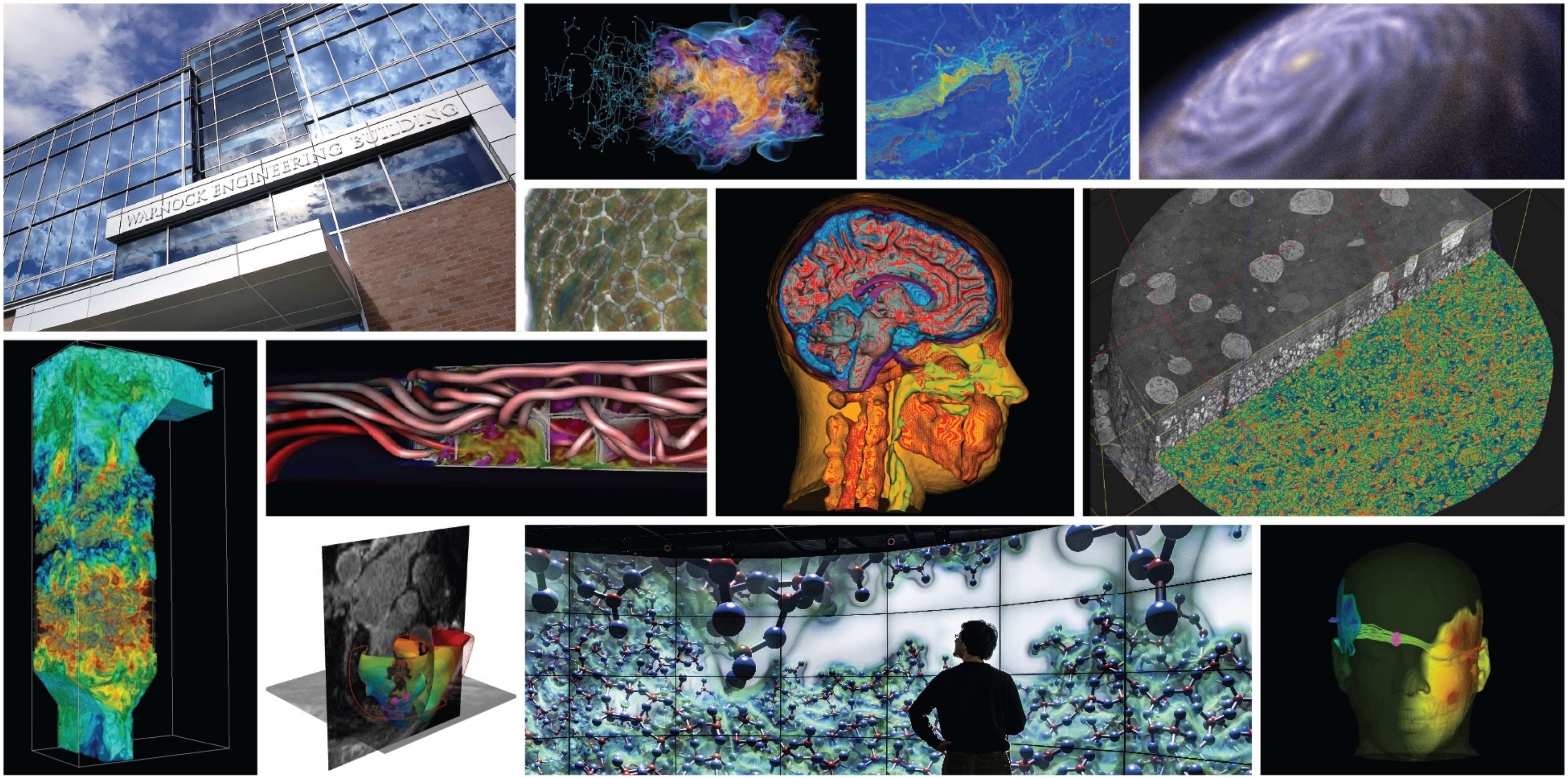
Uncertainty Visualization



Scientific Computing and Imaging (SCI) Institute Faculty


Manish Parashar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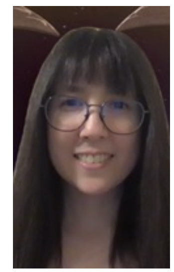
Tamara Bidone


Shireen Elhabian


Chuck Hansen


Kate Isaacs


Sarang Joshi


Mike Kirby


Alex Lex


Rob MacLeod


Akil Narayan

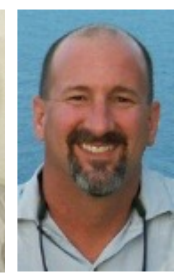

Valerio Pascucci


Paul Rosen


Tolga Tasdizen


Bei Wang


Bao Wang


Jeff Weiss


Ross Whitaker


Benjamin Ellis

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SCI: Collaboration With National Labs

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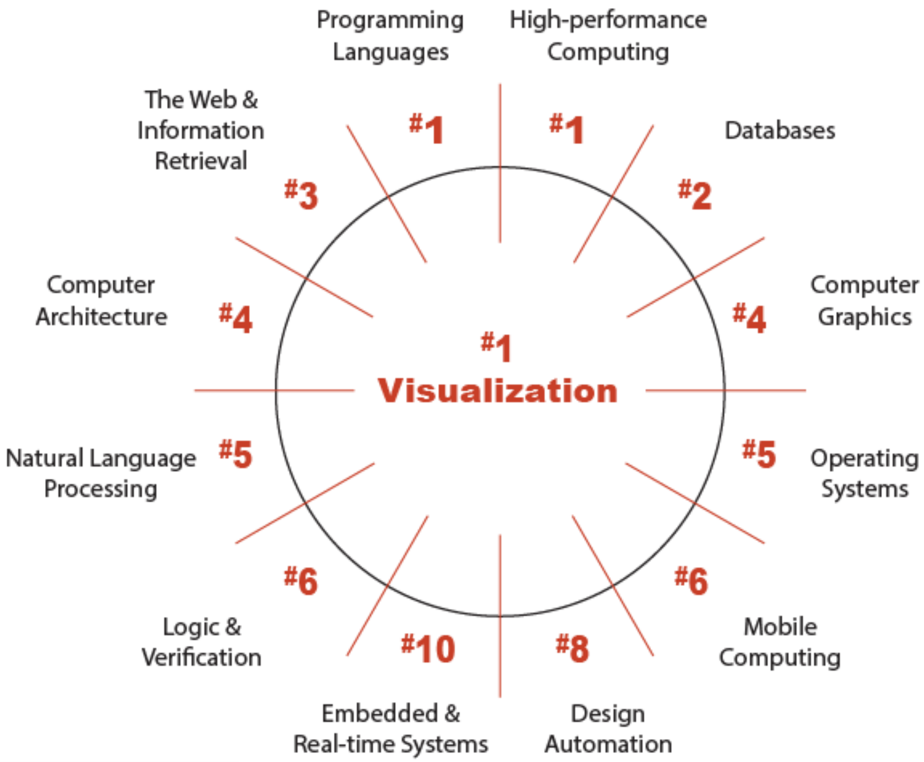

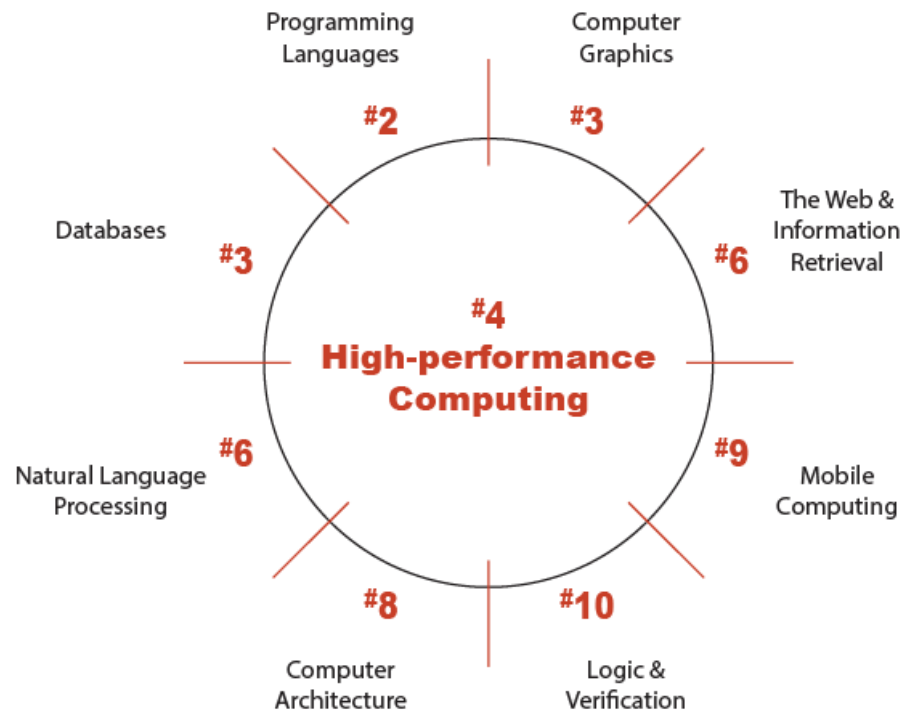

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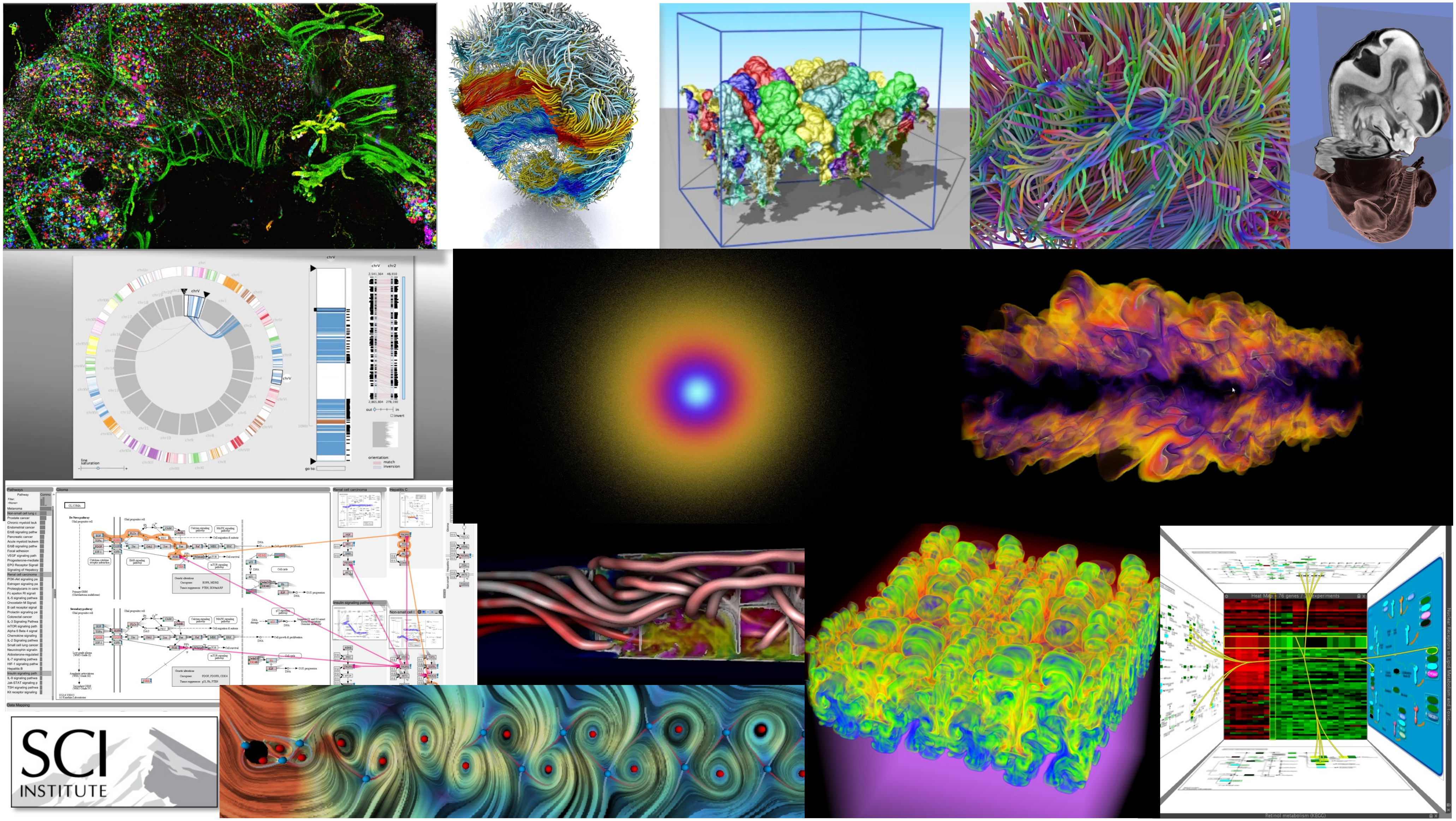
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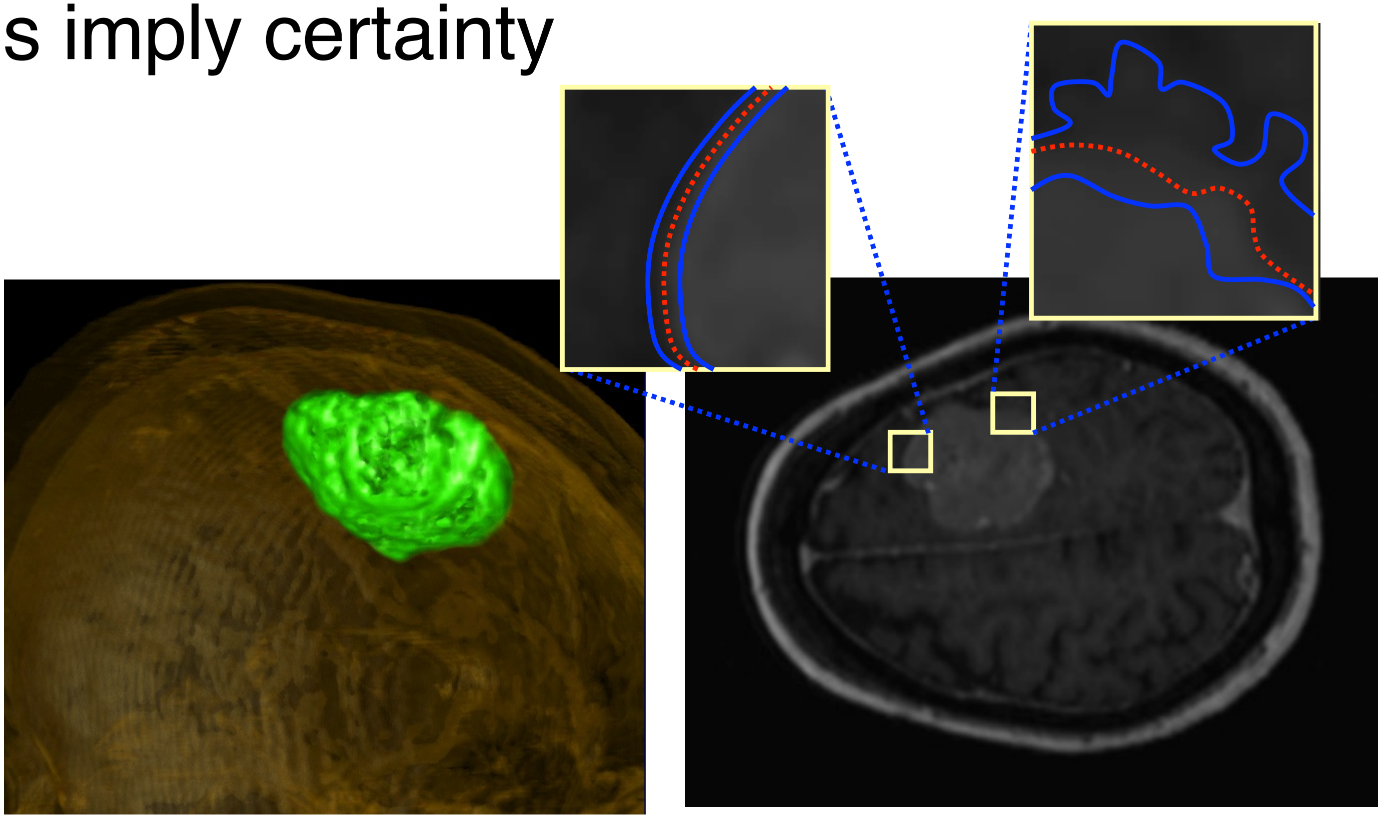
Decision Making Under Uncertainty

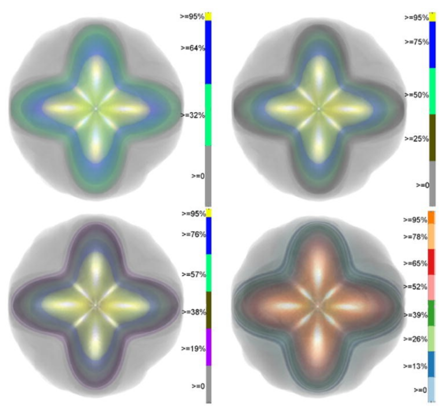
Surfaces imply certainty



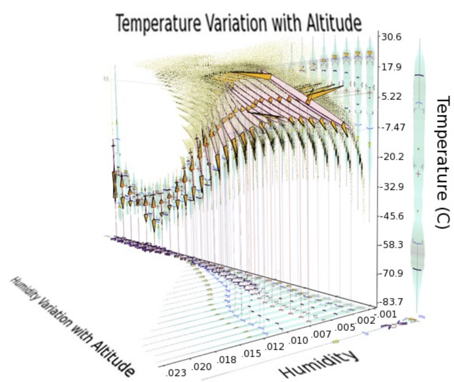
Uncertainty Quotes

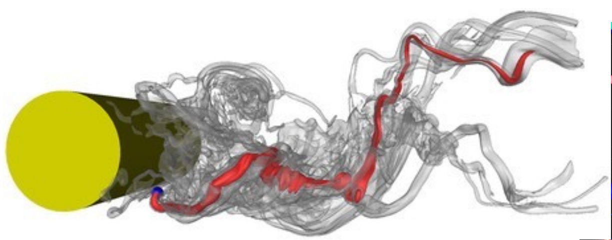
- Richard Feynman: *What is not surrounded by uncertainty cannot be the truth.*
- Richard Feynman: *If you thought that science was certain, well, that is just an error on your part.*
- George Box: *All models are wrong. Some models are useful.*
- John W. Tukey: *Far better an approximate answer to the right question, which is often vague, than an exact answer to the wrong question, which can always be made precise.*
- Francis Bacon - If we begin with certainties, we shall end in doubts; but if we begin with doubts, and are patient in them, we shall end in certainties
- Winston Churchill: *True genius resides in the capacity for evaluation of uncertain, hazardous, and conflicting information.*

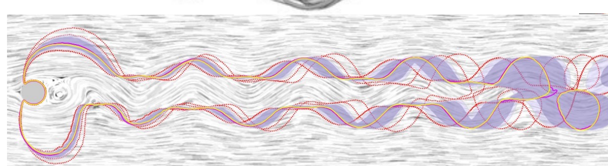
Uncertainty Visualization

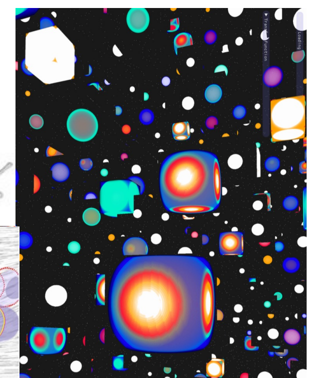


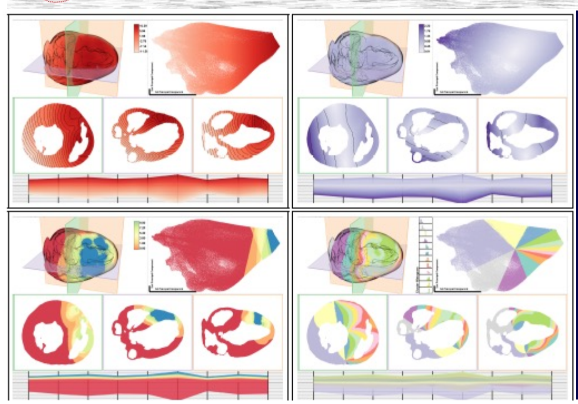
When is the last time you've seen an error bar in a visualization of complex data ?

