Incubation project report:

Computational Topology for Exploring Time-varying Volume Data

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Collaborators

Students

- Lorenzo Ibarria, Byung-Moon Kim (Georgia Tech)
- Ajith Mascarenhas, Martin Isenburg (UNC)

Faculty/Researchers

- Peter Lindstrom, Valerio Pascucci (LLNL)
- Andrzej Szymczak (Georgia Tech)
- Herbert Edelsbrunner, John Harer, (Duke U.)

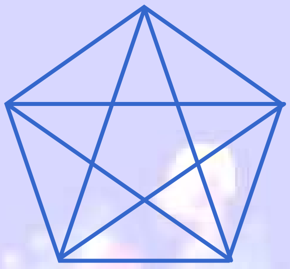
Focus on huge 4D scalar fields

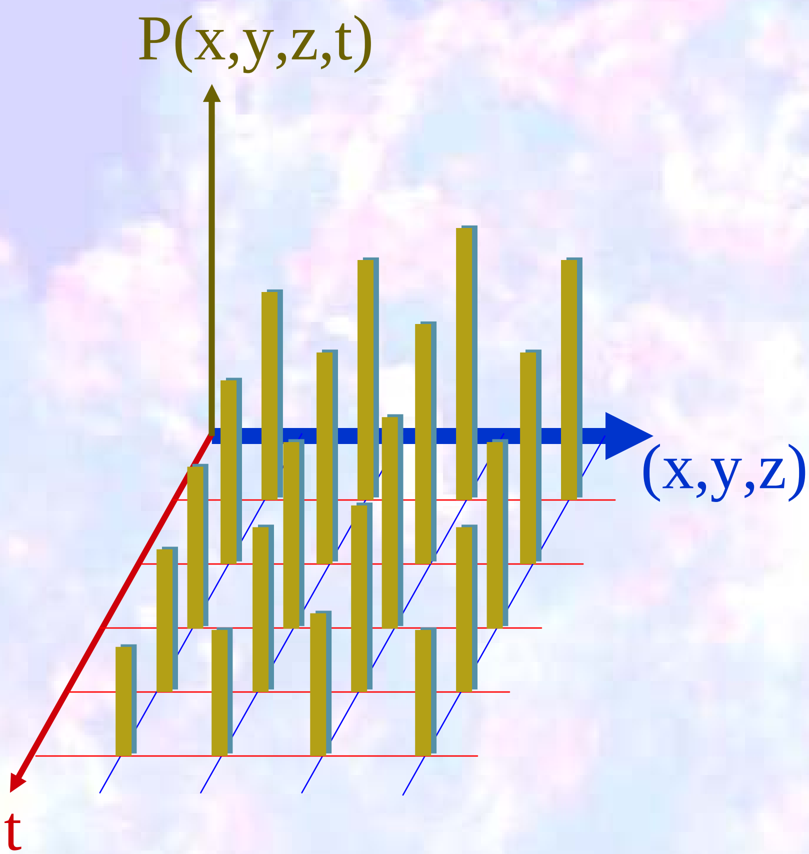
Input: P(x,y,z,t) sampled on regular 4D grid

