Report from Dagstuhl Seminar 18442

Visualization and Processing of Anisotropy in Imaging, Geometry, and Astronomy

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 18442, "Visualization and Processing of Anisotropy in Imaging, Geometry, and Astronomy", which was attended by 30 international researchers, both junior and senior. Directional preferences or anisotropies are encountered across many different disciplines and spatial scales. These disciplines share a need for modeling, processing, and visualizing anisotropic quantities, which poses interesting challenges to applied computer science. With the goal of identifying open problems, making practitioners aware of existing solutions, and discovering synergies between different applications in which anisotropy arises, this seminar brought together researchers working on different aspects of computer science with experts from neuroimaging and astronomy. This report gathers abstracts of the talks held by the participants, as well as an account of topics raised within the breakout sessions.

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1 Executive Summary

Andrea Fuster (TU Eindhoven, NL)
Evren Özarslan (Linköpings Universitet, SE)
Thomas Schultz (University of Bonn, DE)
Eugene Zhang (Oregon State University, USA)

Topics and Motivation

Directional preferences or anisotropies are encountered across many different disciplines and spatial scales. For example, local anisotropies are imprinted in the cosmic microwave background radiation, the human brain contains elongated nerve fibers, etc. Such anisotropies lead to (physical) orientation-dependent quantities, i.e., quantities that take on different values when considered along different directions. Compared to scalar or vector-valued data, it is much more challenging to model, process, and visualize anisotropic quantities. Suitable mathematical models often involve tensors and other higher-order descriptors, and pose specific research challenges in several areas of computer science, such as visualization, image analysis, and geometry processing.

In order to explore synergies between different fields, to inform computer scientists about open application challenges, and domain experts about existing solutions, this seminar brought together researchers from three different disciplines:

- Medical **imaging,** where several modalities are now available to probe anisotropic behavior. In particular, Diffusion Weighted Magnetic Resonance Imaging (DW-MRI) is based on measuring anisotropic diffusion. It makes it possible to visualize and quantify microstructural information in fibrous tissues such as white-matter and muscles, and to infer larger-scale structures, such as fiber tracts in the human brain.
- Computer graphics and **geometry processing,** where tensor fields have a wide range of applications, such as quadrangular and hexahedral geometry remeshing, street network modeling, geometry synthesis, computational architecture, and path planning for environment scans.
- Cosmology and **astronomy,** where anisotropy plays a crucial role. For example, anisotropies in the cosmic microwave background (CMB) consist of small temperature fluctuations in the blackbody radiation left over from the Big Bang. Anisotropies are also found in the CMB in the form of a polarization tensor field, and they arise in the field of "cosmography", where efforts are united to map (parts of) the cosmos, e.g. the large-scale distribution of matter in the Universe or cosmic web.

Organization of the Seminar

This seminar was the seventh in a series of Dagstuhl seminars that was started in 2004, and has been devoted to the visualization and processing of tensor fields and higher-order descriptors. This particular instance of the seminar series focused on anisotropy in the fields of imaging, geometry, and astronomy.

To ensure a steady inflow of new ideas and challenges, we put an emphasis on inviting researchers who previously did not have the opportunity to attend one of the meetings in this series. This was true for almost half the attendees in the final list of participants.

The seminar itself started with a round of introductions, in which all participants presented their area of work within 100 seconds with help of a single slide. This helped to create a basis for discussion early on during the week, and was particularly useful since participants came from different scientific communities, backgrounds, and countries.

A substantial part of the week was devoted to presentations by 29 participants, who spent 20 minutes each on presenting recent advances, ongoing work, or open challenges, followed by ten minutes of discussion in the plenary, as well as in-depth discussions in the breaks and over lunch. Abstracts of the presentations are collected in this report. On Wednesday we held the traditional social event which was joined by almost all participants, and offered additional welcome opportunities for interaction.

A total of six breakout sessions were organized in the afternoons of Monday and Tuesday. Moderators summarized the respective discussion in the plenary on Thursday afternoon. The organizers came up with initial suggestions for session topics, which were refined further after discussion with the seminar participants. The session topics were as follows:

- Astronomy
- Time-varying anisotropy
- Theoretical tools
- Visualization
- Diffusion MRI
- Geometry

Notes were taken during all sessions, and the main points are summarized later in this report.

Outcomes

The participants all agreed that the meeting was inspiring and successful. It also stimulated new scientific collaborations and joint grant proposals. In addition we plan to publish another Springer book documenting the results of the meeting. Participants have pre-registered seventeen chapters already during the seminar, and we are in the process of collecting additional contributions both from participants and from researchers working on closely related topics who could not attend the meeting. We expect that the book will be ready for publication in 2020.

Acknowledgment

The organizers thank all the attendees for their contributions and extend special thanks to the moderators of the breakout sessions and the team of Schloss Dagstuhl for helping to make this seminar a success. As always, we enjoyed the warm atmosphere, which supports both formal presentations as well as informal exchanges of ideas.

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3 Overview of Talks

3.1 Quadrilateral and Hexahedral Mesh Generation

David Bommes (Universität Bern, CH)

Joint work of Heng Liu, Paul Zhang, Edward Chien, Justin Solomon, David Bommes
Main reference Heng Liu, Paul Zhang, Edward Chien, Justin Solomon, David Bommes: "Singularity-constrained octahedral fields for hexahedral meshing", ACM Trans. Graph., Vol. 37(4), pp. 93:1–93:17, 2018.
URL http://dx.doi.org/10.1145/3197517.3201344

Automatically generating quadrilateral and hexahedral meshes that smoothly align to freeform surfaces and offer a high amount of regularity and low distorted elements is a notoriously challenging task. Novel algorithms based on global optimization rely on the construction of integer-grid maps, which pull back a Cartesian grid of integer isolines from a 2D or 3D domain onto a structure aligned quadrilateral or hexahedral mesh. Such global optimization algorithms do not suffer from limitations known from local advancing front methods, as for instance a high rate of irregularity, and enable meshes comparable to manually designed ones by finding a good compromise between regularity and element distortion. The key for finding good solutions are 3D cross-fields that are employed to globally optimize the orientation and sizing of mesh elements. In my talk, I will give an overview of the state of the art and discuss the strengths and weaknesses of available algorithms, including open challenges for hexahedral meshing.

