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Laramee, RS, Carr, H, Chen, M et al. (2014) Future Challenges and Unsolved Problems in Multi-field Visualization. In: UNSPECIFIED Mathematics and Visualization, 37. Springer, London, pp. 205-211. ISBN: 978-1-4471-6496-8. ISSN: 1612-3786. EISSN: 2197-666X.

https://doi.org/10.1007/978-1-4471-6497-5_19

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Future Challenges and Unsolved Problems (in Multi-Field Visualization

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1 Introduction

Robert S Laramee:

Evaluation, solved and unsolved problems, and future directions are popular themes pervading the visualization community over the last decade. The top unsolved problems in both scientific and information visualization was the subject of an IEEE Visualization Conference panel in 2004 [10]. The future of graphics hardware was another important topic of discussion the same year [6]. The subject of how to evaluate visualization returned a few years later [3, 12]. Chris Johnson published a list of top problems in scientific visualization research [4]. This was followed up by report of both past achievements and future challenges in visualization research as well as financial support recommendations to the National Science Foundation (NSF) and National Institute of Health (NIH) [5]. C. Chen recently published the first list of top unsolved information visualization problems [1]. Future research directions of topology-based visualization was also a major theme of a workshop on topology-based methods [2, 11]. Laramee and Kosara published a list of top future challenges in human-centered visualization [7].

These pervasive themes coincide roughly with the 20^{th} anniversary of what is often recognized as the start of visualization in computing as a distinct field of research [8]. Consensus is growing that some fundamental problems have been solved and a re-alignment including new directions is sought. In accordance to this redirection, we present a list of top unsolved problems and future challenges in multi-field visualization. Our list draws upon discussions at the Dagstuhl Workshop in Scientific Visualization 2011 as well as our own first hand experiences.

2 Challenges

Hamish Carr on Topology:

While scalar and vector topology have received a lot of attention, multifield topology and visualisation techniques based on it have not. Moreover, where a large body of literature existed on topological analysis of scalar or vector data, the same is not true for multi-field topology. For example, Morse-Smale complexes are based on gradient lines, but in multifield data, the gradient is replaced by the Jacobian, a tensor quantity, and it is far from clear what the equivalent of a gradient line might be. Even were there to be an equivalent, the mapping to features in the underlying phenomena is not clear - where the Morse-Smale complex can be understood in terms of drainage patterns, such metaphors are not immediately obvious for multifields. As a result, the challenges related to multifield topology are manifold, including developing the underlying mathematics, insight and metaphors, as well as the usual topological feature descriptions, algorithms, data structures, visualization methods, and interfaces.

Min Chen on Standard Protocols:

One of the most fundamental challenges in multi-field visualization is to establish a set of intuitive and effective protocols for using visual channels. Given a multi-field data set, a "brute-force" visual design would be to juxtapose the visualizations of individual fields. However, such a visual design cannot support many comparative or combinational tasks effectively because of the difficulties in visual search for spatially corresponding positions across many images. An alternative approach is to depict information in the multi-fields in a comparative or combinational manner. However, as existing visual representations have largely been developed for single field visualization, combining such visual representations into a single visualization will inevitable cause conflicts in using visual channels. For instance, if the color channels are being used for one field, the other fields may have to make use of less desirable channels. Furthermore, there is no commonly agreeable means to depict the effect of constructive operations on different fields. For example, if one has used the texture channel to depict the similarity and difference between two scalar fields, perhaps one should not use such a channel for depicting the addition or union of these two fields in the same application. Hence, we may challenge ourselves with the following questions. Should there be some standard (or de facto standard) visual designs or visual metaphors for depicting different constructive operators (e.g., addition, subtraction, mean, OR, AND, etc.)? Should there be some standard (or de facto standard) protocols for visualizing some common configurations of multi-fields, such as two or a few scalar fields, on scalar field and one vector field, and so on? Can we evolve such protocols from some ad hoc visual effects, to commonly adopted visual metaphors, and eventually to standardized visual languages?

Helwig Hauser on Multi-dimensional, Scientific Visualization:

One common notion of scientific data is to consider it as a mapping of independent variables – usually space and/or time in scientific visualization – to a set of dependent values, very often resembling some measurements or computational simulation results that represent different aspects of a natural or man made phenomenon. Traditionally, neither the spatio-temporal domain nor the dependent variables are of higher dimensionality. A larger number of dependent values, however, leading to multi-variate data (as a special case of multi-field data), however, has recently lead to interesting visualization research. Highly interesting and very challenging, also, the emergence of higher-dimensional scientific data (in the sense of a higher-dimensional domain) leads to new visualization questions. Multi-run/ensemble simulation data, for example, includes parameters as additional independent variables. New approaches are needed to deal with this situation, especially in the context of scientific visualization, where generally a stronger and more immediate relation is present between the domain of the data and the visualization space (and to establish this relation in an effective way becomes more challenging, obviously, the more dimensions the data domain has). The integration of descriptive statistics, for example, is one opportunity that allows to perform a linked interactive visual analysis both on aggregation level as well as on the original multi-run data. It seems clear, however, that more research is needed to more thoroughly discuss, what the best possible approaches are.

