Modelling Interactive, Three-Dimensional Information Visualizations

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Abstract. Research on information visualization has so far established an outline of the information visualization process and shed light on a broad range of detail aspects involved. However, there is no model in place that describes the nature of information visualization in a coherent, detailed, and well-defined way. We believe that the lack of such a lingua franca hinders communication on and application of information visualization techniques. Our approach is to design a declarative language for describing and defining information visualization techniques. The information visualization modelling language (IVML) provides a means to formally express, note, preserve, and communicate structure, appearance, behaviour, and functionality of information visualization techniques and applications in a standardized way. The anticipated benefits comprise both application and theory.

1 Introduction

Research on information visualization has so far established an outline of the information visualization process and shed light on a broad range of detail aspects involved. However, there is no model in place that describes the nature of information visualization in a coherent, detailed, and well-defined way. We believe that the lack of such a lingua franca hinders communication on and application of information visualization techniques. This paper addresses this challenge.

Our approach is to design a declarative language for describing and defining information visualization techniques. The information visualization modelling language (IVML) provides a means to formally express, note, preserve, and communicate structure, appearance, behaviour, and functionality of information visualization techniques and their applications in a standardized way.

Such a language needs to rest on solid foundations. The information visualization modelling language puts into practice a formal model that reflects the concepts and relationships of information visualization as it is understood today. To the best of our knowledge, no such integrated model exists. On our way towards the information visualization modelling language, first we survey and discuss extant models of which each covers selected facets of (information) visualization (section 2). The survey fo-

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cuses on work that devised classification schemas. Our supposition that the presence of classifications indicate an elaborated level of formalization is the rationale behind this selection. Second, we provide an overview of the entire set of models under investigation and discuss the coverage of and the relationships between the models (section 3). Next, we present computational requirements as well as requirements imposed by the application the information visualization modelling language has to fulfil (section 4). We conclude by sketching an application scenario that illustrates the language's benefits (section 5). Throughout this paper, we will refer to the visualization reference model in order to organize our investigations.

2 Information Visualization Models

"Classification lies at the heart of every scientific field." (Lohse, Biolsi, Walker & Rueter, 1994) In striving for a better understanding of information visualization, a variety of classification schemes have been proposed over the past years. Depending on provenance and intention, they shed light on the information visualization process, its application, or its utility. Information visualization techniques, applications, systems, and frameworks can be classified according to the data types they can display, user tasks they support, characteristics of visual representations they deploy as well as cognitive aspects of their visual appearance.

Reference Model for Visualization. Card, Mackinlay & Shneiderman (1999) introduced a reference model for information visualization (Fig. 1), which provides a high-level view on the (information) visualization process.

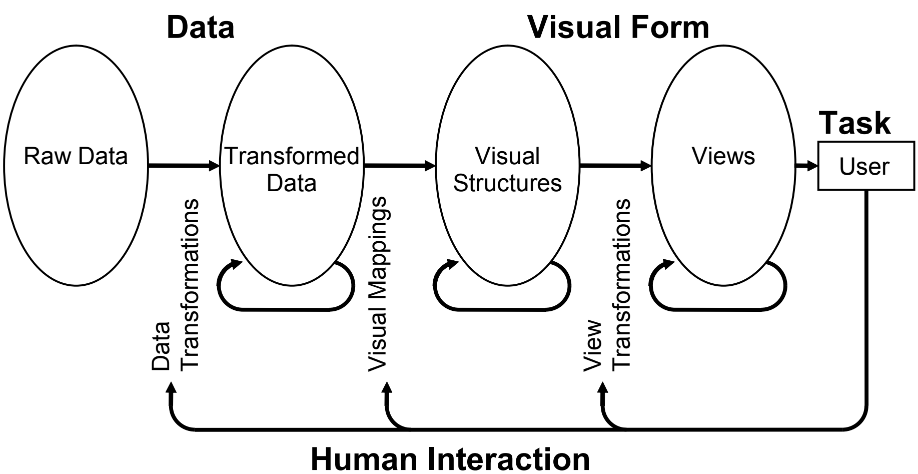

Fig. 1. Reference model for visualization

The model assumes a repository of raw data, which exist in a proprietary format, be it structured or unstructured. To get to a visualization of this data, data have to first undergo a set of transformations. Data transformations comprise filtering of raw data, computation of derived data as well as data normalization. These steps result in a set of transformed data in a unified structure. Visual transformations map the transformed data onto a corresponding visual structure. From this visual structure, a set of views can now be generated, which allow users to navigate through the display. User interactions can the transformation process at different stages. Users can adjust their view on the data, change the visual structure, or even affect the data transformation. The cyclic arrows in the diagram refer to the fact that the processes involved in the distinct steps are of an iterative nature and can occur repeatedly before the next step follows.