3.2 A Unifying Approach to the Processing of Polyspectral Images

Bernhard Burgeth (Universität des Saarlandes, DE) and Andreas Kleefeld (Jülich Supercomputing Centre, DE)

The processing of colour images is still an active field of research, especially if there are more than 3 or 4 channels. For instance, modern astronomical satellites provide polyspectral images with more than 100 channels. In this talk we propose generalizations of mathematical operations, such as linear combinations, multiplication, maximum, and minimum, that is, the fundamental building blocks in any image processing algorithm, to polyspectral data. The proposed technique takes advantage of the methodologies already available for tensor fields, and appears to be extendible to general vector data. This is joint work in progress with Andreas Kleefeld

3.3 Enforcing necessary constraints for common diffusion MRI models using sum-of-squares programming

Tom Dela Haije (University of Copenhagen, DK)

Diffusion-weighted magnetic resonance imaging (MRI) captures local micro-structural information by observing diffusing (water) molecules probing their surroundings at a microscopic scale. In order to analyze this type of data one can either estimate parameters that describe the diffusion itself, which provides a somewhat abstract but accurate description of the observed stochastics, or one can use a model of the ambient structure that re-expresses the observed diffusion in terms of more intuitive structural parameters. Both cases generally rely on optimization to reconstruct the descriptive parameters from diffusion-weighted images, and in this presentation I will introduce a specific set of basic constraints to improve such model reconstructions. These constraints are based on the non-negativity of the so-called ensemble average propagator or associated functions, but reformulated as the (relaxed) condition that these functions can be written as a sum of squared polynomials. For many commonly used models and basis expansions these constraints take the form of a positive-definiteness condition on a matrix that is linear in the model parameters, which can thus be enforced through the use of semidefinite programming or nonlinear optimization alternatives. In preliminary results I will show that the application of these constraints can be considered essential in many situations despite the associated computational costs.

3.4 Multiscale Visualization of 3D-Polarized Light Imaging Fields

Ali Can Demiralp (RWTH Aachen, DE)

3D-Polarized Light Imaging (3D-PLI) is a recent neuroimaging technique which is able to record the spatial orientation of nerve fibers within the micrometer range. This method utilizes the optical birefringence properties of myelin sheaths surrounding the axons, yielding a vector field corresponding to mean orientations of the nerve fibers. In this talk, I will focus on interactive visualization of 3D-PLI outputs including extraction of spherical harmonic representations through downscaling the vector field, which in turn may serve as guidance to the registration of the slices (a central problem in 3D-PLI data acquisition) as well as providing opportunities for voxel-wise comparison with diffusion Magnetic Resonance Imaging.

3.5 Geometry in uncertainty quantification

Aasa Feragen (University of Copenhagen, DK), Anton Mallasto, and Søren Hauberg

Main reference Anton Mallasto, Aasa Feragen: "Learning from uncertain curves: The 2-Wasserstein metric for Gaussian processes", in Proc. of the Advances in Neural Information Processing Systems 30: Annual Conference on Neural Information Processing Systems 2017, 4-9 December 2017, Long Beach, CA, USA, pp. 5665–5674, 2017.
URL http://papers.nips.cc/paper/7149-learning-from-uncertain-curves-the-2-wasserstein-metric-for-gaussian-processes

In this talk, discussed recent work with Anton Mallasto and Søren Hauberg on the role of geometry in quantification of uncertainty.

First, we discussed the situation where data is estimated from data, and therefore should be considered stochastic. This is a common scenario in medical imaging, where raw data is heavily preprocessed to create an image, which is next further processed in order to extract the data points of interest, for instance organ segmentation boundaries. While such boundaries are routinely considered deterministic data points, they should, in principle, be considered stochastic variables following a distribution. This is particularly relevant when data quality is low, or model fit is poor. We discuss the role of geometry in population analysis [2] when such data points (in our examples, white matter tracts [3]) are stochastic, and represented as Gaussian Processes.

Next, we moved to the situation where data is known to reside on a Riemannian manifold, where we discuss uncertainty quantification in submanifold learning [1]. Here, we introduced the Wrapped Gaussian Process Latent Variable Model, which learns a stochastic embedding of data into the Riemannian ambient manifold. We discussed the relation between sample size and prior knowledge, and how the manifold constraint becomes particularly important for quantifying uncertainty.

References

1. A. Mallasto, S. Hauberg, A. Feragen, Probabilistic Riemannian submanifold learning with wrapped Gaussian process latent variable models, AISTATS 2019 (to appear)
2. A. Mallasto, A. Feragen, Learning from uncertain curves: The 2-Wasserstein metric for Gaussian processes, NIPS 2017
3. S. Hauberg, M. Schober, M. Liptrot, P. Hennig, A. Feragen, A Random Riemannian Metric for Probabilistic Shortest-Path Tractography, MICCAI 2015

3.6 Control Triads for Geodesic Tractography in Diffusion Weighted Magnetic Resonance Imaging

Luc Florack (TU Eindhoven, NL)

Joint work of Rick Sengers, Stephan Meesters, Lars Smolders, Andrea Fuster, Luc Florack

We propose a novel (preliminary) Riemann-geometric method for geodesic tractography in diffusion tensor imaging (DTI) that lacks the rigidity of most existing ones. It does not presume a well-posed relation between DTI data evidence and tracts. Instead, it is endowed with control parameters for optimal adaptation to fiducial 'ground truth' tracts in (real or synthetic) data, in which data-extrinsic knowledge might be incorporated (e.g. provided by expert annotations or edits, statistically inferred via machine learning, etc.).

