit their needs.

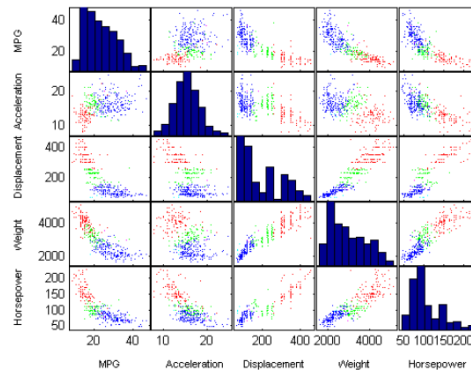


Figure 2. An instance of scatterplot matrix

- ② Prosecution Matrix: Prosecution was first introduced by Furnas and Buja [30]; Tweedie and Spence [31] later extended it to prosecution matrix which supports a higher dimensionality. Akin to scatterplot matrix, prosecution matrix is also consist of many prosecution graph elements. These graphs are capable to select appropriate parameter range by representing data items lying in the range with different colors. A typical prosecution is shown in Fig. 3. The yellow rectangles in Fig. 3 indicate the tolerances on parameter values, Yet it gives less information about the correlations between more than two attributes.

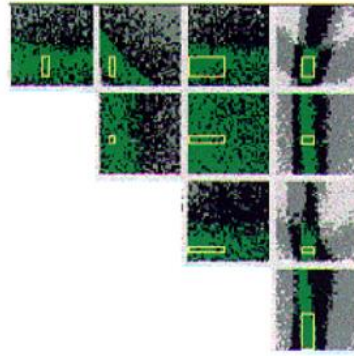


Figure 3. A typical Prosecution Matrix

- ③ Hyperslice: The most significant improvement of hyperslice over scatterplot is the interactive data navigation around a user defined focal point [32]. An enhanced hyperSlice was also proposed [33] which incorporate the concept of display resolution supported by space projection, together with the concept of data resolution provided by wavelets to form a powerful multiresolution visualization system. Fig. 4 presents a hyperslice for 4D function [32].

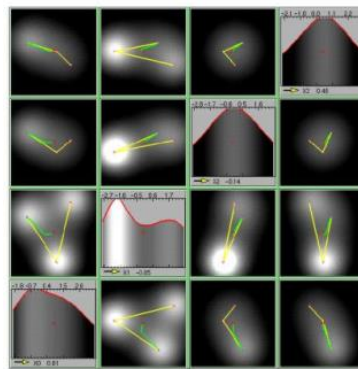


Figure 4. Hyperslice for 4D function [32]

- ④ hyperbox: Like the above techniques, hyperbox [32] indicates to visualize data with a box rather than a matrix. It can be a more powerful tool as it is possible to map variables to both size and shape of the face. Hence emphasizing or de-emphasizing certain variables [32] is also permitted. Whereas, due to the limitation of 2D to depict high-dimension figures, the length and orientation may mislead the information as it violates the “banking to 45 degrees” principle [34].

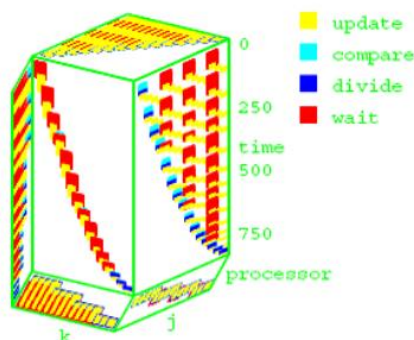


Figure 5. An example of hyperbox [32]

- ⑤Parallel Coordinates [35]: Parallel Coordinates is a well-known technique where attributes are represented by parallel vertical axes linearly scaled within their data range. Each data item is represented by a polygonal line that intersects each axis at respective attribute data value, as Fig. 6 shows.

Parallel coordinates can be used to study the correlations among attributes by spotting the locations of intersection points [32]. Also, they are effective to reveal the data distributions and functional dependencies. Nevertheless, one major limitation is the limited space available for each parallel axis. Visual clutters can severely hamper the user's ability to interpret the visualizations and interact with it. Akin to former methods, brushing technique is also applicable in this case.

- ⑥Andrews Curve: data items are plotted as Fourier transforms [20]. It's useful to detect clusters and outliers [21] and extensible to many dimensions, but computationally expensive to handle huge datasets.

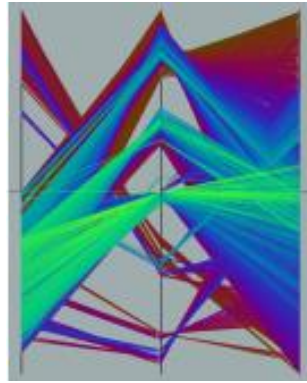


Figure 6. A demonstration of parallel coordinates [6]

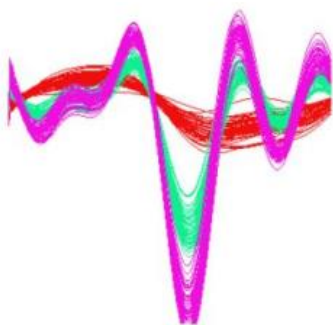


Figure 7. Andrew curves [20]

- ⑦Star Coordinates: Star coordinate [36] is an extension of typical scatterplots to higher dimensions. Data items are presented as points and attributes are represented by the axes arranged on a circle.

Users can apply scaling transformations to change the length of an axis, which increases or decreases the contribution of an attribute. It also provides rotation

transformations that change the direction of an axis, so the angles are no more equal and thus making an attribute more or less correlated with other attributes. An example of star coordinates after transformation is shown in Fig. 8. It has been found to be useful in gaining insight into hierarchically clustered datasets and for multi-factor analysis for decision-making [3].

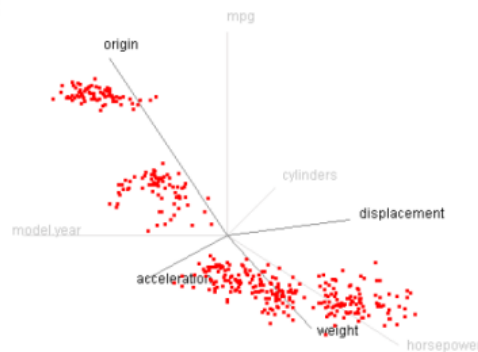


Figure 8. Star coordinate with transformation [36]

- ⑧ Table Len: A display of data enable each row to represent a data item and the columns refer to the attributes [37]. Table lens was motivated by the regularity nature of traditional tables, where information along rows or columns is interrelated and can be interpreted as a coherent. It therefore takes advantage in using a concept which we are familiar with. Fig. 9 provides a paragon of typical table len. As it shows, each attribute can be viewed as a histogram or as a plot.

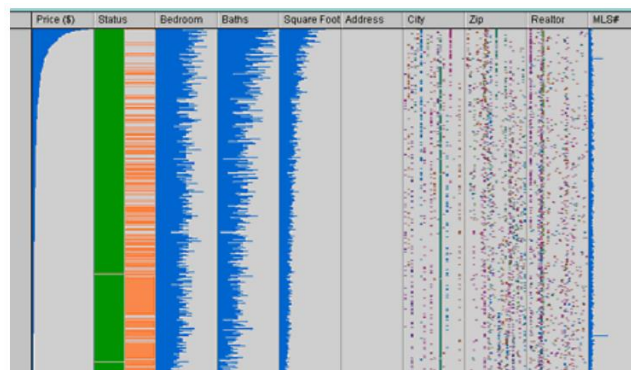


Figure 9. A paragon of typical table len [38]

1.4.2. Pixel-oriented Techniques

Pixel-oriented techniques enable each data item to be mapped into a pixel, hence avoidance is acquired for record overlap and visual clutter [27].

These techniques can be further divided into two subgroups, query-independent and query-dependent. Query-independent techniques are favored by data with a natural order according to one attribute, while query-dependent visualizations are more appropriate if the feedback to some query is of interest [39]. For the latter, the distances of attribute values to the query, instead of the absolute values, are mapped to colors.

- ① Space Filling Curves [8]: Space Filling Curves is a query-independent method that provides an excellent clustering of closely related data items [27]. For multivariate data, curves of particular attributes are display in separate windows. The length and width of window, as well as pixel color can represent one vital data attribute, respectively. By this way, data items with akin attributes will converge spontaneously. Some well-known space filling curves are curves by Peano-Hibert [40] and Morton [41], as shown in Fig. 10.

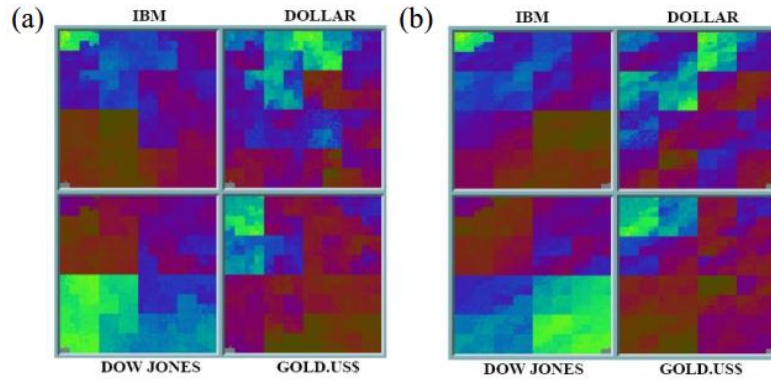


Figure 10. Space filling curves (a) Peano-Hibert (b) Morton

- ② Recursive Pattern [9]: Recursive Pattern draws space filling curves in an iterative and recursive way, i.e. each element in a pattern window is also the window of its child pattern, similar to hierarchical technique. Besides, all of child patterns together decide its feature. Recursive pattern overcomes the liability of Peano-Hibert and Morton in intelligibility, establishment of correlation among sub-windows, and reciprocity with users. It allows us to conceive the architecture of figures, which contributes to better presentation performance. Whereas, once the data becomes overwhelming, its capacity of complex architecture will fade the role of any single attribute inevitably. Fig. 11 exhibits a simple instance of recursive pattern.

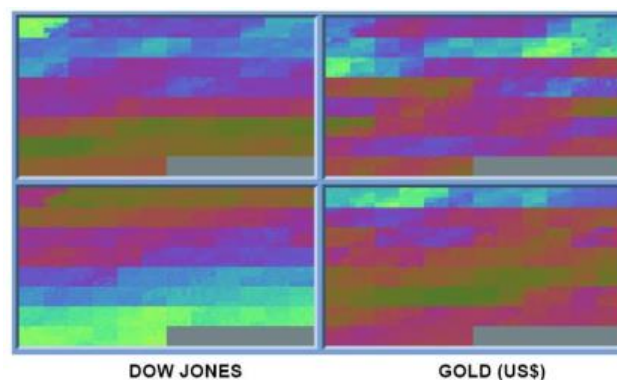


Figure 11. a simple instance of recursive pattern

- ③ Spiral and axes technique: the 100% correct answers are presented in the middle of the window and the approximate answers sorted according to their overall distance (or relevance) in a generalized spiral form around this region [39]. Axes technique [42] improves the spiral one by including feedback on displacement, by dividing the window to sub-windows as per the sign of distances on respective

dimensions. Fig. 12 shows their implementation intuitively.

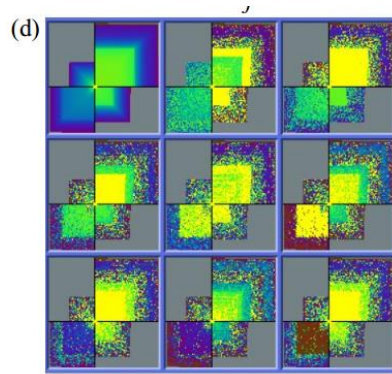


Figure 12. Spiral and axes technique result of an 8-dimensional dataset

- ④ Circle Segment [11]: each segment represents a dimension, and data items are identified by respective distances to center. The ordering and colors of the pixels are similarly determined by their overall distance to the query. Fig. 13 is an example of circle segment visualization.

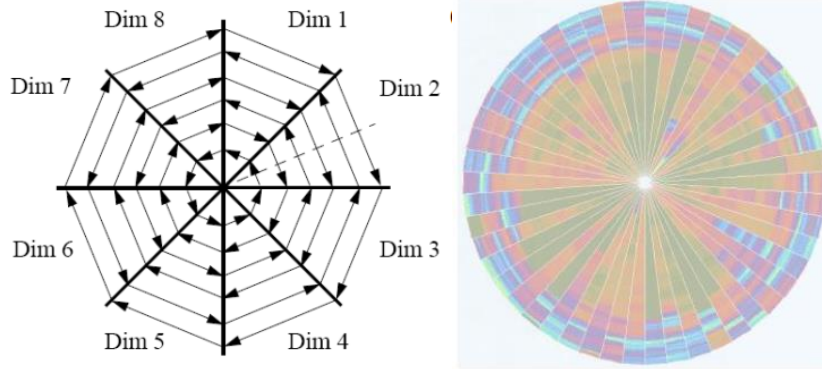


Figure 13. (a) Circle segment arrangement for 8-dimensional data

(b) An example of circle segments

- ⑤ Pixel Bar Chart [12]: derived from regular bar chart, presents data values directly instead of aggregating them into a few data values. Each data item is represented by a single pixel and is placed in the bars accordingly. For higher-dimensional data, multi-pixel bar charts are proposed, see Fig. 14. Charts are duplicated and different attribute is colored-coded for each chart.

