Report from Dagstuhl Seminar 14231

Scientific Visualization

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14231 "Scientific Visualization". It includes a discussion of the motivation and overall organization, an abstract from each of the participants, and a report from each of the working groups.

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1 Executive Summary

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Scientific Visualization (SV) is the transformation of digital data, derived from observation or simulation, into readily comprehensible images, and has proven to play an indispensable part of the scientific discovery process in many fields of contemporary science. Since its inception two decades ago, the techniques of Scientific Visualization have aided scientists, engineers, medical practitioners, and others in the study of a wide variety of data including, for example, high-performance computing simulations, measured data from scanners (CT, MR, confocal microscopy, satellites), internet traffic, and financial records. One of the important themes being nurtured under the aegis of Scientific Visualization is the utilization of the broad bandwidth of the human sensory system in steering and interpreting complex processes and simulations involving voluminous data across diverse scientific disciplines. Since vision dominates our sensory input, strong efforts have been made to bring the mathematical abstraction and modeling to our eyes through the mediation of computer graphics. This interplay between various application areas and their specific problem-solving visualization techniques has been the goal of all the Dagstuhl Scientific Visualization seminars and was emphasized in the seminar which took place June 1–6, 2014.

Our seminar was focused on four research themes that will have significant impact in the coming years. These four themes reflect the heterogeneous structure of Scientific Visualization and the current unsolved problems in the field. They represent cross-cutting topic areas where applications influence basic research questions on one hand while basic research drives applications on the other. This cross-cutting feature makes Dagstuhl a unique setting in the research community, as the scientific coverage of the seminar is broader than other more focused workshops and seminars hosted at Dagstuhl while much more focused and forward-looking than general conferences. Our four themes were:

Uncertainty Visualization: Decision making, especially rapid decision making, is always made under uncertain conditions. As former English Statesman and Nobel Laureate (Literature), Winston Churchill said, "True genius resides in the capacity for evaluation of uncertain, hazardous, and conflicting information." and echoed by Nobel Prize winning physicist Richard Feynman, "What is not surrounded by uncertainty cannot be the truth." Uncertainty visualization seeks to provide a visual representation of errors and uncertainty for three-dimensional visualizations. Challenges include the inherent difficulty in defining, characterizing, and controlling comparisons among different data sets and in part to the corresponding error and uncertainty in the experimental, simulation, and/or visualization processes.

Integrated Multi-field Visualization: The output of the majority of computational science and engineering simulations is typically a combination of fields, generally called multi-field data, involving a number of scalar fields, vector fields, or tensor fields. Similarly, data collected experimentally is often multi-field in nature (and from multiple sources). The ability to effectively visualize multiple fields simultaneously, for both computational and experimental data, can greatly enhance scientific analysis and understanding. Multi-scale problems with scale differences of several orders of magnitude in computational fluid dynamics, material science, nanotechnology, biomedical engineering and proteomics pose challenging problems for data analysis. The state of the art in multi-scale visualization considerably lags behind that of multi-scale simulation. Novel solutions to multi-scale and multi-field visualization problems have the potential for a large impact on scientific endeavors.

Environmental Scientific Visualization: Environmental scientific visualization or environmental visualization refers to a collection of visualization applications that deal with captured and simulated data in climate research, atmospheric and environmental sciences, earth science, geophysics and seismic research, oceanography, and the energy industry (e. g., oil, gas and renewable energy). Research in these application domains has a huge impact on mankind, and typically faces serious challenges of data deluge (e. g., very large volumes of multi-spectral satellite images, large data collections from different sensor types, ensemble computation of very large simulation models, scattered, time-varying, multi-modal data in seismic research). In comparison with biomedical visualization and small-to-medium scale computational fluid dynamics, the effort for developing visualization techniques for such applications has not been compatible with the importance and scale of the underlying scientific activities in these application domains. Scientific progress in the areas of the environment and sustainability is critical in the solution of global problems and scientific visualization has great potential to support this progress.

Scientific Foundation of Visualization: The rapid advances in scientific visualization have resulted in a large collection of visual designs (e. g., for flow visualization), algorithms (e. g., for volume rendering), and software tools and development kits. There have also been some scattered investigations into the theoretic and perceptual aspects of visualization. However, many fundamental questions remain unanswered, such as, why is one visual design more effective than another, can visual designs be optimized and how, what is the role of visualization in a scientific workflow and how can such a role be formalized in a scientific workflow, can visualization quality be measured quantitatively and how, and what is the most effective way to conduct perceptual and usability studies involving domain experts? With the experience of delivering technical advances over the past two decades, it is timely for the visualization community to address these fundamental questions with a consorted effort. Such an effort will be critical to the long-term development of the subject, especially in building a scientific foundation for the subject.

The format of the seminar was two-part: having groups of four to five shorter talks followed by a panel of the speakers which encouraged discussion and breakout groups on the four topics as well as topics which came up at the meeting. The scientific presentations were scheduled at the beginning of the week in order to simulate the discussions from a broad perceptive. Unlike the typical arrangement, all presentations in each session were given in sequence without a short Q&A session at the end of each talk. Instead, all speakers of a session were invited to sit on the stage after the presentation, and answer questions in a manner similar to panel discussions. This format successfully brought senior and junior researchers onto the same platform, and enabled researchers to seek a generic and deep understanding through their questions and answers. It also stimulated very long, intense, and fruitful discussions that were embraced by all participants. The breakout groups focused on the general themes and are reported in the following sections.

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3 Overview of Talks

3.1 Implications of Numerical and Data Intensive Technology Trends on Environmental Scientific Visualization

James Ahrens (Los Alamos National Lab., US)

Technology trends in numerically and data intensive computing have the potential to reshape and significantly improve how we visualize and analyze the massive data streams resulting from environmental scientific simulations. Next generation exascale supercomputers are bound by power and storage constraints, requiring our current visualization approach to transform from the general post-processing analysis of raw results to the automated generation of in situ reduced-sized data products during a simulation run. Current data intensive technology trends provide inexpensive access to powerful commodity parallel computing resources for an important class of structured problems. In addition, intuitive, web-based and query-driven interfaces to access and understand data are now the norm. In this talk, I will describe these trends in more detail and challenge the community to think about how these trends integrate with their research approaches. As an example, I will present a novel scientific visualization and analysis process that leverages both numerical and data intensive technology trends.