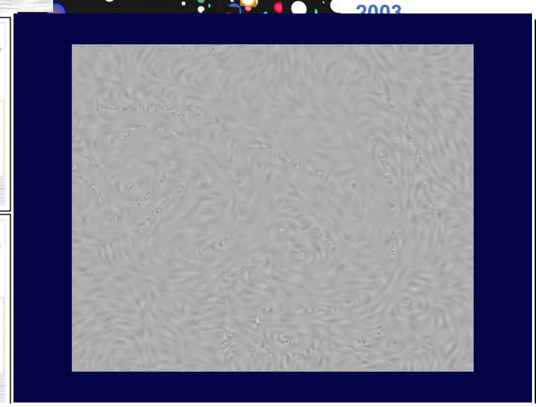


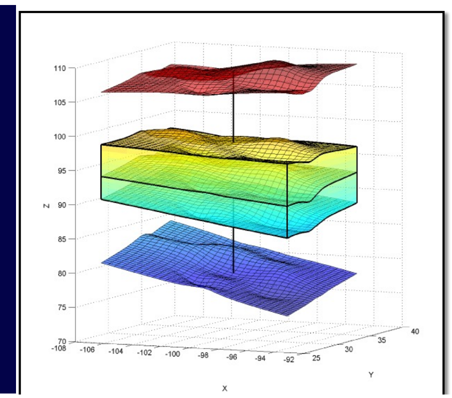












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G.P. Bonneau, H.C. Hege, C.R. Johnson, M.M. Oliveira, K. Potter, P. Rheingans, T. Schultz. "Overview and State-of-the-Art of Uncertainty Visualization," In *Scientific Visualization: Uncertainty, Multifield, Biomedical, and Scalable Visualization*, Edited by M. Chen and H. Hagen and C.D. Hansen and C.R. Johnson and A. Kauffman, Springer-Verlag, pp. 3-27. 2014.

M.G. Genton, C.R. Johnson, K. Potter, G. Stenchikov, Y. Sun. "Surface boxplots," In *Stat Journal*, Vol. 3, No. 1, pp. 1-11. 2014.

K. Potter, P. Rosen, C.R. Johnson. "From Quantification to Visualization: A Taxonomy of Uncertainty Visualization Approaches," In *Uncertainty Quantification in Scientific Computing*, IFIP Series, Vol. 377, Springer, pp. 226-249. 2012.

K. Potter, A. Wilson, P.-T. Bremer, D. Williams, C. Doutriaux, V. Pascucci, C.R. Johnson. "Ensemble-Vis: A Framework for the Statistical Visualization of Ensemble Data," In *Proceedings of the 2009 IEEE International Conference on Data Mining Workshops*, pp. 233-240. 2009.

C.R. Johnson, A.R. Sanderson. "A Next Step: Visualizing Errors and Uncertainty," In *IEEE Computer Graphics and Applications*, Vol. 23, No. 5, pp. 6-10. September/October, 2003.

Sources of Uncertainty

- Experimental (observational, equipment limits, multiple trials)
- Numerical (approximation, interpolation, extrapolation)
- Mathematical Model (approximation to true physics/biology)
- Geometric Model (accuracy compared to true geometry)

Statistical Uncertainties - Common in Visualization

- Probability Distribution Functions (PDFs) - approximate outcome through a probability function
- Probability Density - continuous random variables, frequency of outcome values
- Statistics on PDFs - mean, median, standard deviation

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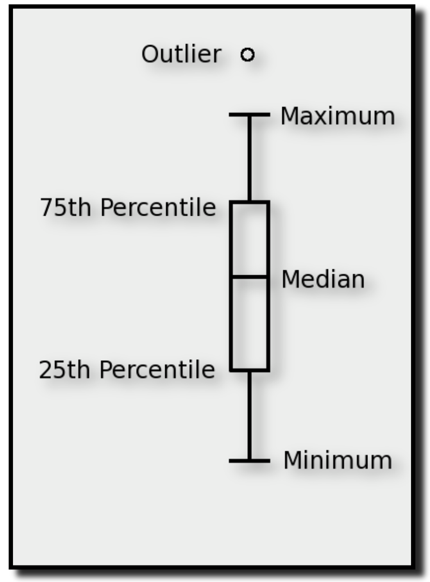
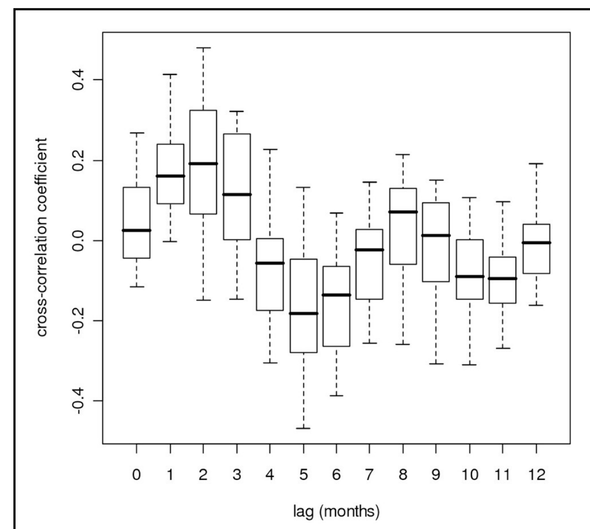
Traditional Display of Uncertainty

Boxplots (Tukey, 1977)

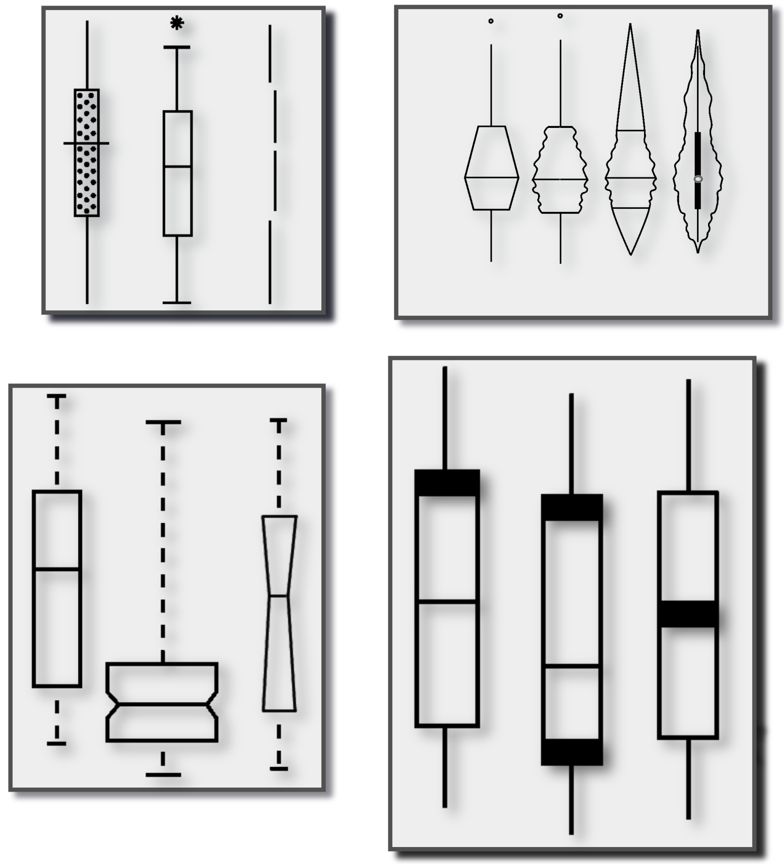
- Quartile range including median
- Outliers
- Assume Gaussian





Boxplot Modifications

- Visual Modifications
  - Refinement for aesthetic purposes
- Density indications
  - Use the box sides to encode
- Data Characteristics
  - Sample size, confidence levels
- Additional Statistics
  - Skew, modality



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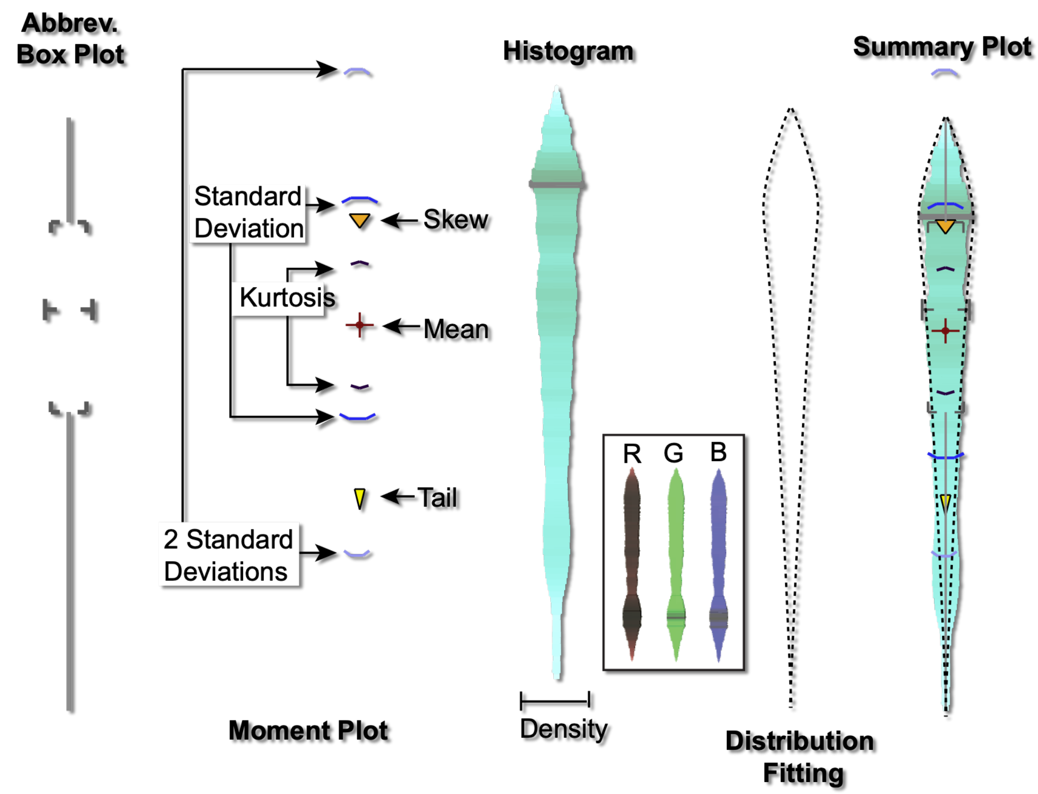
The Summary Plot

- Augment boxplot with numerous display techniques
- Emphasize characteristics other than mean/variance
- Indicate quantity and location of uncertainty



K. Potter, J. Kniss, R. Riesenfeld, C.R. Johnson. "Visualizing Summary Statistics and Uncertainty". *In Proc Eurovis 2010, 29(3), 2010.*

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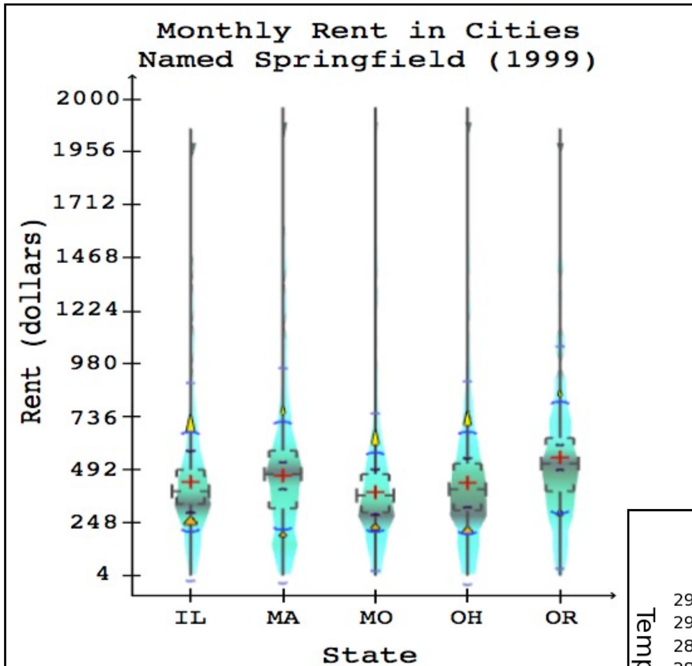