Data Type. Shneiderman (1996) suggested a taxonomy for information visualization designs built on data type and task, the type by task taxonomy (TTT). He distinguished seven data types: *1-dimensional*, *2-dimensional*, *3-dimensional*, *temporal*, *multi-dimensional*, *tree*, and *network*. High-level abstractions and specific datatypes are treated as subordinates of the types presented. A variety of consecutive taxonomies proposed extensions to the TTT, but were never as widely adopted as Shneiderman's work. In his summary, Keim (2002) discards few of the data types and introduces software and algorithms as new data types that could be visualized.

Visual Representations. Visual representations, in general, are structures for expressing knowledge. Long before computer technology emerged, visualizations were well-established and widely used. In their empirical study Lohse, Biolsi, Walker & Rueter (1994) investigate how people classify two-dimensional visual representations into meaningful categories. From this survey, a structural classification of visual representations became apparent: *graphs*, *tables*, *time charts*, *network charts*, *diagrams*, *maps*, *cartograms*, *icons*, and *photo-realistic pictures*.

Visualization Techniques. In the last decade, a large number of novel information visualization techniques have been developed. Good overviews of the approaches can be found in a number of recent books (Card, Mackinlay & Shneiderman, 1999) (Ware, 2000) (Spencer, 2000). Keim (2002) concentrates on the design of the visual environment and suggests a classification of visualization techniques that takes into consideration recent developments in information visualization: *standard 2D/3D displays*, *geometrically transformed displays*, *icon-based displays*, *dense pixel displays*, and *stacked displays*.

Tasks. Bundled with the type taxonomy, Shneiderman (1996) enumerated seven tasks users could perform on the data: *overview*, *zoom*, *filter*, *details on demand*, *relate*, *history*, and *extract*.

Interaction. The information visualization process of transforming data into visual representations is a one-way street unless the human perceiver is given the opportunity to intervene. Human interaction completes the loop between visual forms and control of the visualization process. It includes controlling the mappings performed in the visualization process (Card et al., 1999). Although interactive techniques and metaphors differ in design, Chuah & Roth (1996) have identified primitive interactive components visualization systems have in common. Composing these primitives can model the complex behaviour of visualization system user-interfaces at the semantic level of design. The functional classification distinguishes between three main types of basic visualization interactions: *graphical operations*, *set operations*, and *data operations*. Each main type ramifies to a hierarchy of more specific interaction types.

View Transformations. The visual mapping process results in graphical structures that represent information. In a final step, views render these graphical structures and make them accessible to the human perceiver, on computer screens, for example. View transformations specify graphical parameters that influence the view such as position, scaling, and clipping. Varying view transformations can reveal more information from one and the same graphical structure than static visualizations possibly could. Card, Mackinlay & Shneiderman (1999) distinguish three common view transformations: *location probes*, *viewpoint controls*, and *distortion*. Scales, as introduced by Theus (2003), encompass location probes and viewpoint controls. Leung & Apperley (1994) introduce transformation and magnification functions for various distortion-oriented presentation techniques.

Multiple View Coordination. Multiple view systems "use two or more distinct views to support the investigation of a single conceptual entity." (Wang Baldonado, Woodruff & Kuchinsky, 2000). To fully exploit the potential of multiple views, sophisticated coordination mechanisms between views are required: *navigation slaving*, *linking*, and *brushing*. Roberts (2000) identified three ways in which multiple views may be formed according to stages in the information visualization process comparable to the reference model (Fig. 1).

Cognition. By definition, the purpose of information visualization is to "communicate properties of information to a human". The research on information visualization must not stop at producing and designing visualization but must also consider how visualizations affect the human observer. Wiss & Carr (1998) propose a framework for classification of 3D information visualization designs based on three cognitive aspects: *attention*, *abstraction*, and *affordances*. A survey revealed that information visualization systems have come up with a variety of solutions in order to guide user attention, abstract from complex data and indicate available functionality and interaction modes.