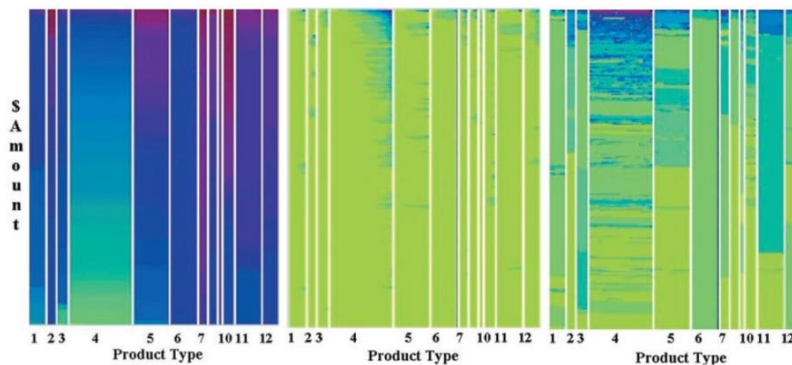


Figure 14. Multi-pixel bar chart with color encoding different attributes

1.4.2. Hierarchical Techniques

Hierarchical techniques target to process organized data as per hierarchical format within database. Its critical idea is to divide n-dimension space into a certain number of subspaces, and then iteratively divide these subspaces. Below, some usual hierarchical techniques are introduced:

- ① Hierarchical Axis: A method of putting many attributes into one screen [13]. Axes are laid out horizontally in a hierarchical fashion as illustrated in Figure 15.

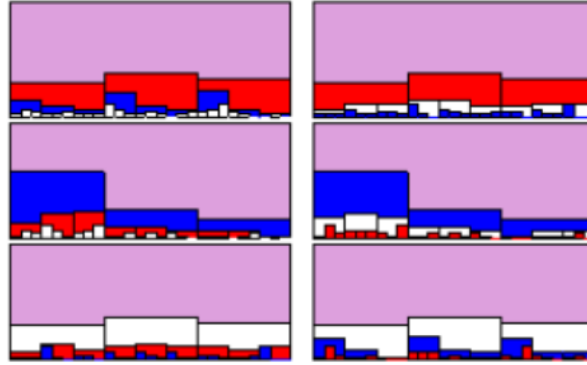


Figure 15. Histograms within histograms matrix

- ② Dimensional Stacking: A variation of hierarchical axis, or to segment the data space into 2-dimensional subspaces stacked into each other, which is suitable for discrete categorical or binned ordinal values [13]. The grids in Fig. 16 indicate visualization of any two different attributes, represented by horizontal axis and vertical axis respectively. Another comprehension of dimensional stacking from a unique view is interesting: The extended implementation of hierarchical axis in 2-dimensional environment.

(a)

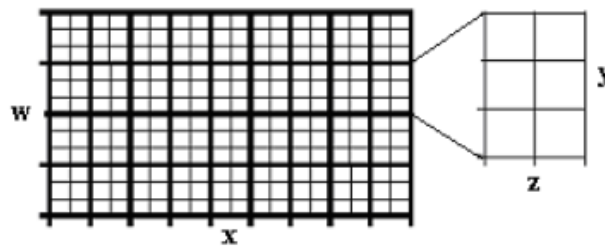


Figure 16. Partition of dimensional stacking

- ③ World within world, or n-vision [14]: It generates an interactive hierarchy display, instead of the static objects in the previous one, by using powerful 3D rendering [22]. It allows the exploration of n-dimensional function spaces, but could also be adapted to n-dimensional datasets [20]. Fig. 17 is given to show one of its example.

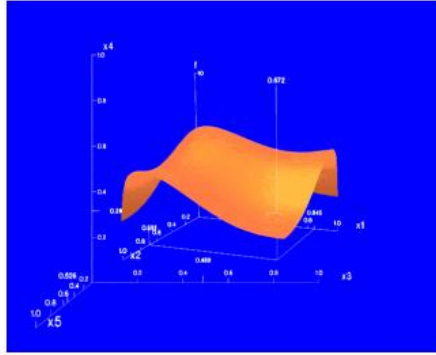


Figure 17. N-Vision

- ④ Treemap: suitable to obtain an overview on large datasets with multiple ordinal attributes [15]. Furthermore, it subdivides the display in a space-filling manner that fully utilizes the available display space [43]. Fig. 18 presents a typical treemap. As it shows, each standard rectangular area represents a subclassification. Furthermore, the bigger square the area has, the higher level of subclassification is.



Figure 18. Typical Treemap

1.4.4. Iconography Techniques

Iconographic or icon-based techniques map each multidimensional data item to an icon or a more characteristic glyph, where visual features coincide to data attribute values. Several graphical parameters are usually contained in an icon, which makes it possible to handle multidimensional data. Besides, observations of graphical features are pre-attentive which is welcomed by human. However, unlike geometric techniques that treat all the dimensions equally, some features in glyphs are more salient than others, and adjacent elements are easier to be related and accuracy of perceiving different graphical attributes varies between humans tremendously. It thereby introduces biases in interpreting the result [3].

- ① Chernoff Faces: attributes are represented by organs on face. Its shortcoming is that different features cannot be compared to each other. One common issue to all multidimensional icons, including Chernoff faces, is that the semantic relation to the task has significant impact on the perceptive effectiveness [44]. Yet it will then very much depend on the application domain. Fig. 19 is a

paragon of chernoff faces.

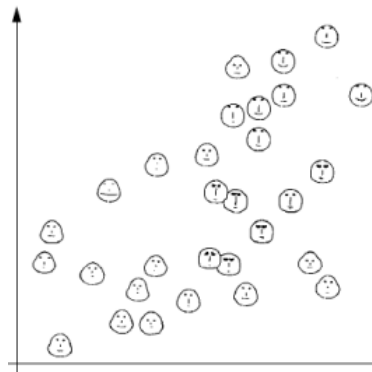


Figure 19. Chernoff faces in various 2D positions

- ② Star glyph: There are many variants in the glyph family for displaying multidimensional data; star plot [45] is one of the most widely used glyphs. Whereas, it is only effective when data size is moderate. An instance of star glyph is given in Fig. 20. Besides, star plots can be further combined with other glyphs to encode extra information, as shown in Fig. 21.

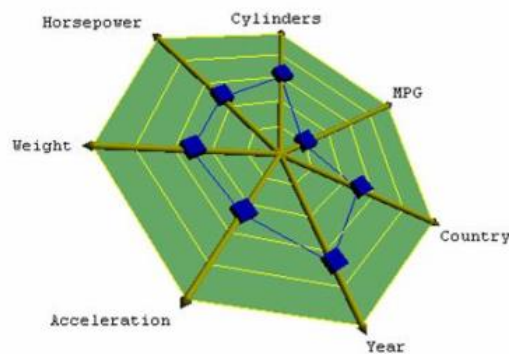


Figure 20. Architecture of a star plot

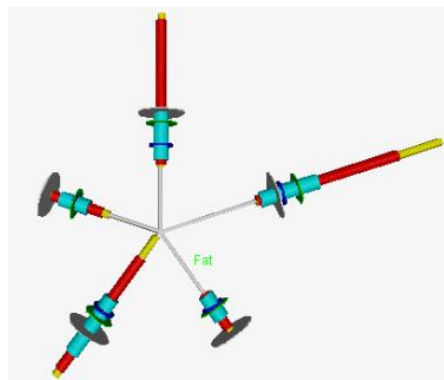


Figure 21. Box plot stars

- ③ Stick Figure: map two attributes to the display axes and the remaining to the rotation angle, length and etc, its deterministic factor is graphical attribute. Fig. 22 is a stick figure for visualizing 5D image data. It provides a meticulous presentation to visualize data, and hence affects audiences aesthetically. However, the liability of this feature also exists — extremely strict requirement for

resolution ratio of screen and for visual sharpness of observer's eyes.

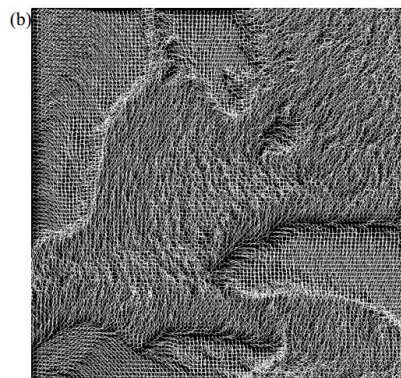


Figure 22. 5D image data using stick figures

- ④ Color Icon: is a combination of the pixel-based spiral axes and icon-based shape coding techniques, merging color, shape and texture perception for iconographic integration [16]. As shown in Fig. 23, pixel in spiral curve is replaced by pixel array, whose element stands for a single attribute. In the center of picture, the yellow arrays state those data items satisfying query completely. Along the spiral curve, satisfying degree of presented data items for query declines constantly.

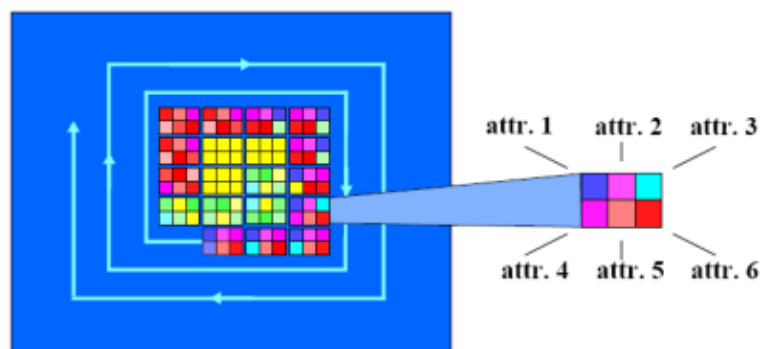


Figure 23. Color Icon Spiral Curve

- ⑤ Texture: allow users to gain insight into the overall relationships between attributes and it is supported by recent advanced texture synthesis techniques [17], [18]. Fig. 24 presents a texture application in visualization of weather conditions.

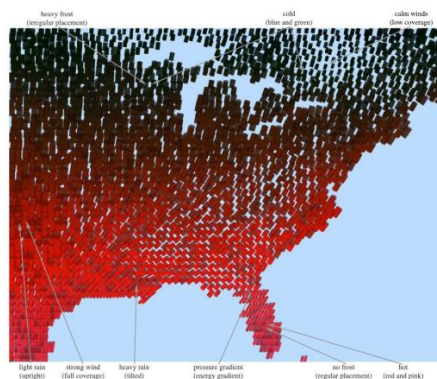


Figure. 24 Texture visualization of weather conditions

1.5. Usual Symbols Used in Data Visualization

To present data in a meaningful way, some intelligible symbols are favored and commonly used by public. Usual symbols used for visualizing can be categorized as per entity state, including static traits, change types, and change dynamics [19].

1.5.1. Static traits

Symbols belonging to this type tend to reflect innate feature of entities, like composition, correlation and etc. Fig. 25 shows several familiar symbols to describe static traits, including construction, segmentation, distribution, similarity, boundedness.

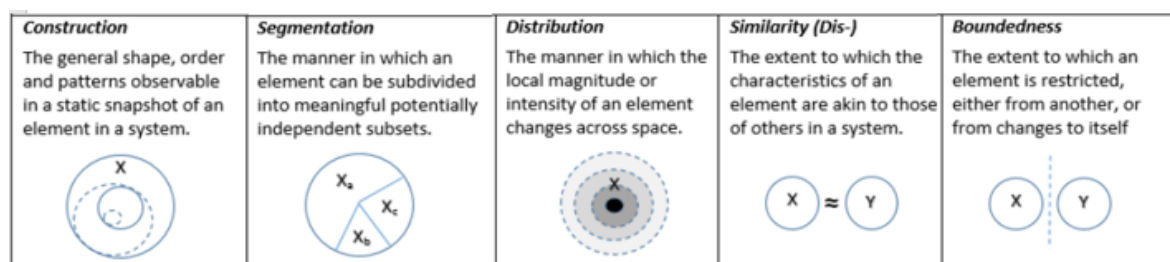


Figure 25. Visual denotation of static traits

1.5.2. Change types

Some symbols are used to depict variation of entity. Unlike static traits, change type underscores entity transformation rather than entity itself. Usual transformation refers to geographic position, shape, size, as well as other individual attributes of entity. Fig. 26 demonstrates four kinds of change types, namely movement, growth, combination, and transformation, respectively.

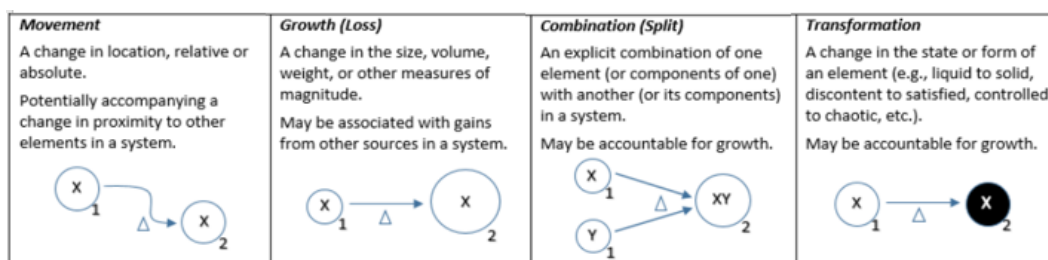


Figure 26. Visual denotation of change types

1.5.3. Change Dynamics

If change is found to happen with specific rule, the transforming rule should also be illustrated in view, i.e. so-called change dynamics. Fig. 27 gives some typical instances, including simultaneity, causality, sequence, cycle. It is obvious that each symbol of change

dynamics contains at least two entities with different attributes, which is akin to usual change type. But the most understanding discrepancy between the two categories lays in whether these entities have strong correlation in terms of time, order, or variation requirement.

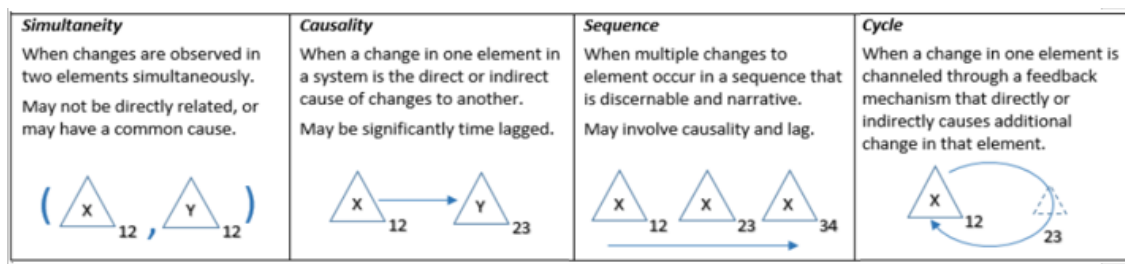


Figure 27. Visual denotation of change dynamics

2. Libraries and Software

2.1. Programming Libraries for Data Visualization

With the development of internet technologies in recent years, massive data are convenient to be displayed on computer. As a result, programming inclines to become a popular method to realize data visualization. So far, class libraries based on different programming languages have been constructed and shared in the world, which turns data presentation into simple coding stuff with complex structure or titanic size.

