OLAP Visualization: Models, Issues, and Techniques

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INTRODUCTION

The problem of efficiently *visualizing multidimensional data sets* produced by scientific and statistical tasks/processes is becoming increasingly challenging, and is attracting the attention of a wide multidisciplinary community of researchers and practitioners. Basically, this problem consists in visualizing multidimensional data sets by capturing the *dimensionality* of data, which is the most difficult aspect to be considered. Human analysts interacting with high-dimensional data often experience disorientation and cognitive overload. Analysis of high- dimensional data is a challenge encountered in a wide set of real-life applications such as (*i*) biological databases storing massive gene and protein data sets, (*ii*) real-time monitoring systems accumulating data sets produced by multiple, multi-rate streaming sources, (*iii*) advanced *Business Intelligence* (BI) systems collecting business data for decision making purposes etc.

Traditional DBMS front-end tools, which are usually tuple-bag-oriented, are completely inadequate to fulfill the requirements posed by an interactive exploration of high-dimensional data sets due to two major reasons: (*i*) DBMS implement the OLTP paradigm, which is optimized for transaction processing and deliberately neglects the dimensionality of data; (*ii*) DBMS operators are very poor and offer nothing beyond the capability of conventional SQL statements, what makes such tools very inefficient with respect to the goal of visualizing and, above all, interacting with multidimensional data sets embedding a large number of dimensions.

Despite the above-highlighted practical relevance of the problem of visualizing multidimensional data sets, the literature in this field is rather scarce, due to the fact that, for many years, this problem has been of relevance for life science research communities only, and interaction of the latter with the computer science research community has been insufficient. Following the enormous growth of scientific disciplines like *Bio-Informatics*, this problem has then become a fundamental field in the computer science academic as well as industrial research. At the same time, a number of proposals dealing with the multidimensional data visualization problem appeared in literature, with the amenity of stimulating novel and exciting application fields such as the visualization of *Data Mining* results generated by challenging techniques like clustering and association rule discovery.

The above-mentioned issues are meant to facilitate understanding of the high relevance and attractiveness of the problem of visualizing multidimensional data sets at present and in the future, with challenging research findings accompanied by significant spin-offs in the *Information Technology* (IT) industrial field.

A possible solution to tackle this problem is represented by well-known OLAP techniques (Codd et al., 1993; Chaudhuri & Dayal, 1997; Gray et al., 1997), focused on obtaining very efficient representations of multidimensional data sets, called *data cubes*, thus leading to the research field which is known in literature under the terms *OLAP Visualization* and *Visual OLAP*, which, in the remaining part of the article, are used interchangeably.

Starting from these considerations, in this article we provide an overview of OLAP visualization techniques with a comparative analysis of their advantages and disadvantages. The outcome and the main contribution of this article are a comprehensive survey of the relevant state-of-the-art literature, and a specification of guidelines for future research in this field.

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BACKGROUND

Formally, given a relational data source $\mathcal{R}$, a data cube $\mathcal{L}$ defined on top of R is a tuple $\mathcal{L} = \langle \mathcal{C}, \mathcal{J}, \mathcal{H}, \mathcal{M} \rangle$, such that: (*i*) $\mathcal{C}$ is the data domain of $\mathcal{L}$ containing (OLAP) *data cells* storing *SQL aggregations*, such as those based on SUM, COUNT, AVG etc, computed over tuples in $\mathcal{R}$; (*ii*) $\mathcal{J}$ is the set of *functional attributes* (of $\mathcal{R}$) with respect to which $\mathcal{L}$ is defined, also called *dimensions* of $\mathcal{L}$; (*iii*) $\mathcal{H}$ is the set of *hierarchies* related to dimensions of $\mathcal{L}$; (*iv*) $\mathcal{M}$ is the set of *attributes of interest* (of $\mathcal{R}$) for the underlying OLAP analysis, also called *measures* of $\mathcal{L}$. OLAP data cubes can thus be used to effectively visualize multidimensional data sets and also support interactive exploration of such data sets using a wide set of operators (Han & Kamber, 2000), among which we recall: (*i*) *drill-down*, which descends in a dimension hierarchy of the cube by increasing the level of detail of the measure (and decreasing its level of abstraction); (*ii*) *roll-up*, which is a reverse of drill-down used to aggregate the measure to a coarser level of detail (and a finer level of abstraction); (*iii*) *pivot*, which rotates the dimensions of the cube, thus inducting data re-aggregation. Apart the visualization amenities, OLAP also offers very efficient solutions to the related problem of *representing multidimensional data sets* by means of a wide set of alternatives (Han & Kamber, 2000) according to which data cubes are stored in mass memory: (*i*) ROLAP (*Relational OLAP*), which makes use of the storage support provided by conventional RDBMS (i.e., relational tables); (*ii*) MOLAP (*Multidimensional OLAP*), which employs multidimensional arrays equipped with highly-efficient indexing data structures; (*iii*) HOLAP (*Hybrid OLAP*), which combines the two previous alternatives via storing portions of the cube on a relational support, and other portions on an array-oriented support (depending on various parameters such as the query-workload of the cube). Without further details, it is worth noticing that the efficiency of the data representation has a great impact on the effectiveness of data visualization and exploration activities.