The method is not limited to DTI/Riemannian geometry, but can be (nontrivially) extended to generic diffusion MRI models in the context of Finsler geometry.

3.7 Local anisotropies in spacetime

Andrea Fuster (TU Eindhoven, NL)

Joint work of Andrea Fuster, Cornelia Pabst, Christian Pfeifer
Main reference Andrea Fuster, Cornelia Pabst, Christian Pfeifer: "Berwald spacetimes and very special relativity", Physical Review Vol. 98(8), pp. 084062, 2018.
URL https://doi.org/10.1103/PhysRevD.98.084062

In this talk I consider an scenario where local anisotropies may be present in spacetime, as suggested by Cohen and Glashow in the context of very special relativity (VSR). It turns out that the geometry underlying VSR is of a very particular type. But where is gravity?

3.8 Crease Enhancement Using MAFOD Filter

Shekoufeh Gorgi Zadeh (Universität Bonn, DE)

Main reference Shekoufeh Gorgi Zadeh, Stephan Didas, Maximilian W. M. Wintergerst, Thomas Schultz: "Multi-scale Anisotropic Fourth-Order Diffusion Improves Ridge and Valley Localization", Journal of Mathematical Imaging and Vision, Vol. 59(2), pp. 257–269, 2017.
URL http://dx.doi.org/10.1007/s10851-017-0729-1

Before extraction of the centerline (crease line) or the core-surface (crease surface) of anisotropic structures, such as vessels or brain's white matter skeleton in fractional anisotropy images, applying crease enhancing filters can improve the localization. For this purpose, we propose a multi-scale anisotropic fourth-order diffusion (MAFOD) filter that performs better than the other existing isotropic and anisotropic fourth-order filters. Plus we show that the 3D MAFOD filter can be steered to either enhance crease lines, or crease surfaces, or both at the same time.

References

1 Gorgi Zadeh, S., Didas, S., Wintergerst, M. W. M., Schultz, T.: Multi-scale Anisotropic Fourth-Order Diffusion Improves Ridge and Valley Localization. Journal of Mathematical Imaging and Vision 59(2):257–269 (2017)

3.9 Variance measures of diffusion tensors

Magnus Herberthson (Linköping University, SE)

Joint work of Magnus Herberthson, Evren Özarslan, Carl-Fredrik Westin

Calculating the variance of a family of diffusion tensors involves the formation of a fourth order tensor with the same symmetry properties as the elasticity tensor. This tensor has been studied w.r.t many properties: degrees of freedom, representations, invariants, decomposition, the equivalence problem et cetera. In this talk we discuss some of these properties, both in two and three dimensions.

3.10 Robust Extraction and Simplification of 2D Symmetric Tensor Field Topology

Ingrid Hotz (Linköping University, SE)

In this work, we propose a controlled simplification and smoothing strategy for symmetric 2D tensor fields that is based on the topological notion of robustness. Robustness measures the structural stability of the degenerate points with respect to variation of the underlying field. We consider an entire pipeline for the topological simplification of the tensor field by generating a hierarchical set of simplified fields based on varying the robustness values. Such a pipeline comprises of four steps: the stable exaction and classification of degenerate points, the computation and assignment of robustness values to the degenerate points, the construction of a simplification hierarchy, and finally the actual smoothing of the fields across multiple scales. We also discuss the challenges that arise from the discretization and interpolation of real world data.

3.11 Maximizing the information content of diffusion-relaxometry MRI data

Jana Hutter (King's College London, GB)

Novel acquisition techniques beyond traditional diffusion MRI include both variation in the shape of the diffusion encoding and the combination with relaxometry techniques (T1/T2). A versatile sequence, allowing variation in all dimensions are presented and possible alternatives in the sampling discussed.

3.12 Deep Learning-based tractogram filtering

Daniel Jörgens (KTH Royal Institute of Technology – Stockholm, SE)

Joint work of Daniel Jörgens, Philippe Poulin, Rodrigo Moreno, Pierre-Marc Jodoin, Maxime Descoteaux

Diffusion magnetic resonance imaging (dMRI) provides the opportunity to non-invasively obtain measures that relate to the human brain tissue microstructure. A common approach to analyze the global white matter architecture based on this modality is tractography. The basic idea of this technique is to create trajectories which are aligned with the local diffusion measurements at each point. The set of the trajectories (or streamlines) derived in this way is usually referred to as a tractogram.

Despite the existence of a variety of tractography methods, all these suffer from inherent limitations due to the relatively low spatial and angular resolution of dMRI as well as the generally ill-posed nature of the inverse problem they aim to solve. It has been shown that this often results in a large number of anatomically implausible streamlines.

Several approaches for 'cleaning' tractograms have been proposed whose aim is to classify streamlines as being anatomically plausible or implausible. In general, these are based on different features derived either from the streamlines or from samples of the diffusion data along them. Inspired by recent proposals which successfully employed machine learning in the step-wise creation of streamlines, we propose to use a machine learning-based, binary classifier for this task. In this talk, I will present our preliminary results in this context. In particular, we investigate different settings to train a binary classifier which is able to separate a tractogram into sets of plausible and implausible streamlines. In this work, we assess the performance of a) convolutional vs. recurrent neural network architecture, b) relying solely on dMRI as input features, and c) training on a single set of ground truth labels vs. training on a composition of several sets.

3.13 A path to process general matrix fields

Andreas Kleefeld (Jülich Supercomputing Centre, DE)

Joint work of Bernhard Burgeth, Andreas Kleefeld

A general framework is presented that allows for transferring data-processing algorithms for scalar to arbitrary matrix fields. That means to find analogues for fundamental operations such as linear combinations and maximum/minimum in this setting. Furthermore, we aim to process fields consisting of certain subsets such as the symmetric, skew-symmetric, Hermitian, and the general and orthogonal group. Some numerical examples concerning the special orthogonal group and the general linear group connected to Moebius transforms in hyperbolic geometry are presented.