Information Visualization Operating Steps. The data state reference model (Chi, 2000) describes visualization techniques with a focus on data and its transformations. The model breaks down the information visualization process into four data stages: value, analytical abstraction, visualization abstraction, and view. Three types of data transformation operators carry over into states: *data transformation*, *visualization transformation*, and *visual mapping transformation*. Based on the data state model, Chi decomposed the data processing pipelines of visualization techniques and identified operating steps they share.

3 Information Visualization Model Consolidation

With our approach, we do not intend to substitute information visualization models and classifications that have evolved so far. Instead, best-of-breed will be selected and combined into one consolidated formal model describing information visualization.

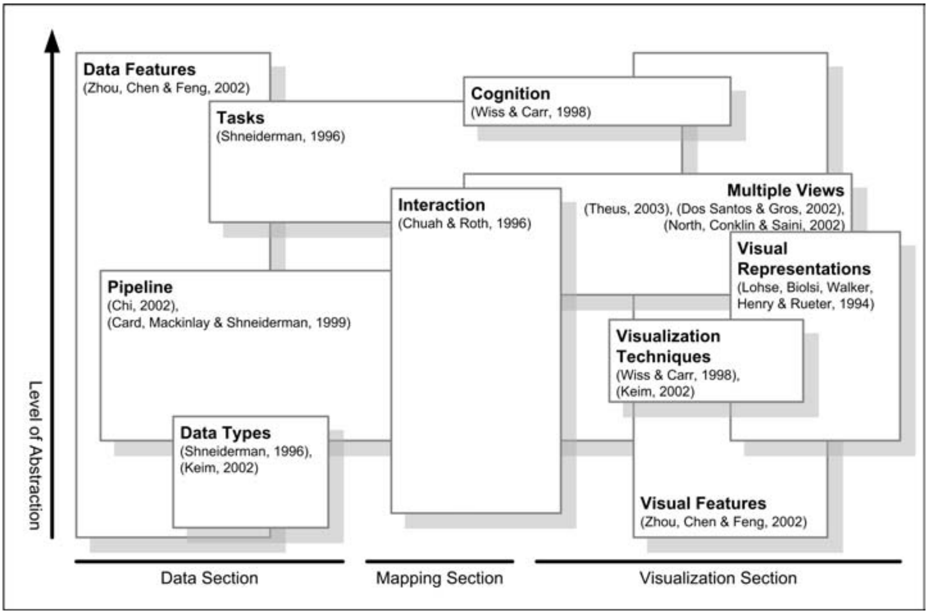

Fig. 2. Interrelationship of information visualization models in information visualization model space

3.1 Information Visualization Model Space

All the classification models presented describe selected subsets of the complex area of information visualization. Our attempt to arrive at a consolidated model for information visualization starts out with the analysis of what areas these discrete models cover and how they are mutually related (Fig. 2). To answer that question, we locate information-visualization models within *model space* for information visualization. There are two axes that span model space. The first dimension reflects the processing pipeline for (information) visualizations as introduced by the reference model for visualization (Fig. 1). Roughly speaking, three sections subdivide this pipeline. Beginning with the data section, data is transformed and mapped into graphical objects in the visualization section. Of course, models describing data properties, for example, are located to the left whereas multiple views and their coordination cover the area from the middle to the right. The second dimension expresses dependencies between models as well as the level of abstraction from the actual task of handling (computer) data. On the lowest level, models deal with data properties and visual attributes, whereas at the upper levels, models such as cognition abstract away from implementation details. Upper level models depend on their subordinates. The absence of visual objects and their properties would render talking about cognition futile.

Of course, as information visualization model space lacks metrics, positions and borderlines get blurred. So far, the diagram reflects our subjective assessment. Furthermore, drawing rectangles is a simplification. More often than not, single models do not handle all aspects at one constant level of abstraction and vice versa. This holds true especially for substantial models. Hence, the areas in the diagram depict an approximation of the real state of affairs.

3.2 Coverage and Ambiguity

The first overview reveals that there is little white space in the diagram. Judging from that, the extant models in total cover nearly all facets of information visualization as we know it today.