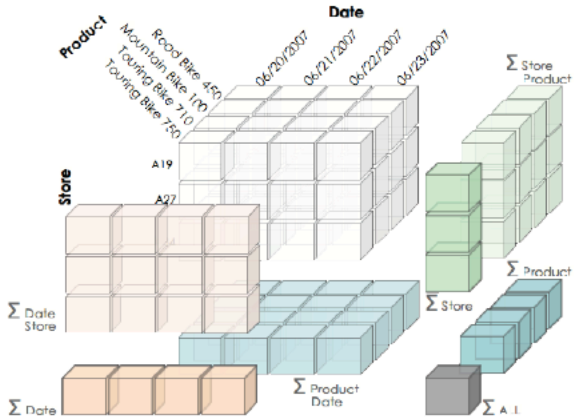
Visual OLAP results from the convergence of BI techniques and the achievements in the scientific areas of *Information Visualization* and *Visual Analytics*. Traditional OLAP front-end tools, designed to support reporting and analysis routines primarily, use visualization merely for expressive presentation of the data. In the Visual OLAP approach, however, visualization plays the key role as the method of *interactive query-driven analysis*. A more comprehensive analysis of such a kind includes a variety of tasks such as: examining the data from multiple perspectives, extracting useful information, verifying hypotheses, recognizing trends, revealing patterns, gaining insights, and discovering new knowledge from arbitrarily large and/or complex volumes of multidimensional data. In addition to conventional operations of analytical processing, such as drill-down, roll-up, slice-and-dice, pivoting, and ranking, Visual OLAP supports further interactive data manipulation techniques, such as zooming and panning, filtering, brushing, collapsing etc.

OLAP VISUALIZATION: A SURVEY

First proposals on using visualization for exploring large data sets were not tailored towards OLAP applications, but addressed the generic problem of visual querying of large data sets stored in a database. Early experiences related to multidimensional data visualization can be found in real-life application scenarios, such as those proposed in (Gebhardt et al., 1997), where an intelligent visual interface to multidimensional databases is proposed, as well as in theoretical foundations, such as those stated in (Inselberg, 2001), which discusses and refines general guidelines on the problem of efficiently visualizing and interacting with high-dimensional data. Keim and Kriegel (1994) propose *VisDB*, a visualization system based on an innovative query paradigm. In *VisDB*, users are prompted to specify an initial query. Thereafter, guided by a visual feedback, they dynamically adjust the query, e.g. by using sliders for specifying range predicates on singleton or multiple attributes. Retrieved records are mapped to the pixels of the rectangular display area, colored according to their degree of relevance for the specified set of selection predicates, and positioned according to a grouping or ordering directive.

A traditional interface for analyzing OLAP data is a *pivot table*, or *cross-tab*, which is a multidimensional spreadsheet produced by specifying one or more measures of interest and selecting dimensions to serve as vertical (and, optionally, horizontal) axes for summarizing the measures. The power of this presentation technique comes from its ability in summarizing detailed data along various dimensions, and arranging aggregates computed at different granularity levels into a single

Figure 1. A three-dimensional data cube $\mathcal{L}$ (left) and the pivot table computed on top of $\mathcal{L}$ (right)