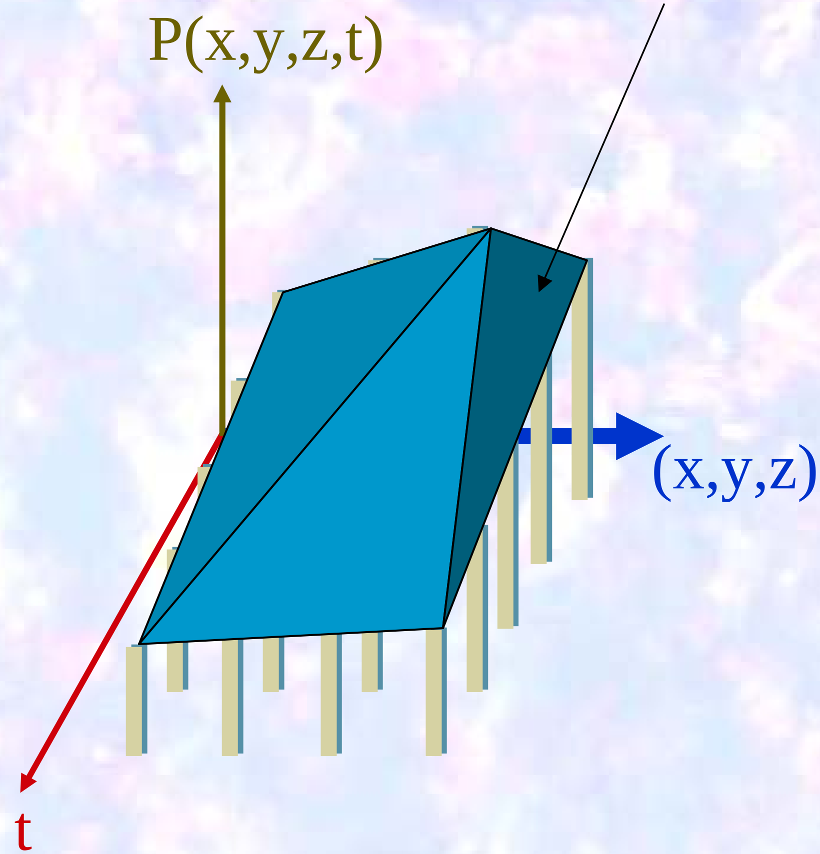
OUTLINE

- Out-of-core compression/decompression
- Adaptive simplification of penta-mesh
- Iso-surface extraction {(x,y,z):P(x,y,z,t)=p}
- Iso-surface compression/decompression
- Interactive exploration

Regular… or not?





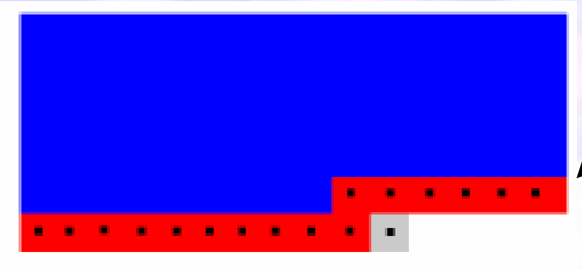


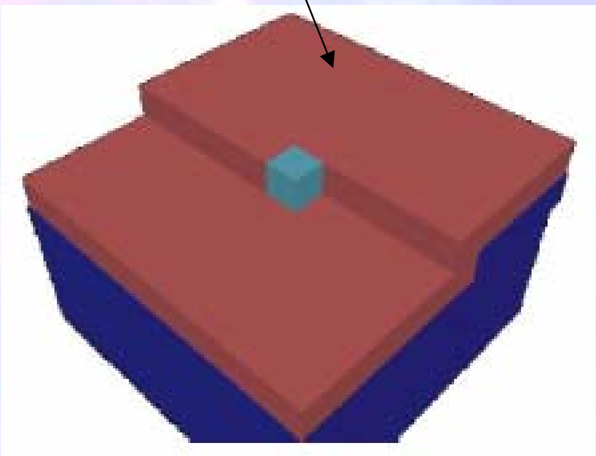
Lossless compression

- **Out-of-core compression/decompression of large n-dimensional scalar fields**
  - Lawrence Ibarria (Georgia Tech)
  - Peter Lindstrom (LLNL)
  - Jarek Rossignac (Georgia Tech)
  - Andrzej Szymczak (Georgia Tech)
- To appear in Proc. of Eurographics'03