3.14 Mapping scalar and tensor magnetic susceptibility of biological tissues

Chunlei Liu (University of California at Berkeley, US)

Magnetic susceptibility of biological tissues is intrinsically of tensor nature. In some cases, it can be approximated as a scalar quantity. Methods and challenges will be discussed for quantifying magnetic susceptibility based on MRI.

3.15 A Deep Learning Approach to Identifying Shock Locations in Turbulent Combustion Tensor Fields

Timothy Luciani (University of Illinois – Chicago, US)

Joint work of Mathew Monfort, Jonathan Komperda, Brian Ziebart, Farzad Mashayek, G. Elisabeta Marai
Main reference Matthew Monfort, Timothy Luciani, Jonathan Komperda, Brian Ziebart, Farzad Mashayek, G. Elisabeta Marai: "Deep learning features of interest from turbulent combustion tensor fields", Modeling, Analysis, and Visualization of Anisotropy, Springer, pp. 375-392, Feb., 2017.
URL https://doi.org/10.1007/978-3-319-61358-1_16

We introduce a deep learning approach for the identification of shock locations in large scale tensor field datasets. Such datasets are typically generated by turbulent combustion simulations. In this proof of concept approach, we use deep learning to learn mappings from strain tensors to Schlieren images which serve as labels. The use of neural networks allows for the Schlieren values to be approximated more efficiently than calculating the values from the density gradient. In addition, we show that this approach can be used to predict the Schlieren values for both two-dimensional and three-dimensional tensor fields, potentially allowing for anomaly detection in tensor flows. Results on two shock example datasets show that this approach can assist in the extraction of features from reacting flow tensor fields.

3.16 Tensor Approximation for Multidimensional and Multivariate Data

Renato Pajarola (Universität Zürich, CH)

Tensor decomposition methods and multilinear algebra are powerful emerging tools to cope with current trends in computer graphics, image processing and data visualization, in particular with respect to compact representation and processing of increasingly large-scale, high-dimensional and multivariate data sets. Initially proposed as an extension of the concept of matrix rank for 3 and more dimensions, tensor decomposition methods have found applications in a remarkably wide range of disciplines. We will briefly review the most successful tensor decomposition models and their applications in graphics and visualization, as well as describe specific benefits and features exploited for visual data compression, signal processing and interactive data manipulation. Furthermore, we will include a first outlook on porting these techniques to multivariate data such as vector and tensor fields.

3.17 Detecting and Describing Ultra Diffuse Galaxies and Faint Galaxy Streams

Reynier Peletier (University of Groningen, NL)

Recent astronomical surveys are so deep that many objects, which up to now were invisible, can be detected. One detects for example large numbers of Ultra Diffuse Galaxies, and also around larger galaxies often stellar streams are found that are remnants of previous galaxy-galaxy interactions. I am interested in developing methods that detect these faint features, but also to describe them in an objective way, so that they can be compared with galaxy formation simulations to study how galaxies formed. This work is done in collaboration with astronomers and computer scientists across Europe.

3.18 Exploiting the Signal's Spherical Mean to Calculate the Minimal Anisotropic Kernel

Marco Pizzolato (EPFL – Lausanne, CH)

Main reference Marco Pizzolato, Demian Wassermann, Rachid Deriche, Jean-Philippe Thiran, Rutger Fick: "Orientation-Dispersed Apparent Axon Diameter via Multi-Stage Spherical Mean Optimization," in CDMRI, 2018.
URL https://infoscience.epfl.ch/record/257227

The spherical mean of the diffusion MRI signal, process also known as "powder averaging", has revealed powerful for estimating the "microscopic" kernel, irrespective of its alignment in the 3d space. While tensorial kernels have been used due to the availability of explicit solutions for their spherical mean, through approximation it is possible to calculate generic micro-kernels. Moreover, the dimensionality reduction in the parameter space granted by powder averaging can be exploited to improve stability, speed, and limit degeneracy during parameter estimation of functions that convolve such kernels with 3d spatial distributions. Finally, leveraging our control over MRI acquisition parameters we may infer on further explorable properties of these kernels, such as their dependence on curvature.

3.19 Tensor Visualization Using Fiber Surfaces of Invariant Space

Gerik Scheuermann (Universität Leipzig, DE)

Symmetric second order tensor fields appear in medicine, astronomy, geometry, as well as mechanics. If one is interested in the invariants, one is left with a three dimensional space. For a typical application in medicine or mechanics, and sometimes in geometry or astronomy, the domain is also three-dimensional. Therefore, a symmetric second-order tensor field over a three-dimensional domain defines a mapping from its domain into three-dimensional space. This allows for interactive exploration. For this purpose, we define the preimage of a surface in the invariant space as fiber surface and demonstrate an algorithm to compute these surfaces. So far, the algorithm assumes a tetrahedral grid with linear interpolation of the invariants to keep things simple. In the following, we indicate how this construction may allow for a formulation of a topology of tensor invariant map which complements the classical tensor field topology in a strict sense.

3.20 Explicit and Implicit Prior Knowledge in fODF Estimation: The Best of Both Worlds

Thomas Schultz (Universität Bonn, DE)

Joint work of Ankele, Michael; Groeschel, Samuel; Lim, Lek-Heng; Patel, Kanil; Schultz, Thomas
Main reference Kanil Patel, Samuel Groeschel, Thomas Schultz: "Better Fiber ODFs From Suboptimal Data With Autoencoder Based Regularization", in Proc. Medical Image Computing and Computer Assisted Intervention (MICCAI), 21st International Conference, Granada, Spain, September 16-20, 2018, Proceedings, Part III LNCS, vol. 11072, pp. 55–62, Springer, 2018.
URL https://doi.org/10.1007/978-3-030-00931-1_7

Estimating fiber orientation distribution functions (fODFs) from diffusion MRI is an ill-conditioned problem, and especially challenging when dealing with sub-optimal data that has been acquired in a clinical setting. We improve results by investing two types of prior knowledge: First, a positive definiteness constraint enforces that fODFs will not contain any negative contributions. Second, we regularize the estimation from sub-optimal data based on learning the distribution of plausible fODFs from high-quality data. We combine both strategies in a way that preserves their respective advantages, and eliminates the need for frequent re-training.