Dimensions		Measures							
		Quantity				Amount			
		Store							
Product	Date	A19	A27	A34	Total Store	A19	A27	A34	Total Store
– **Road Bike 450**	06/20/2007	2	7	4	13	498	1743	996	3237
	06/21/2007	9	12	10	31	2241	2988	2490	7719
	06/22/2007	3		7	10	747		1743	2490
	06/23/2007	5	1	9	15	1245	249	2241	**3735**
Total Road Bike 450		19	20	30	69	4731	4980	7470	17181
– **Mountain Bike 100**	06/20/2007	8	10	3	21	6392	7990	2397	16779
	06/21/2007	5	11	4	20	3995	8789	3196	15980
	06/22/2007	9	7		16	7191	5593		12784
	06/23/2007	6		4	10	4794		3196	**7990**
Total Mountain Bike 100		28	28	11	67	22372	22372	8789	53533
– **Touring Bike 710**	06/20/2007	5		9	14	2995		5391	8386
	06/21/2007	7	2	12	21	4193	1198	7188	12579
	06/22/2007	4		13	17	2396		7787	10183
	06/23/2007		2	8	10		1198	4792	**5990**
Total Touring Bike 710		16	4	42	62	9584	2396	25158	37138
+ **Total Touring Bike 750**		19	12	15	46	10621	6708	8385	25714
Total Product		82	64	98	244	47308	83765	49802	133566

view preserving the "part-of" relationships between the aggregates themselves. Figure 1 exemplifies the idea of "unfolding" a three-dimensional data cube (left side) into a pivot table (right side), with cells of the same granularity marked with matching background color in both representations. However, pivot tables are inefficient for solving non-trivial analytical tasks, such as recognizing patterns, discovering trends, identifying outliers etc (Lee & Ong, 1995; Eick, 2000; Hanrahan et al., 2007). Despite this weakness point, pivot tables still maintain the power of any visualization technique, i.e. saving time and reducing errors in analytical reasoning via utilizing the phenomenal abilities of the human vision system in pattern recognition (Hanrahan et al., 2007).

OLAP interfaces of the current state-of-the-art enhance the pivot table view via providing a set of popular business visualization techniques, such as bar-charts, pie-charts, and time series, as well as more sophisticated visualization layouts such as scatter plots, maps, tree-maps, cartograms, matrices, grids etc, and vendors' proprietary visualizations (e.g., decomposition trees and fractal maps). Some tools go beyond mere visual presentation of data purposes and propose sophisticated approaches inspired by the findings in Information Visualization research. Prominent examples of advanced visual systems are *Advizor* (Eick, 2000) and *Tableau* (Hanrahan et al., 2007). *Advizor* implements a technique that organizes data into three perspectives. A perspective is a set of linked visual components displayed together on the same screen. Each perspective focuses on a particular type of analytical task, such as (*i*) single measure view using a 3D multi-scope layout, (*ii*) multiple measures arranged into a scatter plot, and (*iii*) anchored measures presented using techniques from multidimensional visualization (box plots, parallel coordinates etc). *Tableau* is a commercialized successor of *Polaris*, a visual tool for multidimensional analysis developed by Stanford University (Stolte et al., 2002). *Polaris* inherits the basic idea of the classical pivot table interface that maps aggregates into a grid defined by dimension categories assigned to grid rows and columns. However, *Polaris* uses embedded graphical marks rather than textual numbers in table cells. Types of supported graphics are arranged into a taxonomy, comprising rectangle, circle, glyph, text, Gantt bar, line, polygon, and image layouts.

Back to basic problems, (Russom, 2000) summarizes trends in business visualization software as a progression from rudimentary data visualization to advanced forms, and proposes distinguishing three life-cycle stages of visualization techniques, such as maturing, evolving, and emerging. Within this classification, Visual OLAP clearly fits into the emerging techniques for advanced interaction and visual querying. In the spirit of Visual OLAP, ineffective data presentation is not the only deficiency of conventional OLAP tools. Further problems are cumbersome usability and poor exploratory functionality. Visual OLAP addresses those problems via developing fundamentally new ways of interacting with multidimensional aggregates. A new quality of visual analysis is achieved via unlocking the synergy between the OLAP technology, Information Visualization, and Visual Analytics.

The task of selecting a proper visualization technique for solving a particular problem is by far not trivial as various *visual representations* (also called *metaphors*) may be not only task-dependent, but also domain-dependent. Successful Visual OLAP frameworks need to be based on a comprehensive taxonomy of domains, tasks, and visualizations. The problem of assisting analysts in identifying an appropriate visualization technique for a specific task is an unsolved issue in state-of-the-art OLAP tools. Typically, a user has to find an appropriate solution manually via experimenting with different layout options. To support a large set of diverse visualization techniques and enable dynamic switching from one technique to another, an abstraction layer has to be defined in order to specify the relationships between data and their visual presentation.

