Multiple-View and Multiform Visualization

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ABSTRACT

Visualization is about discovery and understanding; the user wishes to gain a correct insight into the underlying information, to explore and analyze how different parts are related. Thus, presentation, exploration and explanation tools are used with manipulation and investigative techniques to display, discover and gain a 'correct dissemination' of the information. Moreover, by displaying the information simultaneously in multiple ways the user is aided in their investigation.

Such multiform techniques may be generated through various algorithms; we organize these methods according to how they apply to the individual stages of the dataflow paradigm. These multiforms may be displayed in separate windows. Multiple views are useful (1) to overcome misinterpretations and provide additional insight, (2) for scientific exploration tasks of relating, coupling and to aid the 'drilling down' of information, and (3) to provide alternative viewpoints by expressing different user-interpretations of the same information. Finally, to use multiple views effectively they should be, among other things, easily created, automatically coupled to other views and dynamically manipulated.

Keywords: Visualization, Multiple views, Multiform, Abstraction

1. INTRODUCTION

Often, within the spoken language, we all have had people say to us "sorry, I didn't quite understand that, could you explain it again". Perhaps they have heard the 'words' but the content has not been grasped. We then endeavour to repeat the explanation in a different way, perhaps more slowly, using simpler vocabulary and words. Likewise within visualization, we (as the user) are seeking to understand the underlying aspects to the information, and by presenting the information in *multiples* a better understanding of the information may be formed.

Far too often we rely on one view: one visualization. It is true that this may be the traditional, simplest and most common method to represent the information, as a detailed complex diagram containing many legends, scales, annotations and helpful graphics. But, are we perhaps missing out on the richness of the data? Indeed, we may believe we have understood the content, but in fact, due to various reasons, we have not realized the implications of the realization and the fullness of the data. We may not actually understand the underlying information.

Multiples are one of several ways that aid the user to generate a correct understanding. Indeed, presentation, exploration and explanation tools are used with manipulation and investigative techniques to display, discover and gain a 'correct dissemination' of the information. Specifically, we believe, that multiple-view and multiform techniques enable the user in this exploration, and enable a deeper understanding of the information.

There are many reasons why multiplicity may not so often be used. It may be that the visualization system does not encourage such action, and perhaps due to time constraints it is not possible to repeat a complex visualization in a different form, or the scientific field requires that the data is depicted in a specific fashion. Alternatively, such techniques have been merely overlooked.

Multiples encourage comparison, by enabling the data to be displayed in different forms. The diverse forms provide contrasting views that reinforce, intensify and provide a deeper understanding of the information. Multiplicity may include replication, to act as a visual history of the visual exploration, or it may provide redundancy that (say) reinforces a continuum (over boundaries and limitations of size of a window). Additionally, multiplicity may be used in the temporal domain to allow animations to be repeated time-on-time, depict the temporal data as a series of multiple individual images, or encourage the user to 'try out' different scenarios using various parameters (displayed in different views).

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Within this paper we:

1. define and clarify the concepts and terminology;
2. describe why multiple views may be useful;
3. present how multiple views and multiform visualization techniques may be generated; and
4. discuss related issues regarding the creation and presentation of multiple views.

2. CONCEPTS AND TERMINOLOGY

Edward Tufte in his excellent book 'Visual Explanations'[1] presents a chapter on 'Multiples in space and time'. He says "multiple images reveal repetition and change, pattern and surprise – the defining elements in the idea of information'. Indeed, it is possible to see that 'multiple images breeds reassurance' in the realization. Where as the image is represented in (perhaps) different ways it is harder to miss the underlying trends in both.

Below, we present some brief definitions of the terms used in this paper.

Multiples and multiplicity are general terms that we use to represent a number of components or a number of views of the data.

Multiple views describes multiplicity in visualization, where various realizations of the data are depicted in separate windows.

Multiform realizations represent a change in the visual representation method: describing a realization that is depicted in a 'different form'. It suggests that separate algorithms have been applied to the *same* data to generate a new view of that information, and that the realizations are displayed in neighbouring windows.

Parallel presentations exist when different views are placed alongside each other and represent the same information, or directly relate to each other.

Time Multiples allow temporal data to be represented as a series of separated (film strip) images; Figure 1, for example.