Scanline codecs

foot-print ≈ 1 slice





For t=0 to t_{max} do

For z=0 to z_{max} do

For y=0 to y_{max} do

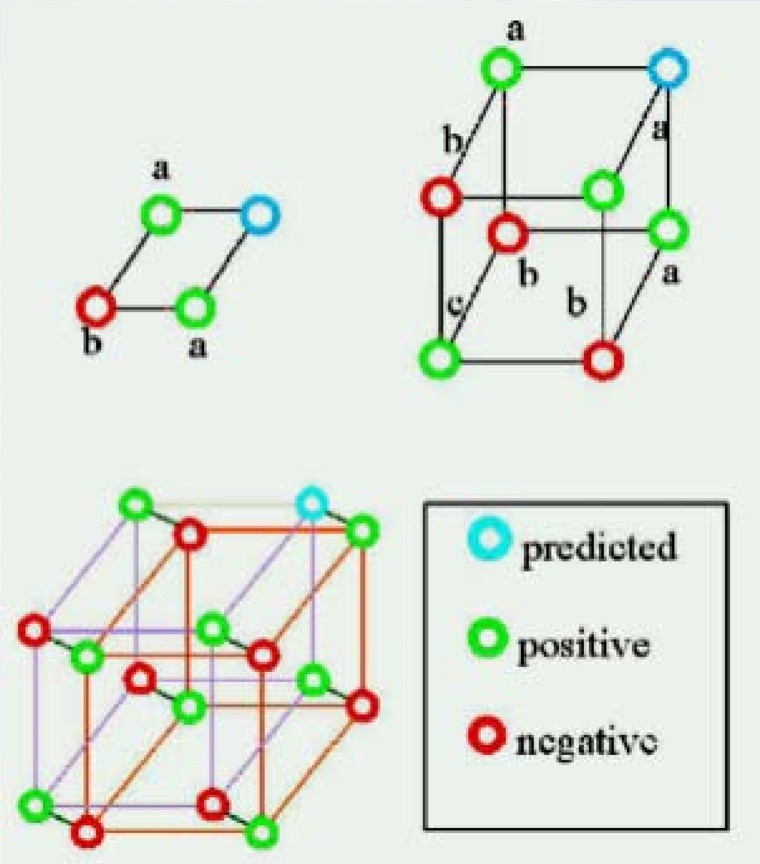
For x=0 to x_{max} do {

Predict P(x,y,z,t) from visited neighbors

Encode/decode the correction}

Lorenzo predictor

- Predict P at corner of hypercube from values at the other corners
  - Set origin at opposite corner
- 2D: P(1,1)=P(1,0)+P(0,1)-P(0,0)
- 3D: P(1,1,1)= ∑a–∑b+c
- 4D: P(1,1,1,1)= $\sum n_1 - \sum n_2 + \sum n_3 - n_4$
  - n_i is reachable through i edges
  - Exact predictor for cubics in 4D



Results for lossless compression

- Small memory footprint
- Easy to implement
- Exactly reconstructs polynomials of degree n–1
- Can outperform wavelets

DataSet	4D Lorenzo Predictor	Cubic Wavelets
Smooth 64^4	0.16 Bits/Symbol	0.20 Bits/Symbol
Harsh 64^4	3.73 Bits/Symbol	3.28 Bits/Symbol
Harsh 128^4	1.75 Bits/Symbol	1.80 Bits/Symbol

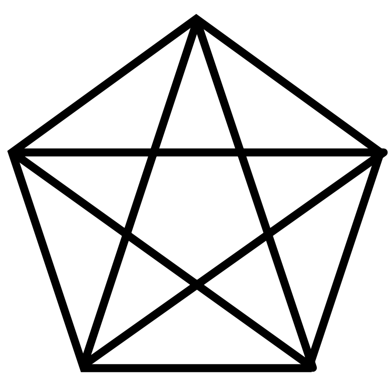
Table 1: *This shows the entropy of the residuals computed with wavelets and the Lorenzo predictor for a 4D dataset, in a lossless fashion.*