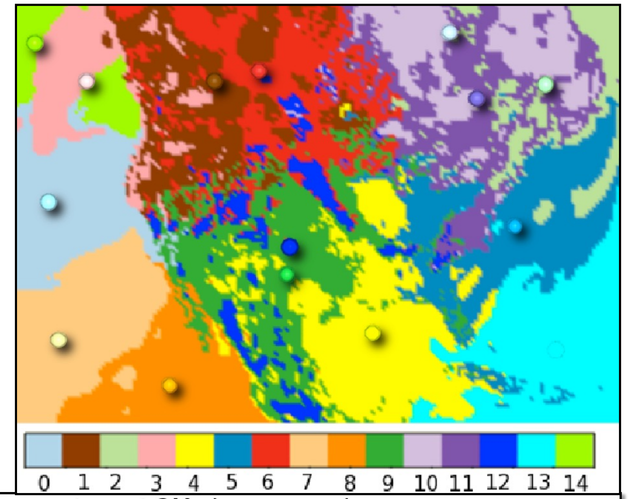

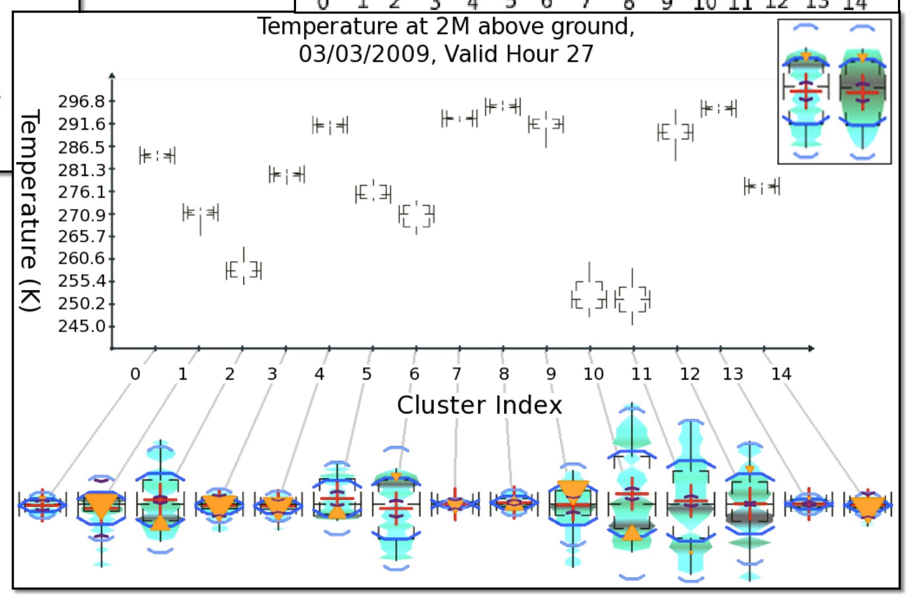

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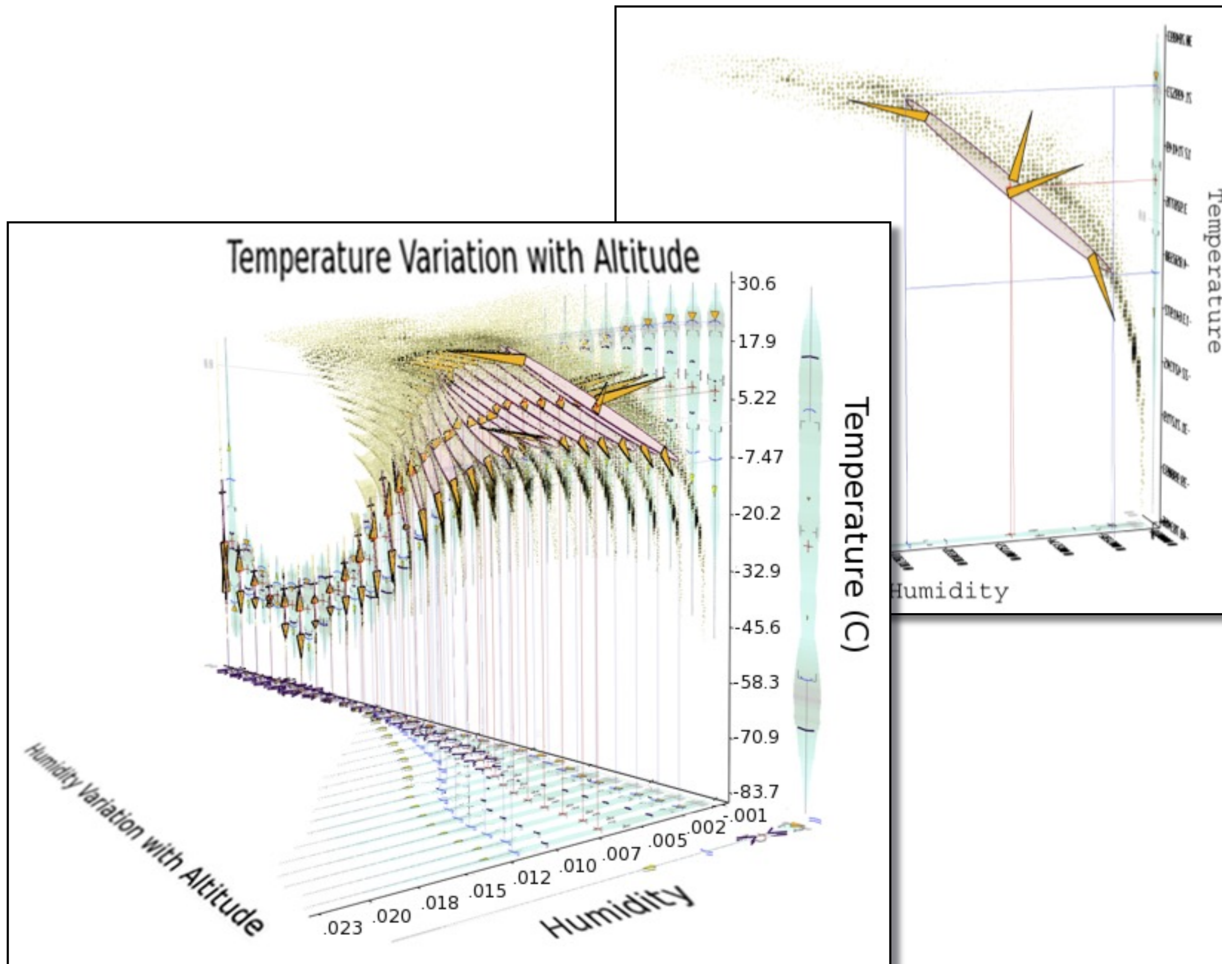
Summary Plot in Higher Dimensions

- Statistics similar to summary plot
- Highlight correlations



K. Potter, J. Kniss, R. Riesenfeld, C.R. Johnson.
"Visualizing Summary Statistics and Uncertainty".
In Proc Eurovis 2010, 29(3), 2010.

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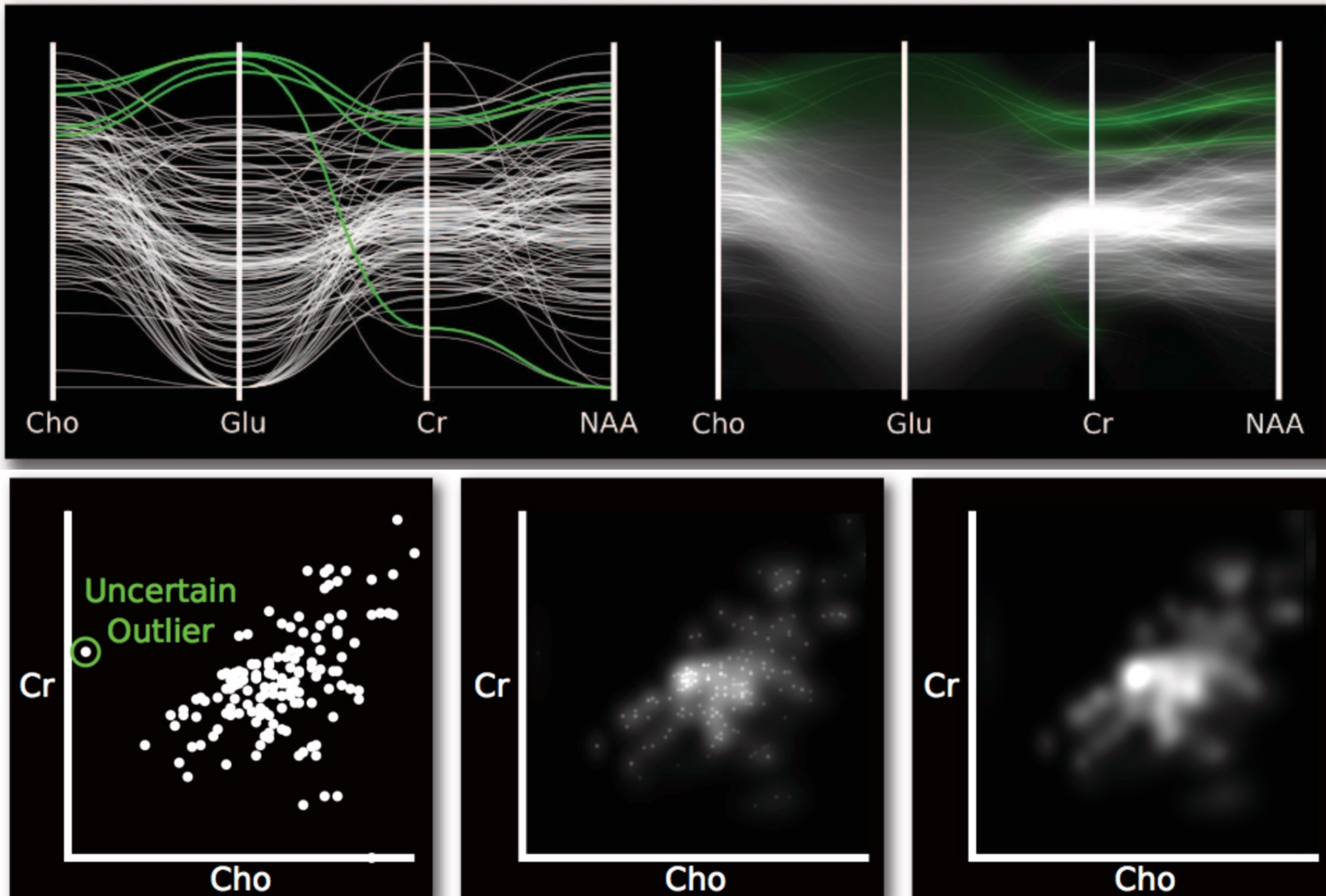

Feng, D., Kwock, L., Lee, Y., & Taylor, R. M., 2nd (2010). Matching visual saliency to confidence in plots of uncertain data. *IEEE transactions on visualization and computer graphics*, *16*(6), 980–989. doi:10.1109/TVCG.2010.176

Visual Entropy

Holliman, N. S., Coltekin, A., Fernstad, S. J., Simpson, M. D., Wilson, K. J., & Woods, A. J. (2019). Visual entropy and the visualization of uncertainty. arXiv preprint arXiv:1907.12879.

Fig. 10. The urban temperature data visualization showing both hourly mean temperature values using the MetOffice color scale and the variance of those values using our new visual entropy scale, this image is an example of the high uncertainty target-present stimulus used in the experiment described below.

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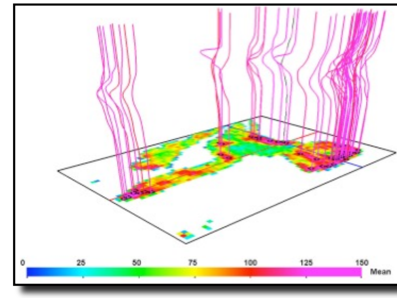
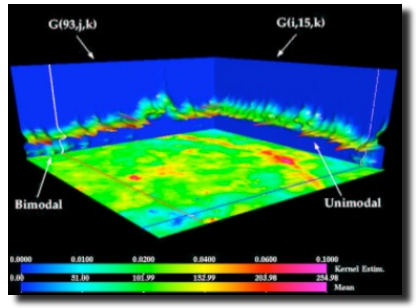
Ensembles / 2D Distributions

- Multi-run/model simulations
- Distribution of data at every point
- Mean/std dev may not be appropriate

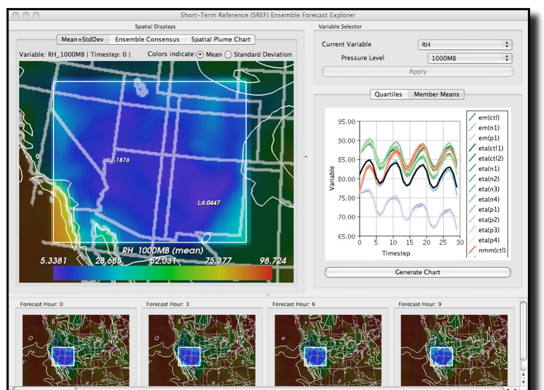


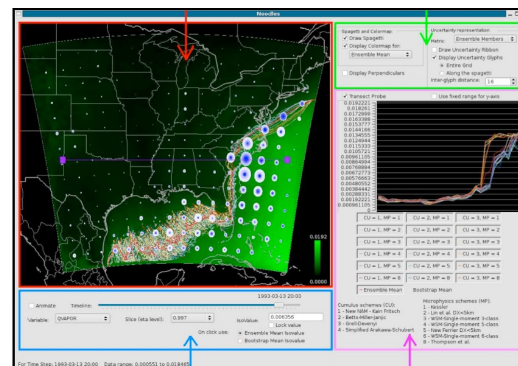
D. Kao, M. Kramer, A. Luo, J. Dungan, A. Pang.
Visualizing Distributions from Multi-Return Lidar Data to Understand Forest Structure.



D. Kao, A. Luo, J. Dungan, A. Pang.
Visualizing Spatially Varying Distribution Data.
In Proc Information Visualisation, 2002.

K. Potter, et al.
Ensemble-Vis: A Framework for the Statistical Visualization of Ensemble Data.
In IEEE ICDM Workshop on Knowledge Discovery from Climate Data: Prediction, 2009.





. Sanyal, S. Zhang, J. Dyer, A. Mercer, P. Amburn.
Noodles: A Tool for Visualization of Numerical Weather Model Ensemble Uncertainty
In Proc IEEE Vis, 2010.

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Streamline Variability Plots for Characterizing the Uncertainty in Vector Field Ensembles

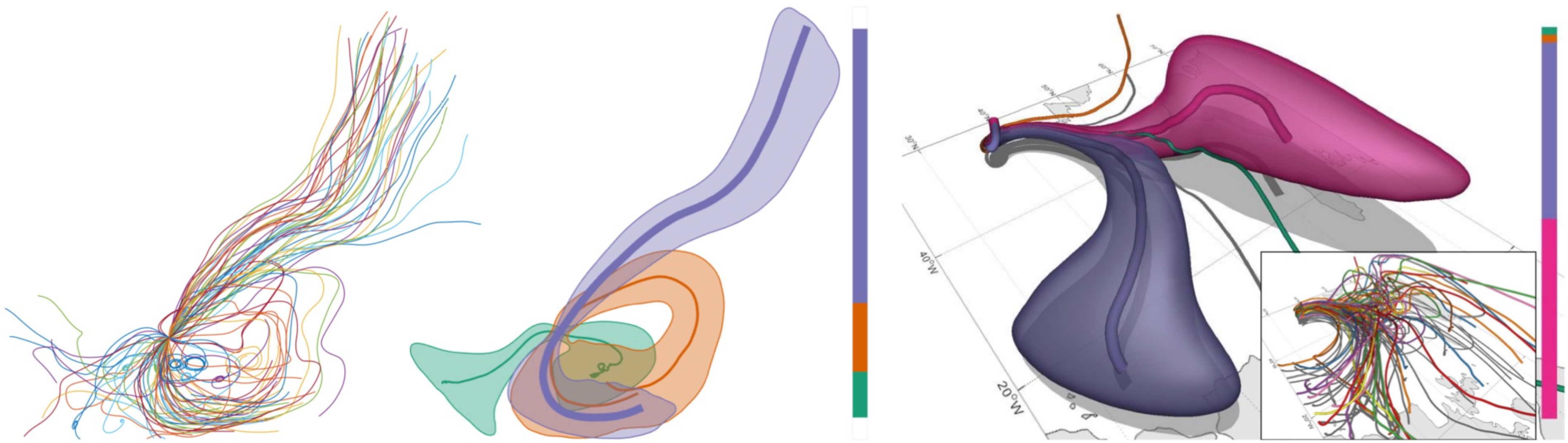

Fig. 1. From a set of streamlines in an ensemble of vector fields (left), our method generates an abstract visualization of the major trends in this set (middle). For each trend, a region of high confidence and a representative streamline-median is extracted. The relative strength of a trend is indicated by the thickness of its median line and by the bar plot on the right. Our method works in 2D and 3D (right), as well as for particle trajectories in time-dependent fields.

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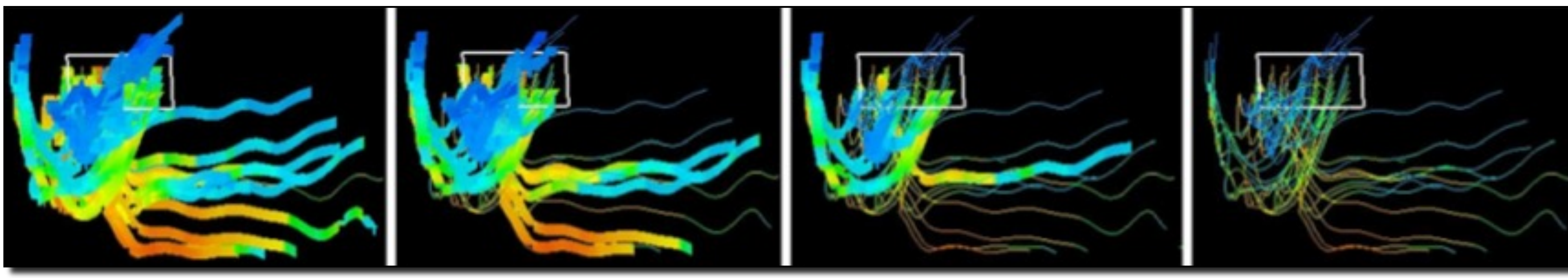
Ferstl, F., Bürger, K., & Westermann, R. (2015). Streamline variability plots for characterizing the uncertainty in vector field ensembles. IEEE Transactions on Visualization and Computer Graphics, 22(1), 767-776.

3D Meteorological Trajectory

- Estimate uncertainty due to interpolation
- User seeded trajectories
- Prune trajectories with high uncertainty



R. Boller, S. Braun, J. Miles, D. Laidlaw.
Application of Uncertainty Visualization Methods to Meteorological Trajectories.
In Earth Science Informatics, 3(1-2), 2010.

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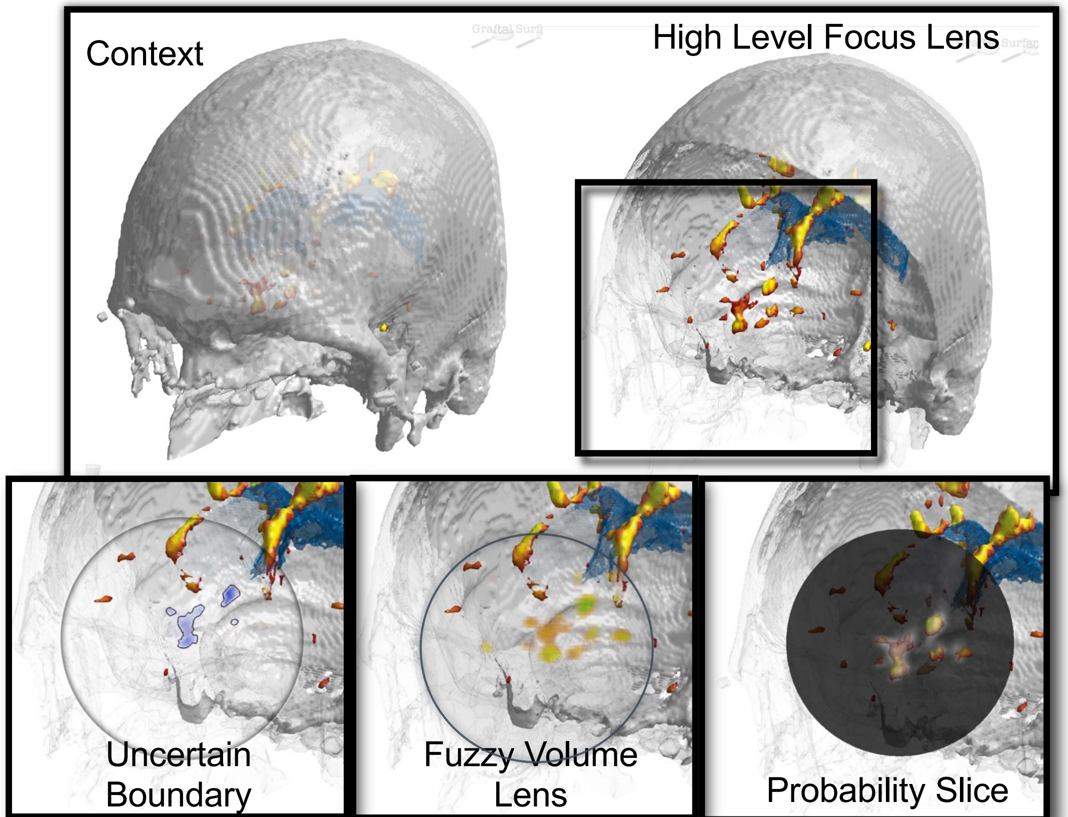
QuizLens: A Multi-lens approach for uncertainty exploration

- Global information important for qualitative evaluation & context
- Local information necessary for quantitative understanding
- Interchangeable lenses to explore various data characteristics



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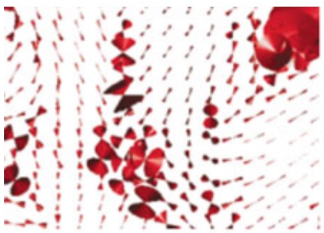
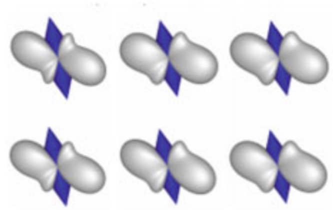
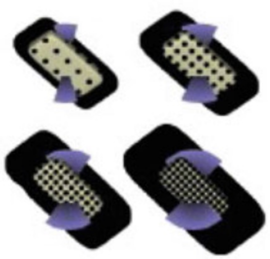
DTI Tensor Uncertainty Visualization



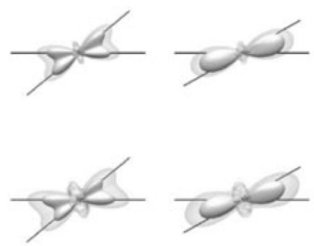
(a) Uncertainity cones [50]



(b) HiFiVE Glyphs [90]

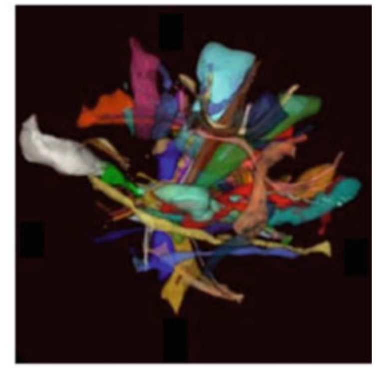


(c) Decomposed ensemble representation [110]



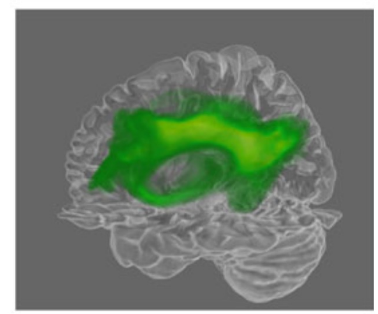
(d) ODF glyphs [96]

(a) Spaghetti plot [51]



(b) Wrapped streamlines [19]

(c) Illustrative visualization [15]



(d) Connectivity mapping [55]

Siddiqui, F., Höllt, T., & Vilanova, A. (2021). Uncertainty in the DTI Visualization Pipeline. Anisotropy Across Fields and Scales, 125.