Considering current context, JavaScript provides the most libraries among programming languages, numbered around 30. Python follows, numbered 20 plus. But other numerous languages also offer special capacities to data visualization.

Existed libraries based on various languages are:

- ① JavaScript: Chart.js, D3.js, FusionCharts, JavaScript InfoVis ToolKit, JQuery Visualize, ZingChart, Flot, Gephi.
- ② Python: matplotlib, mayavi.
- ③ Classical math analysis tools: Mathematica, Matlab, Maple.
- ④ R: ggplot2, Java: JFreeChart.
- ⑤ Plotly, gnuplot, origin, sigmaplot, Microsoft Math, SciLab, visio.
- ⑥ GeoGebra(based on Java), processing(based on Java), jpGraph(based on PHP), NodeBox(based on Python)

2.2. Tools for Data Visualization

As a saying goes, “Sharp tools make good work”. To keep pace with technology development and application requirement of data visualization, lots of powerful and easy-to-use tools have been released in recent years. Some common visualization tools are displayed here, and

several typical tools are introduced and commented briefly.

2.2.1. Common Visualization Tools

This section displays common visualization tools employed in different fields.

- ① Coding independent visualization tools: Tableau, Raw, Infogram, ChartBlocks, Visualize Free Visual.ly, iCharts
- ② Geography visualization tools: CartoDB, InstantAtlas, Polymaps, OpenLayers, Kartograph, Exhibit, Modest Map, Leaflet
- ③ Financial visualization tools: Dygraphs, Highcharts
- ④ Time axis visualization tools: Timeline, Dipity
- ⑤ Function and Formula visualization tools: WolframAlpha, Tangle
- ⑥ Other visualization tools: Better World Flux, Google Charts, Crossfilter

2.2.2. Typical Visualization Tools

Promoted by industrial market requirements for efficient and professional visualization, sorts of commercial products or free products have been released by now. This section introduces several typical visualization tools and make brief comments on them respectively.

- ① Excel: Excel has always been a ubiquitous visualization tool since Microsoft released it. As a rudimental tool, it is quite ideal for ordinary users to analyze data rapidly. Excel has capacity to draw a majority of usual data charts, but it shows boundedness in selectable colors, lines, and forms, which indicates it is hard for Excel to draw charts meeting standards of professional publication or official websites.



Figure 28. Microsoft Excel

- ② Charting Fonts: Charting Fonts combines symbols and fonts, and hence smart vector icons are created.



Figure 29. Symbols used in Charting Fonts

- ③ Gephi: Gephi is a visualization tool focused on social mapping. Besides the ability to handle large-scale datasets, Gephi is also a visual internet exploring platform, used to construct dynamic, hierarchical data charts. It is based on Netbeans platform and JAVA programming language, and OpenGL serves as its engine for visualization.

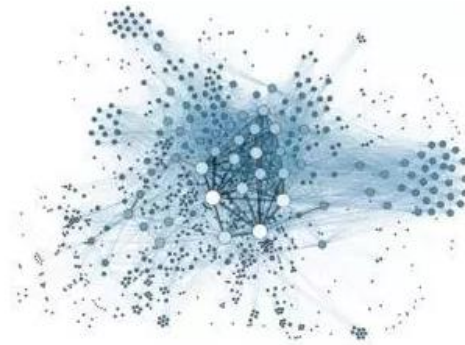


Figure 30. Gephi platform

- ④ CartoDB: CartoDB is an open source internet application and a reciprocal mapping tools that you should not miss. CartoDB is famous for one-button mapping function, which enables you to pertain table data and geographical map. And it is always the best choice to do this job.

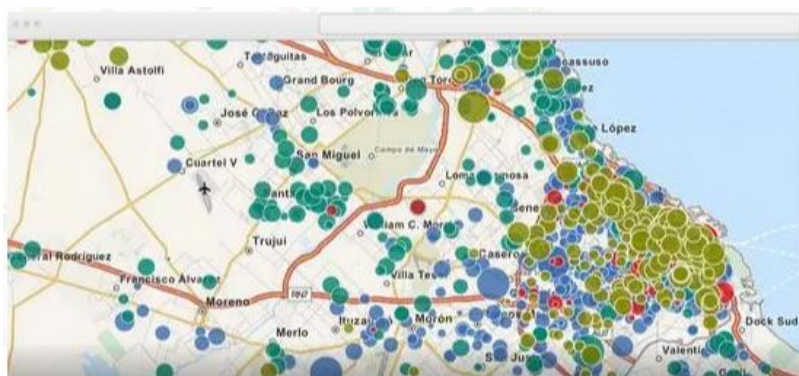


Figure 31. An implementing example of CartoDB

- ⑤ Google Chart API: Google Chart provides a relatively perfect method to visualize data, which mainly reflects in a number of possessed icon types, ranging from simple lineal chart to complex hierarchical tree map. Build-in animation and user

reciprocity are also permitted in Google Chart.

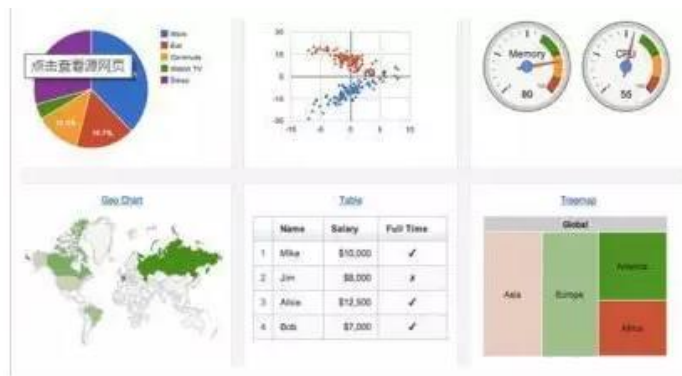


Figure 32. Typical charts of Google Chart

- ⑥ Data driven document (D3): D3 is a JavaScript library for manipulating documents based on data. It allows you to bind arbitrary data to a Document Object Model (DOM), and then applied data driven transformation to the document. In this way, proprietary representation is avoided and extraordinary flexibility can be afforded, exposing the full capability of several typical website standards, e.g. HTML, SVG, CSS. Besides the aforementioned features, D3 is capable to draw maps and charts with intricate formats, e.g. Voronoi map, tree map, circular clutter, and word cloud.



Figure 33. Word cloud drawn by Data driven document

- ⑦ **Crossfilter:** Crossfilter is not only a chart, but also a smart routine of reciprocal graphical user's interface. Once input range is modified in a chart, corresponding change occurs automatically in other relative charts.

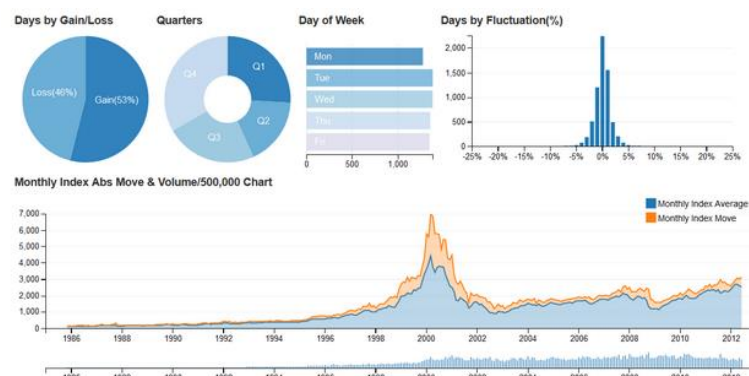


Figure 34. A group of correlative charts in Corssfilter

- ⑧ Raphael: Raphael is a JavaScript library for establishing charts and figures. It is cross-browser and supporting numerous common browsers, such as Internet Explorer 6.0+, Firefox 3.0+, Chrome 3.0+, Safari 3.0+, Opera 9.5+. Being different to other tools, its biggest peculiarity is sole permission to SVG and VML on output format.

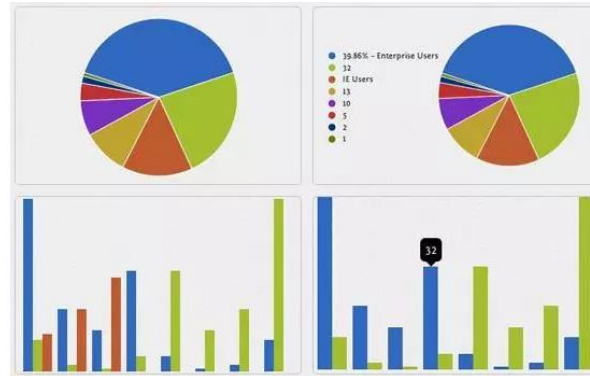


Figure 35. Pie chart and histogram drawn by Raphael

- ⑨ Visual.ly: Visual.ly defines itself as — an online market of information graph designer, i.e. it is a commercial website. Accompanying with it, all of its service is marked with price on the website. Visual.ly attracted crowds in 2012 by its first released tool — Visual.ly Create, which is used to online drawing. It provides numerous templates for users, more than that, users do not have responsibility to offer data to be visualized. Visual.ly Create can realize visualization by accessing accounts of users on other websites, e.g. google, twitter, facebook. Hence, if we want information graph rather than simple data visualization.

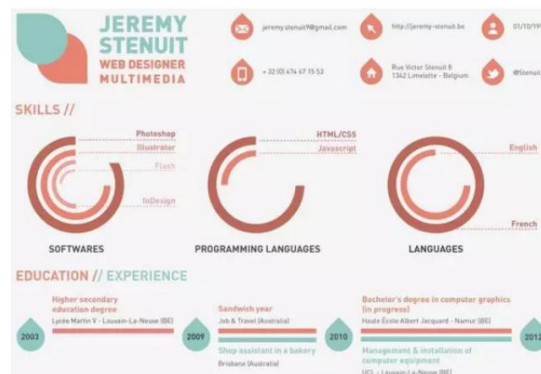


Figure 36. Information graph drawn by Visual.ly

- ⑩ Waikato Environment for Knowledge Analysis (Weka): Weka is a free, uncommercial software focused on data mining and machine learning. Weka is grounded on Java, converging numerous machine learning algorithms to take data mining tasks, including pre-processing, sorting, retrieving, pertaining as well as visualization on novel reciprocal interface. It is surely an undoubtable tool to clutter massive data by attributes sorting, but it also can be employed to draw some rudimental figures and charts. There is an anecdote that the abbreviation Weka is also the name of a bird inhabiting in New Zealand, a place where core developers of Weka come from.

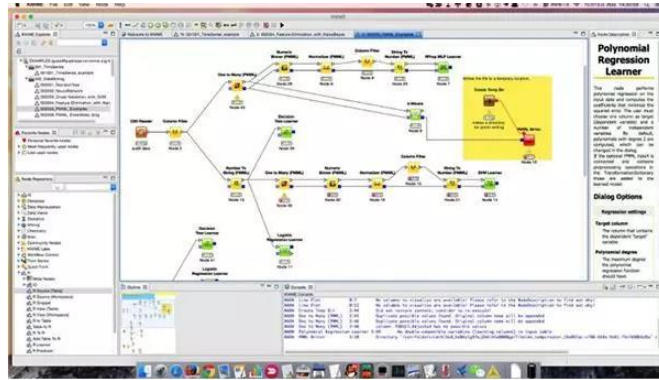


Figure 37. Visualization of machine learning process by Weka

- ⑪ NodeBox: NodeBox is an application based on Python to establish 2D figures and visualization. NodeBox is akin to Processing, another visualization tool, but does not own similar reciprocity function. Other than equipped with individual graphic library, it also allows importing vector graph from photoshop and illustrator, or custom figures and animations by coding. Visualized file by NodeBox can be outputted as PDF or Quick Time file.

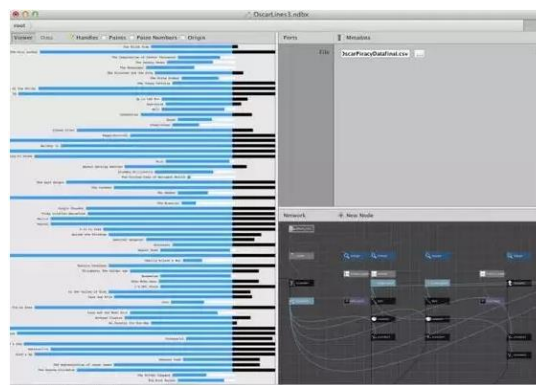


Figure 38. Typical visualization by NodeBox

- ⑫ Processing: Processing can be regarded as a signature tool of data visualization. Original goal of designing Processing was to develop graphical sketchbook and environment, and then to facilitate teaching in terms of computer science. After that, it tended to be an environment used to create professional project with respect to graphical visualization. Nowadays, a community has been established around Processing, devoting to structure numerous libraries for improving the ability of Processing in animation, visualization, network programming, as well as many other applications. Processing runs on GNU/Linux, Mac OS X and Windows, it also supports various file types to save exported figures. For dynamic application, Processing can even be exported as Java applet and used in Web environment. In terms of programming, Processing is based on Java but simplify it. As a result, some senior specialties of Java are not reflected in Processing.