Small Multiples are 'thumbnail' representations of the data. This is a term mentioned by Tufte,[2] who encourages the use of small, shrunken graphics that purely contain the depiction of the information.

Redundancy may be used, in the context of multiplicity, to describe information that has been replicated (usually in the same view) to, for example, reinforce a continuous visual effect.

Multiple views may be gained from a strategy of *replication*, where the image or realization is duplicated and displayed in a separate window, section 4 categorises where and how the different views may be generated. However, multiple views is only one method of exploration within visualization. It is common to *replace* the current visualization with a new one (that may be generated, as an update, from a change in parameter values) or it may be appropriate to *overlay* and include the previous/current realization with the new representation. The latter operation allows the single window to include different multiform methods in one view. This has the advantage that the information is easily comparable (as it is in the same space), but parts of one visualization may obscure objects of another realization.

3. WHY MULTIPLE VIEWS?

From the introduction and the previous section, we start to see that there are many reasons why we should depict the data in multiple views. We believe that these may be categorized into five groups: Correct Dissemination, Scientific Exploration, Alternative Viewpoints, Realization Comparison and Collaboration.

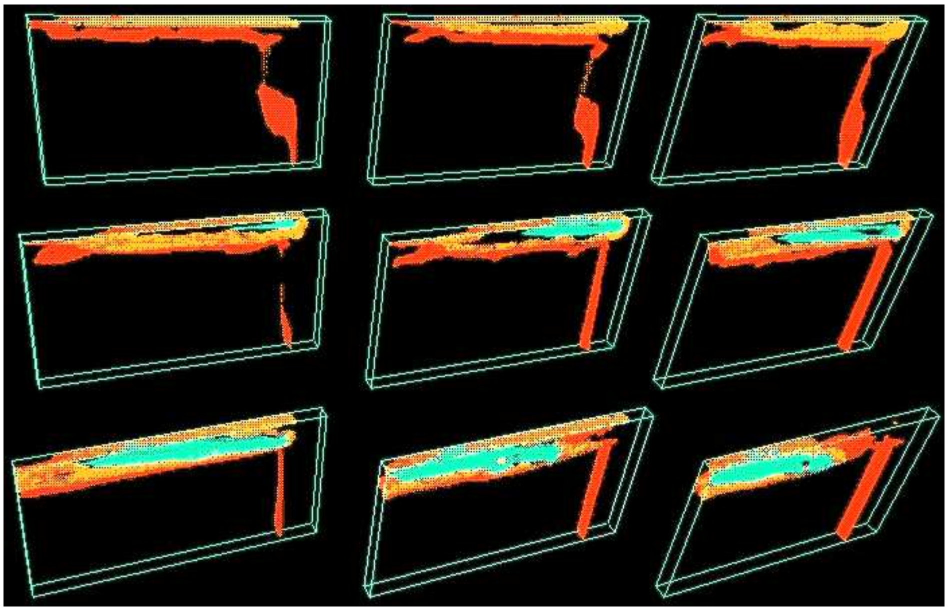

Figure 1. Realization of the temporal domain in a series of separate visualizations. Each may be individually manipulated and zoomed. The multiples are also closely coupled, enabling joint manipulation of the images. The visualizations depict the growth and movement of plumes of algae in an ideal fjord.

3.1. Correct Dissemination

The user obviously wishes to gain a correct understanding of the data. The Multiform views may aid in a true dissemination, as each view could emphasise different facets of the underlying information, provide additional insight, and help overcome possible misinterpretations.[3]

This is recommended by Yagel et al[4] who, within the area of fluid dynamics, group four volume renderers to generate low quality to high quality images of the same data. These different views (multiple images), of the same data, aim to provide the user with a better understanding of the underlying data.

The different visualization techniques may be used to 'enhance' the visual appearance, or augment the display in such a way as to provide additional information to the user to aid them in their understanding. These may include (1) adding visualization *cues*, such as shading or colour to aid in depth perception and the understanding of spatial relationships[5]; (2) including *context* information such as bounding boxes, backgrounds, rulers and scales, and other visualizations, or (3) providing *uncertainty* visualization methods that include, for example, 'error bars', depictions of missing values or other uncertainty cues.[6]

Such techniques, that augment or adjust the information, also aid to overcome possible occlusion problems within three-dimensional visualizations. For example, the position of some objects may be distorted to provide a clear field of view to an interesting object,[7] or surfaces may be cut-away or clipped[8] to enable internal objects to be viewed.