3.2 Reconstruction of Functions from Simplified Morse-Smale Complexes

Georges-Pierre Bonneau (INRIA Rhône-Alpes, FR)

We will give an overview of our on-going work on topology-based visualization of scalar data. In this area we propose the use of piecewise polynomials interpolants to reconstruct data based on their simplified Morse-Smale complexes. We show how it is possible to define monotonic polynomial interpolants that can be used as patches to represent the data inside each Morse-Smale cells.

3.3 Exploring Glyph-based visualization for Multivariate and Multidimensional data

Rita Borgo (Swansea University, UK)

Simultaneous visualization of multi-dimensional and multivariate data is a complex task. An adequate choice of visual encoding must keep into consideration both expressiveness (e. g. number of parameters easily representable), and comprehensibility of design (e. g. interpretation). Glyph, or iconic, visualization represents an attempt at encoding multivariate information in a comprehensible format, allowing multiple values to be encoded in the parameters of the glyphs. Geometric encoding allows to integrate multiple variables within a single item and therefore the creation of a unique image, or signature, to be constructed for each data point. However, as the number of data points displayed increases, the amount of visible variation per glyph decreases, potentially obscuring the visibility of interesting structures and patterns in the data. When locality is lost global structures can still emerge by exploiting local characteristic of glyph's geometry to obtain texturing effects, going beyond the expressive extent of the single glyph.

The Glyph paradigm remains to be productive in different contexts from scientific and information visualization to computer vision. Several questions still remain open in terms of design, usability, learnability. In this talk I will review most relevant contributions in glyph-based visualization, report and discuss on recent results and set out future line of work to bring forward research in the field.

3.4 Evolutionary Visual Exploration

Nadia Boukhelifa (University Paris-Sud – Gif sur Yvette, FR)

Joint work of Boukhelifa, Nadia; Bezerianos, Anastasia; Cancino, Waldo; Lutton, Evelyne
Main reference N. Boukhelifa, Waldo Gonzalo Cancino Ticona, A. Bezerianos, E. Lutton, "Evolutionary Visual Exploration: Evaluation With Expert Users," iComputer Graphics Forum, 32(3pt1):31–40, 2013.
URL http://dx.doi.org/10.1111/cgf.12090

The purpose of visual exploration is to find meaningful patterns in the data which can then lead to insight. In a high-dimensionality context, this task becomes rather challenging as viewers may be faced with a large space of alternative views on the data. In this talk I will describe a framework that combines visual analytics with stochastic optimisation to aid the exploration of multidimensional datasets characterised by a large number of possible views or projections. I will present initial results and highlight some challenges in designing visual analytics tools that combine user input and automatically calculated metrics to guide user exploration.

3.5 <Mathematical, Visual> Foundations of <Visualisation, Mathematics>

Hamish Carr (University of Leeds, UK)

We are accustomed to thinking of visualisation as being built on mathematics, but the truth is that mathematics is also built on visualisation and visual thinking. As a result, visualisation drives mathematics nearly as much as mathematics drives visualisation. I will discuss some aspects of this reciprocal relationship.

3.6 Analyzing User Interactions for Data and User Modeling

Remco Chang (Tufts University, US)

User interactions with a visualization system reflect a great deal of the user's reasoning process and personality. In this talk, I will present techniques that we have developed to analyze the user's interactions in order to (a) model the data in the form of metric learning that reflect a user's understanding of high-dimensional data, and (b) model the user and learn the user's individual differences and analysis behavior. In addition, I will discuss the relevant cognitive traits and states that influence a user's analysis process and conclude by suggesting how this research form the basis of mixed-initiative visual analysis systems.

3.7 Some thoughts on using signs to think

Jian Chen (University of Maryland, Baltimore Country, US)

From Bertin's semiotics theory to MacKinlay's automatic design of encoding based on symbolic rankings to the commercial software of Tableau, the study of signs has had great impact on how we understand large abstract information in the so-called information visualization. In scientific visualization, implicit and explicit in our visualization of spatial data are also symbols. With the realm of the computing moves from petascale into the exascale, beyond the challenges of efficiently executing scientific rendering and simulation, perhaps even greater, there are challenges of visualization and interpretation of results produced by massive heterogeneous datasets. Deriving insights for diverse analytical tasks and results have been forced to struggle with evolving visualizations that are beyond our mental grasp.

In this talk, I will address evolving visualization issues. I think the cornerstone is to support human limited working memory with sign manipulation. I will discuss how the theory of sign can be extended to unify scientific and information visualizations and analytical process. I will discuss issues related to the tradeoffs between physical large space and virtual large space + spatial index. And I will also discuss the categories of visual dimensions or metaphors or abstractions that we use to make data comprehensible in bat flight motion analysis.

3.8 Exascale Computing and Uncertainty Visualization

Hank Childs (University of Oregon, US)

Exascale computers – computers that can do 10^{18} floating point operations per second – are predicted to arrive in the next four to six years. To field such a machine, hardware architects must make difficult decisions on where to spend their money, between network, I/O, memory, and compute. Of these four factors, I/O bandwidth is increasingly viewed as a luxury, and disks are not keeping pace with overall machine improvement. Reduced I/O bandwidth creates an I/O bottleneck, and data compression is one technique frequently considered for this emerging problem. With this presentation, I will discuss the opportunity for uncertainty visualization in this compression process and the resulting visualizations.

3.9 Representing Chronological Events with Heatmaps

João Luiz Dihl Comba (Federal University of Rio Grande do Sul, BR)

Heatmaps are well-known visual representations of data that employ a color- coded array of values disposed in a matrix format. In this talk I will review my recent experience on using heat maps to describe chronological events over different types of datasets. In the first example, I will show how heatmaps were used to encode heart-rate effort of several people during a running race. There are many ways to explore the data disposed in this heat map, and I will discuss several interesting alternatives to look at this data from different perspectives. The second example is related to the problem of monitoring forest ecosystems using digital cameras, which allows the study several aspects of tree phenology, such as leaf expansion and leaf fall. Since phenological phenomena are cyclic, the comparative analysis of successive years is largely used to identify interesting variation on annual patterns that have been related, for instance, to changes on temperature due to global warming. Usually, phenologists draw, for each year, a 2D-plot of the average of a given quantity in an image (e. g., average of green information) against the days of the year. I will show how a special-type of heat map, called Chronological Percentage Maps (CPMs), is a more expressive and compact visual representation to support phenological analysis from vegetation digital images. We demonstrate the use of CPMs in three different datasets, comprising data of up to 9 consecutive years, and discuss the further applications on phenology.