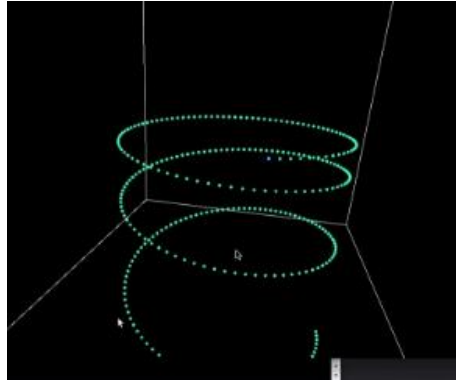


Figure 39. Particle fall visualization realized by Processing

- ⑬ Leaflet: Leaflet is the leading open-source JavaScript library for mobile-friendly interactive maps. Weighing just about 38 KB of JS, it has all the mapping features most developers ever need. Leaflet is designed with simplicity, performance and usability in mind. It works efficiently across all major desktop and mobile platforms, can be extended with lots of plugins, has a beautiful, easy to use and well-documented API and a simple, readable source code that is a joy to contribute to. It takes advantages of HTML5 and CSS3 in advanced browsers, and supports older browsers meanwhile.

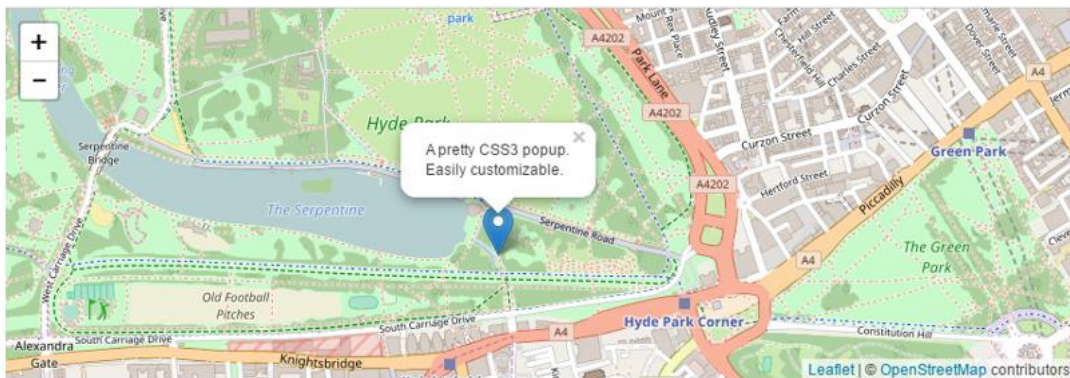


Figure 40. Example map drawn by implementing Leaflet

- ⑬ Openlayers: Openlayers is a complete open source JavaScript package supplied to developing WebGIS client and used to realize geographical data access with standard format. OpenLayers makes it easy to put a dynamic map in any web page. It can display map tiles, vector data and markers loaded from sorts of sources, including Google Maps, Yahoo, Virtual Earth released by Microsoft, and etc. Furthermore, Openlayer also supports network service standard constituted by Open GIS association, such as Web Mapping Service (WMS) and Web Feature Service (WFS), and hence enables loading geographical data released as per OGC format to client of Openlayers based on browsers by remote service.



Figure 41. Simple GIS presented by Openlayers

- ⑭ Polymaps: Polymaps is a free JavaScript library for making dynamic, interactive maps in modern web browsers. Polymaps provides speedy display of multi-zoom datasets over maps, and supports a variety of visual presentations for tiled vector data, in addition to the usual cartography from OpenStreetMap, CloudMade, Bing, and other providers of image-based web maps.

Because Polymaps can load data at a full range of scales, it's ideal for showing information from country level on down to states, cities, neighborhoods, and individual streets. Since Polymaps uses SVG (Scalable Vector Graphics) to display information, familiar, comfortable CSS rules can be used to define the design of your data. As Polymaps uses the well-known spherical mercator tile format for its imagery and its data, publishing information is a snap.

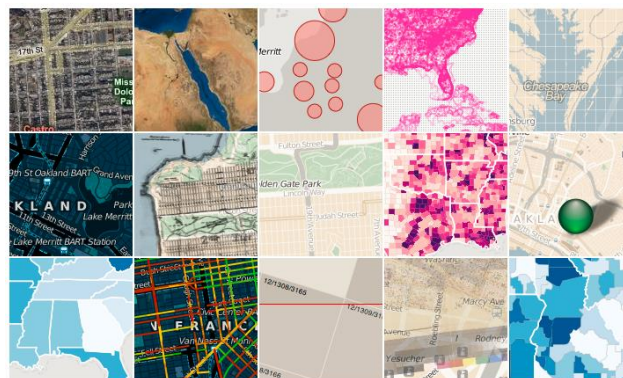
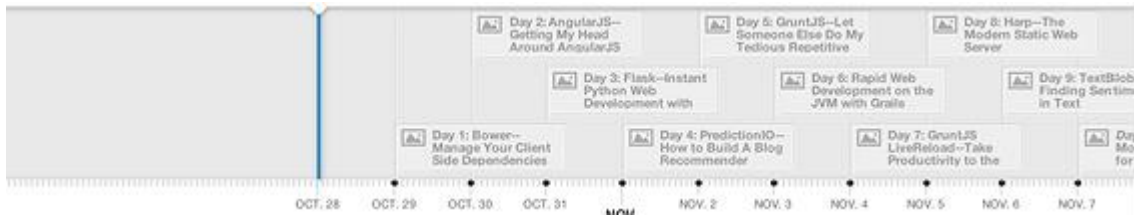
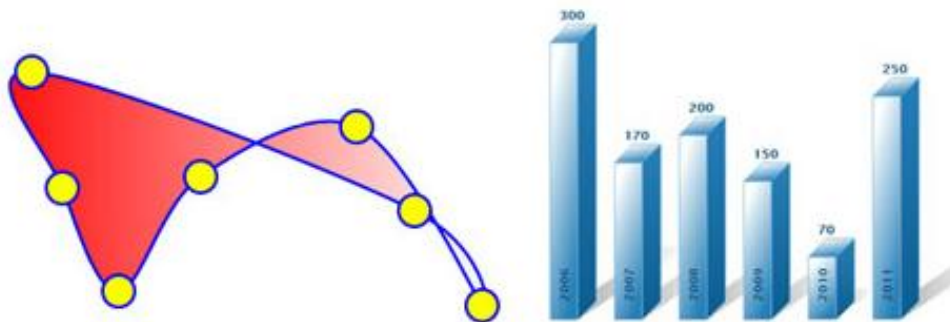


Figure 42. An overview of Polymaps implementation

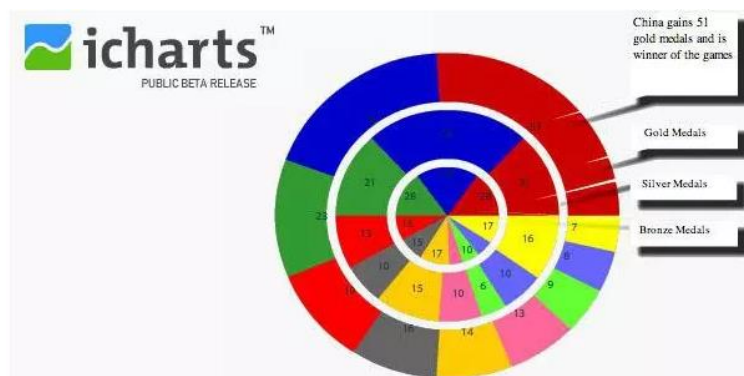
- ⑮ Timeline: TimelineJS is an open-source tool that enables anyone to build visually rich, interactive timelines. Beginners can create a timeline using nothing more than a Google spreadsheet. Experts can use their JSON skills to create custom installations, while keeping TimelineJS's core functionality. It can derive media files from numerous sources, e.g. Twitter, Google Plus, Flickr, YouTube and Google Maps.



⑩ jsDraw2DX: jsDraw2DX is an independent and object-oriented JavaScript library used to draw any kinds of interactive SVG figures. Besides basic figures, curves, function drawing, and Bezier in any extent also can be presented by jsDraw2DX.



⑪ iCharts: iCharts is a U.S. based SaaS company providing enterprise-grade, cloud-based visual analytics and reporting tool for NetSuite and the Google Cloud Platform. iCharts was named the winner of the 2016 NetSuite SuiteApp of the Year. The company's vision is to empower every business to become more data-driven by making business intelligence more accessible, more actionable, and more assistive. iCharts provides a managed resolution to create and present attractive charts. It guarantees reciprocity as well, but its free version permits the employment of basic graph types only, which are allowed in paid version.



⑱ AnyChart: AnyChart focus on supplying cross-platform resolution, software, and control product to enterprise, IT practitioners, and PC users. Attributing to its live figures and cross-platform capacity, AnyChart has been employed by certain famous industrial leaders, e.g. Oracle, 3M, Lockheed Martin. AnyChart Flash Chart is based

on Flash/JavaScript, figures drawn by implementing it can be used in instruments, reports, data analysis, finance, statistics. The newest version of AnyChart has supported HTML5, and in a manner of speaking, it performs well on nearly all of PC platforms and mobile platforms, including Chrome, Safari, Firefox, Internet Explorer, Opera, Android (2.2+) and iOS (iPhone, iPad, iPod Touch).

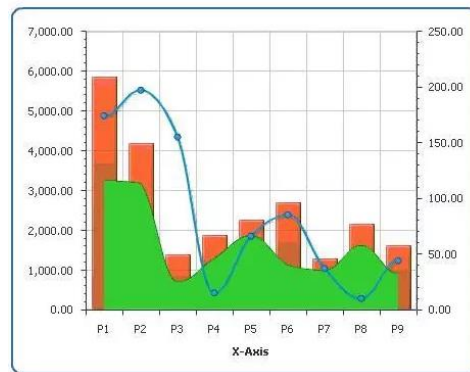


Figure 45. A typical implementation of AnyChart

- ①9 Kartograph: Kartograph is a framework used to create interactive map without support of any map service providers, such as Google Maps. It is consist of two class libraries——a Python library aiming to transform vector maps of shapefiles or PostGIS to SVG format, and another JavaScript library used to draw interactive map by utilizing these SVG data.

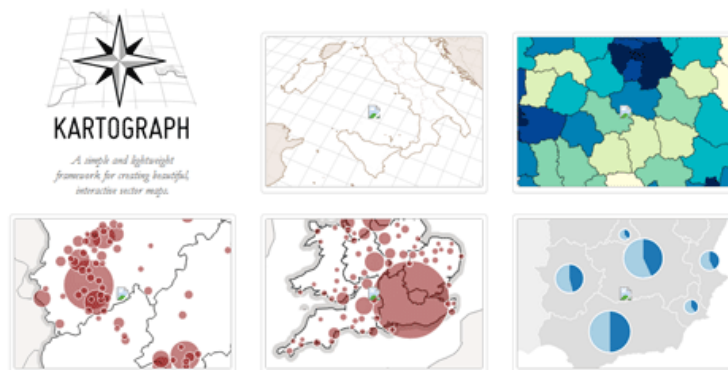


Figure 46. Several examples of Kartograph

- ②0 ECharts: EChart is a JavaScript library designed by the front-end technical section of Baidu enterprise for data visualization. Its bottom relies on a novel lightweight canvas class library, namely ZRender. EChart is compatible to a majority of browsers, such as IE8/9/10/11, Chrome, Firefox, Safari. Moreover, more and more visualization products of Baidu tend to adopt ECharts as their tool to realize visual effects.

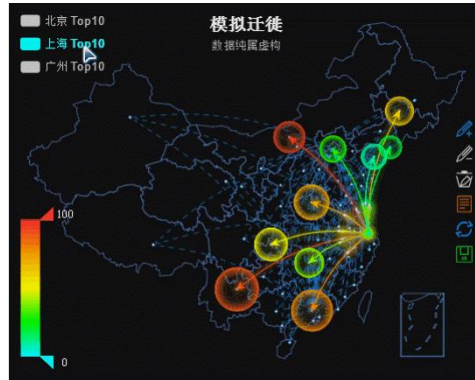


Figure 47. Migrate simulation by implementing ECharts

② Zoho Reports: Zoho Reports is an online reporting and business intelligence service that helps you to easily analyze your business data, and create insightful reports & dashboards for informed decision-making. It is an application based on SASS cloud computing platform. Because of its online mode, users have no incentive to install and maintain preparation that conventional report engine needs. Besides, Zoho Reports reserves data in relational databases, and utilizes tables to manage and organize data. Spontaneously, SQL query is completely supported in Zoho Reports.

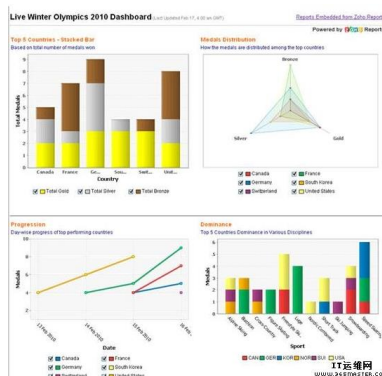


Figure 48. Implementing Zoho Reports in analyzing data of the Olympic Games

② Quantum GIS (QGIS): QGIS is a desktop software used to present, edit, and analyze GIS data. It is developed by Gary Sherman in 2002, and the first version is released in 2009. QGIS is written by C++, and QT library is employed to realize its GUI. Besides QT, QGIS also relies on GEOS and SQLite. It supports integrated plug-in component written by C++ or Python, and can be run on various operating system, like Mac OS X、Linux、UNIX and Microsoft Windows. Compared to commercial software, QGIS owns less file volume, lower memory and processing requirement. Numerous types of data are accepted in QGIS, e.g. Shapefile、Coverage and Personal Geodatabase, MapInfo、PostGIS. Furthermore, QGIS provides integration to other open source GIS software package, including PostGIS、GRASS 和 MapServer.