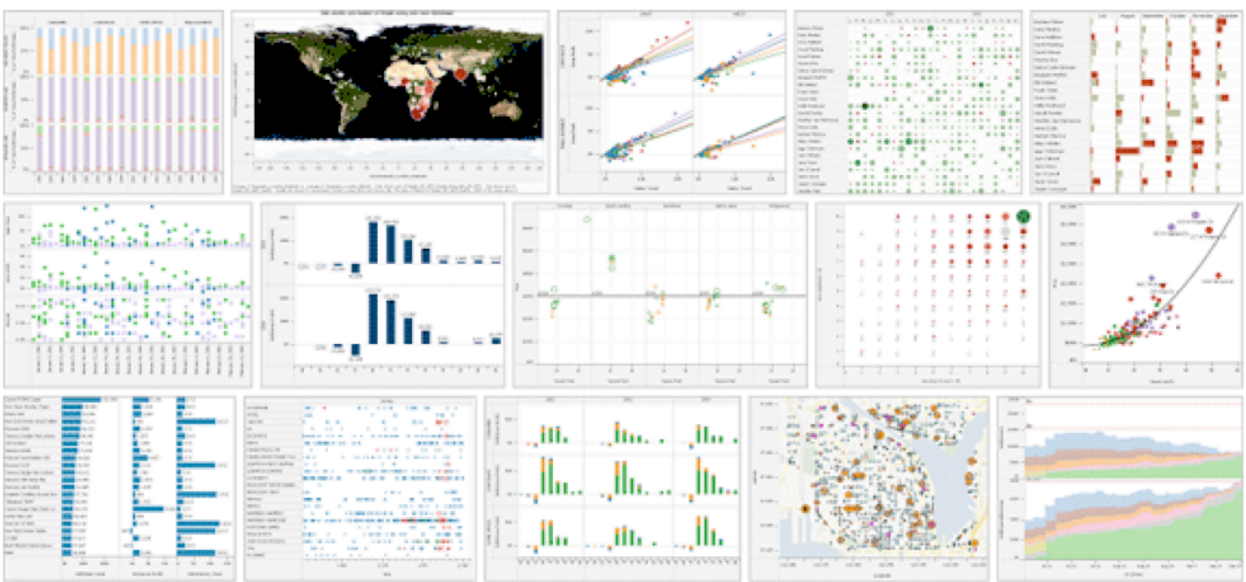
Following this approach, the *Tape* model, proposed by Gebhardt et al. (1998), suggests to represent and visualize multidimensional data domains using the metaphors of *tapes* and *tracks*, enhanced with the possibility of defining *hierarchical structures* within a tape.

Maniatis et al. (2003a; 2003b) propose an abstraction layer solution, called *Cube Presentation Model* (CPM), which distinguishes between two layers: a (*i*) *logical layer*, which deals with data modeling and retrieval, and a (*ii*) *presentation layer*, which provides a generic model for representing the data (normally, on a 2D screen). Entities of the presentation layer include points, axes, multi-cubes, slices, tapes, cross-joins, and content functions. Authors demonstrate how CPM constructs can be mapped onto advanced visual layouts at the example of *Table Lens*, a technique based on a cross-tabular paradigm with support for multiple zoomable windows of focus.

A common approach to visualization in OLAP application relies on a set of templates, wizards, widgets, and a selection of visual formats. Hanrahan et al., (2007) argue however that an open set of requirements cannot be addressed by a limited set of techniques, and choose a fundamentally different approach for their visual analysis tool *Tableau*. This novelty is represented by *VizQL*, a *declarative visual query language*. *VizQL* offers high expressiveness via allowing users to create their own visual presentation by means of combining various visual components. Figure 2 illustrates the visualization approach of *Tableau* via showing just a small subset of sophisticated visual presentations created by means of simple *VizQL* statements not relying on any pre-defined template layout.

Designers of *Tableau* deliberately restrict the set of supported visualizations to the popular and proven ones, such as tables, charts, maps, and time series, as doubting general utility of exotic visual metaphors (Hanrahan et al., 2007). Thereby, *Tableau* approach is constrained to generating grids of visual presentations of uniform granularity and limited dimensionality. Other researchers suggest that Visual OLAP should be enriched by extending basic charting techniques or by employing novel and less-known visualization techniques to take full advantage from multidimensional and hierarchical properties of data (Tegarden, 1999;

Figure 2. VizQL at work (Used by permission of Tableau Software, Inc.)