It is often beneficial to use *parallel* representations that display the 'different forms' alongside non-distorted views, enabling comparison and providing context information.

3.2. Scientific exploration

The multiple views and multiform realizations may be used to aid exploration. Some representations provide detailed and measurable views, these are useful for presentations. Others are generated with less detail and are more appropriate for browsing or navigating, such as provided by the VolVis system.[9] These 'less detailed' and simplified views may depict the structure of the underlying data – useful to an investigator who has no intuitive feel of the data – or may provide information related (or calculated from the data) that describes (say) the connectivity of internal objects.

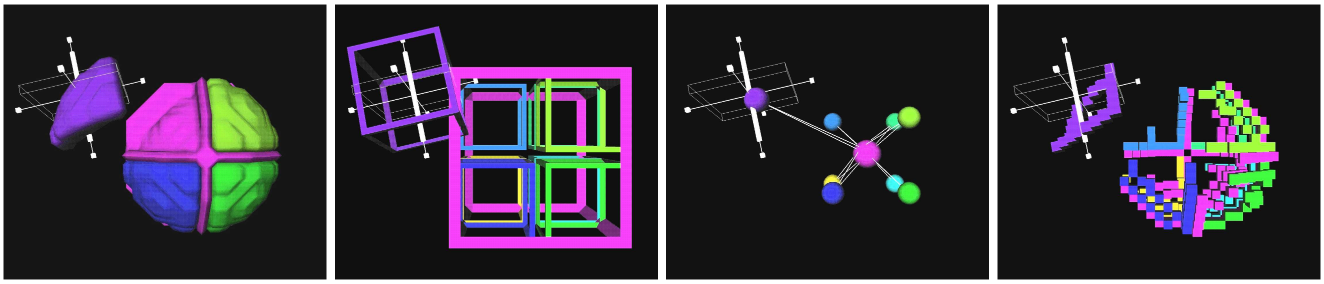

Figure 2. Multiform views of a 3D test volume dataset. The views are coupled together and show joint manipulation of an object. From left to right, surface representation, bounding boxes view, connecting-spheres showing the centre of the objects and 3D adjacency information, a skeletoned view.

The underlying structure

Simplification and abstract techniques are useful to display, for example, streams on a land-map. These could be simplified to a few large arrows that show the general direction of the water flow. The information has been abstracted to depict fundamental information, in this case the flow of water, at the expense of ignoring information about curvature, width or depth of the river-bed.

Some views may allow internal objects – otherwise obscured – to be viewed. For example, the outer surface of an isosurface visualization may obscure internal parts to the model, whereas when the objects are represented by bounding boxes the internal objects may be easily 'viewed'.

Exploration, coupling and brushing

Obviously the box-representation (in Figure 2) depicts the information in an abstract form. This allows the internal objects to be easily selected and manipulated (as the inner parts are less-obscured in this multiform). The Figure also shows the elements being jointly manipulated – the multiple views are coupled together; here, similar elements in each view may be jointly manipulated, selected and highlighted by operating any elements in one view.

These exploration techniques form a 'focus and linking' method. In general the manipulation information in one view may be 'directed' to other related views.[10] These multiple views may be described as being closely coupled. Over the years, especially within information visualization, such 'focus and linking'[11] methods have been widely advocated. Not only the control and viewing commands are passed between views, but data and information may be exchanged. Here, elements in one view may be *brushed*[12,13] (touched and selected by the mouse pointer) to be specifically highlighted or displayed in a corresponding display. Such techniques are often utilized for multivariate visualization. These operations may be described as a graphical spreadsheet, with multiple views representing the many cells.[14,15]

An exploration History

The multiple views may provide a history of the visualization exploration, by using a *replication* strategy of operation (as opposed to the overlay or replacement methods). Here the multiple views are kept throughout the life-cycle of an investigation, and thus provide a 'history of exploration'. This style of history mechanism is used within Waltz.[3] Other systems overcome the transient nature of the display by storing past visualization commands (as data or variable values) in a database, see GRASPARC[16] and Tioga.[17] Also, Patten and Ma[18] store the rendering parameters, to provide an unstructured history and other visualization

3.3. Alternative viewpoints

The multiple views may be an expression of different peoples' interpretations of the same information.[19] The views may be accompanied by related descriptions and discussions, which describe in parallel the realizations.