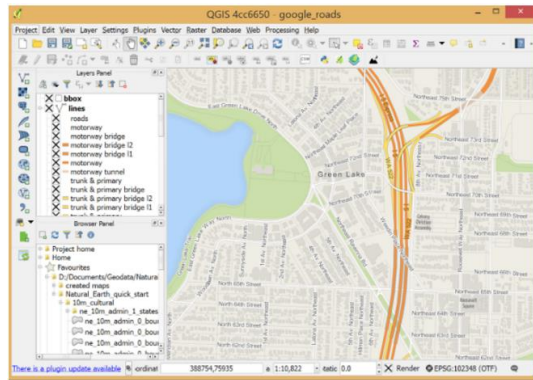


Figure 49. The running interface of QGIS

②3 Tableau: Tableau is a business intelligence presenting tool located at speedy development and realization of data visualization. It enables interactive, visual analysis and panel application. The biggest specialty of Tableau presents on its user-friendship. Different many other visualization products underscoring on IT techniques, Tableau can be easily grasped by any individuals or enterprises. Besides, Tableau abandons usual relational database, but create novel VizQL database revolutionarily. And interactive data can be issued on websites by users for sharing and cooperating. Based on the aforementioned features, Tableau is acknowledged as an outstanding representative of lightweight visualization tool in business intelligence field. In terms of data source, Tableau permits accessing to various data sources simultaneously, e.g. ECEL files, SQL databases, Oracle databases, and multidimensional databases. Furthermore, Tableau enables join operation on correlated data reserved in multi-files, which facilitates data mining. As for API, Tableau provides data extracting API for C, C++, Java and Python; platform integrating API for JavaScript; and integrating interface for R. So far, Tableau has released three primary products, namely Tableau Desktop, Tableau Server, and Tableau Public, respectively.



Figure 50. GUI of Tableau Public

②4 Paper.js: Paper.js is an open source script using vector figures. It is based on Scriptographer and run on HTML5 Canvas. Hence, it only supports advanced browsers. Paper.js provides a clear canvas/document object and numerous powerful

function for users to create vector figures and Bezier Curves.



Figure 51. the icon of Paper.js

②5 Dundas: Dundas chart for .NET is a powerful figure control, acknowledged by famous enterprises in the world. It provides comprehensive resolution to data processing and visualizing. Whether Web applications or Windows form applications can employ it to create precise digital panel or realize other digital visualization. Dundas chart keeps leading the field of NET chart processing control, and has been purchased by Microsoft in 2009. Part of its function is integrated into Visual Studio.

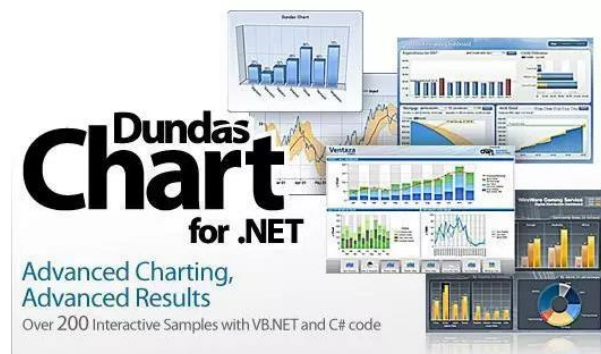


Figure 52. An overview of charts drawn by Dundas

②6 TimeFlow: TimeFlow Analytical Timeline is a visualization tool for temporal data. The current release is “alpha” software—a very early version that may have bugs and glitches.

The tool helps analyze temporal data with five different displays:

- Timeline View: plots events over time on a scrollable, horizontal timeline
- Calendar View: plots events by day, month, and year in calendar format
- Bar Chart View: a flexible, aggregate view of data points. It allows users to aggregate data by any header in the data set.
- Table View: a straightforward table view of all data points

- List View: a simple list of events shown on the timeline, complete with description and metadata about each data point

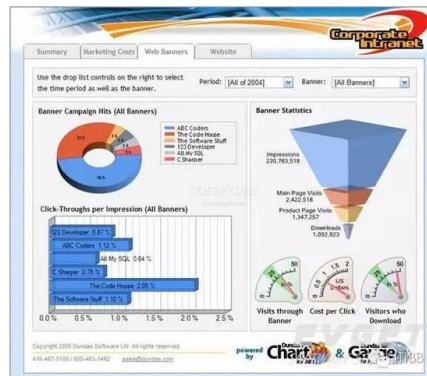


Figure 53. An overview of charts drawn by TimeFlow

②7 Gantt: Gantt is an open source PHP class for creating spontaneous Gantt charts.

Gantt purely relies on HTML-CSS3 and has nothing to do with JavaScript. Output format of Gantt is smart, but users still can improve it with SASS format. Generally speaking, browsers belonging to IE 7+ are supported by Gantt.



Figure 54. Charts group of Gantt

②8 Smoothie Charts: Smoothie Charts is a simple library for displaying smooth live time lines. It displays real-time data stream by forwarding a webSocket, which is exactly something it is good at. Smoothie Charts only supports Chrome and Safari. Besides, inscription or pie charts are not available in Smoothie Charts.

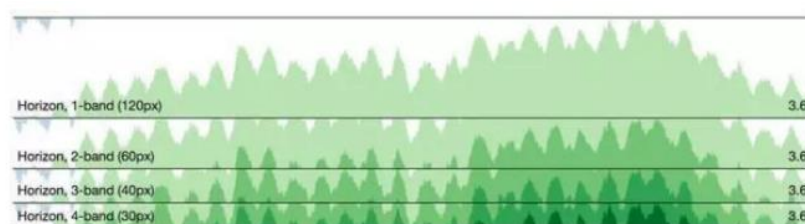


Figure 55. Data streams presented by Smoothie Charts

②9 Flot: Flot is a pure JavaScript plotting library for jQuery, with a focus on simple

usage, attractive looks and interactive features. Flot adopts Canvas to immediately painting figures on client, and numerous browsers are supported by it, including IE6/7/8/9, Firefox 2.x+, Safari 3.0+, Opera 9.5+, Konqueror 4.x+.



Figure 56. Charts drawn by Flot

③ Pizza Pie Charts: Pizza Pie Charts is a responsive pie charts. It is based on Adobe Snap SVG framework, and focused on replacing JavaScript object with HTML mark and CSS, which facilitates integrating various advanced techniques. Surely, JavaScript objects are still supported by Pizza Pie Charts.

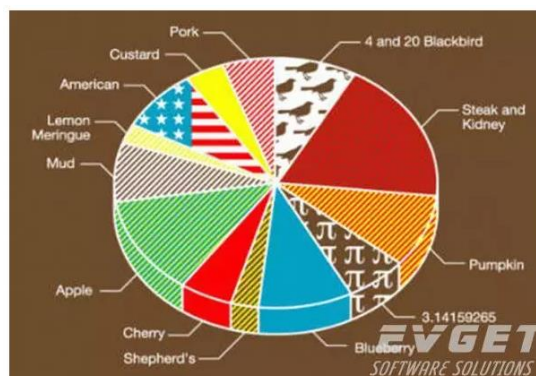


Figure 57. Typical pie chart

③ Fusion Charts Suit XT is a professional and advanced JavaScript chart library, including FusionCharts XT, PowerCharts XT, FusionWidgets XT, FusionMaps XT. It adopts several output formats, such as JPEG, PNG, PDF and SVG. Within Fusion Charts Suit XT, over 900 maps and over 90 kinds of charts are supported, e.g. 3D chart, gantti, gauges chart, funnel chart. Furthermore, it is cross-platform and corss-browser. Hence, numerous languages are supported by it, such as ASP, ASP.NET, PHP, JSP, ColdFusion, Ruby on Rails, JavaScript, and even simplest HTML page.



Figure 58. Overview of charts drawn by Fusion Charts Suit XT

③② Protovis: Protovis is a free and open source tool for chart visualization, developed by Mike Bostock and Jeef Heer from Stanford University's Visualization Group. It is based on JavaScript and SVG technique.

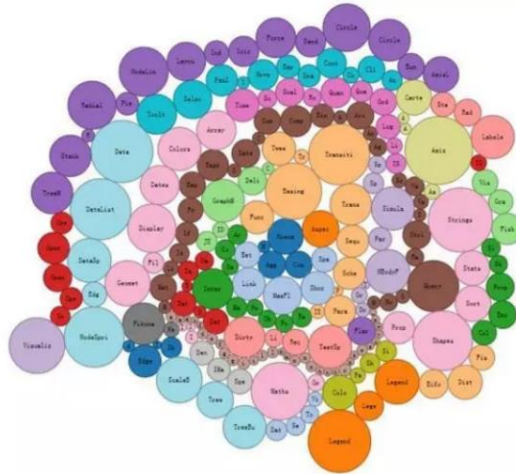


Figure 59. Pie clutters drawn by Protovis

③③ Arbor.js: Arbor is a graph visualization library built with web workers and jQuery. Rather than trying to be an all-encompassing framework, arbor provides an efficient, force-directed layout algorithm plus abstractions for graph organization and screen refresh handling.

It leaves the actual screen-drawing to users, which means users can use it with canvas, SVG, or even positioned HTML elements; whatever display approach is appropriate for your project and your performance needs. Besides, it proposes an efficient and force-oriented disposing algorithm for organizing figure and refreshing screen.

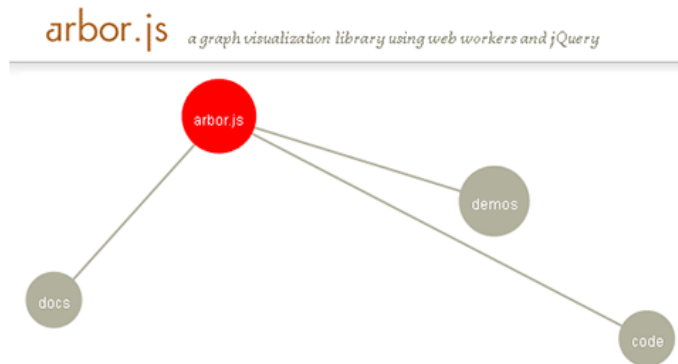


Figure 60. Relations among arbor.js and other elements in visualization

③④ Circos: Circos is a free software written by Perl. Circos adopts GPL admission, and can be run on any operating systems with Perl interpreter. It is a piece of cake for Circos to transform imported data to PNG or SVG by pure-text configuring files. Circos was devised for data visualization with respect to genome sequence in the beginning, and has been extended to various fields now, such as individual's relationship analysis, logistic prediction.

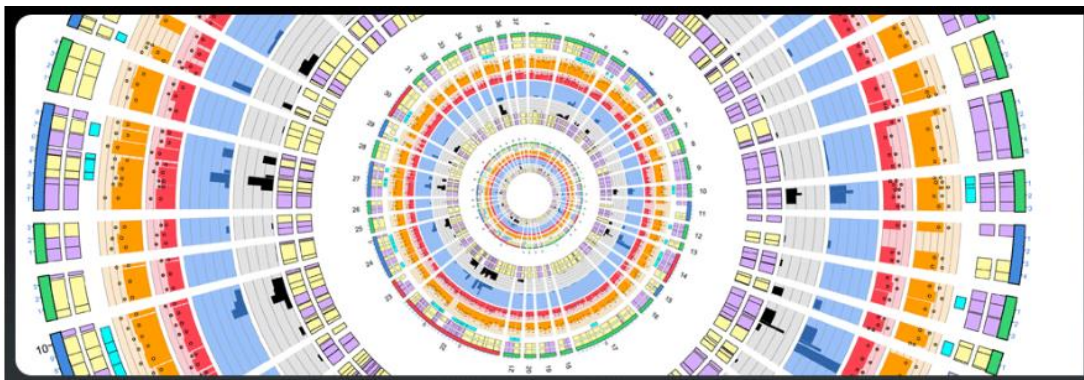


Figure 61. Visualization of genome sequence

③⑤ BirdEye: BirdEye is a community project to advance the design and development of a comprehensive open source information visualization and visual analytics library for Adobe Flex. It is based on Action Script language. The actionscript-based library enables users to create multi-dimensional data visualization interfaces for the analysis and presentation of information.

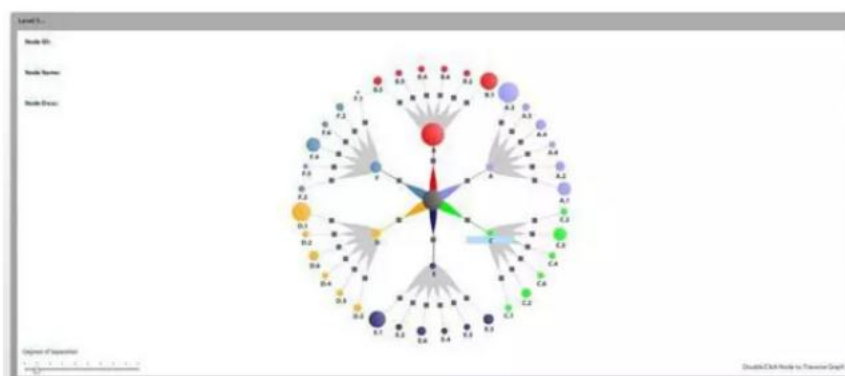


Figure 62. typical chart drawn by BirdEye

③⑥ Visualize Free: Visualize Free is a free visual analysis tool based on the advanced commercial dashboard and visualization software developed by InetSoft, an innovator in business intelligence software since 1996. Visualization is the perfect technique for sifting through multi-dimensional data to spot trends and aberrations or slice and dice data with simple point-and-click methods.

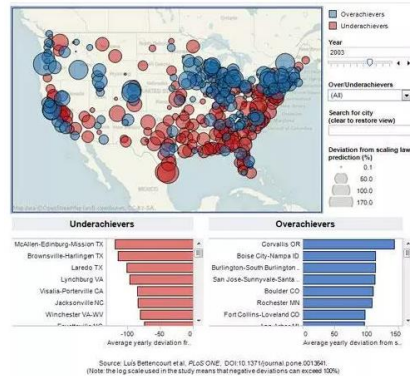


Figure 63. typical chart drawn by Visualize Free

3. Data Visualization Research

Brought by data boost generated in new information age, data visualization leaps into a hotspot in scientific community and industry immediately. Recent years, numerous study aiming to resolve issues in visualization field have occurred, in terms of texture drawing, natural evolution simulating, device or software conceiving for augmented reality or virtual reality, real-time and lightweight applications on website visualization, as well as psychological experiment to human vision etc.