3.10 A hierarchical approach to topological data analysis and visualization

Leila De Floriani (University of Genova, IT)

Topology plays a very relevant role in analyzing shapes defined by a finite set of data points in three dimensions and higher and discretized as simplical or cell complexes. In this talk, I discuss the application of algebraic topology tools, namely homology and topological structural descriptors rooted in Morse theory, to the analysis and understanding of such shapes. The fundamental issues in computing topological invariants and descriptors for real data sets are the size and the dimension of the data. This poses challenging theoretical and computational problems. This talk focuses on hierarchical approaches to homology computation and to the construction of multi-resolution topological descriptors which highly improve both the effectiveness and the efficiency of such topological tools.

3.11 Recent Multifield Applications in Biophysics and Future Visualization Engineering Research

Thomas Ertl (Universität Stuttgart, DE)

This talk reports on recent multifield visualizations performed in the context of a biophysics application and on an engineering-type research proposal for quantifying visual computing systems. Our physics colleagues in the collaborative research center on particle simulation are interested in understanding new methods for DNA sequencing based on nanopores. They perform molecular dynamics simulations of DNA strands getting pulled through a nanopore by an electric field and surrounded by Ka+ ions. The simulation confirms that DNA consisting of CG base pairs only results in a lower measured current than DNA consisting of AT base pairs only. A visual analysis of the aggregated density and velocity fields confirms that this is due to the lower mobility of ions moving close to the CG DNA groove than the more outside and more freely moving ions in the AT case. Closer inspection of the ion flux vector glyphs reveals an unexpected phenomenon where ions seem to move against the electric field. Predicting the application performance of a visualization application running on a complex visual computing hardware is difficult due the manifold variations of algorithms, application parameters, and hardware setups. We propose to predict such interactive application performance based on highly parameterized performance models and collections of performance statistics. We also argue that the engineering aspects of building systems in general have been underrated in visualization research.

3.12 Contractible Parallel Coordinates for Sparse Modeling

Issei Fujishiro (Keio University, JP)

Sparse modeling is intended to exploit the inherent sparseness that can be commonly observed in huge quantities of high-dimensional scientific data, and thereby enabling to extract the maximum amount of information from the data effectively and efficiently. In order to come up with a visualization platform for facilitating such sparse modeling, we have focused primarily on the contractility of parallel coordinates. In this talk, we will present two promising schemes: one is to use spectral graph analysis of correlation among axes and the other is to rely on biclustering to identify clusters of data samples and groups of highly-correlated axes simultaneously. Enhanced visualization capabilities of contractible parallel coordinates will also be discussed.

3.13 Topological Visualization of Multivariate Data

Christoph Garth (TU Kaiserslautern, DE)

The talk briefly describes recent research on the characterization of joint extremal structures of multiple scalar functions over a common domain. Adapted from concepts introduced in the field of non-linear optimization, and motivated by applications in flow and ensemble visualization, Pareto sets over multivariate scalar fields capture jointly minimal and maximal structures. Furthermore, a brief survey is given on open problems in multivariate topological visualization.

3.14 Interactive Visualization of High Resolution Planetary Data

Andreas Gerndt (DLR – Braunschweig, DE)

Earth and planetary exploration missions produce huge amount of data from different sensors and cameras. Those datasets are stored in open access databases but are not exploited at all as appropriate architectures and interactive tools for remote access and analysis are missing. One approach is to convert terrain data in LOD data structure for interactive visualization in virtual environments. On top of that, additional methods can offer tools to measure features and retro-deform the surface to assess geodetic hypotheses. Haptics rendering can improve perception and speed-up the workflow. Such environments can be used to incorporate more data types like sub-surface data and atmospheric science data. Also rover operations can be planned in advance and during on- going missions. But not only the data but also the scientist are distributed all over the world. 3D tele-presence can also bridge this problem to discuss scientific findings in immersive virtual environments.

3.15 Towards Comprehensible Modeling

Michael Gleicher (University of Wisconsin – Madison, US)

Building (mathematical) models is one of the main ways we deal with large amounts of data. There is a diverse range of usages of models, and a myriad of mathematical modeling methods have been developed. Some goals of modeling are well understood, for example predictive accuracy, descriptive fidelity, and robust generalizability. However, one aspect of modeling seems to be under-explored: comprehensibility, or, more generally, usability. Comprehensibility of models is likely to become more important as we expand the range of applications and users where modeling is applied, enlarge the range and sophistication of modeling techniques, and attempt to model increasingly complex phenomena and larger data sets.

In this talk, I will raise the issue of comprehensibility in modeling as a new core challenge for visualization research. I will attempt to raise some of the questions involved, in part through examples of our early attempts to address them. I will discuss our limited understanding of model comprehensibility, I will describe some initial efforts to give users control over the tradeoffs between the comprehensibility of models and more traditional model qualities, such as predictive accuracy, through the development of new analytic approaches. I will show some of our attempts to create visualization tools specifically designed to help users understand models.

3.16 Comparative and Quantitative Visualization in Material Sciences

Eduard Groeller (TU Wien, AT)

Materials like multi-material components (MMC) and carbon fiber reinforced polymers (CFRP) require novel non-destructive testing approaches. 3D XRay Computed Tomography (XCT) and X-Ray Fluorescence (XRF) are scanning modalities for the analysis and visualization of features and defects in industrial work pieces. Several application scenarios in the area of nondestructive testing are treated in this respect. Examples are porosity maps, mean objects, and fuzzy CT metrology. The rich data sources require integrated and aggregated visualization approaches. Despite various causes of uncertainty, quantitative visual representations are necessary. Additionally interactive visual inspections allow the domain expert to cope with data complexity. Due to the rapid development of scanning devices, material sciences and non-destructive testing constitute a challenging application domain for innovative visualization research. Potential research directions will be discussed at the end of the talk.

3.17 Uncertainty in medical imaging on the example of Electrical Impedance Tomography

Hans Hagen (TU Kaiserslautern, DE)

Electrical Impedance Tomography (EIT) is a fast, cheap, risk-free, and convenient imaging technique for conductivity changes in the body. It suffers from low spatial resolution and noise, and only displays a 2D projection of the 3D conductivity changes. Furthermore, image reconstruction from measurements is an ill-posed inverse problem.