References

1 Ankele, M., Lim, L. H., Groeschel, S., Schultz, T.: Versatile, robust, and efficient tractography with constrained higher-order tensor fODFs. Int'l J. of Computer Assisted Radiology and Surgery 12(8), 1257–1270 (2017)

3.21 Increasing the dimensionality and size of the MRI parameter space for microstructure imaging: cure or curse?

Chantal Tax (Cardiff University, GB)

Diffusion MRI (dMRI) is the preferred tool for studying tissue microstructure in vivo, with the dMRI literature growing exponentially. However, current technology does not always allow comprehensive assessment, and fundamental issues challenge interpretation of results. We have reached a hiatus in advancing tissue characterization by dMRI alone, advocating the combination of multiple MRI-modalities. Instead of separately acquiring different contrasts, their joint information can be optimally exploited by simultaneously varying multiple experimental variables, an approach common in physical-chemistry NMR. The latest ultra-strong gradient MRI technology facilitates the translation of multidimensional MRI to human brain by greatly extending the size of the available measurement space. However, as the dimensionality and size of this space increase, efficient data acquisition and representation become more challenging. This talk aims to debate how multidimensional MRI and ultra-strong gradients could help our understanding of brain microstructure, and to identify open challenges in experiment design and analysis that hamper clinical translation of comprehensive and efficient microstructural MRI.

3.22 Topological Structures and Comparative Measures for Tensor Fields

Bei Wang (University of Utah – Salt Lake City, US)

This talk summarizes some speculative thinking regarding the topological structures and comparative measures for tensor fields. Suppose we are given a number of tensor fields defined on a common domain, we are interested in developing comparative measures that capture the relationship between two or more tensor fields. Similarly to the study of scalar fields (and to some extent, vector fields), it seems natural to construct a topological structure (e.g., a contour tree, a Reeb graph or a Morse-Smale complex) as a summary for each tensor field and use such a topological summary for comparison. It is also possible to take a Morse-theoretic approach to study the relationship between two or more tensor fields via an analog of the Jacobi set. In this talk, we will discuss some of these possibilities and challenges in establishing mathematical and algorithmic foundations for the study of multiple tensor fields.

3.23 Cosmic Microwave Background and the very early Universe

Dong-Gang Wang (Leiden University, NL)

In this talk I will give a brief introduction to the physics and observation of Cosmic Microwave Background (CMB) anisotropies. CMB is the relic radiation of the Big Bang, which was formed when the Universe was 380000 year old. After 13.7 billion years, today the CMB photons have a thermal black body spectrum at a temperature of 2.73K. More importantly, this temperature has tiny fluctuations across the whole sky, which is believed to be generated in the very early stages of the Universe. Therefore, through the measurement of the CMB anisotropies, we can extract a lot of information about the Big Bang. In particular, I will focus on the leading scenario of the primordial Universe — inflationary cosmology, and how much information CMB can tell us about it. Although current CMB data fits the standard predictions of inflation very well, there are some future observations, like primordial gravitational waves, non-Gaussianities, features and anomalies, which could reveal some new physics beyond our current understanding. I may elaborate on one to-be-confirmed observational anomaly, hemispherical power asymmetry, and show why its explanation poses a challenge for theoretical cosmologists.

3.24 Multidimensional diffusion MRI

Carl-Fredrik Westin (Harvard Medical School – Boston, US)

We recently proposed a new multidimensional diffusion MR framework for imaging and modeling of microstructure that we call q-space trajectory imaging (QTI). QTI framework enables microstructure modeling that is not possible with the traditional pulsed gradient encoding as introduced by Stejskal and Tanner. In this talk I will review this multidimensional diffusion MRI framework, and present novel extensions related to multidimensional diffusion MR and introduce relaxation to this model. The approach is inspired by multidimensional correlation spectroscopy, which improves differentiation of heterogeneous media in the field of NMR. I will discuss a six order tensor cumulant expansion of the diffusion MRI signal and present intuitive scalar invariants that can be derived from the moments of the expansion.

3.25 Geometry and data representation

Hsiang-Yun Wu (TU Wien, AT)

Joint work of Kazuho Watanabe, Yusuke Niibe, Shigeo Takahashi, Issei Fujishiro
Main reference Kazuho Watanabe, Hsiang-Yun Wu, Yusuke Niibe, Shigeo Takahashi, Issei Fujishiro: "Biclustering multivariate data for correlated subspace mining", in Proc. of the 2015 IEEE Pacific Visualization Symposium, PacificVis 2015, Hangzhou, China, April 14-17, 2015, pp. 287–294, IEEE Computer Society, 2015.
URL http://dx.doi.org/10.1109/PACIFICVIS.2015.7156389

Large datasets collected through advanced measurement techniques lead to increasing computation costs on analysis, formulation, and verification processes. In this presentation, we discuss the possibilities and the challenge of the analysis of high-dimensional data since human intuition about the geometry of high dimensions often diverges. Some applications, such as correlation analysis was introduced to initialize the discussion. The present techniques include Parallel Coordinate Plots, which has become a standard tool to analyze high-dimensional data and its extension Many-to-Many Parallel Coordinate Plots being developed to investigate all pairs of relations between dimension axes. Except directly plotting numerical data on screen space using visual encoding, including positions, colors, and shapes, alternatively, adding text or image labels enable another representation of additional information to the target of interests.