Such techniques are useful when the data is extremely sparse (such as in archaeology) or ambiguously complicated. Thus, these multiple views, perhaps created by an expert, would allow the user to generate a more reasoned interpretation of the actual underlying information.

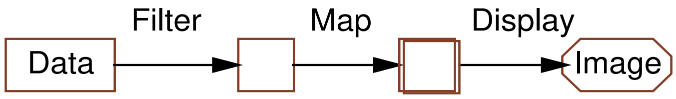

Figure 3. Traditional Data flow Model

Statistics and visualization are powerful! It is so easy to lie, say nothing[20] or convince the reader that the depictions are correct. Visuals are convincing! However, getting the correct message across is more difficult. Perhaps it is better to provide a visualization with some form of uncertainty[6] rather than a 'single viewpoint visualization' or using methods that allow the user to dynamically adjust the depicted information within given constraints.

3.4. Realization Comparison

Tufte[1] says "the scientific principle 'make controlled comparisons' also guides the construction of data displays, prescribing that the ink or pixels of graphics should be arranged so as to depict comparisons and context". Thus, it is useful to depict multiple representations to enable comparison.

A visual comparison, of results from similar visualization algorithms, may be performed on multiple views presented side-by-side. The observer may detect the slight algorithmic differences of the (say) faster algorithm compared to a slower algorithm. Additional visualizations may be generated to aid this comparison.[21]

3.5. Collaboration

Additionally, multiple views are the essence of collaborative visualization; where, the each participant may view the same image. Here, each user often requires to see an identical visualization, whereas, with single-user multiple-viewing the user would often require visualizations being of multiform.

For example, Klinker[22] describes an environment for collaborative data exploration, implemented in an extended and adapted version of AVS. The extensible system provides methods for the user to probe the data by probes of arbitrary shapes, to transform the selected data, linking the cursors between different displays (and windows, and screens), in order to show arbitrary relationships creating a collaborative environment. Moreover, Wood et al[23] use IRIS Explorer for their collaborative visualization implementation.

4. MULTIPLES IN VISUALIZATION – GENERATING MULTIPLE VIEWS

We base our evaluation, of how multiple views may be formed, on the traditional dataflow model, Figure 3 (Upson et al[24] and Haber and McNabb[25]). Here the visualization process is treated as a pipeline of commands: the data is *filtered*, to create a subset of the data, that is then *mapped* into a representation which can be *displayed*. Multiple views may be formed through different algorithms applied to different stages of the visualization process. Specifically, multiple views may be generated, from any of the three stages of the visualization pipeline, by altering the parameters or exchanging the visualization algorithm.

Thus, we first categorize *where* then *how* the multiple views may be formed.

4.1. Multiple views from the Filter level

Traditionally, users aim to segment the data into specific objects of interest. These areas of interest are often named *features*.[26] A set of features can be generated by an expert classifying individual elements, algorithmic methods that automatically dissect the data into groups of like-elements, or semiautomatic techniques that allow the user to select the start-point and steer the bounds of the segmentation algorithm.

Different segmentations and selections of the data may generate different realizations. Thus we state, 'at the data level multiple views may be generated from alterations in the selection of the data-elements'.

The feature-sets represent groups of information that may be displayed as one entity (an object). For example, Silver[27] generates objects of like-data points that may be tracked as they evolve over time. Moreover, the same data elements may be grouped, using different criteria, into disparate feature-sets that contain the same data-elements but result in different visualizations.