The frayed right side of the visualization section indicates that information visualization model space has no clearly marked border in this direction. Multiple views, visual representations, cognition, and interaction not only apply to information visualization exclusively. Partially, these models belong to visualization in general. From our point of view, visualization model space begins in the visualization section and extends beyond the diagram.

The next observation is that rectangles in the diagram overlap. If this occurs within one section, the models involved compete. Such conflict can be observed, for example, between data types, as introduced by Shneiderman's TTT, and the data features invented by Zhou et al. Sorting out the differences and matching concepts are the anticipated tedious tasks required in order to arrive at a joint model. The above presentation of information visualization models discusses corresponding models. Note that the collection of models portrays selected samples. Less important items have already been omitted.

Sections cannot always be clearly separated without ambiguity. Cross-section overlapping arises when one and the same phenomenon of information visualization is covered by various models starting out from different perspectives. For instance, interaction and the processing pipeline are closely interwoven. From the standpoint of the reference model, view transformations are modifications that are likely to be triggered by human interaction. Conversely, interaction claims that location probes and viewpoint controls are their terrain, and terms them interactive filtering, interactive zooming, interactive distortion, and interactive linking and brushing.

3.3 Quality and Level of Granularity

As the diagram suggests, the area of information visualization has been thoroughly researched and only few white spaces remain. Yet the stake the various models claim reflects neither the model quality nor its level of detail. There are always two sides to quality: correctness and completeness. Before they can be integrated into the coherent model, extant models need to be assessed with care. More easy to judge is the model's level of granularity. Classification systems vary in how detailed a way they have been conceived. Generally, coarse models leave space for alternatives and variations, whereas in depth models provide better guidance. To illustrate the difference, the interaction model with three hierarchy levels of classes is far more detailed than the data types according to the TTT. Then again, not all facets of information visualization share the same level of complexity. It is natural that different areas feature different numbers of classes.

4 Information Visualization Modelling Language

Current practice in information technology favours the use of formal languages as representation formalisms which abstract away from details of specific realisation. The information visualization modelling language enables the declarative description of an information visualization need or solution in preference to describing the steps required in order to realise the visualization process. It is a formal language; it has a set of strings which can be derived from a (formal) grammar consisting of a deductive system of axioms and inference rules (Partee, ter Meulen & Wall, 1990). We give the term information visualization modelling language *blueprint* to the formal description of an information visualization technique or application expressed by the language. A blueprint is composed of a number of sections. Blueprint sections are legal combinations of language elements derived from the grammar.

Conceiving the information visualization modelling language may follow two simple rules of thumb. First, concepts identified within the model constitute the vocabulary. Secondly, relationships between concepts determine the grammar. Presumably, however, relationships from the model will also contribute to the language vocabulary. The information visualization modelling language will constitute a specific encoding of the consolidated information visualization model. In order to be useful, its design has to meet requirements for both computation and application.

4.1 Computational Desiderata

The information visualization modelling language (IVML) carries knowledge about information visualization within its schema. Moreover, information visualizations denoted in the language are formal structures which represent knowledge about information visualization techniques, applications, and requirements, respectively. Hence, the information visualization modelling language can be considered a meaning representation language. Meaning representation languages need to meet a number of practical computational requirements (Jurafsky & Martin, 2000).

Verifiability is the most basic requirement for a meaning representation: “it must be possible to use the representation to determine the relationship between the meaning of a sentence and the world as we know it.” In the case of the IVML, it can (say) describe information visualization techniques and data types these techniques are capable of displaying. These descriptions establish knowledge. Demands for visualization of data of a specific type can be considered a question expressed in IVML. If there is no visualization technique that can handle the requested data type, matching will fail. In general, sentences can have different meanings depending on the circumstances in which they are uttered. Since the IVML is intended to be the means we reason about and act upon, it is critical that blueprint sections expressed in the language (analogous to natural language sentences) have single unambiguous interpretations. The IVML is required to be an *unambiguous representation*. Conversely, distinct sentences in general may have the same meaning. Such a situation is highly problematic, since it hinders verification and adds complexity to reasoning. Therefore, the IVML should follow the doctrine of *canonical form*: Sentences that mean the same thing should have the same representation. More complex requests cannot be answered solely on the basis of verification and canonical form. Let's agree that whilst traditional diagrams in general are suitable for presentation purposes, they are not a good choice to pursue data exploration. Pie charts belong to this class of traditional visualization techniques. To meet the demand for visualization of data for presentation purposes using pie charts, *inference* is required. It must be possible to draw conclusions about propositions that are not explicitly represented, but are nevertheless logically derivable from the knowledge available. Finally, in order to be useful, the IVML must be *expressive* enough to treat a wide range of the subject matter of information visualization. But, since research in this area is ongoing, the IVML cannot be expected to be complete.