Data visualization techniques involve a number of disciplines, including statistics, data mining, machine learning, neural networks, social network analysis, signal processing, pattern recognition, optimization methods and visualization approaches [46].

Some typical techniques, mainly belonging to artificial intelligence algorithms, e.g. simulated annealing, adaptive simulated annealing, genetic algorithm, evolutionary programming as well as particle swarm optimization are useful to resolve global optimization problem [46].

Social Network Analysis (SNA) is now commonly available as a consumer tool. Linear mapping methods, such as principal component analysis (PCA) and factor analysis, are popular linear dimension reduction techniques. Non-linear techniques include kernel PCA, manifold learning techniques such as Isomap, locally linear embedding (LLE), Hessian LLE, Laplacian eigenmaps, and LTSA. To visualize temporal aspects, Pencil icons are used for linear time axes and helix icons are applied for cycle time [55].

In the rest part of this section, development is introduced as per three categories according to their respective target subfields: Computer graphics, visualization realizing, and augmented or virtual reality.

3.1. Research Development in Computer Graphics

Computer graphics are graphics created by computers and, more generally, the representation and manipulation of pictorial data by a computer. Since data visualization takes figure and icon as elements, the study concerning computer graphics is concerned by specialists and engineers to construct effective presentation all the time. Several development outcomes are introduced as below:

① In terms of data visualization, one area which has received more attention is path planning in large point clouds and the ability to quickly compute proximity queries (collision, distance, etc.). Path-planning through environments consisting of triangle meshes has been studied intensively and there exists a significant amount research on the subject [56-58].

David Eriksson and Evan Shellshear propose a novel efficient algorithm for the rapid computation of exact shortest distances between a point cloud and another object (e.g. triangulated, point-based, etc.) in three dimensions [59]. It extends the work presented in Eriksson and Shellshear (2014) where only approximate distances were computed on a simplification of a massive point cloud. The approach works for massive point clouds even with a small amount of RAM and is able to provide real time performance. Given a standard PC with only 8GB of RAM, this resulted in real-time shortest distance computations of 15 frames per second for a point cloud having 1 billion points in three dimensions.

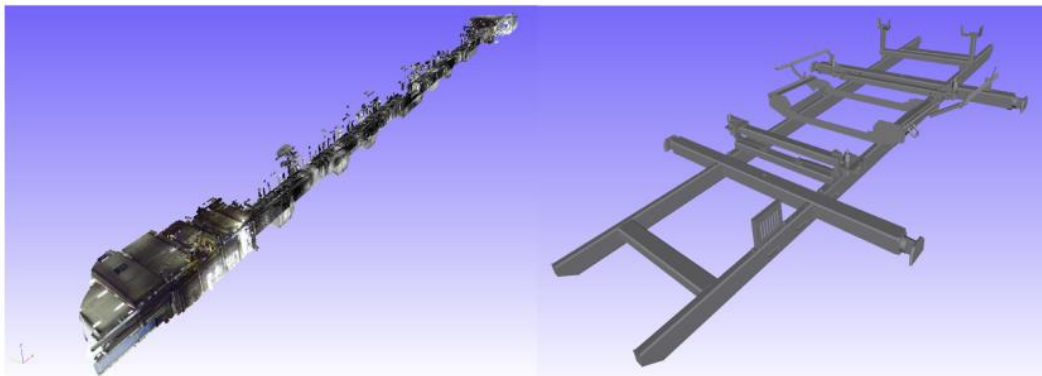


Figure 64. The original point cloud and triangulated object moved through the point cloud

② Symmetry is an important clue for geometry perception: it is not only in many man-made models, but also widely exists in the nature [63]. However, existing symmetry detection algorithms still have much room for improvement in terms of both simplicity and efficiency in detecting symmetry planes, as well as the degree of freedom to find approximate symmetry

planes for a roughly symmetric 3D model. In addition, most of the existing symmetry detection methods are geometry-based, thus their computational efficiency will be tremendously influenced by the number of vertices of a model.

Bo Li et al. presents a simple and efficient view-based reflection symmetry detection method based on the viewpoint entropy features of a set of sample views of a 3D model. Besides, to avoid the high computational load resulting from a directly combinatorial matching among the sample views, they develop a fast symmetry plane detection method by first generating a candidate symmetry plane based on a matching pair of sample views and then verifying whether the number of remaining matching pairs is within a minimum number.

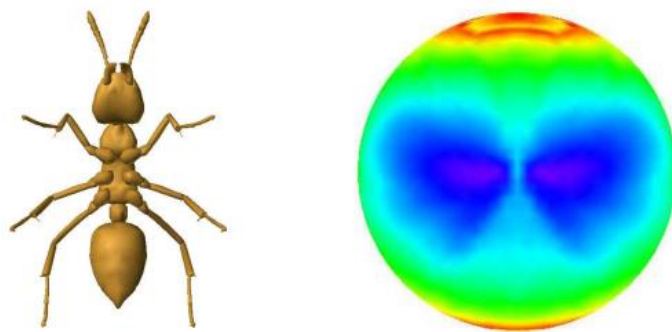


Figure 65. an example of an ant model and its viewpoint entropy distribution

③ The prevalence of weathered rock as visual cue in film indicates that directors find weathered rock useful in telling a story. Sandstone rock, in particular, has been widely used to create a feeling of being somewhere remote, exotic, or unique. Many algorithms have been published for terrain generation in computer graphics but none have adequately addressed the artistic creation of weathered rock. Most algorithms are difficult to control and do not admit concave surfaces [76], [77].

Under this background, Michael D. Jones et al. manage to simplify the creation of weathered rock for use in computer-generated animation or games [78]. They simulate spheroidal and cavernous weathering using curvature estimation on a voxel grid, within which Simulations of rockfall and colluvium deposition further improve realism.

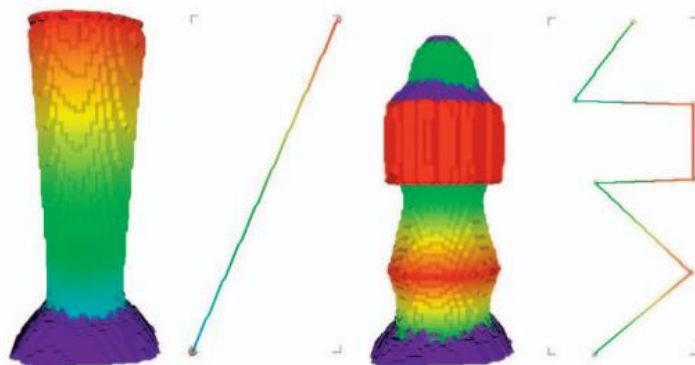


Figure 66. The weathering simulation creates visually plausible models of weathered rock

3.2. Research Development in Visualization Realizing

In data visualization field, the study on visualizing approaches and applications is continually hot these years. Hitherto, there have been numerous sorts of visualizing methods being proposed or updated, involving natural evolution simulating, real-time interaction, application on website and so on. Here, some typical research progresses are shown.

① Dynamic molecular data are usually produced by molecular simulation programs in order to gain insights into the molecular mechanisms on the level of individual atoms. Many existing visualization tools have mainly focused on supporting a single user working on a desktop computer.

So-called trajectories are typically written to a file, and after the simulation completes, a visualization application can be used to load the data for analysis. This offline visualization workflow, which relies on clusters for the simulation and desktop machines for visualization, is the most common nowadays, along with the respective implications for maintaining a working environment on both ends. Browser-based applications, in contrast, have the benefit of not requiring a client-side installation and offer centralized deployment and maintenance, ensuring a common environment for all users. Until recently, however, mapping the offline workflow to a browser-based application, using platform-independent built-in technologies like JavaScript, was unfeasible because loading and processing large data in the browser using JavaScript cannot offer performance comparable to native client software all the time. Specifically speaking, Interactive visualization of dynamic data in a web browser requires fast rendering methods, efficient usage of bandwidth, and low-latency networking.

Considering that technical advancements in browser features increase the potential for the development of web-based collaborative visualization tools, Finian Mwalongo et al. present an efficient web application for visualization of dynamic molecular data using WebGL that exploits HTML5 technologies like WebSockets and Web Workers [60]. GPU-based ray casting techniques offer fast rendering times and produce images with higher visual quality. Efficient data encoding techniques are used to minimize the data transferred to the client — therefore saving bandwidth and improving the transfer times. They demonstrate the feasibility of visualizing large dynamic molecular data with more than one million atoms in the browser at interactive frame rates both on PC and mobile devices. Furthermore, their approach allows scientists at arbitrary locations to concurrently visually analyze the same data.

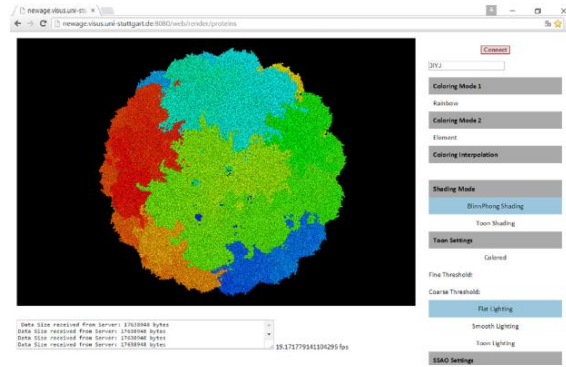


Figure 67. Visualization of dynamic molecular data on website

② With the development of mobile internet, 3D urban visualization or walkthrough applications, especially Web3D-based ones, have become a hot research topic [61]. However, Web3D-based applications are always restricted by limited resources of network transmission, browser equipment, and webpages, etc. Furthermore, for web applications, many other limitations have to be considered, such as the capacity of internet bandwidth, and the performance of internet browsers.

Based on the above background, Xiaojun Liu et al. propose a Web3D-based lightweighting solution for real-time visualization of large-scale BIM scenes, considering the redundancy, semantics, and the parameterization of Building Information Modeling (BIM) data under the limited resources of network bandwidth and web browsers [62]. First, they propose a semantics-guided lightweighting process that combines the semantics with the geometric information, for reducing the amount of raw BIM data. Second, they extract the exterior products of a building scene by using multiple viewpoints projection and removing the interior products data. Finally, they generate the DLSV index structure based on the sparse voxelization idea towards the frustum of interests.

Nevertheless, this work can be only considered as a preliminary investigation and there are certain limitations to the proposed method, since the method for extracting exterior products is suitable only for scenes with occlusion structures like buildings, thus the identification accuracy should be further improved.

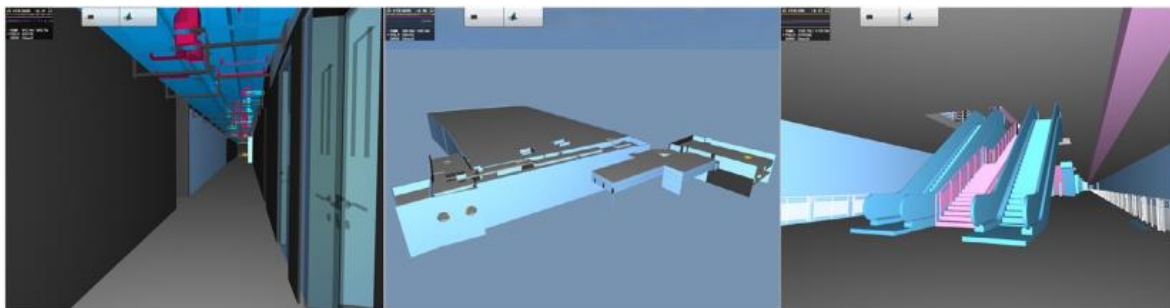


Figure 68. Real-time rendering of a subway image

③ Texture mapping is widely used in graphics community to enhance the visual effect of

realistic rendering. It puts texture skins to a polygon mesh via assigning texture coordinate to each vertex. And the so-called texture coordinates are commonly obtained by planar parameterization, namely embedding a disk-shaped polygon mesh into a 2D texture space [64]. However, it's theoretically and practically impossible to remove all the distortions of such an embedding in general and may cause undesired mapping effects.

Yao Jin et al. conceive a texture mapping method guided by importance map to preserve the shape of the prominent content [65]. They formulate it as an importance-value-weighted parameterization. The mapping distortions are measured by LSCM+ energy, which is capable of decreasing the appearance of shrunken and fold-over triangles as well as shape preservation; and the weights are efficiently calculated by transforming the area integral into a line integral.

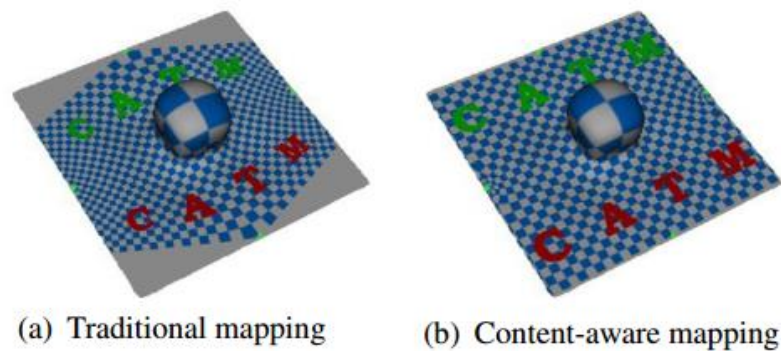


Figure 69. Traditional and content-aware texture mapping

④ Intrinsic shape matching has become the standard approach for pose invariant correspondence estimation among deformable shapes. Most of existing approaches assume global consistency. While global isometric matching is well understood, only a few heuristic solutions are known for partial matching. Partial matching is particularly important for robustness to topological noise, which is a common problem in real-world scanner data.