Taking this operation to the extreme, it is possible to generate a hierarchy of data feature-sets: each a sub-set of the previous. This data-hierarchy technique is useful for exploratory visualization.[3]

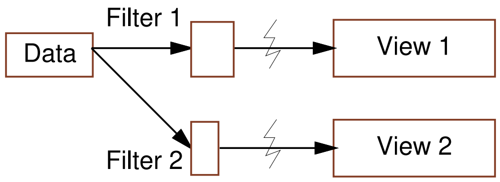

Figure 4. Multiple views of the same data, generated through different filter and selection operations

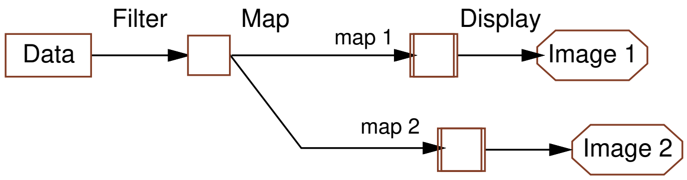

Figure 5. Multiple views of the same data, obtained through different mapping operations.

4.2. Multiple views from different mappings

At the mapping level of the dataflow pipeline, the selected data is mapped into a geometric representation, this Abstract Visualization Object[25] is then rendered into the final visualization.

Obviously, different algorithms would result in different realizations. For example, an surface view may provide information of data at particular iso-values, whereas a volume rendering would provide a gel-like representation of the whole dataset. Additional and separate views may be formed by mapping different attribute and geometry fields (colour, transparency, size and orientation, for example) to the data using the same visualization algorithm. For example, the surface triangle pieces may be exchanged with lines, generating a wire mesh, or point-clouds.

Techniques for multiple views – multiform visualization

In essence Multiform images may be generated by either altering the mapping of the data to the 'display', or by simplifying the 'data' itself. Following Walsum et al,[26] we declare that this is a process of abstraction since the data may be represented at a higher abstract level. Hence, there exists a scale from 'very abstract' to 'less abstract'. Simplifying the display by abstracting the essential information may generate a non-relevant display, either because the information is 'too abstract' or that the context of the information is unknown. Thus abstract views need to be used in parallel with other multiform views.

This two-level Data and Display abstraction classification is similar to the generalization concept of Bertin,[28] where, within the area of cartography, Bertin describes two simplification techniques. First he describes *conceptual generalization* that generates boundary areas within the map, and defines 'how the areas are grouped'[29] and, second, *structural generalization* which generates the underlying structure of information and allows a level of representation change, which, for example, would allow a cluster of points represented by a surface-area to be exchanged for an icon.[26]

These techniques, may be easily applied at the *mapping* stage of the dataflow paradigm. We define four methods to generate different views of the same data:

1. The *graphic-object* being mapped, or the type of representation, can itself be altered. For example, a continuous surface can be exchanged for a surface mesh or a surface of points or a set of icons.[26] Therefore, the style of representation may be changed from an area to a set of lines, points or symbols.[28]

2. The *appearance* of the object can be altered, by exchanging the retinal variables of size, texture, orientation, shape and color (see[28] for details).

3. The mapping of the *position* of the data can be changed. A direct spatial mapping preserves each data position within the screen space, represented using (say) a perspective or parallel projection, whereas a non-direct mapping augments the position to provide a more accessible or interpretable view of the data. Non-linear mappings can clear the 'line line of sight' to display obscured and concealed portions of the data.[30]

4. The graphic-objects themselves can be *simplified*, by smoothing or regionalizing the components; for example, a curved-line can be exchanged for a straight line.

4.3. Display level – multiple views

Multiple views may be formed at the display level by (say) altering the viewport or projection specification. For example, two similar views may be formed using parallel and perspective views of the same model, alternatively, one viewport may show the front of an object whilst another view shows the rear-view of the same object.

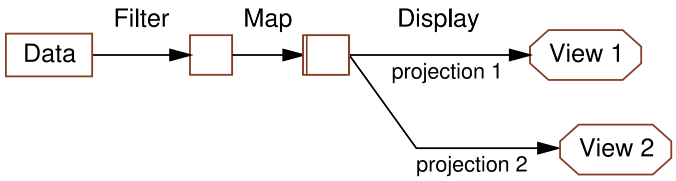

Figure 6. Multiple views of the same data, generated through different mapping operations.