Topological Uncertainty

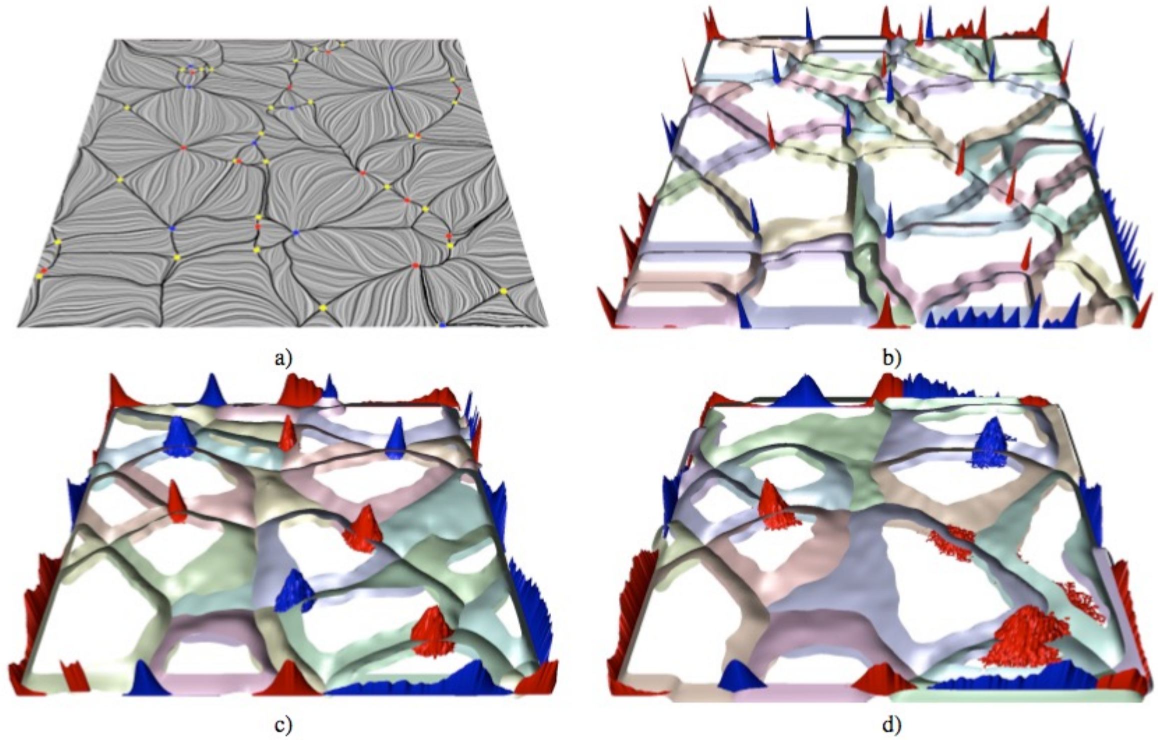


Figure 6: *Increasing the uncertainty of a random vector field: a) certain topology of mean vector field; b)* $\|\mathbf{T}\|_F = 0.2$*; c)* $\|\mathbf{T}\|_F = 2.0$*; d)* $\|\mathbf{T}\|_F = 5.0$.

M. Otto, T. Germer, H.C. Hege, H. Theisel. Uncertain 2D Vector Field Topology. In CGF, 29(2), 2010.

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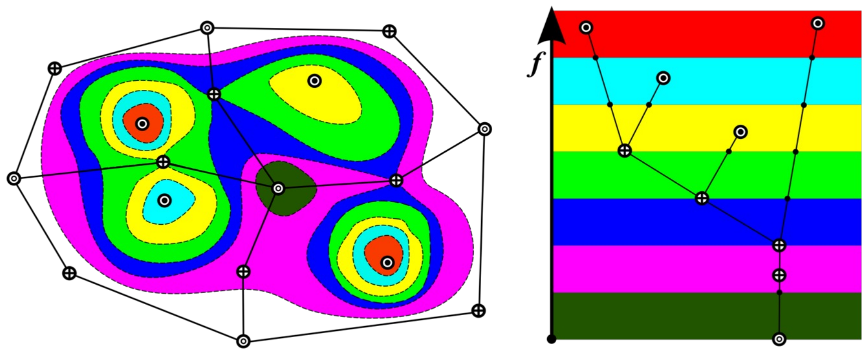
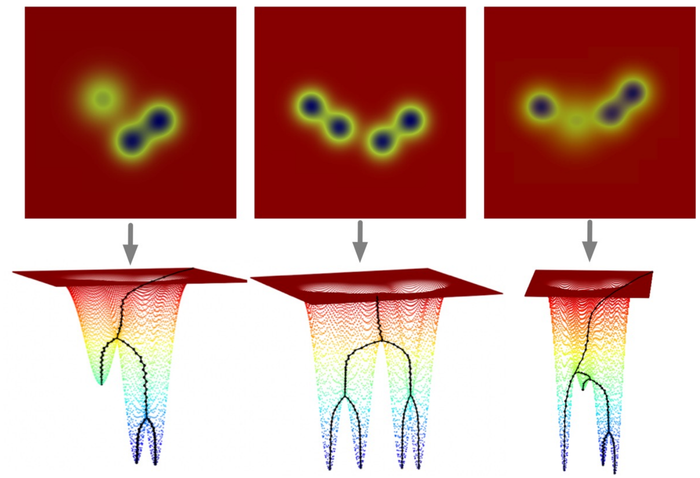
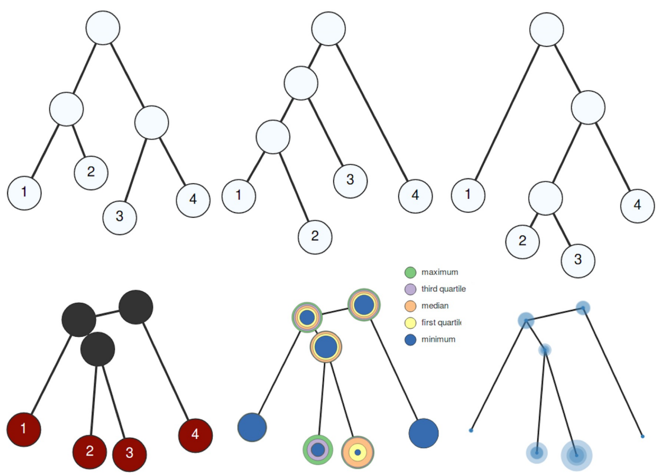
Visualizing uncertainty in topological structures



Merge Tree: a topological summary of scalar fields



Merge trees that arise from an ensemble of scalar fields



1. Compute an average merge tree from an ensemble
2. Uncertainty visualization of the average tree captures structural variations among the ensembles

Lin Yan, Yusu Wang, Elizabeth Munch, Ellen Gasparovic, Bei Wang. A Structural Average of Labeled Merge Trees for Uncertainty Visualization, IEEE VIS, 2019. arXiv: 1908.00113.

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Possibilistic Marching Cubes

Possibility theory is mathematically the simplest uncertainty theory for dealing with incomplete information. It is a natural means for quantifying epistemic uncertainty coming from lack of knowledge.

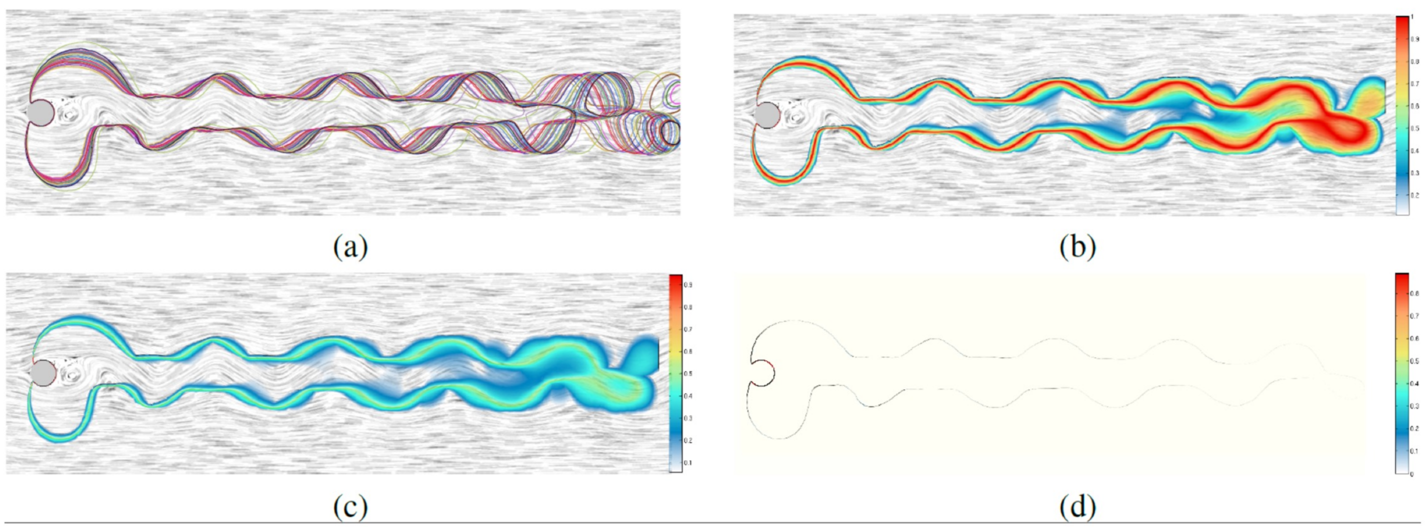
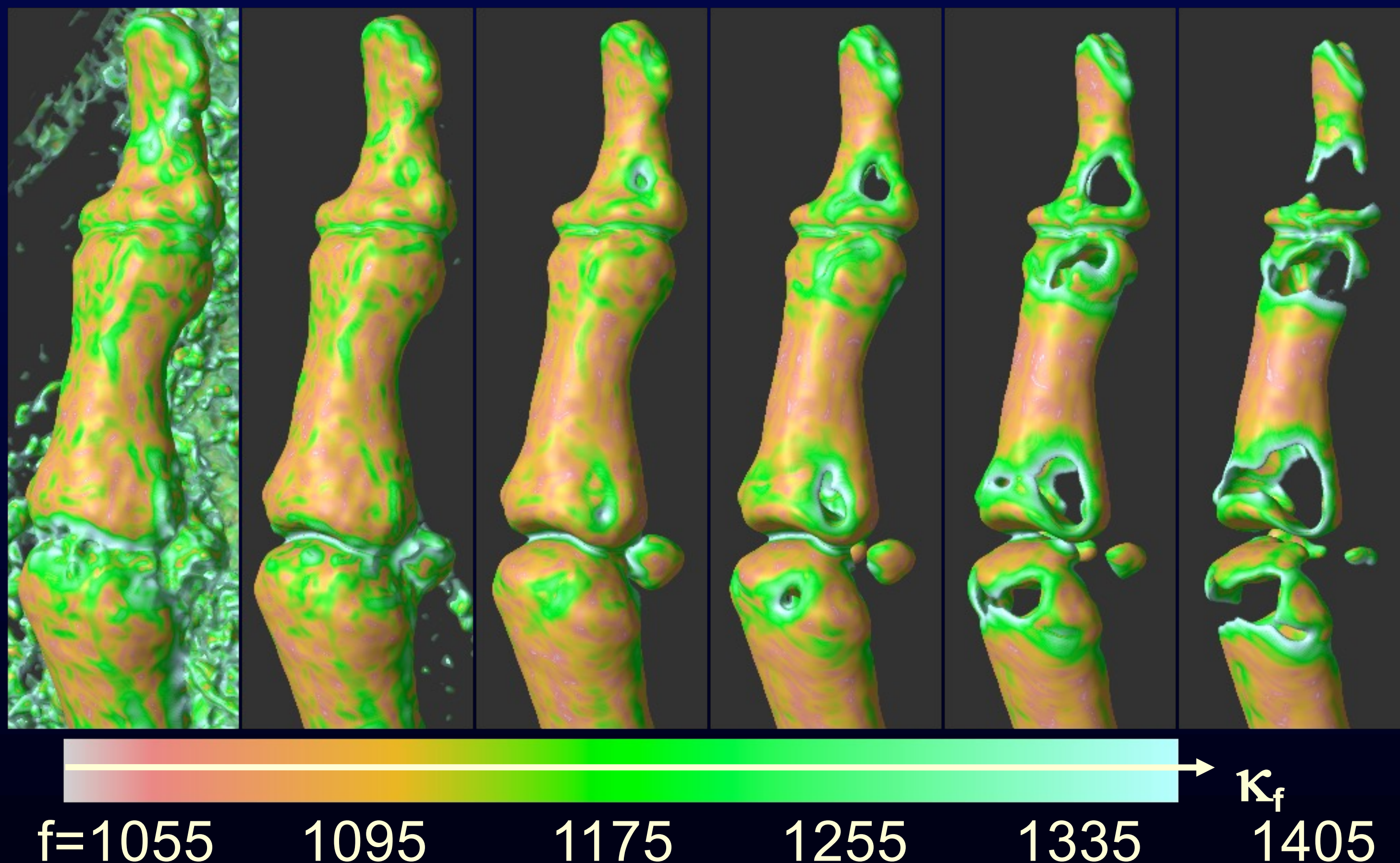


FIG. 7: Uncertain isocontours of the pressure field: (a) Ensemble of isocontours of the pressure field extracted from fluid simulation. (b) Possibilities (from PossMC) visualization. (c) Pignistic probabilities (from PossMC) visualization. (d) Necessities (from PossMC) visualization (the contour is faded looking due to the chosen colorbar: small necessity values are represented by white and light blue colors). The visualization has been overlaid on top of a LIC [49] visualization of one of the ensemble members.

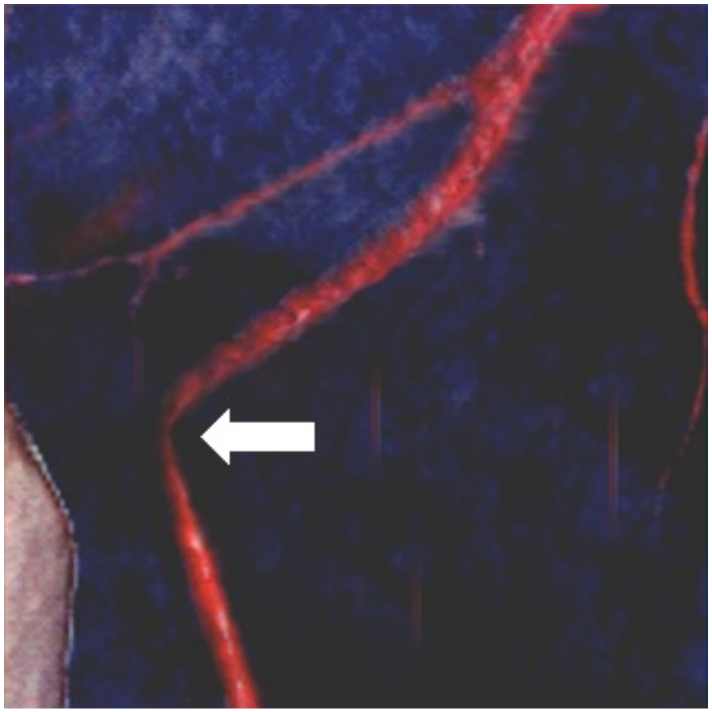
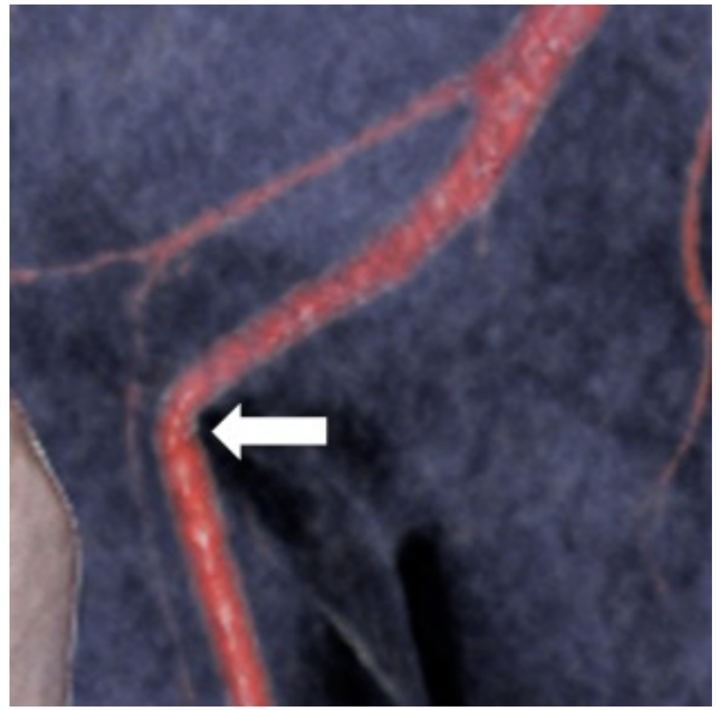
He, Y., Mirzargar, M., Hudson, S., Kirby, R. M., & Whitaker, R. "An uncertainty visualization technique using possibility theory: Possibilistic marching cubes." International Journal for Uncertainty Quantification 5.5 (2015).