On this ground, Alan Brunton et al. introduce a new approach to partial isometric matching based on the observation that isometries are fully determined by local information: a map of a single point and its tangent space fixes an isometry [66]. A new representation is developed in their work for partial isometric maps based on equivalence classes of correspondences between pairs of points and tangent-spaces.

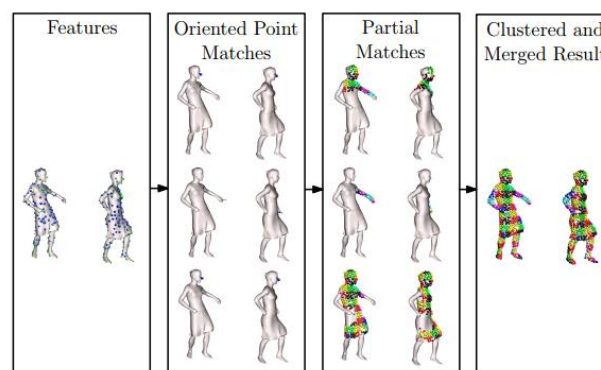


Figure 70. Overview of pairwise matching pipeline

⑤ During the past few years, dramatic progress has been made in the area of image-based object modeling. A typical image-based 3D reconstruction pipeline begins with the acquisition of a photo collection of an object. Then, the camera poses, i.e. the position, orientation and intrinsic parameters of each camera, are estimated using structure-from-motion (SfM) techniques on the photos. Afterwards, a 3D-geometric model is recovered using multi-view stereo (MVS), silhouette and contours cues. Finally, the calibrated images are utilized to generate a texture map for the recovered geometric model. A texture map is an important component that makes the model more realistic and compensates for deficiencies in the camera registration and reconstructed geometry. In the final step, the images are usually back-projected onto the geometric model to generate a texture patch for each surface patch. However, every surface patch is usually visible in several input images and there is often no one-to-one correspondence between texels in the texture and pixels in the images. The measured color and intensity for a surface patch observed in different photos will not agree due to lighting, camera setting and surface reflectance variations across the views. Visible seams and color discontinuities often arise between neighboring texture patches. The problem can be alleviated by blending multiple image views per face and careful selection of views. However, blending often causes image quality degradation due to resampling and misalignment of geometric projections with inaccurate reconstructed geometry and camera parameters.

To eliminate the aforementioned visual seam and color discontinuity, Rongjiang Pan and Gabriel Taubin introduce a color adjustment technique to obtain a seamless texture map from multiple registered images [67]. The method starts from texture coordinates optimization, followed by global adjustment at each corner and local adjustment with Poisson editing. Their color adjustment algorithm is not only independent of the particular choice of view selection and texture representation, but also computationally efficient to obtain high-quality textures for large real-world datasets. Experimental results demonstrate that their method is effective enough to process real-world datasets with hundreds of input images and millions of triangles. However, the method cannot fully avoid out-of-focus image areas in the process of viewing selection.

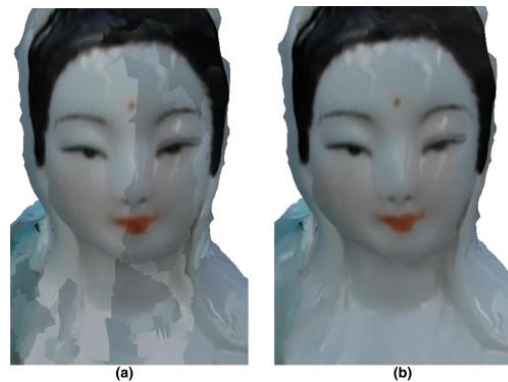


Figure 71. The reconstructed model with texture from registered images
(a) before color adjustment and (b) after color adjustment.

⑥ Animating a crowd of thousands of individuals is a challenging task. Nevertheless, several models exist, that can either rely on per-individual strategies, usually grouped under the denomination of steering behaviors or microscopic models, or in contrast on a global definition of the crowd flow and properties: the macroscopic models. The context of graphics is slightly different since animators usually have a precise idea of what they want to show, which may differ from what is actually given by the simulation models. A possibility is then to tweak the different parameters of the used model, in a trial-and-error fashion, until the simulation is acceptable. This strategy, however, is likely to fail for most simulation models regarding the complexity of the dynamics inherent to the crowd if the animator tries to obtain a desired kinematic or dynamic pattern at a given time in the simulation process. This calls for automatic procedures that can reach those constraints while preserving the specificities of the crowd models, i.e. the trajectories produced by the simulation model are deformed to achieve user constraints, including per-individual constraints and macroscopic constraints.

Hence, Pierre Allain et al propose a combination of a gradient based method along with a heuristic to explore several distinct paths in the solution space, where the control of a crowd is seen as an editing process [68]. In their production pipeline, the user can choose several types of constraints that would best match its need, and also the trade-off between the respect of the considered crowd model and his constraints (expressed through the covariance matrices). And hence this method is mainly dedicated to users (as for example artists) which would desire to correct the output of a crowd simulation by imposing specific behaviors. Whereas, there still exists two defects in the method: it cannot be used in interactive-time applications; additionally, as far as the method is roughly speaking a gradient descent, there is no theoretical guarantee that a global minimum will be found. In the case where the problem is over constrained (such as in the letter formation example), the resolution may be stuck in unsatisfying situation, typical of local minima.

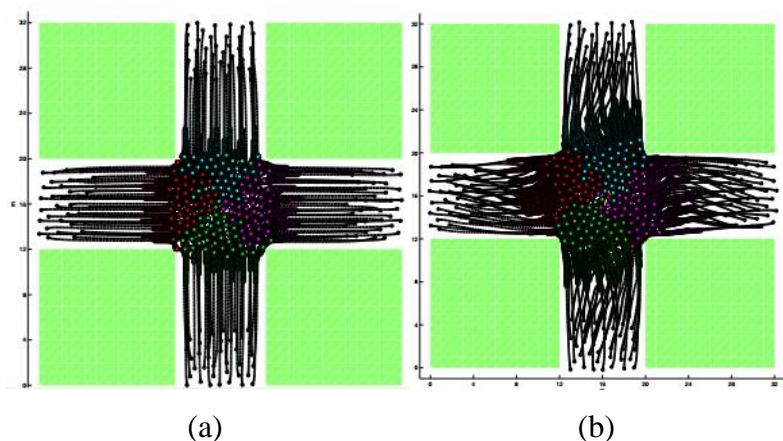


Figure 72. Trajectories of pedestrians for a duration of 20 seconds
(a) output of the crowd simulation, (b) output of the crowd optimization.

⑦ To visualize the contents of a database with a high-dimensional structure, the data can be projected into a 2D space based on some user-defined properties; but it is difficult to

determine the relative weighting to be applied to several properties automatically. A naive approach for visualizing the graphical data set is list-up each data in 2D space without considering its properties. However, in a large database, a user would waste a great deal of time exploring the database to search for the required data. Dimensionality reduction is one way to reduce the dimensionality of a data-set by maximizing the variance of the data [1,2]; however the axes of the 2D space that best achieve this may have little or no intuitive meaning.

Thus, Jong-Chul Yoon and In-Kwon Lee design a novel semi-supervised dimensionality reduction method that can embed data of high dimension in a user-defined 2D coordinate system that is meaningful in terms of the properties of the data [71]. Using data that define the axes of 2D space provided in advance by the user, their system embeds the target data in an axially aligned low-dimensional space with curved axes. Then space warping is applied to convert the curved axes to orthogonal axes and then calculate meaningful coordinates for the data. Whereas the primary disadvantage of this method is defect in robustness.



Figure 73. Two real Cups with augmented with a virtual COKE with different focal distance (a)40cm (b)100cm

⑧ Throughout the years, the prevailing objective within the volume visualization field has been to generate images that closely resemble reality. However, a new volume-rendering branch investigates ways to create illustrative images from three-dimensional scalar data. Techniques from traditional art and illustration are incorporated in the volume-rendering process. The goal is to gain clarity compared to photo-realism by emphasizing important features, improving data exploration. Less relevant details are omitted and important aspects are highlighted, resulting in more comprehensible images [79], [80]. Illustrative rendering applications typically include a substantial number of user-configurable parameters. Fast and reliable interaction with these parameters is of great importance in order to produce the desired illustrative styles.

Thus, Roy van Pelt et al. choose the flexible particle-based approach of the VolumeFlies framework, aiming to achieve interactive parametrization and rendering in illustrative volume visualization [82]. Their main contribution includes (1) a GPGPU paradigm, serving as a model for algorithms varying from data parallel sorting and searching to image

and volume processing, to exploit computational parallelism; (2) A GPU-based generic particle system, employing this paradigm. This system incorporates energy minimization for particle redistribution based on the work by Meyer et al. [81]; (3) An interactive illustrative volume-rendering framework, initiating particle systems to create stylized depictions.

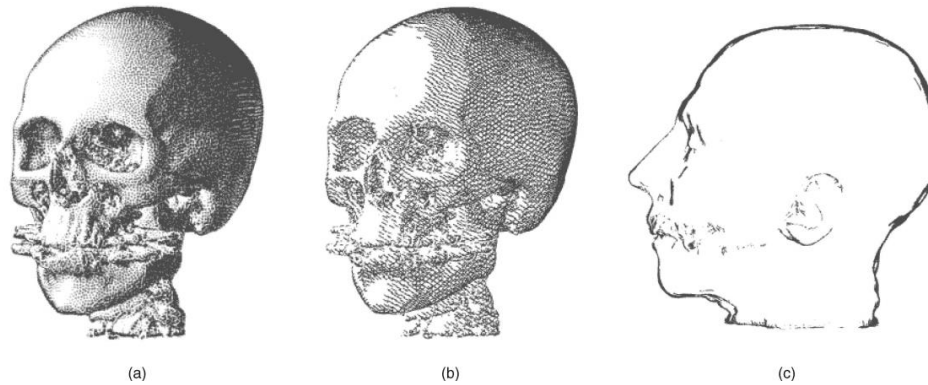


Figure 74. Various illustrative visualization styles

⑨ Generating life-like and responsive human motion has been an important topic in computer animation. Many approaches have been proposed to create the motion of animated characters. Among these approaches, data-driven methods with physically motivated constraints [85], [86] and controller-based physics simulation [87], [88] are two common techniques used to generate physically plausible motion.

Conventional data-driven approaches usually require a large collection of motion data captured from human subjects performing a variety of movements [89], [90]. In order to ensure the physical plausibility in the generated motions, several approaches [85], [86] adopted physics laws such as minimal energy consumption or conservation of momentum as optimization criteria to modify captured motions. Data-driven approaches with physically motivated constraints have demonstrated their success in transferring stylistic human motion to animated characters. While Controller-based approaches generate motions based on forward dynamics simulation. Motions are synthesized using feedback control principles in which the controller exerts torque at each joint of the animated character to perform a desired motion (usually motion capture data) as well as continuously adjust the character's motion to react to variations in the physical world. Most of controllers require careful tuning of parameters such as PD gains, balance feedback gains, machine learning coefficients, and optimization parameters. In controller-based character animation, Proportional-Derivative (PD) controllers and feedback balance controllers are commonly used for their simplicity.

According to the computational performance, existing approaches can be categorized as offline and interactive. All the data-driven approaches [85], [86], and earlier controller-based approach [89] are performed offline. Recent controller-based approaches [90] are interactive as the control parameters for various character sizes/styles can be manually set or automatically optimized. Once the parameters of a controller are specified, the animated character can respond to environmental disturbances in real time. However, considerable

efforts may be required in designing task-specific or character-specific controllers.

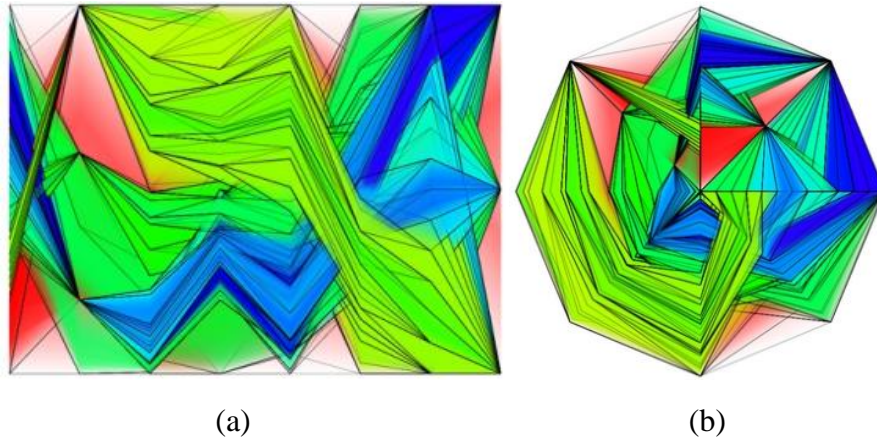
Aiming to resolving biped walking problem, Yao-Yang Tsai et al. present a physics-based controller for animating three-dimensional biped characters that can react to dynamic environments in real time [91]. Their framework employs a balance motion filter that adjusts the desired motion trajectory in an online manner. They conceive biped balancing strategy based on an inverted pendulum model (IPM), which is simplified from a full-body character model. The IPM simplification allows the balance motion filter to produce physically plausible and balanced motion trajectories for controllers to track. The dynamics of the IPM is so simple that the balance strategy can be determined in real time either by solving a closed form (on a flat ground) or through numerical root finding of a simple algebraic equation (on a slope). And a velocity-driven tracking method is adopted to track the target trajectory generated by the balance motion filter. The most memorable work of their work is: Although the IPM has been seen repeatedly in biomechanics and robotics, it has received much less attention in computer animation.



Figure 75. Snapshots of a character's balance-maintaining motion

⑩ Overview is one of the most basic user tasks for information visualization and it is a vital building block for the more complex process of visual exploration—using visualization to form, test, and validate hypotheses about complex or large datasets. However, overview is becoming increasingly difficult to effectively achieve with the ever-increasing size of real-world datasets. For most basic visualization techniques that endeavor to show each item in a dataset—such as scatterplots, parallel coordinates, and treemaps—a massive number of items will overload the visualization, resulting in clutter that both causes technical scalability problems as well as hinders the user's understanding of its structure and contents.