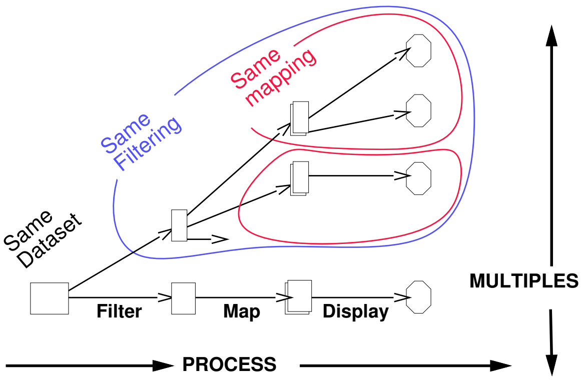

Figure 7. Graph of Process against multiples. Multiple views at different stages of the dataflow paradigm.

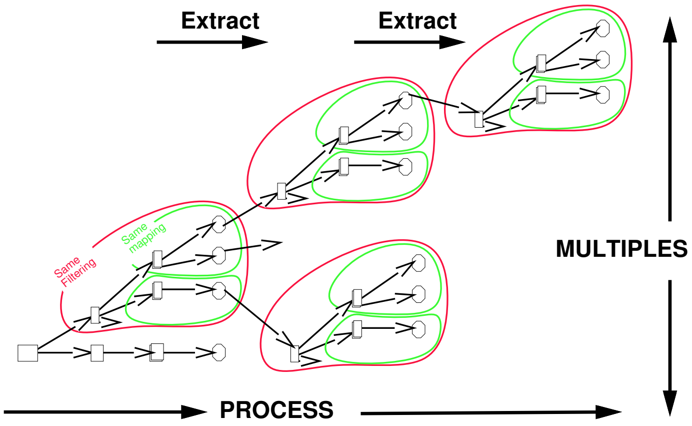

Figure 8. Graph depicting an Extraction hierarchy and the dataflow processes mapped against multiples

5. RELATED ISSUES IN VISUALIZATION MULTIPLES – A CHECKLIST?

It is interesting to note that the different visualizations of the aforementioned classification may be described in a graph of 'process' against 'multiples'. This is shown in Figure 7 where the dataflow process is drawn on the horizontal axis. This fits in well with an hierarchical extraction paradigm (Figure 8). Within such an exploration method, the user is given an overview of the information, and then may 'drill-down' the information and focus on subsets and features of the information. This works well when multiple views and direct manipulation are used,[3] here, the user may directly select and brush the information to be extracted and displayed in further views.

In summary we briefly present some related issues in visualization multiples, they form the start of a checklist for performing multiple-view visualization.

Multiple views should be used to display the same information in separated displays. The overlay technique is also beneficial – to provide a within-view comparison – however, if the replacement strategy is to be used (in visualization exploration) it should be used with a history mechanism.

It is useful to note that there could easily be an 'explosion of views', if for example, a new view pops-up whenever the user *touches* the parameters. This would be annoying, and in practice the important landmark visualization should be replicated and viewed on screen, with the other less-important and intermediate views iconised or deleted from the session.

Multiform views enable different visual forms to be displayed. These may include (1) Abstract or structural representations, (2) distortion techniques or (3) methods that display and visualize the temporal variable in the spatial domain.

Interaction is another powerful exploration tool, enabling the user to directly manipulate and uncover aspects of the displayed information.

Dynamically altering the multiform views may be a useful aid to visualization exploration. Such methods allow the user to alter the data representation by directly moving or changing manipulators attached around the objects. For example, some elements may be reduced in size, so to emphasize other parts of the display. This may be called 'selective dynamic manipulation'.[31]

Coupling of the information in the views should also be used, enabling joint manipulation and brushing of data.

The main issues here include (1) what is coupled together: individual objects or the viewport projection (to jointly rotate each 3D view) (2) how the elements are selected, whether using a lasso method, selected individually or brushed, and (3) who and how the coupling is initiated, whether automatically by the system, or specifically, on a per-object or per-operation basis. For more information about coupling see.[10]

Data Hierarchy approaches to exploration are beneficial. In such an investigation the information is displayed in full, then subset into smaller (more specialized) datasets, to focus on the feature of interest. The issues here are to focus in on the relevant information, to extract and specialize the features, to intuitively interact with the information in real time. Thus, techniques may be used that zoom into an area of interest, enlarge a specific section of the data, and reduce or compress the amount of data enabling the large datasets to be interactively investigated.