Additionally, several causes introduce further uncertainty: Often, the source of an effect is not clear, for example breathing, cardiac activity, organ movement, or a change of the medical condition. Spatial correspondence to organ structures are unclear due to the low image resolution and the projection into 2D. Most importantly for lung researchers and clinicians, the anatomical lung boundary cannot be determined reliably.

In this talk, two of our efforts to tackle this uncertainty will be reported: First, a 3D visualization of patient-specific CT data, augmented with a multi-material segmentation, with an embedding of the time-dynamic EIT images. Second, a study concerning the spatial precision of lung and heart shape in EIT images compared to reference CT data.

3.18 Semi-abstract visualization of rich scientific data

Helwig Hauser (University of Bergen, NO)

In scientific visualization, we are used to mapping the spatial aspects of the data to the axes of the visualization space. As scientific data become more information-rich (e. g., by being time-dependent, multi-variate, or ensemble data), we also map non-spatial aspects of scientific data, following visualization designs which otherwise are known from information visualization (instead of a spatial visualization, or in addition). It seems worthwhile to also consider mixed strategies, where we consider semi-spatial, semi-abstract mapping strategies for visualizing scientific data and it may be promising to explore according opportunities more (as compared to classical mappings) even more in the future. In addition to bringing this thought (and discussion) to the seminar, we also look at selected examples of visualization designs which were inspired by this idea.

3.19 Liberate Visualization!

Hans-Christian Hege (Konrad-Zuse-Zentrum – Berlin, DE)

For cross-disciplinary exchange and public communication of an academic discipline, necessary prerequisites are clearly defined terms, conceptual clarity, a well-conceived taxonomy and a comprehensible division into sub-areas. Our young and transforming discipline does not yet fulfill these preconditions. This becomes particularly clear when looking at the division of the field into subfields, which currently is determined more by sociological and political than substantive considerations.

Instead of delving into the debate about a sensible definition of our sub-areas and their denominations, in this talk the title of our discipline, "visualization", shall be discussed. Its etymological roots, the Latin verb 'videre' and the noun 'visus', date back at least 3000 years. These Latin terms carried a multiplicity of meanings, which is still reflected in the variety of meanings of the English term 'vision'. The derived late Latin term "visualia", meaning 'organ of sight' or 'eye', has been used since the 4th century AC and 'visualis', meaning 'being attained by sight', since the 6th century AC. Both terms are precursors of the English words 'visual', 'to visualize' and 'visualization', which appeared in scientific texts in the 15th century, in the year 1817 and in 1883, respectively. The new English terms inherited the semantic ambiguities of the Latin antecedents. Particularly the two fundamental kinds of seeing are not distinguished: (1) seeing with the mind's eye, i. e. imagining things or conceiving mental images based on internal information, and (2) perceiving with the physical eye, i. e. sensing external visual information. Nowadays, were much finer distinctions are made, these broad terms often are less suited.

For instance, regarding external visualizations, one should differentiate whether the input information is internally represented (art works; visualizations of concepts, knowledge or mental images), or externally (photography; imaging; data visualization). The semantics of "visualization" in the public, however, is far from all these meanings. Concluding from the bestselling English books carrying "visualization" in their title, it denotes a specific internal visualization, namely a technique for focusing on positive mental images in order to achieve particular goals. But even in science, when talking or writing about external visualization, the term “visualization” often does not mean “data visualization”, but “imaging”, i. e. capturing physical observables with a device.

In conclusion, “visualization” and its Latin antecedents are very old terms, whose multiple meanings have changed only gradually since their invention. Nevertheless, since about 25 years our small community in computing science entitles its discipline “visualization” significantly confining the traditional meaning of the term. In order to facilitate cross-disciplinary and public communication, we should instead agree on a technical term that denotes our field of activity and thereby reliberate “visualization”.

3.20 Simplified vector field representations

Mario Hlawitschka (Universität Leipzig, DE)

We create simplified vector field representations by approximating fields using a pre-defined allowable error. We use these fields to derive visualizations of the data in a simplified way. On the other hand, these approximations can be seen as a simplification of the data that will serve as the basis for efficient implementations of various data analysis techniques.

3.21 Moment Invariants for Flow Fields Analysis

Ingrid Hotz (DLR – Braunschweig, DE)

The analysis of flow data is often guided by the search for characteristic structures with semantic meaning. In this work we consider structures as non-local flow patterns which can be defined in an analytical way with respect to some flow model; or they could be identified by a human observer. Flow analysis then means finding similar structures in the same or other datasets. The major challenges related to this task are to specify the notion of similarity and define respective pattern descriptors. While the descriptors should be invariant to certain transformations, as rotation and scaling, they should provide a similarity measure with respect to other transformations, as deformations. In this work, we use moment invariants as pattern descriptors.

3.22 Taking Stock of Visualization Research and Education

Christopher R. Johnson (University of Utah, US)

It has been more than ten years since I gave a presentation at a Dagstuhl Scientific Visualization Workshop that resulted in my Visualization Viewpoints article on visualization research challenges: C.R. Johnson. "Top Scientific Visualization Research Problems," In IEEE Computer Graphics and Applications: Visualization Viewpoints, Vol. 24, No. 4, pp. 13-17. July/August, 2004.

In this presentation, I will take stock of visualization research and education and explore both recent trends and possible future needs as we continue to advance as a field.

3.23 The Difficulties with Ensemble Visualization

Kenneth Joy (University of California – Davis, US)

Whereas historically, most visualization techniques have focused on the analysis of the output of simulations, advances in computational power now enable domain scientists to address conceptual and parametric uncertainty by running simulations multiple times in order to sufficiently sample the uncertain input space, or the uncertain model space. While these approaches help address conceptual model and parametric uncertainties, the ensemble datasets produced by this technique present a special challenge to visualization researchers as the ensemble dataset records a distribution of possible values for each location in the domain. Contemporary visualization approaches that rely solely on summary statistics (e. g., mean and variance) cannot convey the detailed information encoded in ensemble distributions that are paramount to ensemble analysis; summary statistics provide no information about modality classification and modality persistence. In this presentation, we review a number of techniques that address these model and parametric uncertainty analysis problems, and give examples of their usage.