Flow-line curvature results

Thumb from Visible Human Female, fresh CT:



Uncertainty Visualization

Images Courtesy of Claes Lundström, Patric Ljung, Anders Persson, Anders Ynnerman

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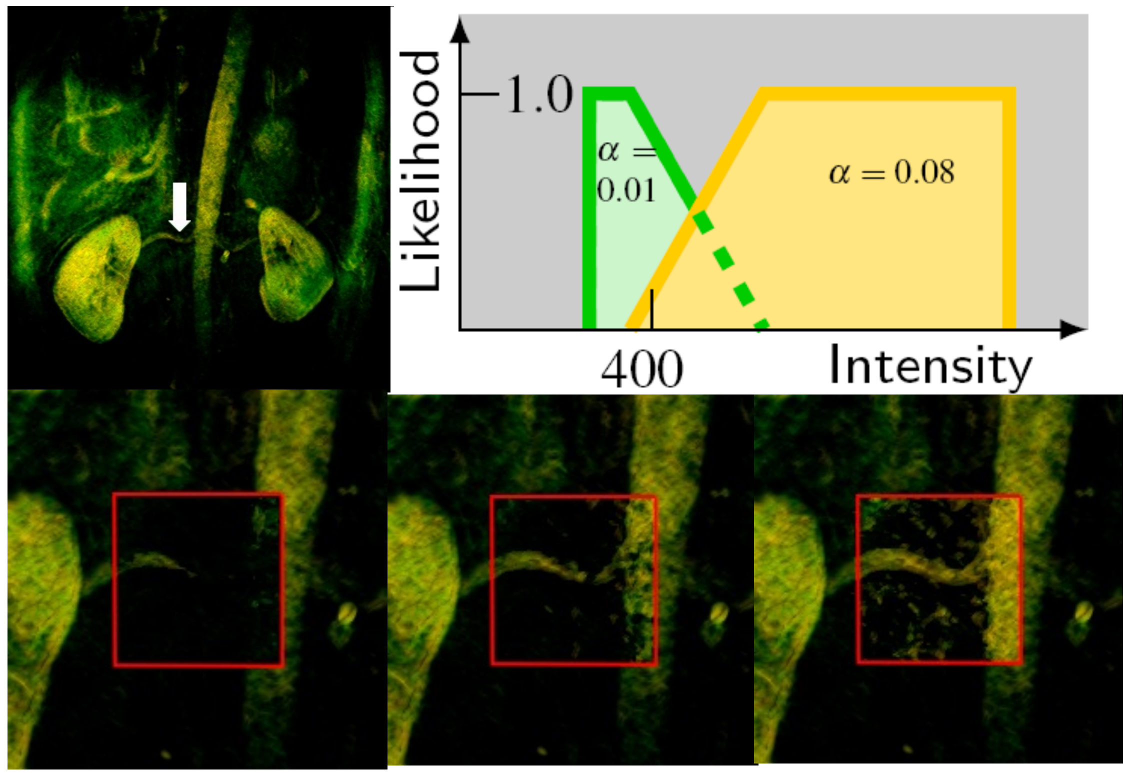
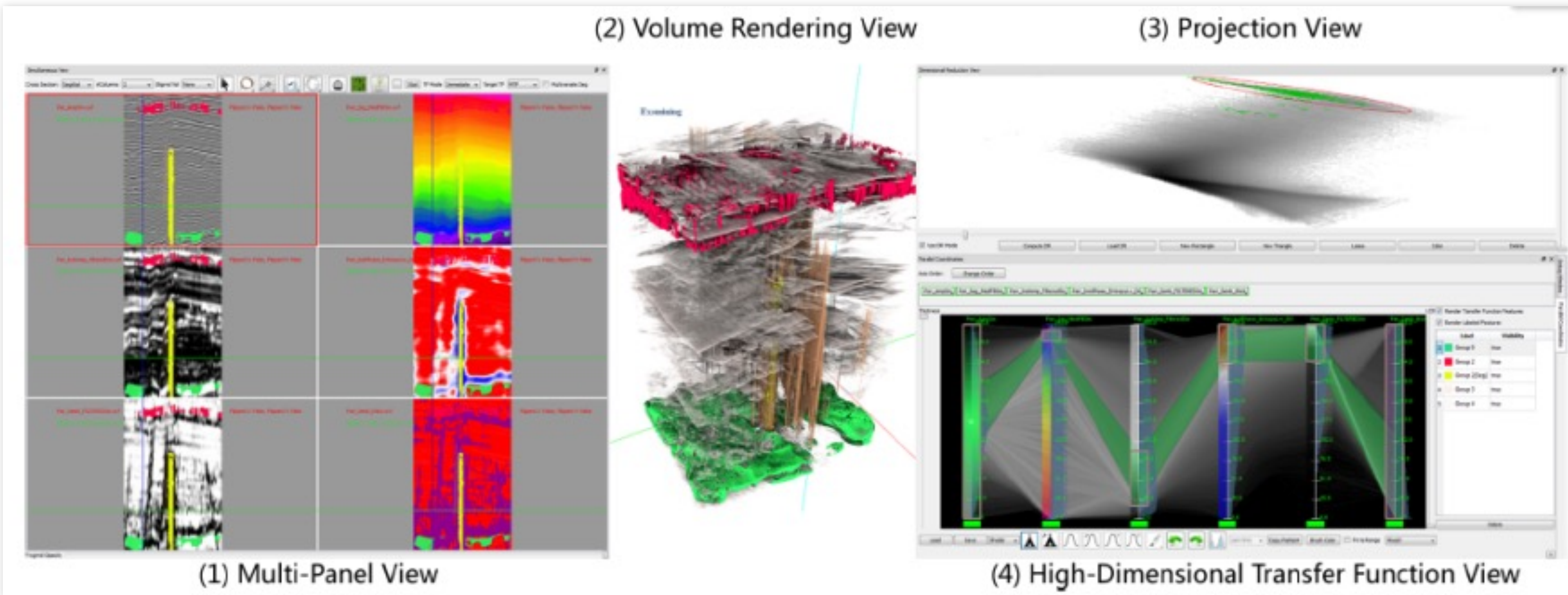
Uncertainty Visualization



Claes Lundström, Patric Ljung, Anders Persson, Anders Ynnerman. Uncertainty Visualization in Medical Volume Rendering Using Probabilistic Animation, IEEE Transactions on Visualization and Computer Graphics, 13(2007): no. 5

Volume Rendering using High Dimensional Transfer Functions

- Create Transfer Functions (TFs) from user selected samples in spatial domain and error/uncertainty.
- Multiple linked views.



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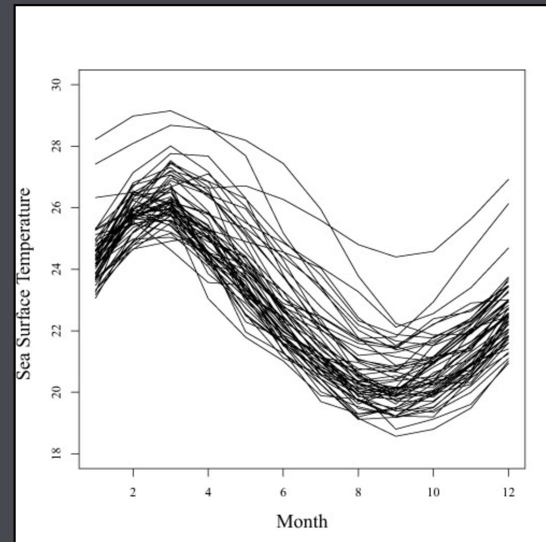
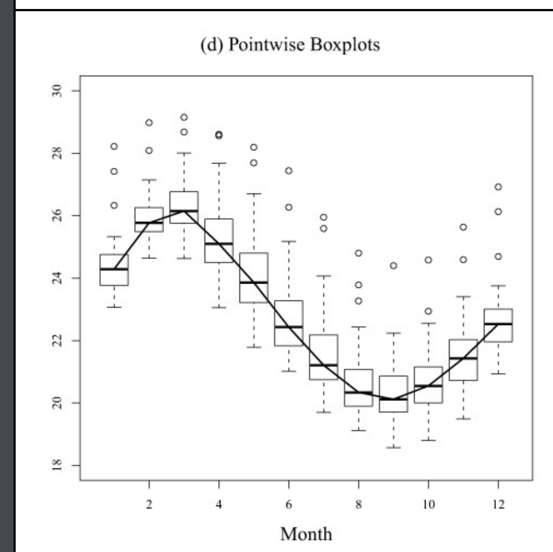
Functional Box Plot

Boxplot statistics on 2D functions

Defined on the function, rather than point-wise





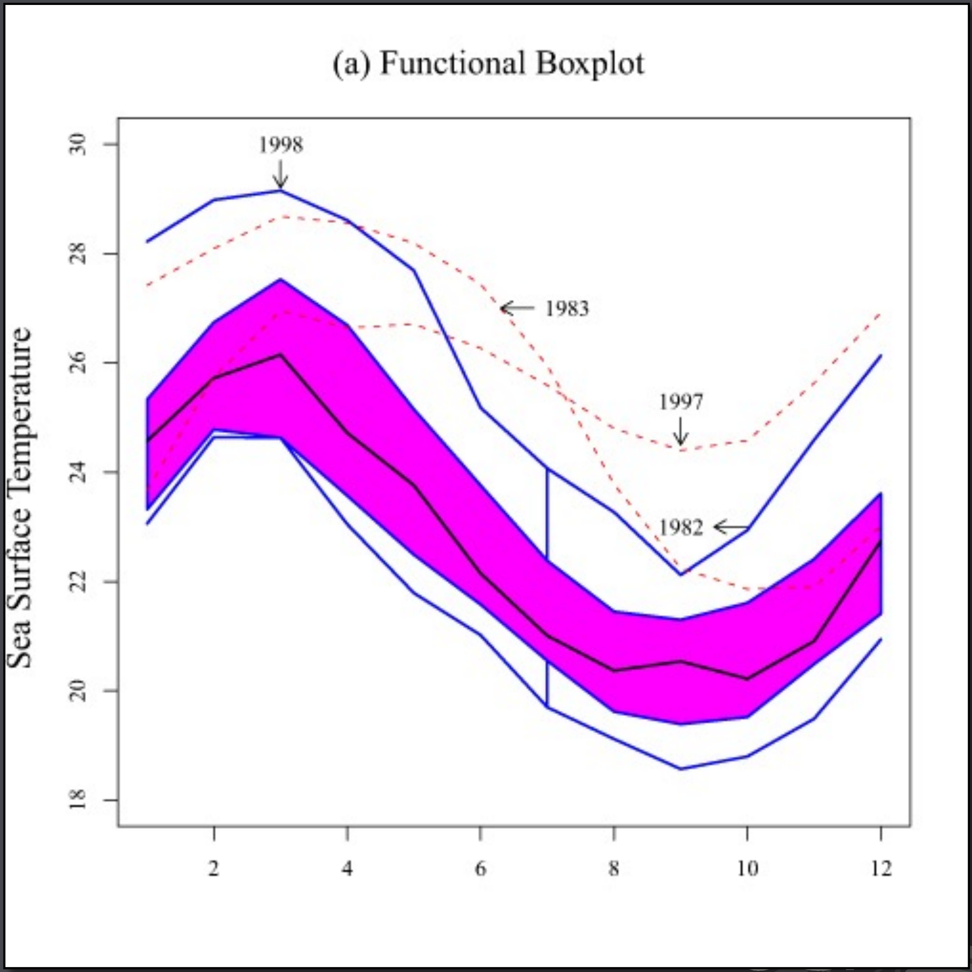
Functional Boxplots.
Ying Sun, Marc G. Genton.
J. of Comp. and Graphical Statistics 20:2, 2011, 316-334.

Functional Box Plot

Band Depth

The amount of time a function lies within the set of functions

Functional Boxplots.
Ying Sun, Marc G. Genton.
J. of Comp. and Graphical Statistics 20:2, 2011, 316-334.



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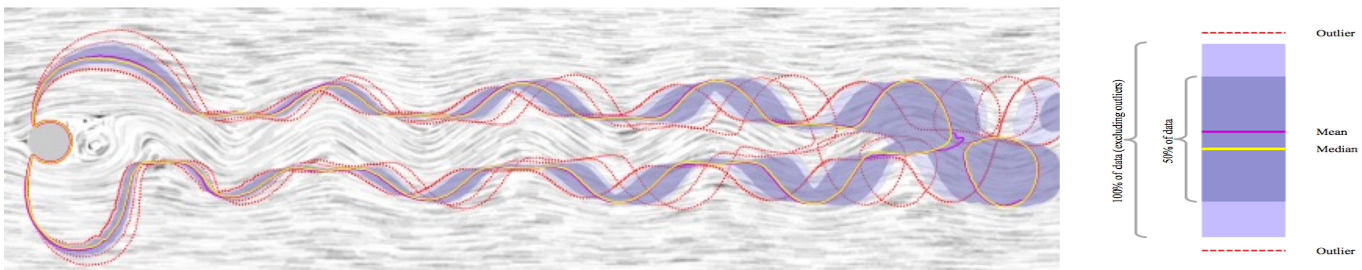
Contour Box Plots

$$S \in \mathrm{sB}\left(S_1, \ldots S_j\right) \iff \bigcap_{k=1}^{j} S_k \subset S \subset \bigcup_{k=1}^{j} S_k.$$



Whitaker, Mirzargar, Kirby, *IEEE Transactions on Visualization and Computer Graphics*, Vol. 19, No. 12, pp. 2713--2722, 2013.

M.G. Genton, C.R. Johnson, K. Potter, G. Stenchikov, Y. Sun. "Surface boxplots," In *Stat Journal*, Vol. 3, No. 1, pp. 1-11. 2014.

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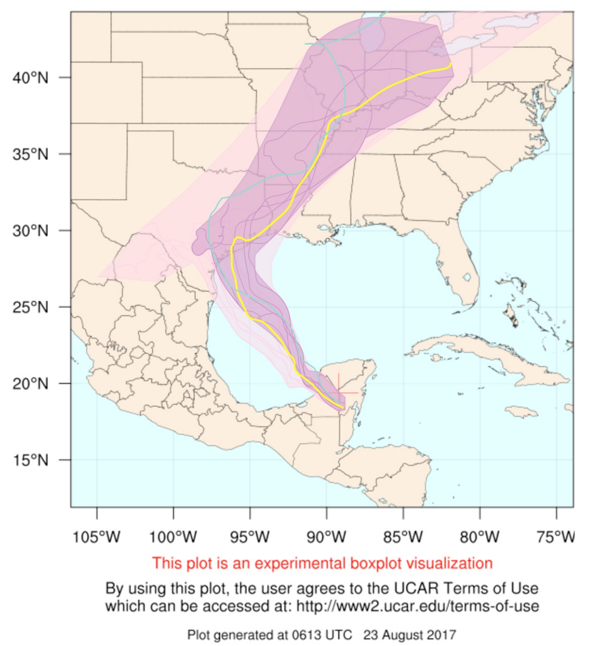
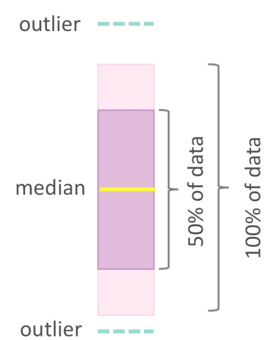
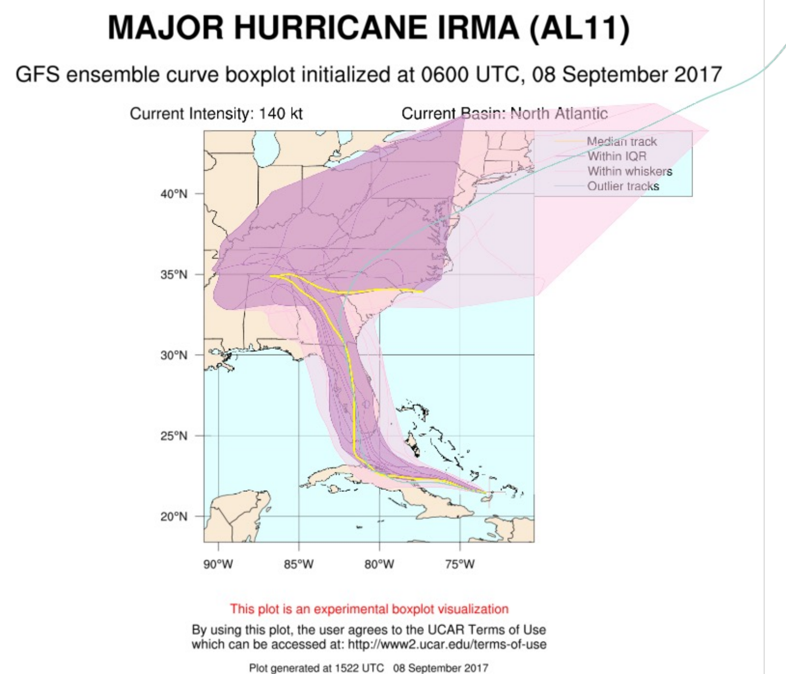
Ensemble Curved Boxplot







NCAR

M. Mirzargar, R. Whitaker, R. M. Kirby. "Curve Boxplot: Generalization of Boxplot for Ensembles of Curves," IEEE Transactions on Visualization and Computer Graphics, Vol. 20, No. 12, IEEE, pp. 2654-63. December, 2014.