3.26 Tensor Field Design in Volumes

Eugene Zhang (Oregon State University – Corvallis, US)

Joint work of Jonathan Palacios, Lawrence Roy, Prashant Kumar, Chen-Yuan Hsu, Weikai Chen, Chongyang Ma, Li-Yi Wei
Main reference Jonathan Palacios, Lawrence Roy, Prashant Kumar, Chen-Yuan Hsu, Weikai Chen, Chongyang Ma, Li-Yi Wei, Eugene Zhang: "Tensor field design in volumes", ACM Trans. Graph., Vol. 36(6), pp. 188:1–188:15, 2017.
URL http://dx.doi.org/10.1145/3130800.3130844

The design of 3D tensor fields is important in several graphics applications such as procedural noise, solid texturing, and geometry synthesis. Different fields can lead to different visual effects. The topology of a tensor field, such as degenerate tensors, can cause artifacts in these applications. Existing 2D tensor field design systems cannot handle the topology of 3D tensor fields. We present, to our best knowledge, the first 3D tensor field design system. At the core of our system is the ability to specify and control the type, number, location, shape, and connectivity of degenerate tensors. To enable such capability, we have made a number of observations of tensor field topology that were previously unreported. We demonstrate applications of our method in volumetric synthesis of solid and geometry texture as well as anisotropic Gabor noise.

3.27 Topological Features in Stress Tensor Fields over Hex Mesh Distribution

Yue Zhang (Oregon State University – Corvallis, US)

Having a quality mesh is important to numerical modeling of physical phenomena. Much research exists to define the quality of the input mesh for a valid simulation and more work is needed to guide the distribution of the quality over the entire mesh. Our analysis here shows the effect of hex meshing with different distribution of quality over a numerical sample on the calculated stress tensor fields. Different topological features are shown for these fields while the distribution of the quality of the mesh varies.

3.28 Anisotropy Measure for Multi-component Shapes

Jovisa Zunic (Mathematical Institute, Serbian Academy of Sciences – Belgrad, RS)

Joint work of Paul L. Rosin, Jovisa Zunic
Main reference Jovisa D. Zunic, Paul L. Rosin, Vladimir Ilic: "Disconnectedness: A new moment invariant for multi-component shapes", Pattern Recognition, Vol. 78, pp. 91–102, 2018.
URL http://dx.doi.org/10.1016/j.patcog.2018.01.010
Main reference Mohamed Ben Haj Rhouma, Jovisa D. Zunic, Mohammed Chachan Younis: "Moment invariants for multi-component shapes with applications to leaf classification", Computers and Electronics in Agriculture, Vol. 142, pp. 326–337, 2017.
URL http://dx.doi.org/10.1016/j.compag.2017.08.029
Main reference Paul L. Rosin, Jovisa D. Zunic: "Orientation and anisotropy of multi-component shapes from boundary information", Pattern Recognition, Vol. 44(9), pp. 2147–2160, 2011.
URL http://dx.doi.org/10.1016/j.patcog.2011.02.018
Main reference Jovisa D. Zunic, Paul L. Rosin: "An Alternative Approach to Computing Shape Orientation with an Application to Compound Shapes", International Journal of Computer Vision, Vol. 81(2), pp. 138–154, 2009.
URL http://dx.doi.org/10.1007/s11263-008-0149-1

We will discuss a recent concept of multi-component shapes, which is applicable to image processing and image analysis tasks. The domain of multi-component shapes is very diverse and includes shapes that correspond to a group of objects that act together (e.g. a fish shoal), natural components of a segmented object (e.g. cells in embryonic tissues), a set of shapes corresponding to the same object appearing at different times (e.g. human gait in an image sequence), and many more.

Multi-component shapes have their specific characteristic (i.e. shape descriptors). Such shape characteristics need to be evaluated numerically, for an easier computer supported processing and analysis. One of them is the anisotropy measure, introduced as a quantity that should evaluate how much the shape components are ordered consistently.

3.29 Neurite morphology and the orientationally-averaged diffusion MR signal

Evren Özarslan (Linköping University, SE)

Joint work of Evren Özarslan, Cem Yolcu, Magnus Herberthson, Hans Knutsson, Carl-Fredrik Westin
Main reference Evren Özarslan, Cem Yolcu, Magnus Herberthson, Hans Knutsson, Carl-Fredrik Westin: "Influence of the size and curvedness of neural projections on the orientationally averaged diffusion MR signal," Front. Phys., vol. 6, 17, 2018.
URL https://doi.org/10.3389/fphy.2018.00017

Anisotropy of the diffusion-attenuated magnetic resonance (MR) signal has been widely utilized in applications such as tractography for mapping the connections between distant regions of the brain. Getting rid of this anisotropy information by orientationally-averaging the signal provides valuable insight into tissue's microscopic anisotropy and structure. We present recent advances on the influence of the geometry of neural projections on the observed diffusion MR signal.

4 Panel discussions

4.1 Astronomy

Andrea Fuster (Eindhoven University of Technology, NL), Reynier Peletier (University of Groningen, NL)

At this session we discussed how techniques in computer science might help processing and analyzing astronomical data. One of the problems treated was how to classify the different components of the large scale structure of the Universe or cosmic web (clusters, filaments, voids and walls) by using data from astronomical surveys. The type of data depends on whether the survey is shallow or deep, i.e. a large part of the sky is covered with a sparse distribution of points such as the Sloan Digital Sky Survey (SDSS), or a small portion of the sky with a higher density of data points. Some suggestions were to classify filaments by computing ridges (one-dimensional curves traced by high-density regions) or using tensor-based measures, and to compare results obtained with each approach. Related topics were the use of interpolation and denoising methods for data from shallow surveys.

Astronomical data acquired at smaller spatial scales, corresponding to objects such as stars, galaxies and galaxy clusters, was also discussed. One of the goals of such studies is to (automatically) classify stars vs. galaxies. One of the problems is that faint galaxies are not detected by the current software tools. One of the suggestions was to attempt a classification based on spectral decomposition. Another problem is how to get rid of artifacts related to optical reflection in images of groups of galaxies. Algorithms for image deconvolution could be used for this purpose.