3.24 Verifiable Visualization: Lessons Learned

Robert Michael Kirby (University of Utah, US)

Joint work of Kirby, Robert Michael; Etiene, Tiago Etiene; Silvia, Claudio

Visualization is often employed as part of the simulation science pipeline. It is the window through which scientists examine their data for deriving new science, and the lens used to view modeling and discretization interactions within their simulations. We advocate that as a component of the simulation science pipeline, visualization itself must be explicitly considered as part of the Validation and Verification (V&V) process. In this talk, we define V&V in the context of computational science, discuss the role of V&V in the scientific process, and present arguments for the need for "verifiable visualization". Using paradigms expressed within the CS&E community, we will attempt to express what a common "V&V in V" language might look like (as a component of possible scientific foundations of visualization). We will then summarize three verification case studies applied to visualization: verification of geometric accuracy in the isosurface extraction process, verification of topological consistency in the isosurface extraction process, and verification of the volume rendering visualization pipeline. We will conclude with some lessons learned in our search for "verifiable visualizations".

3.25 YURT: YURT Ultimate Reality Theater – Why?

David H. Laidlaw (Brown University, US)

L I will motivate and describe a novel 3D stereoscopic display currently nearing completion at Brown University. The display will match many of the perceptual abilities of the human visual system, and so will be, in a sense, an "ultimate" display device. The properties include: one arc-minute of spatial resolution, stereo, 60 frames per second, and a field of view that covers over 90% of the sphere of all viewing directions. The one gap is over the back of the head of a viewer looking at the main wall. The geometry of the display is similar to a yurt, with a full surround curved main wall approximately 16 feet in diameter, a conical partial ceiling, and a fully back-projected floor. All projection is done via 69 stereo 1920x1080 120 Hz projectors. Imagery will be blended to create seamless imagery, a first example of which I will show. We have dubbed the display YURT, for "YURT Ultimate Reality Theater."

3.26 Attribute Space Analysis for Multivariate SciVis Data

Heike Leitte (Universität Heidelberg, DE)

The interactive combination of scivis and infovis techniques proved a valuable tool for multifield analysis in scientific visualization. Many features only become apparent in attribute space and can be readily visualized through linking and brushing. One major issue of this technique is that it assumes a clear separation of features in attribute space, which is commonly not the case for data originating from scientific simulations or measurements on continuous domains. This data often forms large, more or less homogeneous structures in attribute space that are difficult to project. In my talk, I will explore novel directions to describe multidimensional pointclouds that take the continuous nature of the data into account.

3.27 Understanding, Uncertainty and Predictive Analytics

Ross Maciejewski (ASU – Tempe, US)

A key analytical task across many domains is model building and exploration for predictive analysis. Data is collected, parsed and analyzed for relationships, and features are selected and mapped to estimate the response of a system under exploration. One hypothesis is that allowing for a visual exploration of the data and model being used for predictive analytics may enable users to better refine their predictions. In order to explore how predictions might be performed in such a manner, we have developed a visualization system for box office prediction. A user study focusing on social media data as a predictor for movie box-office success was then performed to explore methods of successful interaction and visualization to improve users' understanding of a predictive model.

3.28 The Application/Design Study Playbook

Georgeta Elisabeta Marai (University of Pittsburgh, US)

The Visualization field needs both Design Studies and Technique papers to maintain its vitality. A Design Study typically contributes a domain analysis; a design which is a novel combination of known techniques, developed in collaboration with the domain experts; an implementation of that design; user feedback; and a summary of the design lessons learned. These can be valuable contributions: for example, the domain analysis is a basis on which other, and presumably better, visualization tools can later be built. The analysis typically points out a new type of data, or a new set of requirements, or tasks, or "something" interesting for which the SciVis field does not have a ready solution. This talk will focus on the Design Study Playbook, an outline of what a Design Study should contain to be more relevant to the SciVis community.

3.29 keyvis.org: Visualization as Seen Through its Research Paper Keywords

Torsten Moeller (Universität Wien, AT)

We present the results of a comprehensive analysis of visualization paper keywords supplied for 4366 papers submitted to five main visualization conferences. We describe main keywords, topic areas, and 10-year historic trends from two datasets: (1) the standardized PCS taxonomy keywords in use for paper submissions for IEEE InfoVis, IEEE Vis-SciVis, IEEE VAST, EuroVis, and IEEE PacificVis since 2009 and (2) the author-chosen keywords for papers published in the IEEE Visualization conference series (now called IEEE VIS) since 2004. Our analysis of research topics in visualization can serve as a starting point to (a) help create a common vocabulary to improve communication among different visualization sub-groups, (b) facilitate the process of understanding differences and commonalities of the various research sub-fields in visualization, (c) provide an understanding of emerging new research trends, (d) facilitate the crucial step of finding the right reviewers for research submissions, and (e) it can eventually lead to a comprehensive taxonomy of visualization research. One additional tangible outcome of our work is an application that allows visualization researchers to easily browse the 2600+ keywords used for IEEE VIS papers during the past 10 years, aiming at more informed and, hence, more effective keyword selections for future visualization publications.

3.30 Visualization of Uncertainty: Measures other than Mean

Kristi Potter (University of Utah, US)

The visualization of uncertainty often uses mean and standard deviation to define and quantify uncertainty, however this measure is not always appropriate. In this talk I will present two different approaches to visualizing uncertainty. The first is an approach to comparing a collection of PDFs that does not assume a normal distribution and the other uses entropy, from the field of information theory, to express the uncertainty within the data.