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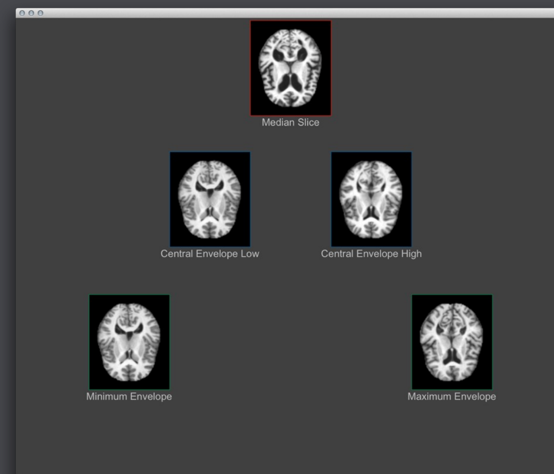
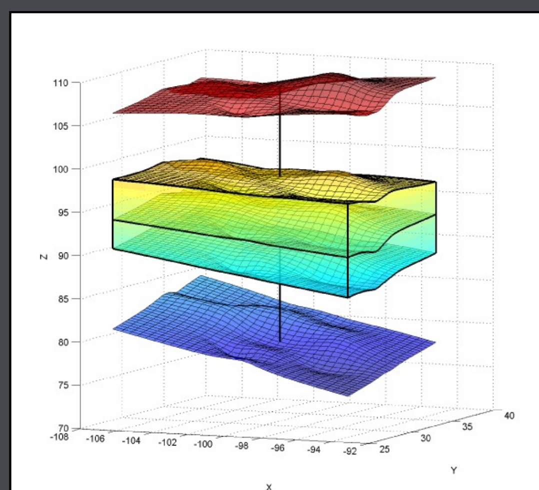
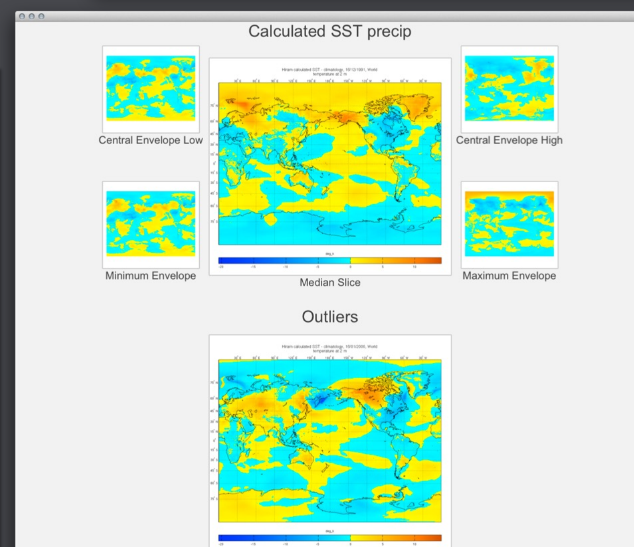
Surface Box Plots

- Extension of band depth to 3D
- *Images rather than curves*
- *Volume-based band-depth*







Surface Boxplots.
Marc G. Genton, Christopher Johnson, Kristin Potter, Georgiy Stenchikov, and Ying Sun.
Stat. 3:1, 2014, 1–11.

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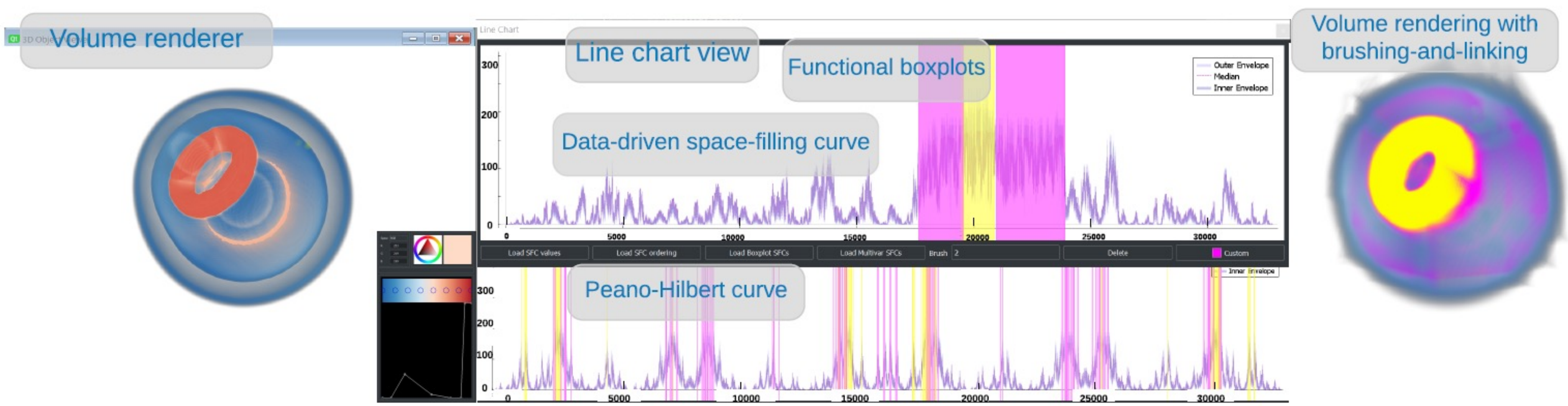
Data-driven space-filling curves

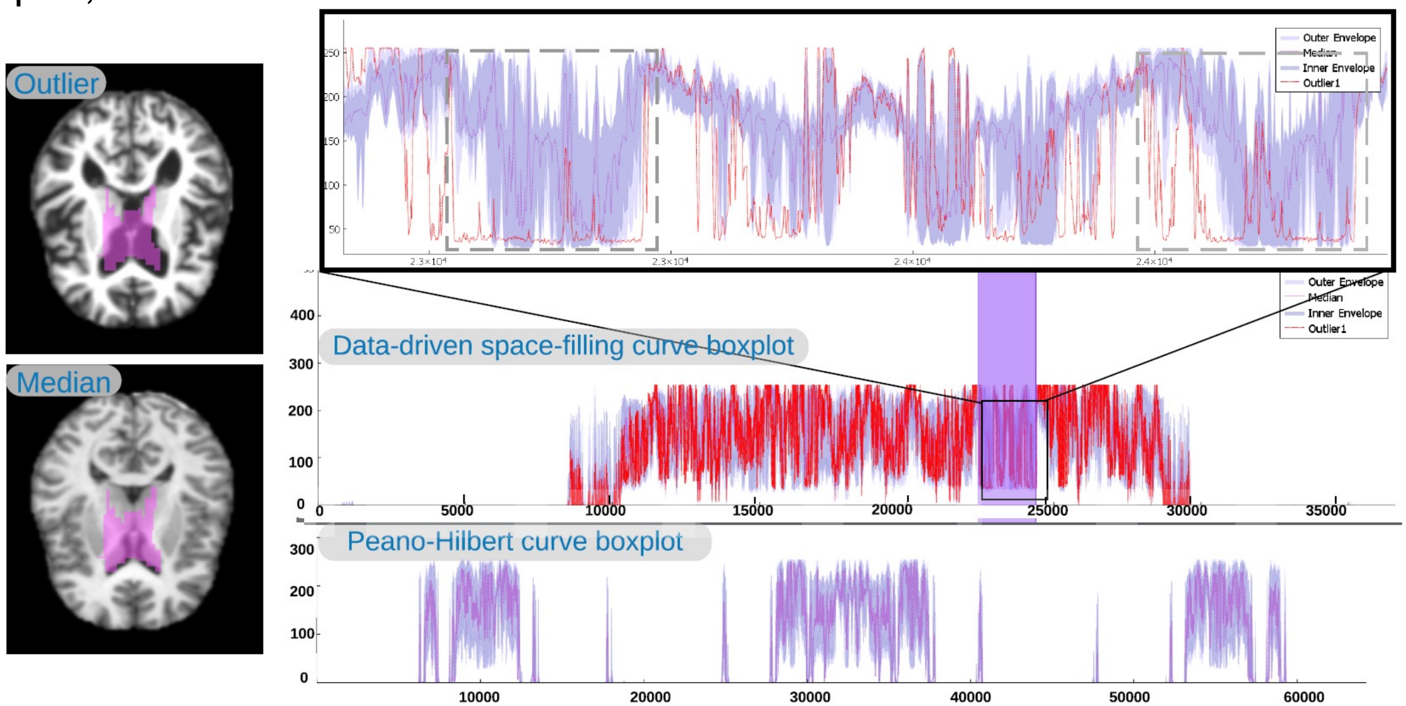
- Data-driven space-filling curves
  - better coherency preservation (data value + position) than existing methods
  - 2D and 3D data
  - regular grids and multiscale
- A flexible Hamiltonian path method



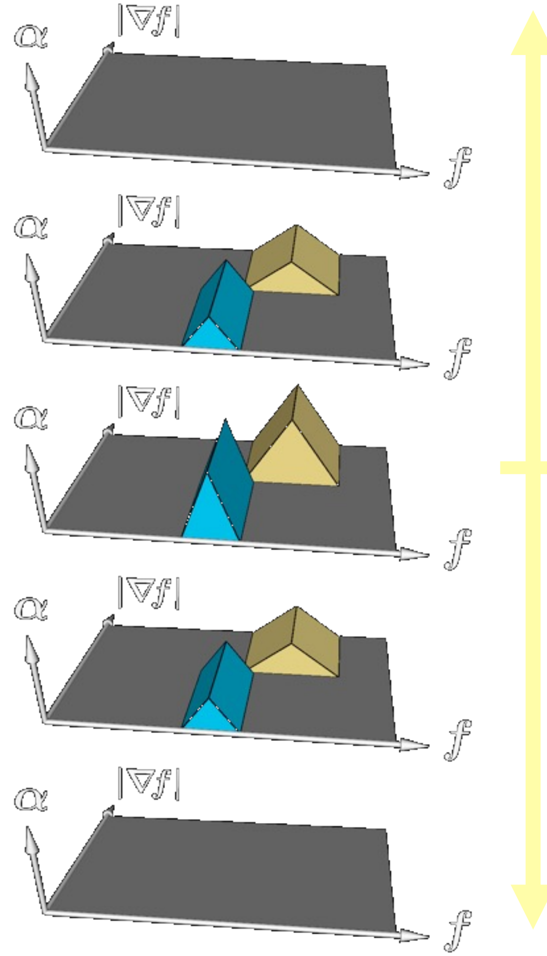
L. Zhou, C. R. Johnson, D. Weiskopf. “Data-Driven Space-Filling Curves,” In IEEE Transactions on Visualization and Computer Graphics, Vol. 27, No. 2, IEEE, pp. 1591-1600. 2021.

Example - Brain Atlas

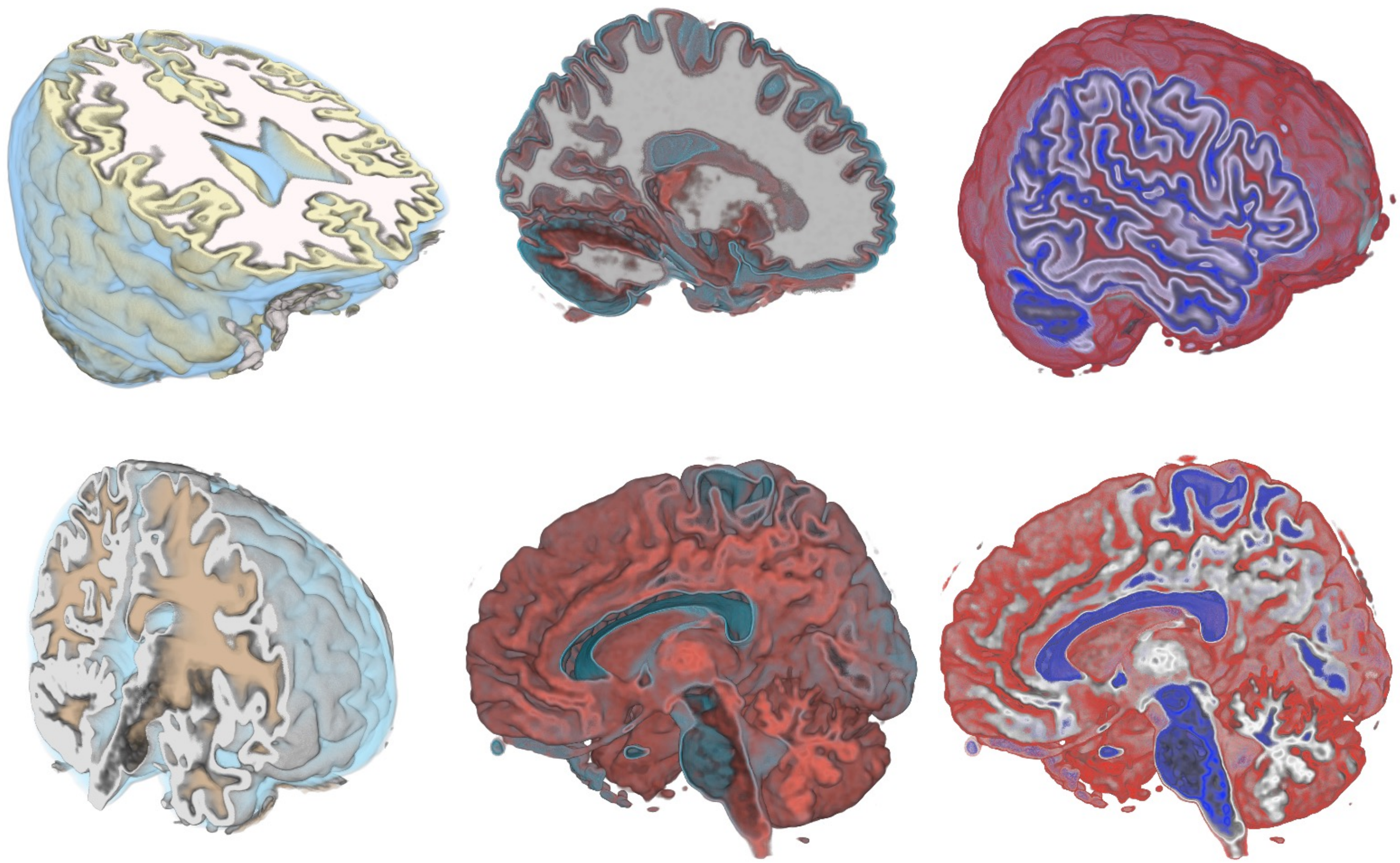
- Brain atlas of 2D MRI scans (176*208 pixels); curve generation time: 3m49s
- Surface Boxplot; linearized based on the median



3D Transfer Function



Visualizing Uncertainty Using Volume Rendering



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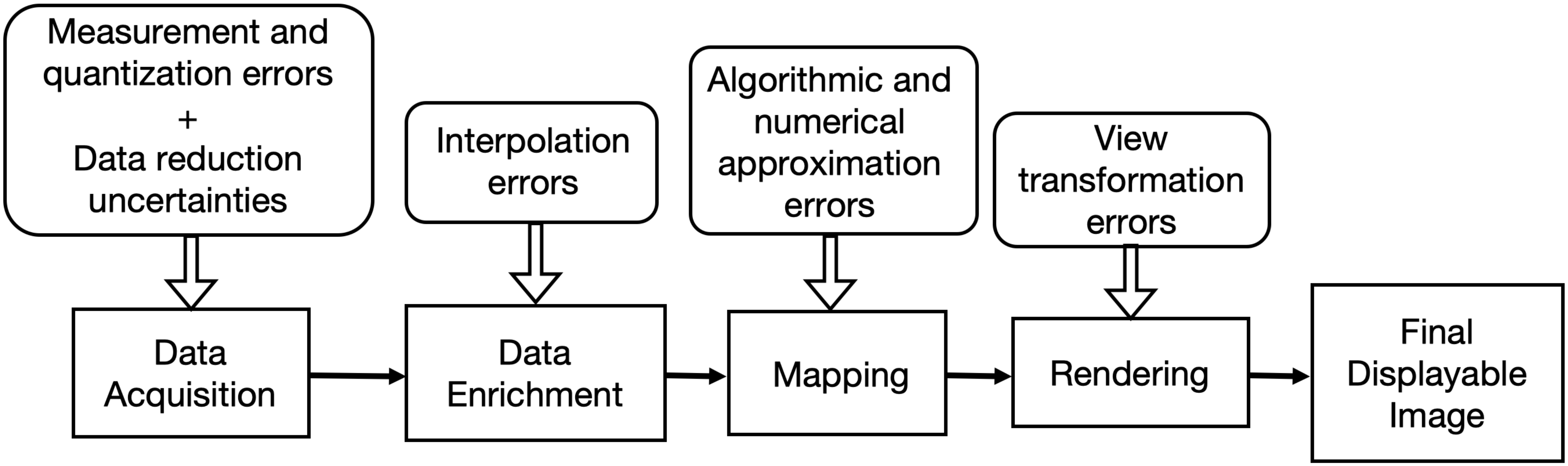
Uncertainty-Aware Volume Visualization



Visualization pipeline
[Brodlie et al., 2012]