4.2 Applicational Desiderata

By analogy with design criteria that underlie related modelling languages (Web3D Consortium, 1997), the information visualization modelling language should meet a set of requirements in order to be useful in application.

Information visualization is a multifaceted subject matter. The formal description of information visualization techniques and applications using the IVML will be accordingly complex. *Composability* provides the ability to use and combine information visualization objects, like data sources, mapping formulas, or view definitions, within an IVML application and thus allows reusability. Depending on the application, the complete set of constructs is not always required. In a single-view application, for example, multiple-view coordination is pointless. The design of the IVML must permit the omission of constructs which are not essential for the given situation. The notion of language constructs which are independent by design is known as *orthogonality*. Since the IVML is anticipated not to cover all future inventions in the area of information visualization, the language has to be *extensible*, allowing the introduction of new concepts. Wherever concepts are missing in the language, *bypass*es help to fill the gaps with alternative solutions. Bypasses also stand in when IVML design does not meet particular requirements. In the case of parsers interpreting the IVML in order to render information visualizations, the bypass addresses purpose-built implementations. The IVML needs to be *authorable*: Computer programs must be capable of creating, editing, and maintaining IVML files, as well as automatic translation programs for converting related data into IVML. More generally, the language must be *capable of implementation* on a wide range of systems. Considering the implementation of software systems, language design must foster the development of scalable high-*performance* implementations. Finally, IVML must *scale* and enable arbitrarily large dynamic information visualization applications.

5 Application Scenario

Imagine a knowledge worker engaged in an information retrieval dialogue with a computer-based interactive information visualization system, seeking to meet an information need he cannot fully specify. Hence, it is impossible for him to formulate a question and have the system answer in a targeted way. Instead, the dialogue is of exploratory nature. During a series of iterative steps the user learns about the data source, locates relevant information, and refines his information need. This process is put into practice by human actions demanding the system to adapt in return. Beginning with an initial setup, interactions manipulate data transformations, visual mappings, and view transformations. Finally, if the dialogue succeeds, the user will not only have come to a relevant data set answering his information needs, but moreover end-up with an information visualization application tailored to the task performed.

Imagine the system was able to export its final state as a blueprint. The information visualization modelling language would then be deployed to formally *express* the information visualization technique that has evolved, allowing it to be *note*d down (electronically). Usually, only content retrieved is retained as a result of the dialogue, discarding the history and the supporting tool's setup. With the various blueprint sections, all these facets of the information retrieval dialogue can be *preserve*d and reused in similar tasks or applied to diverse data sources. With the blueprint the information visualization technique can be communicated in its entirety to third parties.

6 Summary and Conclusion

This article outlines our approach towards the information visualization modelling language (IVML). To lay a sound foundation, we survey the state-of-the-art of information visualization, assess the coverage and relationships between extant models, and identify potential obstacles in the process of setting up an integrated formal model that reflects the concepts and relationships of information visualization as it is understood today. Finally, we present computational requirements as well as those imposed by the application the information visualization modelling language has to fulfil.

The survey focuses on work that devised classification schemas. To assess which facets of information visualization these discrete models cover and how they are mutually related, we established the notion of information visualization modelling space. The analysis suggests three findings. First, the extant models in total cover nearly all facets of information visualization as we know it today. Secondly, areas of information visualization model space are described by rival models, leading to ambiguity. Third, the models vary in the level of detail in which they have been worked out. The information visualization modelling language constitutes a specific encoding of the consolidated information visualization model. Its design has to meet requirements for both computation and application.

The modelling language should provide a means to formally express, note, preserve, and communicate structure, appearance, behaviour, and functionality of information visualization techniques and their applications. This claim will be further motivated in future work along with anticipated benefits in both application and theory.

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