4.2 Time-varying anisotropy

Jana Hutter (King's College London, GB)

In this session, relevant applications of time-dependency in tensors, and the inherent link with anisotropy, were discussed. Potential interests in time-dependency arises for instance in structural mechanics, where the stress tensor is time-dependent even though this information is relevant in specific cases. Deformation is brought as example of a continuous process for which time could be relevant, as well as of periodic loading assessment that is often performed for risks prevention in artificial structures or to test the resistance of machines. Another important field of application of time-varying tensors is computational fluid dynamics, where they are commonly used to identify local density, pressure, and velocity related to shock waves. Medicine is probably the field where data has an inherent time-dependent nature, as it is the case of pathology progression monitoring. However, in this field, the concept of time-dependency is not only explicit (like in the case of the data) but can be implicitly adopted in some processing techniques where time appears as an "artificial" mechanism involved in the generation of heat maps distributions in imaging, or in denoising, or even in the acquired data such as the concept of *diffusion time* in diffusion MRI. The last field of interest discussed in this session was geometrical meshing. A representative example of a time-varying application is computer animation, where a good deformation of meshes during time is the at the core of a successful result.

4.3 Theoretical tools

Magnus Herberthson (Linköping University, SE)

This session aimed at discussing a subset of common mathematical tools involved in the topics discussed in the seminar, with the purpose of becoming more familiar with them, finding cross-field overlaps, and posing fundamental questions to be solved.

The first tool discussed was the Bloch-Torrey equation, which describes the effects of water proton diffusion on the NMR/MRI relaxation phenomena. Particular emphasis was placed on the problem of determining the relaxation times T_1 (longitudinal) and T_2 (transverse) in the presence of complications arising from the presence of diffusion phenomena.

While the direct problem is well-understood and described by the previously mentioned equation, the inverse problem of estimating the parameters has revealed difficulties, with no satisfactory results in the community, up to now. The discussion aimed at tackling the estimation issues from different angles, while suggesting that it is quite likely that this ill-posed inverse problem falls within known classes of "parameter estimation of PDEs." If so, it was noted that there is already a machinery that could be employed, which would involve Tikhonov-regularization, Landweber-iteration, and Frechet-derivative and its adjoint.

Higher order tensors were the focus of the second main point of discussion. Many topics were touched upon, mainly from a theoretical perspective. These included tensor versus matrix formalisms (lower order tensor alternatives), the relation with continuum mechanics, various decomposition approaches, relevant invariants, and the issue of higher order SVD (singular value decomposition).

4.4 Visualization

Ingrid Hotz (Linköping University, SE)

The breakout session on visualization was originally guided by four topics: tensor topology applications in science, (3D) astronomy applications, multi-parameter diffusion imaging, and uncertainty visualization. A first round collecting topics of interest resulted at first in a very broad list, however over the course of the meeting common interests became clearer and are summarized below. One of the key outcomes was stating the need of close interdisciplinary projects to develop solutions that are targeted to the specific needs, ideally developed in a participatory manner between users and visualization experts.

1) There is a large gap between practitioners and the visualization community. The gap between the communities becomes already clear when considering common state-of-the-art visualization methods. While every community seems to have its own domain-specific solutions covering some basic visualization methods, more advanced methods are, to a large extent, unknown to the domain scientists. This seems to be especially true for explorative and analytic methods. For instance, tensor fields are still mostly visualized using derived scalar fields which might be suboptimal.

As one reason for this gap, an insufficient technology transfer and financial support of software development have been identified. There is a large difference between freely available tools and research software, the latter often being not easy-to-use and remaining at a proof-of-concept implementation stage. There exist several state-of-the-art articles, which are, however, targeted mostly towards visualization experts. Available tools include OpenSpace for astronomy data, MRtrix for diffusion MRI, as well as ParaView, VTK, VisIt, and AMIRA (not free) as generic tools for simulation data. Several of them have Python interfaces. It was identified that tensor field visualization tools are few. Some general challenges for visualization:

- specifying what is really needed, often it is unclear what should be visualized (this is often the main part of the problem);
- visualization should simplify the task without hiding information;
- standardization is needed;
- tutorials and learning packages for specific applications are needed in the from of "Cookbooks."

2) Special topics of interest for many participants working with tensor data. Despite the different application areas there were also some issues of joined interest, here listed.

- *Quantification and visualization of uncertainties* of the entire data analysis pipeline. Challenges lie in the integration of global and local measures as well in visualization of uncertainty in its entire complexity, e.g. covariances. This requires the visualization of tensors of higher order. Furthermore, the challenge of finding a good representation of uncertainty without overwhelming the user was discussed.
- *Visualization of higher order or higher dimensional tensors.* In many applications, the interest goes beyond simple second order tensors in three dimensions, e.g., gradients of tensors or tensors in Finsler geometry.
- *Visualization of ensembles allowing comparison* of tensors or groups of tensors. Related applications often involve high dimensional parameter spaces which require explorative visualization at different abstraction levels.
- *Multi-scale visualization.* Topology could be an interesting tool for abstracting data. However, there is a communication gap here as well, since it is not clear what the purpose is and when it should be used.
- *Simple and easy-to-understand visualizations*, such as cartoon-like automatic illustrations.

3) Visualization for different purposes. Some concepts are listed.

- *Visualization for non-experts of generic mathematical concepts* is required, and with different levels of abstraction: for instance, the visualization for clinicians must be different than that for DTI researchers.
- *Visualization for scientific communication*, e.g., 3D rendering on a dome was brought as an example.
- *Specific needs* should be taken into account in the design of visualization techniques: visualization for astronomy was brought as an example, due to its high complexity and the amount of information that needs to be displayed.

4.5 Diffusion MRI

Chantal Tax (Cardiff University, GB), Tom Dela Haije (University of Copenhagen, DK)

This session was mainly oriented towards bringing up topics of interest in Diffusion MRI that could be tackled by participants of the seminars given their knowledge of tools, and their different perspectives on the subject. A relevant macro-topic was tractography, i.e., the generation of a neuroanatomically accurate representation of the three-dimensional geometry of brain white-matter tracts that connect different cerebral regions. The resulting tractogram is typically inferred by processing tensor fields or related variants. The relevance of tractography spans from neurosurgery to the discovery of brain connectivity with serious implications for investigations in neuroscience.