3.31 Paving the Road for Data-Driven Visualization Models

Timo Ropinski (Linköping University, SE)

Visualization is often quoted as a key technology enabling our information- based society to cope with the big data challenge arising from inexpensive data acquisition and storage. However, despite this potential and more than three decades of computer-based visualization research, to a large extent it is not possible to predict the outcome and the benefits of a certain visualization algorithm applied to a particular data set. Even when considering a specific application domain or task, it cannot be determined beforehand to which extent an applied visualization technique will suffice. This is in particular remarkable, as methodologies for analyzing and predicting the complexity of algorithms are as old as computing theory itself. Based on the known model of computation, it is a standard process to perform an asymptotic analysis to investigate algorithm behavior. However, despite the advances in our understanding of the human visual system in the last decades, we still do not have sufficiently detailed computational models to predict the effectiveness of a visualization when viewed by a human observer. This observation is underlined when looking back 30 years, when David Marr initially proposed the idea to formulate computational models of visual processing. Despite this intriguing idea and great enthusiasm spanning several research communities, today we are still far away from such a unified computational model. While this clearly shows the difficulties related to computational models in this area, fortunately, today's information technology gives us the possibility to tackle this problem from a different perspective. In a similar way as modern biology is making sense of the complexity of living processes through high- throughput data acquisition technologies, the effectiveness of visualizations could be investigated by enabling large-scale empirical studies, which facilitate the acquisition of amounts of user data in a dimension that has not been possible before. To realize this acquisition and derive a better understanding of the value of particular visualizations, we have started to develop concepts and technologies to enable high-throughput visualization-centered empirical studies, which enable us and other researchers, to acquire massive amounts of visual response data from visualization users. To collect this data, we have developed a semi-automated study conduction interface, which is directly integrated into a visualization researcher's workflow. Through this interface researchers can initiate and analyze large- scale crowd-sourced user studies with minimal effort, and thus contribute to a massive collection of user response data. Based on the thus acquired data, we plan to develop data-driven visualization models, with the long term goal to support predictive visualization. In my talk I will present our goals as well as the current status of the project.

3.32 The Uncertainty Paradox in Visualization

Holger Theisel (Universität Magdeburg, DE)

Data sets in Scientific Visualization are large and continuously growing, their visualization – even without uncertainty – is challenging. Considering uncertainty, the amount of data even increases. The more complex we model uncertainty, the more data we have to visualize, and the more the data describing the uncertainty exceeds the actual amount of data itself.

Looking at the information to be processed, the situation may change: considering the uncertainty may lead to less information to be presented than in the certain data itself. This gives the potential chance to create uncertainty- scalable visualization techniques. For such techniques, considering uncertainty should simplify the visualization instead of making them more complicated. They should converge to classic visualization techniques for low uncertainty and extremely simple visualizations for high uncertainty. We discuss opportunities to come up with uncertainty- scalable visualization techniques.

3.33 Visualizing Spatio-Angular Fields

Amitabh Varshney (University of Maryland, College Park, US)

Joint work of Varshney, Amitabh; Bista, Sujal; Gullapalli, Rao; Zhuo, Jiachen

Spatio-angular fields are emerging as a new data type in several visualization applications. In this talk, I shall outline some of our initial results in managing, analyzing, and visualizing spatio-angular fields derived from Diffusion Kurtosis Imaging (DKI) as well as identify some future directions.

Diffusion kurtosis imaging has started being used in the medical imaging community as it can reveal subtle changes in both gray and white matter. It has shown promising results in studies on changes in gray matter and mild traumatic brain injuries, where DTI is often found to be inadequate. However, the highly detailed spatio-angular fields in DKI datasets present a special challenge for visualization. Traditional techniques that use glyphs are often inadequate for expressing subtle changes in the DKI fields. Here I shall outline some of our results into the study of the micro-structural properties of the brain.

3.34 Physics-Based Fluid Simulation Coupled to 4D MRI Blood Flow

Anna Vilanova Bartroli (TU Delft, NL)

Modern MRI measurements deliver volumetric and time-varying blood-flow data. Visual analysis of these data potentially leads to a better diagnosis and risk assessment of various cardiovascular diseases. Recent advances have improved the speed and quality of the imaging data considerably. Nevertheless, the data remains compromised by noise and a lack of spatio-temporal resolution. Besides imaging data, also numerical simulations are employed. These are based on mathematical models of specific features of physical reality. However, these models are simplifications of the reality, and require parameters and boundary conditions. Data assimilation can bring measured data and physically-based simulation together, and benefit from both methodologies. Our first steps in this direction and the challenges of this approach will be presented.

3.35 Eye-Tracking Studies in Scientific Visualization

Daniel Weiskopf (Universität Stuttgart, DE)

In this talk, I discuss the role of eye-tracking in user studies in visualization research, in particular, for scientific visualization. We have been witnessing a trend toward the increasing use of experiments that assess user performance and user experience in scientific visualization. So far, however, much less work utilizes eye-tracking measurements in studies. I discuss possible roadblocks in the use of eye-tracking for scientific visualization research along with opportunities and directions for future empirical research.

3.36 Ensemble Visualization

Ruediger Westermann (TU München, DE)

To predict and quantify the uncertainty in numerical simulations of a physical phenomenon, multiple simulations are carried out using different physical or computational models, perturbed initial states or input parameter settings. This results in so-called ensembles, comprising members showing possible occurrences of the phenomenon. Ensemble visualization is of ever increasing relevance in a number of scientific domains, such as meteorology, fluid dynamics, or geology. It aims at identifying similarities and differences among ensemble members and revealing the sensitivity of these members to the input parameters. It further proposes means to track the space-time evolution of specific features and to identify where and how these features diverge in different ensemble members. There is a direct link between ensemble visualization and parameter space navigation: While the latter goes beyond ensemble visualization as it looks at the parameter space and its connection to the output, at the same time it relies upon ensemble visualization techniques to quantify the similarity between different outputs or between an output and a given reference, and thus to help the user controlling the parameter space navigation.

In "Future Challenges for Ensemble Visualization" by Harald Obermaier and Kenneth I. Joy it was recently proposed to classify ensemble visualization techniques into two categories: - Feature-based visualization extracts features from individual ensemble members and compares them across the ensemble. - Location-based visualization compares ensemble properties at fixed locations in the dataset.

Since feature-based visualization can also compare ensemble properties at fixed locations, I recommend renaming the second category into "Summary- based visualization", which compares sample properties at fixed locations and also investigates the spatial relationships between the samples at different locations in the dataset.

Lastly I would like to bring the reader's attention to an interesting problem in ensemble visualization. A widely used ensemble visualization technique simply displays simultaneously in one image the feature present in all ensemble members. Spaghetti plots are an example. An alternative approach is to assume a stochastic uncertainty model, and to consider ensemble members as realizations of a multivariate random number exhibiting certain distributions. Given such a model, one can try to derive probabilities of feature occurrences from the multivariate random field. The problem is, that the field realizations are no longer consistent with the underlying (physical) models used to generate the ensemble members. For instance, let us assume an ensemble comprising incompressible flow fields, and a multivariate vector valued random variable exhibiting a distribution derived from this ensemble. One particular realization of the random variable will not necessarily satisfy the compressibility constraint, resulting in a flow field which would never occur this way in a direct simulation. In my opinion, this mismatch between stochastic uncertainty modeling and the real outcomes of the data generation processes needs some further investigations, in particular regarding the consideration of correlations in the data to further constrain the stochastic data generation process.