Robert S Laramee on Spatial Integration:

Another major challenge of multi-field visualization is the integration (or coupling) of two or more data fields into the same spatial domain from which they originate. A common example is from computational fluid dynamics (CFD) [9]. CFD simulation data generally contains many attributes, e.g., flow velocity, pressure, temperature, kinetic energy, etc. And each multi-attribute data sample is associated with the same spatial domain. It is tempting to separate each attribute into its own visualization space, either abstract or scientific. However, integration of the data attributes into the same spatial domain from which they stem offers distinct advantages. However, how can such an integration be done in a meaningful and helpful way without overcrowding the visualization space?

Lars Linsen on Intuitive Visual Exploration of Multi-variate Features:

Features may have a complicated geometrical structure in the multi-dimensional attribute space. Extracting those features interactively is often tedious, if not impossible. Automatic components can help to compute such features. However, an intuitive visual exploration of such features is crucial to the user's understanding. What is the object space representation and, more importantly, what attribute values correspond to such a feature? Are their other features that are related, which possibly should have been merged by the automatic component? How homogeneous is a feature? Are their sub-regions within a feature that allow for further splitting of the feature? Such questions shall a user be able to answer when exploring the multi-field data. Intuitive visual encodings in object- and attribute-space as well as intuitive interaction mechanisms need to be provided.

Klaus Mueller on Channel Fusion:

The term "channel" is often used in the context of color images, comprised of a regular array of RGB color pixels. By mapping these 3D vector data to the three display primaries, channel fusion can occur directly in the viewers visual system, engaging the tristimulus processes of color perception. However, once the number of channels exceeds three, the fusion must be externalized via some analysis and subsequent transformation to RGB color for display. In essence, one may regard this fusion as a mapping from H to L where H is the original and L the reduced number of channels, with the latter being three in this case. These types of reductive mappings are often encountered in low-dimensional embeddings of high-dimensional data. Such embeddings are ill-defined once the number of significant principal components in H is greater than L, which is most often the case. Hence, when applying such techniques for channel fusion, one must make certain trade-offs which are also determined by the type of dimension reduction technique used. There are a great many of these, some linear (PCA, LDA, and others) and some non-linear (MDS, LLE, and others). The former require some kind of component thresholding for channel reduction, while the latter suffer from distortion problems. Since in our specific case, both thresholding and distortion will affect the color composition of the display – as opposed to the spatial layout – the effects are possibly more noticeable. This leaves much room for further study. For example, it will be interesting to examine to what extent feature analysis and user-defined or learned constraints can be used to alleviate or control the adverse effects of dimension reduction in color display. A targeted and intuitive user interface might be needed to determine the appropriate fusion mapping. Finally, since gradients and higher-order derivatives are often employed in the graphics rendering of the data, it will be beneficial to study how the tensor resulting from high-dimensional derivative calculus can be interpreted for shading and other gradient-enhancements in 3D.

Vijay Natarajan on Categorizing Relationships between Fields:

Scientists try to understand physical phenomena by studying the relationship between multiple quantities measured over a region of interest. A characterization of the relationship between the measured/computed quantities will greatly enable the design of effective techniques for multifield visualization. For example, the dependence between fields could be linear or non-linear, the fields could be statistically correlated, or the relationship can be inferred using information theoretic measures. A challenging problem in this context is the categorization of different types of relationships and the design of measures that quantify the relationship in each case.

Harald Obermaier on Field Prioritization:

Modern simulation and measurement techniques can generate large numbers of fields spanning a wide range of types. While some of these fields may be crucial for the understanding and analysis of the behavior of the system, others may be used to enhance or extend the insights gained by multi-field visualization, while further others are largely irrelevant from an application or visualization point-of-view. Such a static prioritization of fields in a multi-field setting limits the potential of in-depth visual analysis especially in the area of application-driven data analysis, where the focus of interest can change during exploration. Future research in (interactive) multi-field visualization has to develop and integrate techniques that allow for a dynamically changing focus or field prioritization. Especially for inhomogeneous field types the question remains, how and whether multi-field visualization can incorporate such dynamic changes in an intuitive and expressive way.

Ronald Peikert on Feature-based Visualization:

The challenges of multi-field visualization also extend to the area of feature-based visualization. Many useful techniques have been developed for finding inherent features in scientific data. They typically operate on one or at most two scalar, vector or tensor fields. In most cases, such feature detectors are not based on concepts that easily generalize to larger multi-fields containing additional variables. A feature can in the simplest case be represented by scalar field indicating the presence or absence of the feature or, alternatively, a probability for the feature to be present at a given location. But even with this simple notion of a feature, it is not clear how to combine a large number of them in a single visualization. To visualize their statistics, e.g., using uncertainty visualization techniques, can be a solution, but only if the features are based on the same physical quantities and can therefore be directly compared. New approaches are needed if the underlying multi-field represents a multitude of physical quantities, in which case features having different meanings are to be combined in one visualization. Extending other feature concepts, such as geometric or topological ones, to multi-fields will be an additional challenge.

Eugene Zhang on Tensor Fields and their Derived Fields:

Given a tensor field of some order, it is possible to derive a number of tensor fields from it. Examples of this includes the spatial gradient, the Laplacian, and the divergence. The derived fields contain rich information and provide great insight to the original field. However, the derived fields often are of a different order. This leads to the need of simultaneous analysis and visualization of multiple tensor fields of different types. Most existing work on multi-field analysis focuses on fields of the same type, and there has not been much research on higher-order tensor fields due to the mathematical and physics background it often requires.

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