The main challenge with tractography is its ill-posed nature. Every method leads to different results and there is no single ground-truth solution. This problem is deleterious for all applications, especially for delicate matters involving surgery. Because of this, tractography has had limited applicability, and those practitioners who do not rely on tractography need to be well-trained in order to correctly interpret the results.

Despite the abundance of methods present in the literature, none achieves satisfactory results, so that when ranking methods based on synthetic numerical or physical phantoms, the criterion adopted is often the compromise between false positives and false negatives. Indeed, the typical outcome of tractography entails the detection of tracts that do not exist and the lack of others that are known to exist. This is still an open question. Additional or new type of data could help improve the sensitivity and specificity of tractography together with the clever injection of prior knowledge.

As a case example, geodesic tractography was described. This allows for reconstructing the most likely paths of molecules by processing tensor fields according to a Riemannian/Finslerian metric. One of the issues, however, is the presence of many isotropic areas in the tensor field, rendering the main direction uncertain. Another important point is that the tractogram, while having to be geometrically accurate, has to properly describe the connections between different brain regions, and these connections often do not coincide with the most likely paths.

To add to the challenges, it was also mentioned that at the moment there is no real means of knowing the precise brain anatomy and connectivity in order to assess the accuracy of the tractograms. Connectivity, for instance, is not constant across lifetime, and some areas can take over the function of others, such as in the case of post-stroke recovery. These concerns lead to the problem of tractography validation. As a remark on this, it was highlighted that even a technique like polarized light imaging of *ex vivo* samples suffers from registration problems between slices.

To get around this, it was proposed to avoid giving a strict anatomical interpretation to the tractograms, and to develop methods that compute and visualize the possible solutions in a clever manner. Probabilistic approaches can play a great role in this endeavor, provided that neurosurgeons, neuroscientists, and other practitioners are satisfied with such information, although it is well-known that different experts would likely have different needs and opinions. Along a similar line, another approach discussed was making the many parameters behind the generation of tractography explicit. In some sense, by changing one or more parameters in the tractography pipeline (regularization over the tensor field, tract propagation, stopping criteria, etc.), the outcome changes as well. It would be important to define signal-based optimal criteria to avoid basing such choices on empiricism. Moreover, tractography depends on several physical parameters related to the acquisition and, as of now, no attempt to incorporate such information has been done.

Another important point discussed in this session was assessing the role of visualization in tractography. For instance, the need of visualizing all sources of uncertainty in the tractogram while still guaranteeing its intelligibility emerged as a potential goal.

4.6 Geometry

Eugene Zhang (Oregon State University, USA)

The following conclusions and open research questions emerged from discussion in the breakout session on geometry processing:

- Meshes play an important role in shape representation, but now the field is wider with simulation being the main driving force behind high-quality meshes.
- Main challenges include how to define the quality of a mesh and how to generate meshes knowing the quality measure.
- For simulation, the quality measures can be the speed of convergence, numerical accuracy and stability. They will likely be application-dependent.
- The high-quality quad and hex meshes for shape representation are well-researched, with the ability to interact with the mesh generation process through design. However, this does not address the needs for simulations.
- Can we adapt the mesh shop idea from shape representation and 3D printing to simulation? Can we define the price tag for a mesh vs. its utility?
- How to generate anisotropic meshes, which should be better suited for applications involving anisotropy such as processing blood flow data?
- How to make open-source code for high-quality meshing available to practitioners?

5 Schedule

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00	Introductions	Evren Özarslan	Dong-Gang Wang	Bernhard Burgeth	Aasa Feragen
		Luc Florack	Reynier Peletier	Andreas Kleefeld	Tom Dela Haije
		Daniel Jörgens	Andrea Fuster	Timothy Luciani	Jovisa Zunic
10:30	Coffee	Coffee	Coffee	Coffee	Coffee
11:00	Chunlei Liu	Chantal Tax	Bei Wang	Thomas Schultz	Wrap-up
	Ali Can Demiralp	Jana Hutter	Hsiang-Yun Wu	Shekoufeh Gorgi Zadeh	
12:15	Lunch	Lunch	Lunch	Lunch	Lunch
14:00	Yue Zhang	Marco Pizzolato	Social event	Ingrid Hotz	
	David Bommes	C.-F. Westin		Renato Pajarola	
	Eugene Zhang	Magnus Herberthson		Gerik Scheuermann	
15:30	Coffee	Coffee		Coffee	
16:00	Breakout	Breakout		Panel + book	
18:00	Dinner	Dinner		Dinner	

Figure 1 The meeting schedule.

Participants

- David Bommes
Universität Bern, CH
- Bernhard Burgeth
Universität des Saarlandes, DE
- Tom Dela Haije
University of Copenhagen, DK
- Ali Can Demiralp
RWTH Aachen, DE
- Aasa Feragen
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- Luc Florack
TU Eindhoven, NL
- Andrea Fuster
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- Shekoufeh Gorgi Zadeh
Universität Bonn, DE
- Hans Hagen
TU Kaiserslautern, DE
- Magnus Herberthson
Linköping University, SE
- Ingrid Hotz
Linköping University, SE
- Jana Hutter
King's College London, GB
- Daniel Jörgens
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- Andreas Kleefeld
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- Chunlei Liu
University of California at Berkeley, US
- Timothy Luciani
University of Illinois – Chicago, US
- Evren Özarslan
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- Renato Pajarola
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- Donggang Wang
Leiden University, NL
- Carl-Fredrik Westin
Harvard Medical School – Boston, US
- Hsiang-Yun Wu
TU Wien, AT
- Eugene Zhang
Oregon State University – Corvallis, US
- Yue Zhang
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