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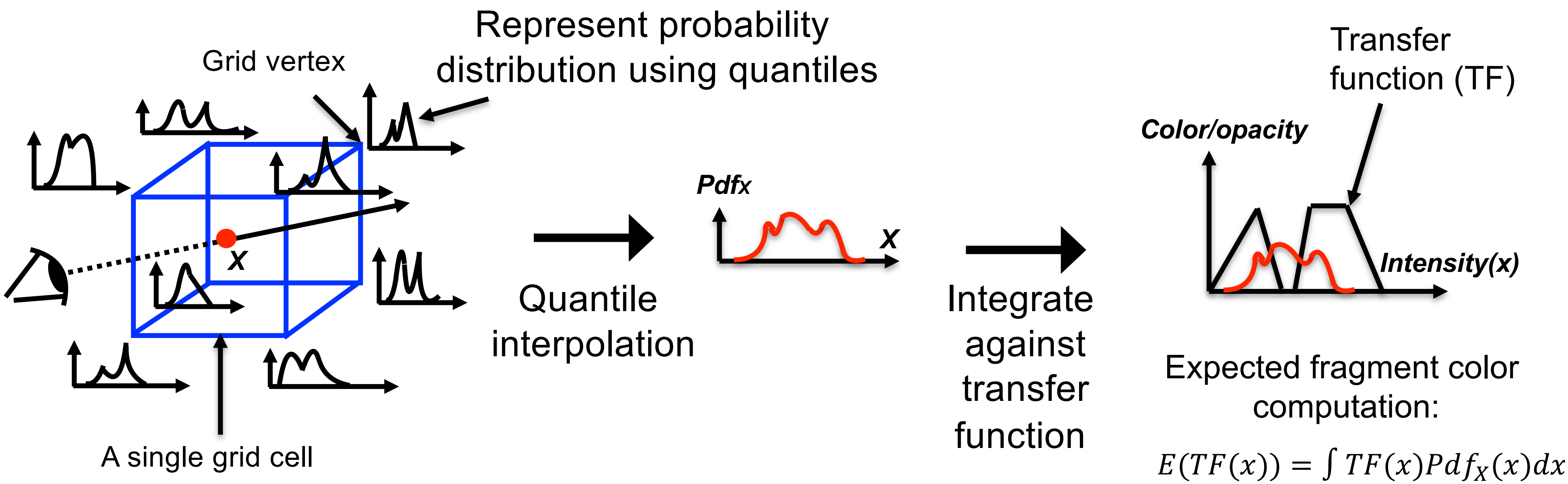
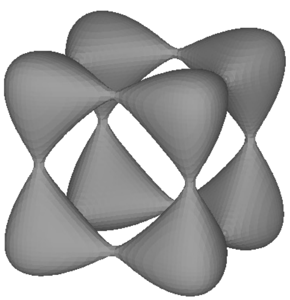
Volume Rendering With Nonparametric Statistics



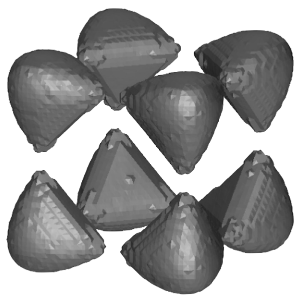
T. Athawale, B. Ma, E. Sakhaee, C.R. Johnson, and A. Entezari. Nonparametric Statistical Framework for Direct Volume Rendering of Uncertain Data. IEEE Visualization 2020, Oct. 2020.

Models of Uncertainty

Ground truth: Tangle function mixed with noise

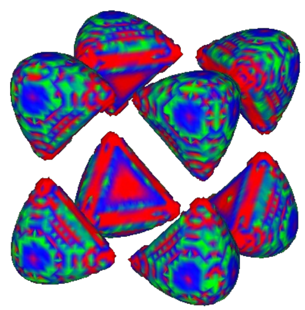


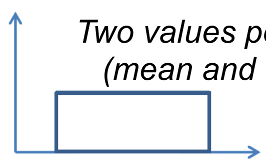
Mean



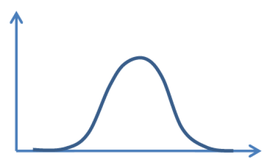
One value per-voxel

Parametric

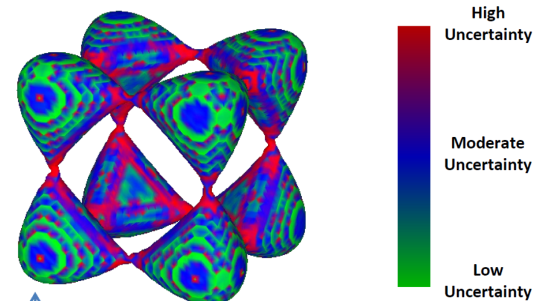


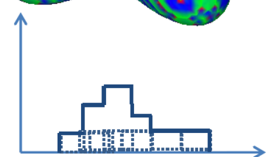


Two values per-voxel (mean and width)

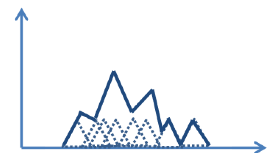


Nonparametric





n representative samples per-voxel (e.g., min, Q1, median, Q2, max)



Probabilistic marching cubes, [Pöthkow et al., 2013];

Uncertainty-aware marching cubes [Athawale et al., 2015]

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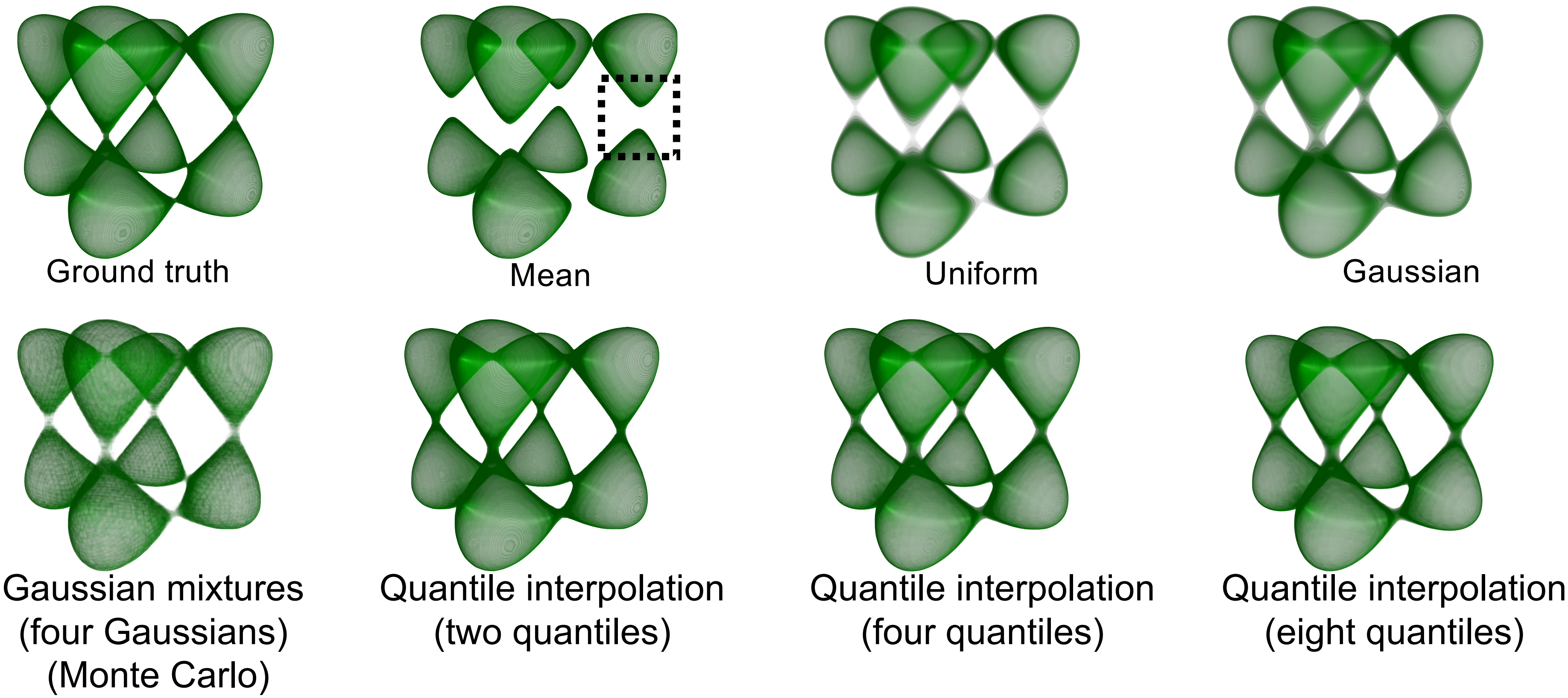
Tangle Function (Qualitative Comparisons)



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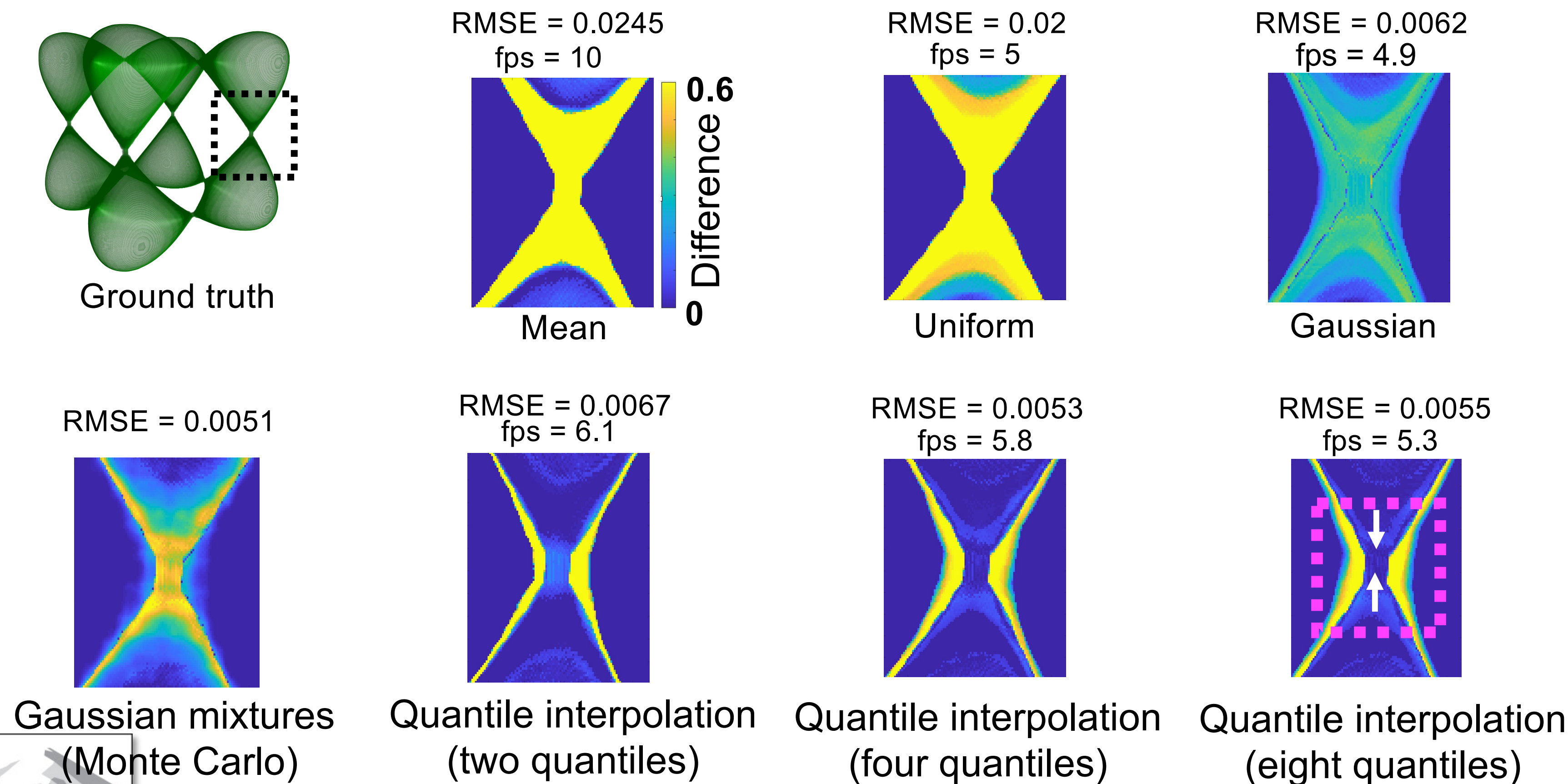
Tangle Function (Quantitative Comparisons)



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Uncertainty Visualization of the Marching Squares and Marching Cubes Topology Cases - VIS 2021

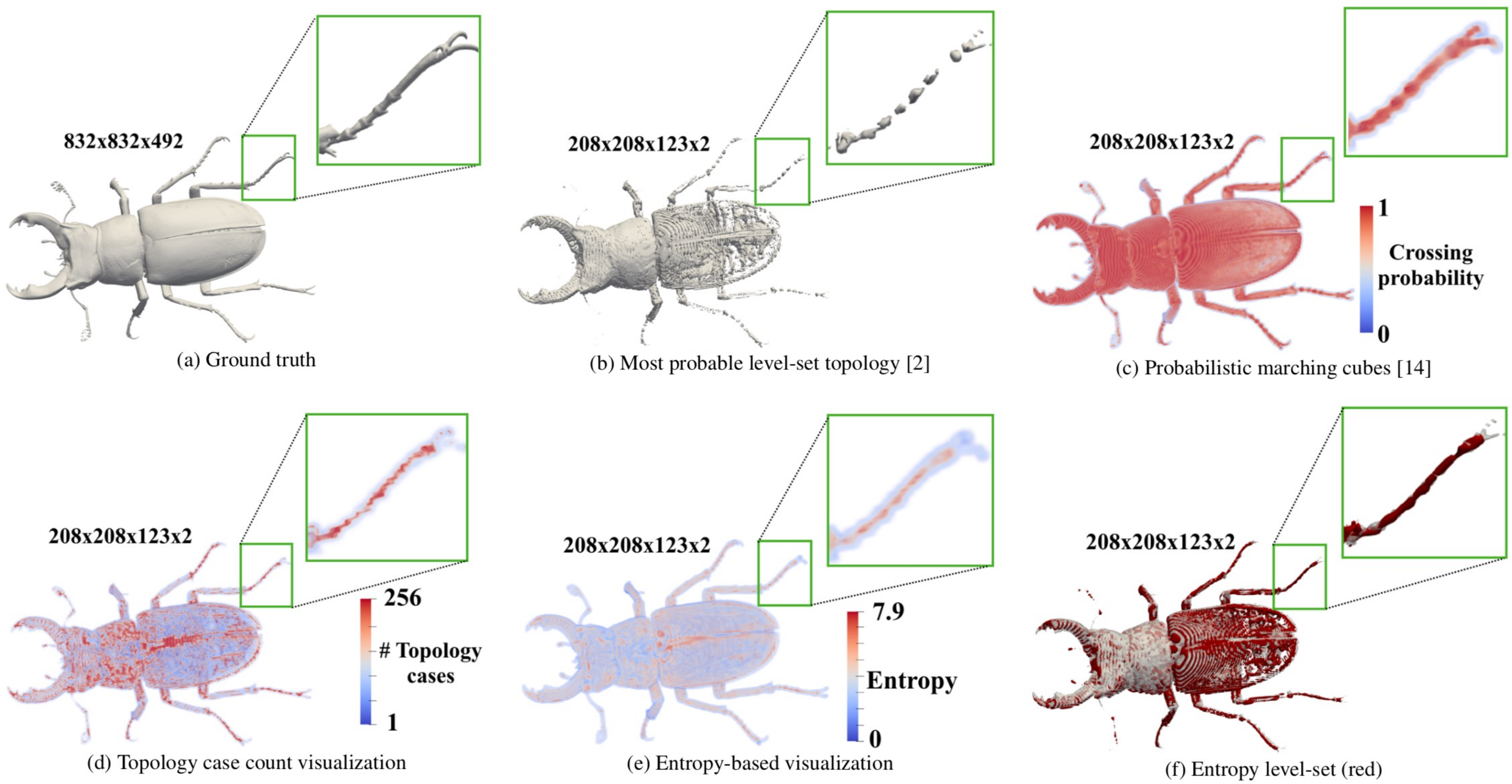

Figure 5: Uncertainty visualizations for the stag beetle [21] hixel dataset at $k = 900$. The noise in the data results in breaking of the beetle leg in image (b). In probabilistic marching cubes, it is difficult to distinguish between the regions of high and topological uncertainty, which is easier using our visualizations in images (d-f). The relatively high sensitivity of the beetle leg topology to noise is detected in images (d-f) by the red regions. In image (f), the most probable level-set (gray) is overlaid with the entropy volume level-set (red) for entropy isovalue 5.