The attempt to draw each item in the dataset, however, is not practical for massive datasets. As a result, Niklas Elmqvist and Jean-Daniel Fekete provide a model for hierarchical aggregation in information visualization for the purpose of improving overview and scalability of large-scale visualization, with extensions to a number of visual representations such as scatterplots, parallel coordinates, and node-link diagrams [92]. Moreover, from their work, it becomes realizable to formulate a set of common design guidelines for building new aggregated visualization techniques.



(a) (b)
Figure 76. Opacity band aggregation for (a) parallel coordinate visualization and (b) Starplot visualization

⑪ Health reports, terrorism alerts, criminal activities, and numerous other incidents need to be analyzed and evaluated, often within the context of related data sets. It is no longer efficient for a single analyst to pull files, take notes, form hypotheses, and request data from different sources. Instead, tools need to be developed that bring varying data sources into a unified framework assisting analysis and exploration. These needs are being addressed by the emergence of a new scientific field, visual analytics. Visual analytics is the science of analytical reasoning assisted by interactive visual interfaces [93]. Major challenges in this field include the representation and linkage of largescale multivariate data sets.

In order to facilitate enhanced data exploration and improve signal detection, Ross Maciejewski et al. develop a linked geo-spatiotemporal visual analytics tool designed for advanced data exploration [94]. Hotspots found in one display method can be selected and immediately analyzed in the corresponding linked view. Furthermore, our work focuses on the early detection and analysis of hotspots facilitated through the use of control charts for alert detection. Alerts generated in the temporal realm can be quickly analyzed in the geo-spatiotemporal interface, helping users find patterns simultaneously in the spatial and temporal domains. Users may select hotspots from the generated heatmaps and analyze historical time series data in the area to look for unusual trends or potential areas of interest. They have also extended their system to include the spatiotemporal history, bivariate and multivariate exploration, thresholding, and color mapping tools. Contour histories provide users with geo-spatiotemporal views of current and past data trends, allowing them to track hotspot movement across time, or look for correlations between multiple variables.

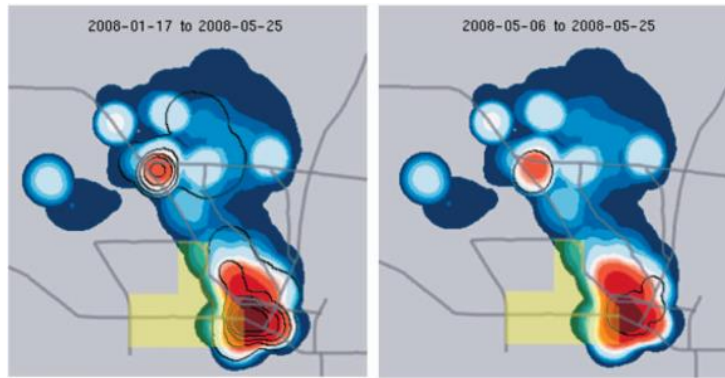


Figure 77. Using visual analytics based on geo-spatiotemporal data for hypothesis testing in crime analysis

3.3. Research Development in Augmented or Virtual Reality

Augmented reality (AR) is a live direct or indirect view of a physical, real-world environment whose elements are augmented (or supplemented) by computer-generated sensory input such as sound, video, graphics or GPS data. It is related to a more general concept called mediated reality, in which a view of reality is modified (possibly even diminished rather than augmented) by a computer. As a result, the technology functions by enhancing one's current perception of reality [95]. By contrast, virtual reality replaces the real world with a simulated one [96], [97]. In the following, several progresses with respect to augmented or virtual reality are introduced:

① In the field of visualization, many approaches to 3-D displays have been proposed in the past, including a typical technique namely head-mounted displays (HMDs) [72], [73]. HMDs provide a good balance on affordability and unique capabilities. For instance, HMDs offer solutions to mobile displays for wearable computing, while in the domain of augmented reality, they are one of the enabling technologies for merging virtual views with physical scenes [74]. Despite much significant advancement on stereoscopic HMDs over the past decades, there exist many technical and usability issues preventing the technology from being widely accepted for many demanding applications and daily usage. It is a fact that most existing stereoscopic displays are capable of rendering a wide range of depth cues such as occlusion, linear perspective, motion parallax, and binocular disparity cues to a great accuracy similar to the real-world viewing condition, they present the projection of a 3-D scene on a fixed two-dimensional (2-D) image plane, and thus, lack the ability to correctly render both accommodation and retinal blur cues. Contrary to the natural vision, all objects in stereoscopic displays, regardless of their location in depth, are seen sharp if the viewer focuses on the fixed image plane, or all objects are seen blurred if the user's accommodation varies with eye convergence.

According to this context, Sheng Liu et al. provide the design and implementation of an optical see-through head-mounted display (HMD) with addressable focus cues utilizing a

liquid lens, which contains two operation modes [75]: a varifocal plane mode in which the accommodation cue is addressable, and a time-multiplexed multi-focal plane mode in which both the accommodation and retinal blur cues can be rendered. By this method, the perceived depths and accommodative responses of the user match with the rendered depths of the virtual display with addressable accommodation cues, approximating the real-world 3-D viewing condition.

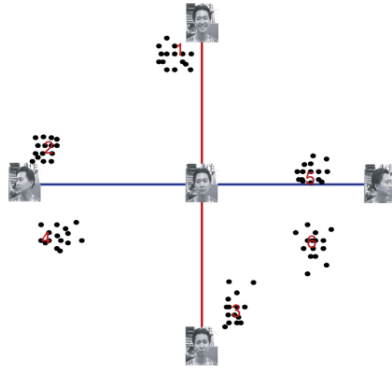


Figure 78. Presenting outcome of raw data through refined dimensional reduction

② In the real world, we navigate with ease by walking, running, driving, etc., but in immersive virtual environments (IVEs), realistic simulation of these locomotion techniques is difficult to achieve. In immersive virtual environments (IVEs), users can control their virtual viewpoint by moving their tracked head and walking through the real world. Usually, movements in the real world are mapped one-to-one to virtual camera motions. With redirection techniques, the virtual camera is manipulated by applying gains to user motion so that the virtual world moves differently than the real world. Thus, users can walk through large-scale IVEs while physically remaining in a reasonably small workspace. While moving in the real world, sensory information such as vestibular, proprioceptive, and efferent copy signals as well as visual information create consistent multisensory cues that indicate one's own motion, i.e., acceleration, speed, and direction of travel. In this context, walking is the most basic and intuitive way of moving within the real world. Keeping such an active and dynamic ability to navigate through large-scale immersive virtual environments is of great interest for many 3D applications demanding locomotion, such as in urban planning, tourism, or 3D entertainment.

To explore the exact discrepancy exists between virtual and physical movements, Frank Steinicke et al. conduct psychophysical experiments with a two-alternative forced-choice task, where they quantified how much humans can unknowingly be redirected on physical paths that are different from the visually perceived paths [83]. They tested 12 subjects in three different experiments: (1) discrimination between virtual and physical rotations, (2) discrimination between virtual and physical straightforward movements, and (3) discrimination of path curvature. Results show that users can be turned physically about 49 percent more or 20 percent less than the perceived virtual rotation, distances can be downscaled by 14 percent and upscaled by 26 percent, and users can be redirected on a circular arc with a radius greater than 22 m while they believe that they are walking straight.

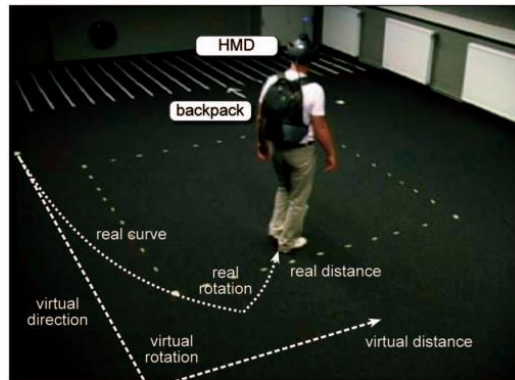


Figure 79. Redirected walking scenario. User walks in the real environment on a different path with a different length in comparison to the perceptual path in the virtual world.

③ Many domains in which augmented reality(AR) could be applied pose two sets of competing constraints. The first set of constraints limits extraneous head, eye, and hand movements beyond the immediate vicinity of a user's current task. For example, a mechanic servicing an engine may find it impractical (or impossible) to reposition their hands to manipulate any device not currently within reach or sight. Likewise, head and eye movements that cause the mechanic to avert their gaze from the repair area can break context and increase task completion time. The second set of constraints relates to various policies, material properties, and physical space limitations that restrict modifications to the application's environment. For example, safety regulations and a confined repair space might preclude the mechanic from bringing in, or installing, certain interface devices (e.g., portable devices or keypads) that might, otherwise, compensate for limited head, eye, and hand movements.

To support these types of AR scenarios, Steven Henderson and Steven Feiner develop a class of interaction techniques namely Opportunistic Controls (OC) [84]. OC is a tangible user interface that leverages naturally occurring, tactilely interesting, and otherwise unused affordances—properties of an object that determine how it can be used. These affordances serve as tactile landmarks that provide inherent passive haptic feedback for hand gestures and are augmented with overlaid 3D widgets to provide visual. This approach creates a tangible user interface with three distinguishing properties:

- 1) leveraging otherwise unused and unassociated objects that are already in the task domain as primary user interface components;
- 2) deliberately exploiting certain features of these objects for passive haptics and hand gesture recognition;
- 3) minimizing the need for external user interface artifacts.

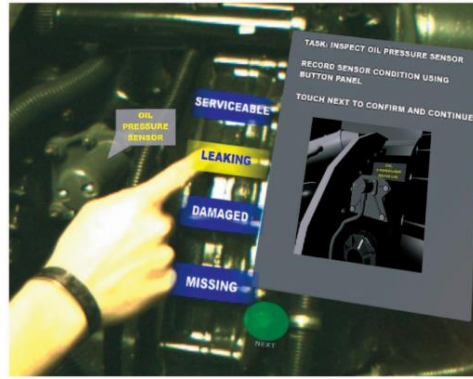


Figure 80. Opportunistic controls in action: A user manipulates a virtual button while receiving haptic feedback from the raised geometry of the underlying engine housing

4. Open Research Problems

In the past decades, significant development has been made in the field of data visualization. However, there still exists numerous interesting directions deserving to explore. In this section, remaining issues to scientific community and industry are introduced.

① An important goal of visualization technology is to support the exploration and analysis of very large amounts of data which are usually stored in databases. Since number and size of the databases is growing rapidly, there is a need for novel visualization techniques which allow a visualization of larger amounts of data. Most of today's databases store typical transaction-generated multi-attribute data which does not have any inherent two- or three-dimensional semantics and therefore does not lend itself to some two- or three-dimensional visualization [42].

② Winnie Wing-Yi Chan refers to the challenge that multivariate visualization faces is: It can be difficult and un-deterministic to find a good visual representation of a problem in terms of mapping, dimensionality, design tradeoff, assessment of effectiveness [3].

To tackle this issue, a common and practical method is to employ feature extraction and a geometric modeling to significantly reduce the data's size before the actual data rendering [47]. Another interest of researchers is to run batch-mode software rendering of the data at the highest possible resolution in a parallel way [46].

③ Kenneth I. Joy regards massive data scale as a crucial issue existing in current data visualization [23] since our ability to generate and collect data is faster than it to display them. He further interprets it as creating new methods that allow the analyst to visually examine this massive, multi-dimensional, multi-source, time-varying information

stream and make decisions in a time critical matter.

Besides, from a cognitive perspective, it does not even make sense to display a very large amount of data. Consequently, a first step in the visualization process is often to reduce the size of the graph to display. They also point out that for layout algorithms predictability and time complexity are two critical issues.

- ④ And Ivan Herman et al. propose another possible issue [24]: When data size is titanic, to display an entire large graph may give an indication of the overall structure or a location within it but makes it difficult to comprehend.

But NicheWorks[25] claims to handle data sets with thousands of elements. NicheWorks is a tool that allows the user to interact with the weighted graph, making it possible to position and focus rapidly on different subsets of the whole by panning, zooming, and rotating operations, thus building up knowledge about the entire graph.

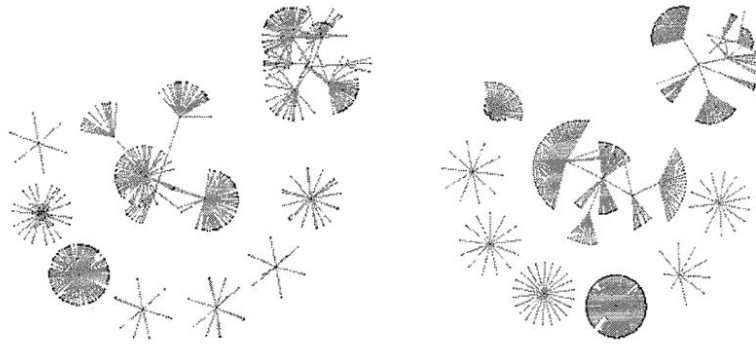


Figure 81. An instance of NicheWorks

- ⑤ The physical limitations of the display devices and our visual system prevent the direct display and instantaneous recognition of structures with higher dimensions than two or three [26]. A variety of approaches have been introduced to visually convey high-dimensional structural information by utilizing low-dimensional projections or abstractions: from dimension reduction to visual encoding, and from quantitative analysis to interactive exploration.
- ⑥ J.Jabanjalin Hilda and C.Srimathi deem four aspects as the goal of geographical visual exploration [46]:
- a. Patterns discovery through similarity representations
 - b. Correlations and relationships exploration of the hypothesis generation
 - c. Exploration of the distribution of the dataset on the map
 - d. And the detection of the irregularities in the data.

Besides, real-time optimization and lightweight web service is also required in many Big

Data visualizing application, such as WSNs and ITSs [46].

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