Management of the multiples should be handled by the visualization system. This is necessary because the many displays clutter up the window space, thus methods should be used that enable the user to understand how each multiple relates to the visualization exploration.

In an exploration setup it is beneficial to have a manager that (1) holds the previous experiments, so the user can view or adapt a previous experiment; (2) organises the displays on the screen, perhaps using a spreadsheet metaphor, or at the least by some sort of naming scheme; and (3) automatically (or semi-automatically) generates the multiple views, to make the replication operation easy, so that the user focuses on the displayed information rather than the visualization process itself.

6. CONCLUSION

We encourage the use of multiple views to provide different windows depicting the same data. They aid correct dissemination, encourage scientific exploration, provide alternative viewpoints and comparison of images and are a tool for collaboration.

It is true that many of the popular dataflow systems allow multiple algorithms and mapping methods to be applied to the data, but it is not so easy to generate multiple views (there are user overheads in duplicating and connecting the modules). A system should encourage the use of multiple views.

Multiform views, especially those that represent abstract or structural views, may enable occluded objects (otherwise unseen) to be selected and manipulated or brushed. These 'control abstractions' are often individually meaningless and must be used in conjunction with other forms.

Thus, it is useful to couple the views together. Context information is regained and the information may appear less-abstract in nature when related to a parallel view. However, the system should aid the user by automatically coupling objects and views together, and should help the user to generate and manage the multiple views on the data, encouraging a new 'multiple window' way of working.

We have categorised *where* and *how* multiple realizations of the same information may be generated and have presented different aspects of multiple-view visualization.