Lee & Ong, 1995; Techapichetvanich & Datta, 2005; Sifer, 2003). Tegarden (1999) formulates the general requirements of *Business Information Visualization* and gives an overview of advanced visual metaphors for multivariate data, such as *Kiviat Diagrams* and *Parallel Coordinates* for visualizing data sets of high dimensionality, as well as 3D techniques, such as *3D scatter-grams*, *3D line graphs*, *floors* and *walls*, and *3D map-based bar-charts*.

An alternative proposal is represented by the DIVE-ON (*Data mining in an Immersed Visual Environment Over a Network*) system, proposed by Ammoura et al. (2001). The main idea of DIVE-ON is furnishing an immersive visual environment where distributed multidimensional data sources are consolidated and presented to users that can interact with such sources by "walking" or "flying" towards them. Thereby, DIVE-ON makes an intelligent usage of the natural human capability of interacting with spatial objects, thus sensitively enhancing the knowledge fruition phase. In its core layer, DIVE-ON exploits the OLAP technology in order to efficiently support the multidimensionality of data. All considering, we can claim that DIVE-ON is one of the most unique experiences in the OLAP visualization research field, with some characteristics that slightly resemble visual entertainment systems.

Another branch of visualization research for OLAP concentrates on developing multi-scale visualization techniques capable of presenting data at different levels of aggregation. Stolte et al. (2003) describe their implementation of multi-scale visualization within the framework of the *Polaris* system. The underlying visual abstraction is that of a zoom graph that supports multiple zooming paths, where zooming actions may be tied to dimensional axes or triggered by different kinds of interaction. Lee and Ong (1995) propose a multidimensional visualization technique that adopts and modifies the *Parallel Coordinates* method for knowledge discovery in OLAP. The main advantage of this technique is its scalability to virtually any number of dimensions. Each dimension is represented by a vertical axis and aggregates are aligned along each axis in form of a bar-chart. The other side of the axis may be used for generating a bar-chart at a higher level of detail. Polygon lines adopted from the original *Parallel Coordinates* technique are used to indicate relationships among aggregates computed along various dimensions (a relationship exists if the underlying sets of fact entries in both aggregates overlap).

Mansmann and Scholl (2007) concentrate on the problem of losing the aggregates computed at preceding query steps while changing the level of detail, and propose using hierarchical layouts to capture the results of multiple decompositions within the same display. Authors introduce a class of multi-scale visual metaphors called *Enhanced Decomposition Tree*. Levels of the visual hierarchy are created via decomposing the aggregates along a specified dimension, and nodes contain the resulting sub-aggregates arranged into an embedded visualization (e.g., a bar-chart). Various hierarchical layouts and embedded chart techniques are considered to account for different analysis tasks.

Sifer (2003) presents a multi-scale visualization technique for OLAP based on coordinated views of dimension hierarchies. Each dimension hierarchy with qualifying fact entries attached as bottom-level nodes is presented using a space-filling nested tree layout. Drilling-down and rolling-up is performed implicitly via zooming within each dimension view. Filtering is realized via (de-)selecting values of interest at any level of dimension hierarchies, resulting either in highlighting the qualifying fact entries in all dimension views (*global context coordination*) or in eliminating the disqualified entries from the display (*result only coordination*).

A similar interactive visualization technique, called the *Hierarchical Dynamic Dimensional Visualization* (HDDV), is proposed in (Techapichetvanich & Datta, 2005). Dimension hierarchies are shown as hierarchically aligned bar-sticks. A bar-stick is partitioned into rectangles that represent portions of the aggregated measure value associated with the respective member of the dimension. Color intensity is used to mark the density of the number of records satisfying a specified range condition. Unlike in (Sifer, 2003), dimension level bars are not explicitly linked to each other, allowing to split the same aggregate along multiple dimensions and, thus, to preserve the execution order of the dis-aggregation task. A technique for finding appropriate representation of multidimensional aggregates, proposed by Choong et al. (2003), may help to improve the analytical quality of any visualization. This technique addresses the problem of ordering aggregates along dimensional axes. By default, the ordering of the measure values is imposed by the lexical ordering of values within dimensions. To make patterns more obvious, the user has to rearrange the ordering manually. The proposed algorithm automates the ordering of measures in a representation as to best reveal patterns (e.g., trends and similarity) that may be observed in a data set.