3.37 Why you should (probably) not be doing "uncertainty visualization"

Ross Whitaker (University of Utah, US)

The visualization of stochastic or uncertain data is typically referred to "uncertainty visualization". However, this terminology implies associated set of assumptions about the paradigm for visualization, which is typically to display an answer that has been modulated or augmented by an associated uncertainty. This however, asserts the existence of a renderable answer, which defies one of the underlying goals or principles of visualization, which is the exploration of data to obtain a holistic understanding or to discover properties that have no associated, a priori hypothesis. An alternative paradigm, is "variability visualization" where the goal of the visualization is to explore or better understand the set of possible outcomes, or the probability distribution, associated with a set of data. One example of such an approach is the method of contour boxplots, which relies on a generalization of data depth, from descriptive statistics, to render the variability of solutions in an ensemble of isocountours.

3.38 Science Portal – Scientific Visualization in the Public Space

Anders Ynnerman (Linköping University, SE)

This talk will show how medical volume visualization can be used in knowledge dissemination in public spaces and discuss the specific challenges posed when working with museum curators and producers to develop robust exhibits based on state-of-the-art visualization techniques.

The main technology used is interactive multi-touch tables which allow visitors to science centers and museums to interactively and intuitively explore the normally invisible and learn about the inside workings of the human body, exotic animals, natural history subjects or even mummies, such as a recent installation at the British Museum. The talk will apart from showing a few interesting examples discuss requirements on the production pipeline from discovery to gallery – The Science Portal.

3.39 Exploring Multivariate and Ensemble Data

Xiaoru Yuan (Peking University, CN)

Understanding multivariate and ensemble data is very challenging due to the complexity of the data nature. The increasing data size further pose serious constrain to visualization solutions on exploring such data sets. We will discuss a few approaches we are trying to handle such problems.

4 Working Groups

4.1 Scientific Foundation of Visualization

A common theoretical and perceptual foundation supports the research across a broad range of types of visualization and application domains. This foundation includes the essential nature of visualization, models of how visualization works, fundamental mathematics, and best practices in design, collaboration, and application. Because of the rather large size of this group, three separate subgroups were formed to explore different aspects of the foundations of visualization. These groups discussed issues of perception and cognition, technology to support visualization, and visualization education. The reports of the discussions of each of these subgroups are below.

Perception and Cognition: The discussion of the perception and cognition subgroup addressed the issues of transferable knowledge from the psychology literature, difficulties of transferring knowledge between domains, approaches for interfacing with the perception community, motivation for collaboration with the perception community, metrics for measuring the quality of a visualization, and resources for supporting researchers in conducting and reporting user studies. Specific questions of interest in transferring perceptual knowledge to visualization research include how do we perceive time in moving animations?, how should color maps and shading be combined?, and how can depth perception be used to design better visualizations? The group identified three grand challenges on the topic of perception and cognition: how to optimize time in the understanding process, how to transfer knowledge from psychology, and why visualization works. The group decided to follow up with a panel, proposed and accepted, on the topic of "New Perceptual and Cognitive Issues for Visualization" that will appear at the 2014 IEEE VIS conference in Paris, France and an article for submission to IEEE CG&A Visualization Viewpoints.

Technology: The technology subgroup concentrated on identifying knowledge and tools from other disciplines of significant relevance to visualization. The discussion addressed the importance of design principles, perceptual mechanisms including Gestalt laws and pre-attentive processing, interaction design, tools such as Design Studio and Tableau, storytelling, acceleration data structures, and application areas and case studies. Algorithms and data analysis techniques of relevance include text mining, feature extraction, 2D geometry, the rendering pipeline, and pre-processing using sampling, interpolation, and filtering.

Education: The discussion of the education subgroup worked to identify knowledge elements that every student should know upon exiting a visualization course. These elements include characteristics of discrete and continuous data, the basics of numerics and signals, fundamentals of the image generation pipeline, basics of perception, classes of data and corresponding methods, data structures, and a core set of display methods. Other possible course components include interaction principles, collaboration skills, visualization toolkits, visual design principles, volume rendering and transfer functions, and evaluation. The group decided to collect examples of syllabi from visualization courses in order to create a repository, as well as provide material to conduct an analysis of commonalities and differences across courses.

4.2 Uncertainty Visualization

The goal of visualization is to effectively and accurately communicate data. Visualization research has often overlooked the errors and uncertainty which accompany the scientific process and describe key characteristics used to fully understand the data. The lack of these representations can be attributed, in part, to the inherent difficulty in defining, characterizing, and controlling this uncertainty, and in part, to the difficulty in including additional visual metaphors in a well designed, potent display. However, the exclusion of this information cripples the use of visualization as a decision making tool due to the fact that the display is no longer a true representation of the data. This systematic omission of uncertainty commands fundamental research within the visualization community to address, integrate, and expect uncertainty information.

The breakout group had a lively discussion of fundamental research issues. Uncertainly in visualization has many forms from parameter space analysis to ensemble visualization to the visualization of uncertainty. In parameter space analysis, sensitivity is one aspect of uncertainty but uncertainty connecting the inputs and outputs is also key. One method to quantify uncertainty is multiobjective optimization coupled with the parameter spaces. In ensemble visualization, uncertainty can come from the sensitivity of ensembles of data that capture the main uses, e. g. elections, weather, climate, etc. Having the ability to visualize the uncertainty aids in risk decision making by understanding the set of possible realities. In the statistics community, there are several types of statistics such as inferential, explanatory, descriptive, or predictive. The group discusses whether uncertainty in visualization capture these concerns as well.

It is our job in visualization to understand uncertainties in the applications and use visualization to present, explain and analyze for risk management and deeper fundamental understanding of the applications. This can be accomplished by quantifying, representing, and displaying the uncertainties in the visualization pipeline in addition to the application.

The group agreed that there are many avenues for future research in uncertainty in visualization and how to best utilize, present and analyze that information. In addition to the concepts outlined in the discussion, many areas of future research were not formally represented by the participants and also form the basis for important future research problems.