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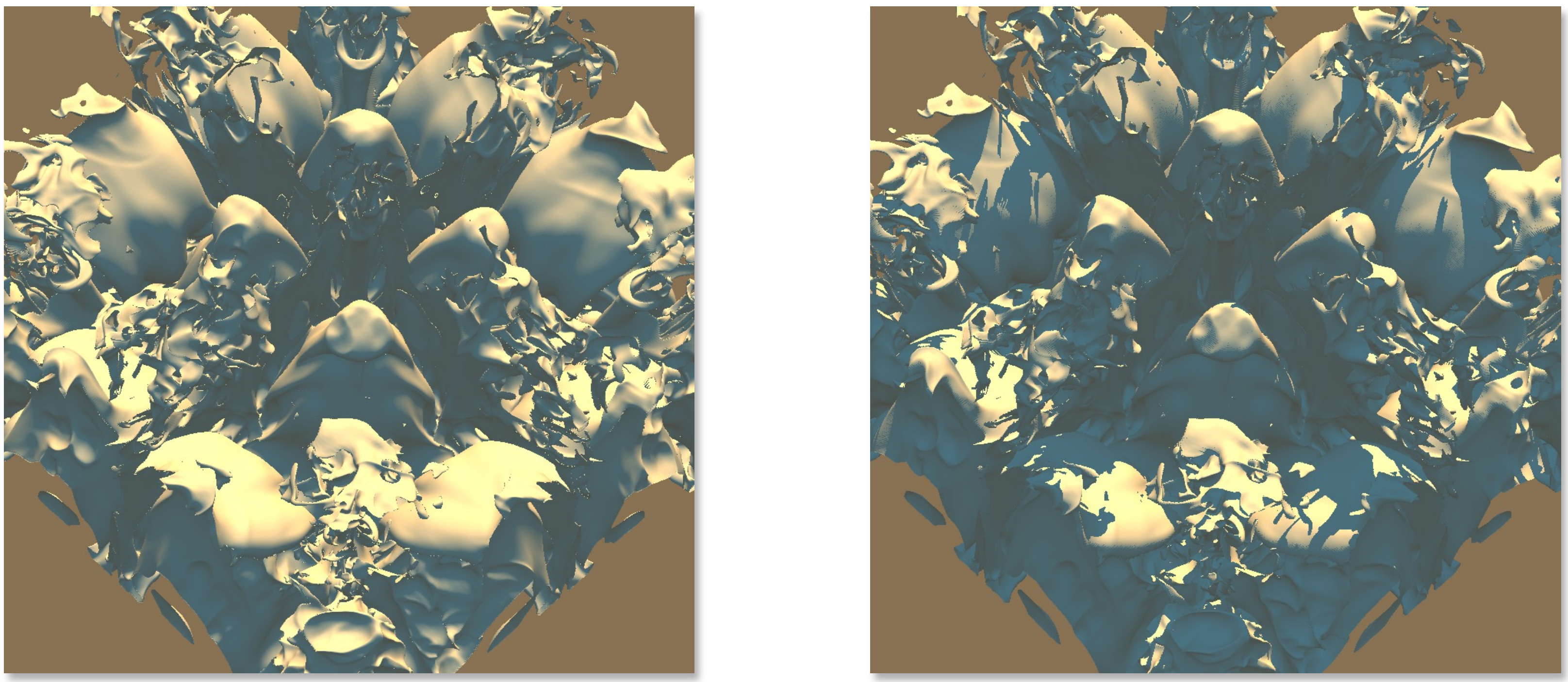
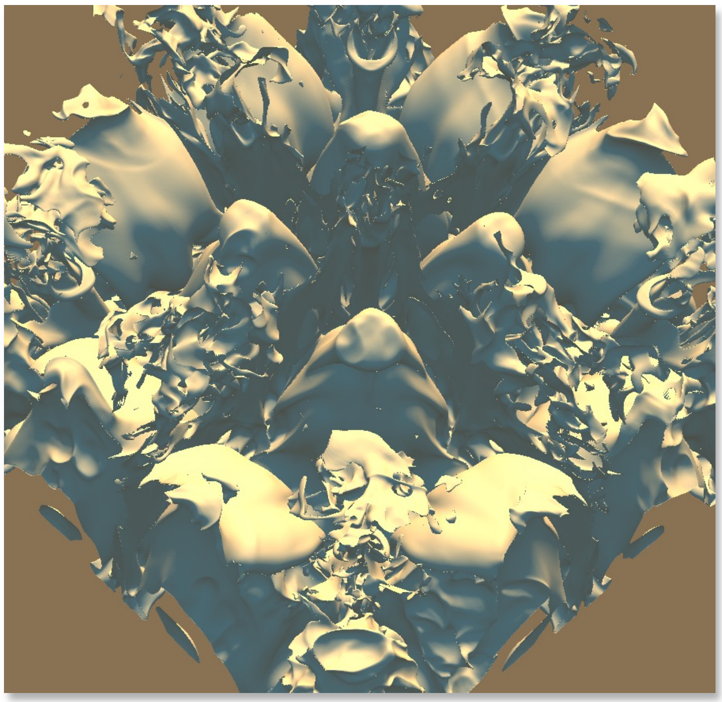
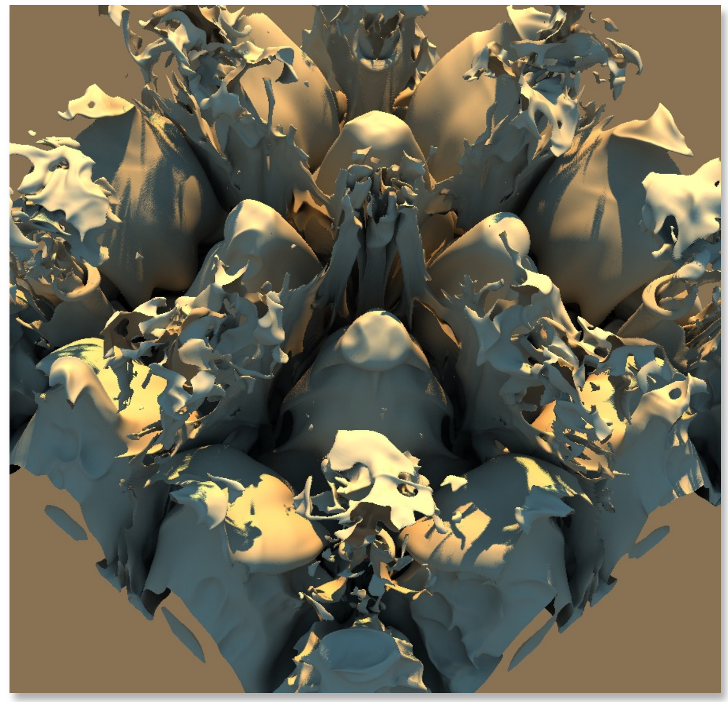
Perceptual Uncertainty

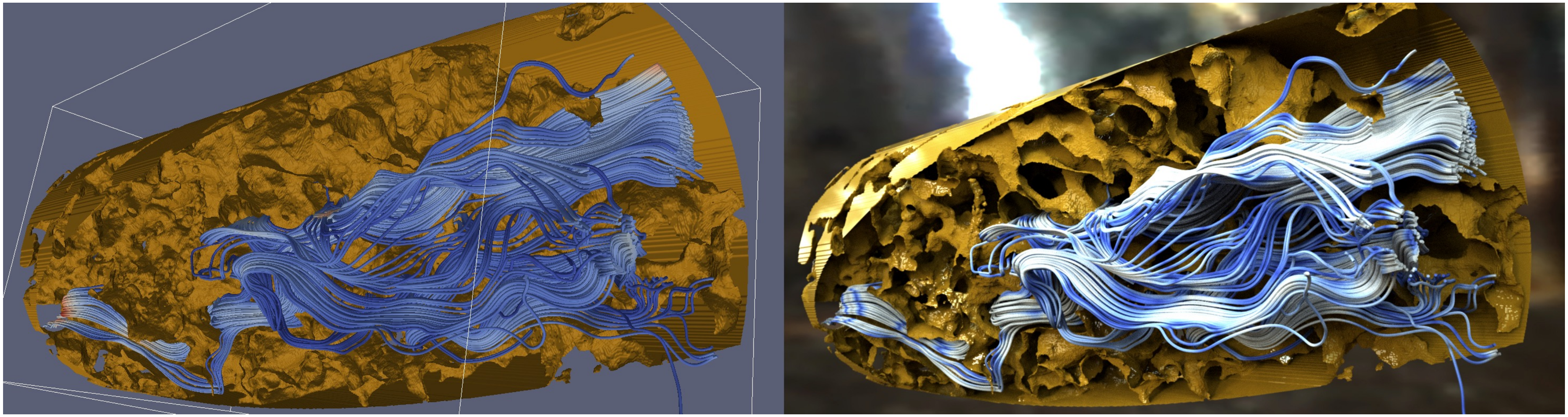


Scientific Computing and Imaging Institute, University of Utah

Perceptual Uncertainty







Path of water through a karst limestone structure of a ground sample analysis visualizing stone porosity and the spatial arrangement of the flow traces.

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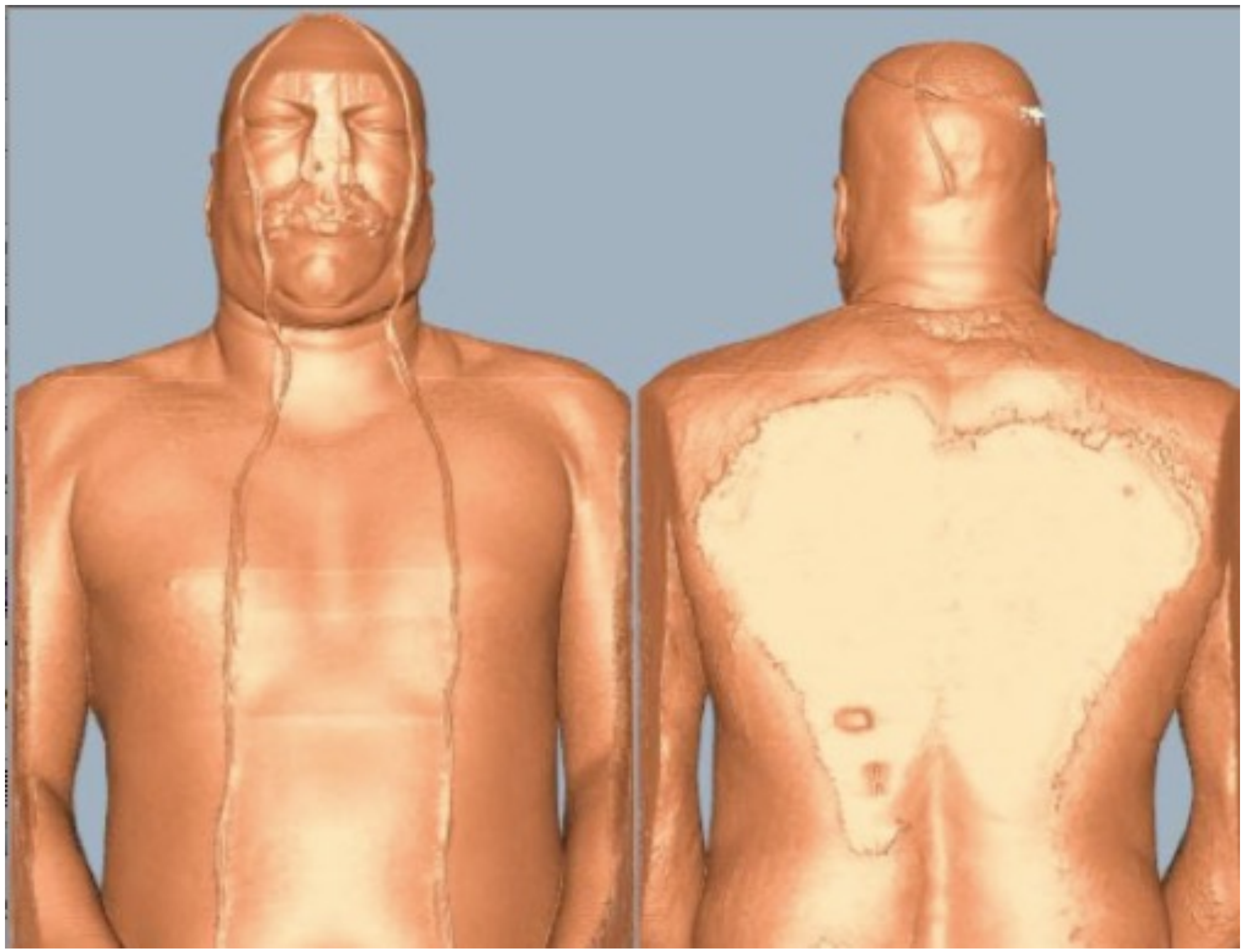
NIH Visible Male



Visible Human - High Resolution

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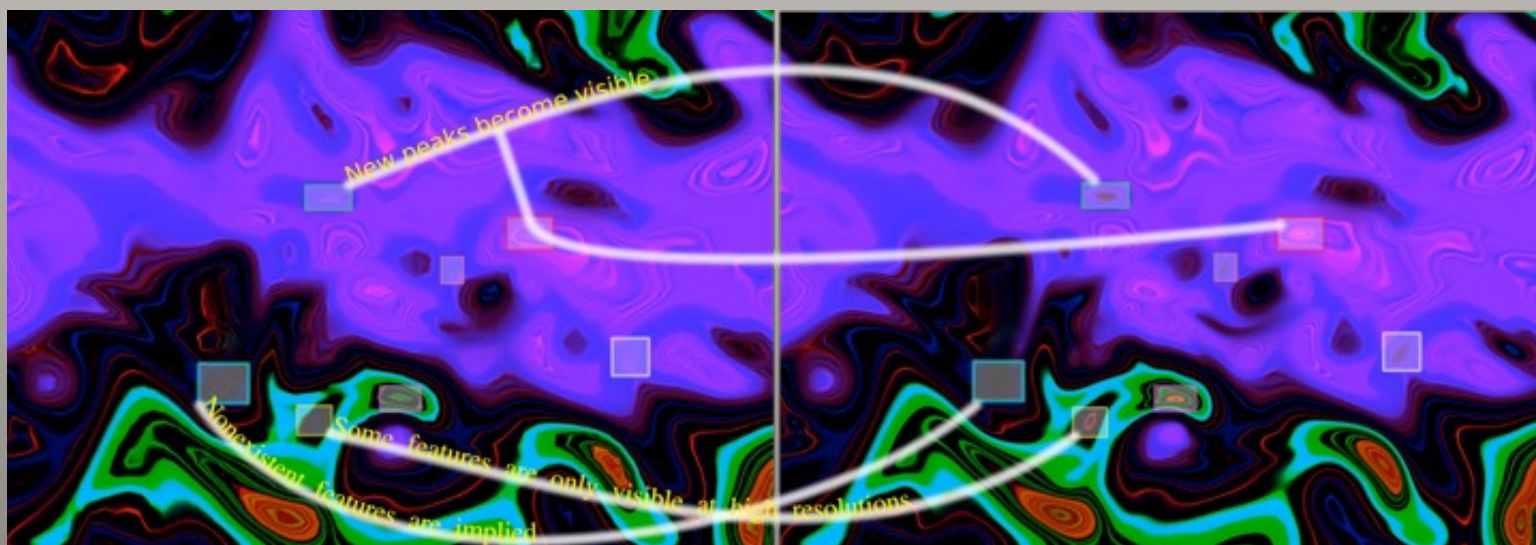
The Need for High Resolution Visualization

"…the data show for the first time how detailed transport and chemistry effects can influence the mixing of reactive scalars. It may be advantageous to incorporate these effects within molecular mixing models. It is worth noting that at present it is impossible to obtain this type of information any other way than by using the type of highly resolved simulation performed here."
Jacqueline Chen, Sandia National Laboratories



Lower Resolution High Resolution

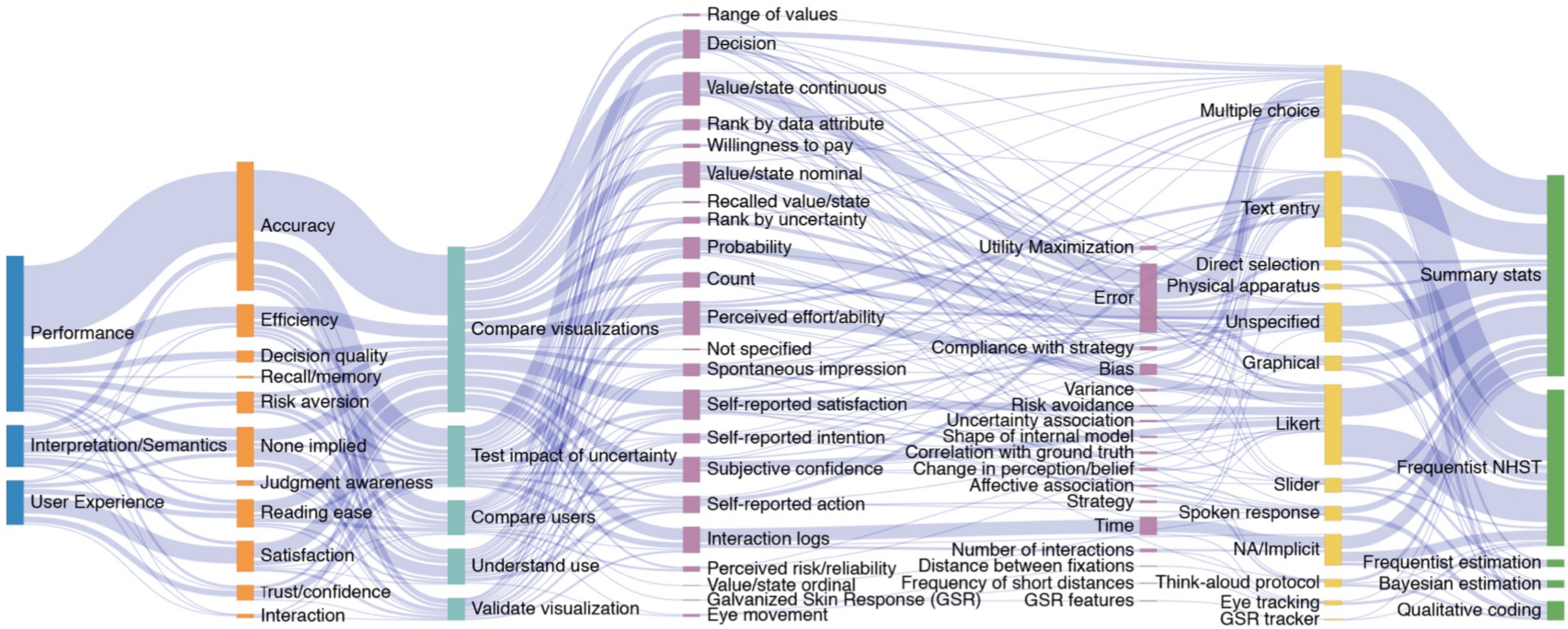


Fig. 2. 372 evaluation paths that we observed across a sample of 86 publications with uncertainty visualization evaluations. The number of inlinks and outlinks differ for some nodes due to the same evaluation path representing multiple codes at a single level (e.g., Analysis).

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In Pursuit of Error: A Survey of Uncertainty Visualization Evaluation

Jessica Hullman, Xiaoli Qiao, Michael Correll, Alex Kale, Matthew Kay

IEEE Trans. Visualization & Comp. Graphics (Proc. InfoVis), 2019

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