More recently, Cuzzocrea et al. (2006; 2007) propose an innovative framework for efficiently supporting OLAP visualization of multidimensional data cubes. This framework has a wide range of applicability in a number of real-life applications, from the visualization of spatio-temporal data (e.g., mobile data) to that of scientific and statistical data. Based on meaningfully handling OLAP hierarchies of the target data cube $\mathcal{L}$, the novelty of the proposed framework consists in computing a *semantics-based partition* of $\mathcal{L}$ that groups OLAP data cells semantically related, thus originating the so-called *semantics-aware buckets*. Thereafter, the resulting partitioned representation is further compressed by means of highly-efficient quad-tree based data structures, what makes the relevant assumption that compressing massive data cubes is a way for efficiently visualizing these data structures. This compressed representation finally originates a novel multidimensional histogram, called *Hierarchy-driven Indexed Quad-Tree Summary* (H-IQTS).

The major benefit of the approach proposed in (Cuzzocrea et al., 2006; Cuzzocrea et al., 2007) is a sensible improvement of visualization and exploration activities on high-dimensional spaces via enabling the user to access and browse sub-partitions of these spaces based on semantics rather than on any other arbitrary partitioning scheme, due to the fact that, during interaction, users are typically interested on specific portions of the overall data domain rather than in the entire domain. On the practical plane, Cuzzocrea et al. (2006; 2007) show that while the compression performance of H-IQTS is comparable with state-of-the-art histogram-based data cube compression techniques, the visualization performance of H-IQTS is several orders of magnitude higher than the one of comparison techniques.

FUTURE TRENDS

OLAP Visualization research is still in its preliminary stage, and a lot of work must be done in this field. A key point for the success of this branch of OLAP research is represented by the relevant range of applicability of Visual OLAP in a plethora of real-life, leading applications such as real-time monitoring of multiple streaming data sources and visualization of results produced by advanced *Knowledge Discovery* tools including clustering, association rule discovery, frequent item set mining, sub-graph mining etc.

Future research directions for OLAP Visualization can be identified in the following three main themes: (*i*) *integration with data warehouse management systems*, which will allow us to complete the overall knowledge generation, processing, and visualization experience over multidimensional data sets; (*ii*) *techniques for visualizing integrated data-cube/data-warehouse schemes*, aiming at studying how to visualize multidimensional data domains obtained from the *integration* of multiple and heterogeneous data sources (i.e., how to furnish the BI and DM analyst with an *integrated, unifying visualization metaphor* over heterogeneous cubes?); (*iii*) *visual query languages for multidimensional databases*, aiming at defining a new paradigm able to support intelligent user interaction with multidimensional data, what also poses challenging theoretical foundations on the designing of a powerful *knowledge extraction language*.

CONCLUSION

Similarly to other fundamental issues in OLAP research, such as data cube indexing and compression, the problem of efficiently visualizing OLAP data is an attractive research topic that demands for innovative models and techniques. At present, there are few initiatives encompassing these issues, and intensive work needs to be carried out in this area.

In the spirit of these considerations, in this article we have provided an overview of OLAP Visualization models, issues and techniques, and also critically highlighted advantages and disadvantages of state-of-the-art approaches, while putting in evidence a number of leading applications of these approaches in modern real-life scenarios.

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KEY TERMS

Data Visualization: The use of computer-supported, interactive, visual representations of abstract data to reinforce cognition, hypothesis building and reasoning, building on theory in information design, computer graphics, human-computer interaction and cognitive science.

Multidimensional Cube (Hypercube): A logical structure for fast data analysis based on re-arranging data into a multidimensional array storing numeric facts called measures within array cells, which are indexed by the values drawn from a set of descriptive dimensions.

Multidimensional Visualization: Visualization techniques seeking to efficiently encode more than three dimensions of information simultaneously in a two (three)-dimensional display for multidimensional data analysis purposes.

Online Analytical Processing (OLAP): A methodology for representing, managing and querying massive DW data according to multidimensional and multi-resolution abstractions of them.

Online Transaction Processing (OLTP): A methodology for representing, managing and querying DB data generated by user/application transactions according to flat (e.g., relational) models.

Pivot Table/Cross-Tab: A standard interface for analyzing OLAP data by arranging the specified set of dimensions and measures to obtain the associated totals and subtotals in a two-dimensional (possibly nested) spreadsheet view.

Visual OLAP: An umbrella term encompassing a new generation of end-user tools for interactive ad-hoc exploration of large volumes of multidimensional data via providing a comprehensive framework of advanced visualization techniques for representing retrieved data set, along with a powerful navigation and interaction scheme for specifying, refining, and manipulating subsets of interest.