4.3 Integrated Multi-field Visualization

This working group consisted of 18 Dagstuhl attendees. This section of the report was written based on Ross Maciejewski's minutes for the two meetings held by the group. The group first reviewed the work by the working group on multi-field visualization in Dagstuhl 2011 seminar, and in particular Part II of the Springer book resulting from Dagstuhl 2011. The group then identified and discussed interests and challenges in the area of multi-field visualization. These included the followings:

- The increasing challenge as our scientific data is becoming richer with different types of fields and multiple-fields of the same kind, making it harder to explore high-dimensional multi-field time series data.
- Mathematical aspects of multi-field data and their need to be informed by applications.
- The challenge of integrating multiple data soruces for the same phenomen, given the limited bandwidth of different visual channels in a single view and the changing validity over time.
- Integrating the different components of space-weather simulation data with 21 different models (multi-scale and multi-modal data) into a consistent view.
- Comparing and correlating data from different sources in the domain of space engineering.
- Understanding the multiple fields making up an underlying model in physics applications.
- The image analysis of bio-medical video data, which often result in many attribute fields.
- The challenge of how to visualize, characterize and compare datasets with an increasing number of variables per point in a volume.
- Developing the capabilities to show the interaction between different variables in order to help domain experts understand how vector fields are changed by tensor fields.
- Building a unified framework for both measured and derived data in order to support the data exploration process in multi-field visualization.
- The integration of spatial and non-spatial information to support the collaboration between structural and non-structural biologists.
- The topological point of view, e. g., looking at persistent homology on two fields (let alone three) is extremely difficult.
- Showing the interplay of multi-variables in order to enable the creation of models that can explain these interplays and interaction, which may be difficult (or impossible) to explain mathematically.
- Visualizing complex geometry and the overlap between geometric structures.
- Particle based simulation where the simulation results are aggregated to create a time-varying field, as well as how this interplays with another field, e. g., comparing physical quantities between fields.
- The challenge of extending basic knowledge about scalar and vector field topology to multi-field topology for use in applications including material sciences and manufacturing.
- Developing new interdisciplinary tools for subspace exploration that would allow us to identify a good subspace that extracts a maximal amount of information using methods beyond topology.

The group then discussed various possible products that the group or different sub-groups (teams) may be able to deliver collaboratively. The options include (a) a viewpoint article that typically involves six to eight people; (b) the visualization corner that could be done by two to three people; (c) writing a survey paper on that topic; (d) producing an edited book on multi-field visualization; (e) writing a small book on a specific aspect of multi-field visualization; and (f) organizing a tutorial or workshop on multi-field visualization. A number of specific planned actions were identified, and group members volunteered to take a lead to coordinate actions or to organize a team to take the action forward. These specific plans include:

- A CG&A viewpoint article that may select a number of interesting examples of multi-field data (e. g., medical, material, biology, geography) and define the challenges involved in such data. **Action:** This effort will be coordinated by Anders Ynnerman.
- A workshop on multi-field visualization. As TopoInVis is more mathematically-focused, the meeting concluded that we could organize a workshop in conjunction with EuroVis 2015, targeting four page short papers. **Action:** Ingrid Hotz will take the lead in forming a workshop organization team.
- A tutorial and/or book, the former in conjunction with his ongoing grant, for the latter in conjunction with a book series led by Tamara Munzner. **Action:** Hamish Carr will coordinate this effort.

4.4 Environmental Scientific Visualization

Environmental visualization refers to a collection of visualization applications that deal with captured and simulated data in climate research, atmospheric and environmental sciences, earth science, geophysics and seismic research, oceanography, and the energy industry (e. g., oil, gas and renewable energy). Research in these applications has a huge impact on mankind, and typically faces serious challenges of data deluge (e. g., very large volumes of multi-spectral satellite images, large data collections from different sensor types, ensemble computation of very large simulation models, multi-model and multi-physics simulations, scattered, time-varying, multi-modal data in seismic research). Scientific progress in the areas of the environment and sustainability is critical in the solution of global problems and scientific visualization has great potential to support this progress.

The breakout group consisted of 14 seminar participants with interest in this broad application domain. In a first step, we discussed current application domains that the group is actively looking at. These areas are climate research including atmosphere, ice, ocean, and land modeling; geology, geography, and geophysics; soil and groundwater research; energy resources and waste management; land use research; biodiversity and ecosystem services; urban data; and finally disaster research with a focus on Tsunami modeling and earthquake modeling. Obviously, this broad agenda requires a lot of different visualization methodologies and opens a wide range of challenges and possibilities, even without looking at the various research challenges in sciences concerned with environmental questions outside this concrete list.

In a second step, our group explained to each other the specific problems that the members are working on. This allowed everyone to get a better understanding of the term "environmental visualization" from a practical point of view. Furthermore, we used it to derive specific visualization challenges that appear in many, if not most of, these applications. Seminar participants were looking into the visualization of fly-over data from airplanes;

geological data from petroleum engineering companies; biological growth monitoring data; species monitoring data; city traffic data and related air pollution data; data on the water, light, and energy consumption of a specific region; earthquake and Tsunami modeling data; and groundwater simulation data of a US state.

We have identified the following main challenges for visualization:

- Visualization in environmental sciences has to address very diverse audiences. First, there are the experts, i. e. scientists and engineers, as in many scientific visualization applications. Second, there is the general public with a high interest in the topic but substantially less prior knowledge on the subject. And third, there are the policy makers who use visualization as a basis for decisions, looking for information on the necessity of decisions and on information about the consequences of decisions. There is a growing demand by the researchers and engineers for the automatic generation of larger reports on a specific environmental question, using updated observations, new measurements or new simulations. Visualization is also asked as a method to narrow the gap between the scientists and policy makers. Regarding the policy makers, we identified a big gap between the visual needs of this group and typical scientific visualization methods. We foresee a large demand for research in this direction.
- As a more specific challenge, we identified the necessity to separate the visual communication of scientific facts from the presentation of derived decisions or recommendations.
- We have also noted that most examples in the group show that one has to solve a serious data integration task prior to visualization.

Overall, the group agreed that environmental visualization is still in its infancy, and will get a lot more attention in the near future because of the high demand in society with respect to the underlying big questions.

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