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REFERENCES

1. Edward R. Tufte. *Visual Explanations – Images and Quantities, Evidence and Narriative*. Graphics Press, 1997.
2. Edward R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, 1983.
3. Jonathan C. Roberts. Waltz: an exploratory visualization tool for volume data using multiform abstract displays. *Visual Data Exploration and Analysis V, Proceedings of SPIE Vol. 3298*, pages 112–122, January 1998.
4. Roni Yagel, David S. Ebert, James N. Scott, and Yair Kurzion. Grouping volume renderers for enhanced visualization in computational fluid dynamics. *IEEE Transactions on Visualization and Computer Graphics*, 1(2):117–132, June 1995.
5. Leonard R. Wanger, James A. Ferwerda, and Donald P. Greenberg. Perceiving spatial relationships in computer-generated images. *IEEE Computer Graphics and Applications*, 12(3):44–58, May 1992.
6. Alex T. Pang, Craig M. Wittenbrink, and Suresh K. Lodha. Approaches to uncertainty visualization. *The Visual Computer*, 13(8):370–390, 1997. ISSN 0178-2789.
7. M. Sheelagh, R. Carpendale, David J. Cowperthwaite, and F. David Fracchia. Extending Distortion Viewing from 2D to 3D. *IEEE Computer Graphics and Applications*, 17(4):42–51, 1997.
8. W. E. Lorensen. Geometric clipping using boolean textures. In Gregory M. Nielson and Dan Bergeron, editors, *Proceedings of the Visualization '93 Conference*, pages 268–274. IEEE Computer Society Press, October 1993.
9. Ricardo S. Avila, Taosong He, Lichan Hong, Arie E. Kaufman, Hanspeter Pfister, Claudio Silva, Lisa M. Sobierajski, and Sidney Wang. Volvis: A diversified volume visualization system. In *Proceedings Visualization '94*, pages 31–38. IEEE Computer Society Press, 1994.
10. Jonathan C. Roberts. On Encouraging Coupled Views for Visualization Exploration. In Robert F. Erbacher, Philip Chen, and Craig Wittenbrink, editors, *Visual Data Exploration and Analysis VI, Proceedings of SPIE*, volume 3643, pages 14–24. IS&T and SPIE, January 1999.
11. Andreas Buja, John Alan McDonald, John Michalak, and Werner Stuetzle. Interactive data visualization using focusing and linking. In *Proceedings Visualization '91*, pages 156–163. IEEE Computer Society Press, 1991.
12. Matthew O. Ward. XmdvTool: Integrating multiple methods for visualizing multivariate data. In *Proceedings Visualization '94*, pages 326–333. IEEE Computer Society Press, 1994.
13. Allen R. Martin and Matthew O. Ward. High dimensional brushing for interactive exploration of multivariate data. In *Proceedings Visualization '95*, pages 271–278. IEEE Computer Society Press, 1995.
14. Allan S. Jacobson, Andrew L. Berkin, and Martin N. Orton. LinkWinds: Interactive scientific data analysis and visualization. *Communications of the ACM*, 37(4):43–52, April 1994.
15. *Spreadsheets for images*. ACM SIGGRAPH, July 1994.
16. Ken Brodlie, Andrew Poon, Helen Wright, Lesley Brankin, Greg Banecki, and Alan Gay. GRASPARC – a problem solving environment integrating computation and visualization. In *Proceedings Visualization '93*, pages 102–109. IEEE Computer Society Press, 1993.
17. Michael Stonebraker, Jolly Chen, Nobuko Nathan, Caroline Paxon, Alan Su, and Jiang Wu. Tioga: A database-oriented visualization tool. In *Proceedings Visualization '93*, pages 86–93. IEEE Computer Society Press, 1993.
18. James Patten and Kwan-Liu Ma. A graph based interface for representing volume visualization results. In *Graphics Interface*, pages 117–124, June 1998.
19. Jonathan C. Roberts and Nick Ryan. Alternative archaeological representations within virtual worlds. In *The Fourth UK VR-SIG Conference – Brunel University*, November 1997.
20. Al Globus and Eric Raible. Fourteen ways to say nothing with scientific visualization. *Computer — IEEE Computer Society*, 27(7):86–88, July 1994.
21. Hans-Georg Pagendarm and Frits H. Post. Comparative visualization - approaches and examples. In *Fifth Eurographics Workshop on Visualization in Scientific Computing*, May 1994.
22. Gudrun J. Klinker. An environment for telecollaborative data exploration. In *Proceedings Visualization '93*, pages 110–117. IEEE Computer Society Press, 1993.
23. Jason D. Wood, Helen Wright, and Ken W. Brodlie. Collaborative visualization. In Roni Yagel and Hans Hagen, editors, *IEEE Visualization '97*, pages 253–260. IEEE, November 1997.
24. C. Upson, T. Faulhaber, D. Kamins, D. Schlegel, D. Laidlaw, F. Vroom, R. Gurwitz, and A. van Dam. The application visualization system: A computational environment for scientific visualization. *IEEE Computer Graphics and Applications*, 9(4):30–42, 1989.

25. R. B. Haber and D. A. McNabb. Visualization idioms: A conceptual model for scientific visualization systems. In B. Shriver, G. M. Nielson, and L. J. Rosenblum, editors, *Visualization in Scientific Computing*, pages 74–93. IEEE Computer Society Press, 1990.
26. Theo van Walsum, Frits H. Post, Deborah Silver, and Frank J. Post. Feature extraction and iconic visualization. *IEEE Transactions on Visualization and Computer Graphics*, 2(2):111–119, June 1996.
27. Deborah Silver. Object-oriented visualization. *IEEE Computer Graphics and Applications*, 15(3):54–62, May 1995.
28. Jacques Bertin. *Semiology of Graphics, translation from Sémilogie graphique (1967)*. The University of Winsonsin Press, 1983. William J. Berg (Translator).
29. Jacques Bertin. *Graphics and graphic information-processing*. Walter de Gruyter, 1981. William J. Berg and Paul Scott (Translators).
30. M. Sheelagh, R. Carpendale, David J. Cowperthwaite, and F. David Fracchia. Distortion viewing techniques for 3-dimensional data. In Stuart Card, Stephen Eick, and Nahum Gershon, editors, *Proceedings '96 Information Visualization*, pages 46–53. IEEE Computer Society Press, 1996.
31. Mei C. Chuah, Steven F. Roth, Joe Mattis, and John Kolojejchick. SDM: Selective dynamic manipulation of visualizations. In *Proceedings of the ACM Symposium on User Interface Software and Technology*, 3D User Interfaces, pages 61–70, 1995.