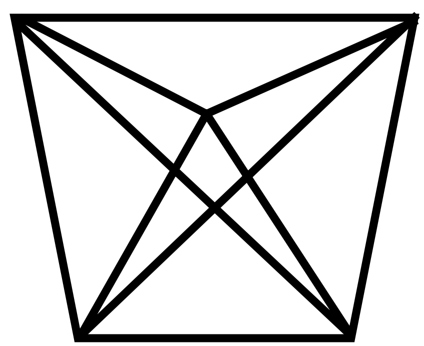
4D Delaunay computation and refinement

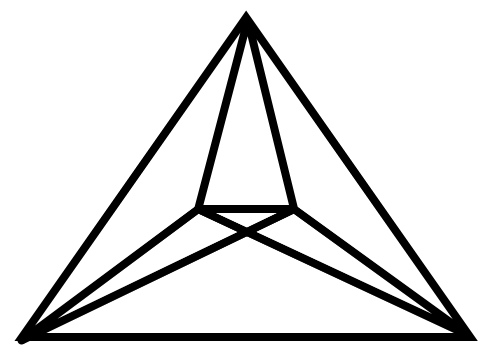
Ajith Mascarenhas and Jack Snoeyink (UNC)

Iso-surfaces from pentatopes

- Mesh of 5-simplices are 4d surface in 5d:
  - Pentatopes (4d)
  - Tetrahedra (3d)
  - Triangles (2d)
- Slice away 2 dimens to form isosurface:
  - Faces (2d)
  - Edges (1d)
  - Vertices (0d)



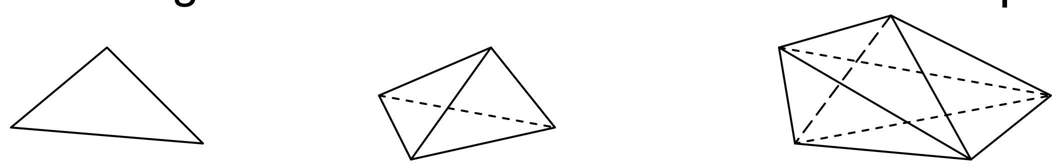




Yes, this is crazy…

- Regular grid stores **values** only
- mesh adds (x,y,z,t) & incidence

	2d: Triangle	3d: Tetrahedron	4d: Pentatope



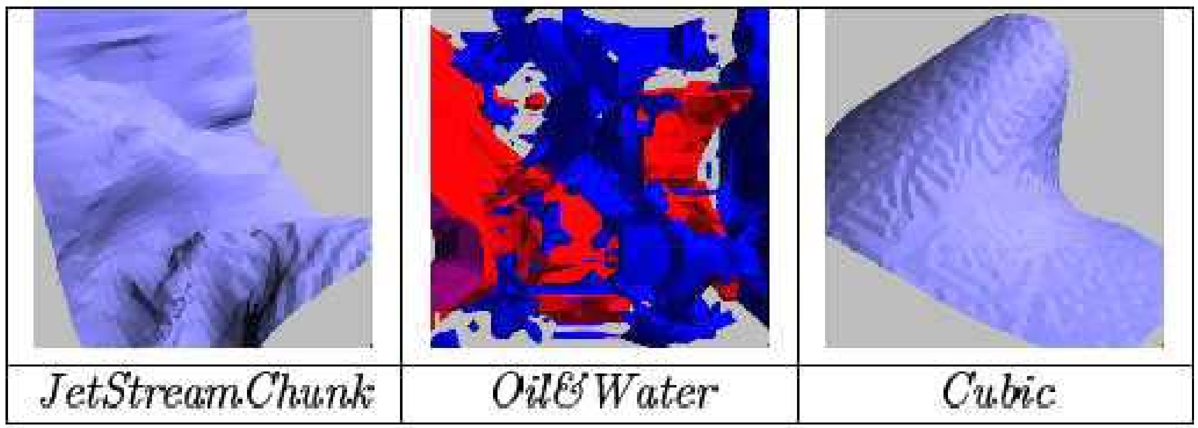
Simp/vertex	2	7	28
Words/vertex	15	51	244

- Allows local refinement, so we try anyway…

Incremental 4D Delaunay

- Can't use simplification (full resolution mesh is too large)
- Implemented insertion heuristic to build interpolating mesh
  - Add points with greatest error to 4D Delaunay and retriangulate

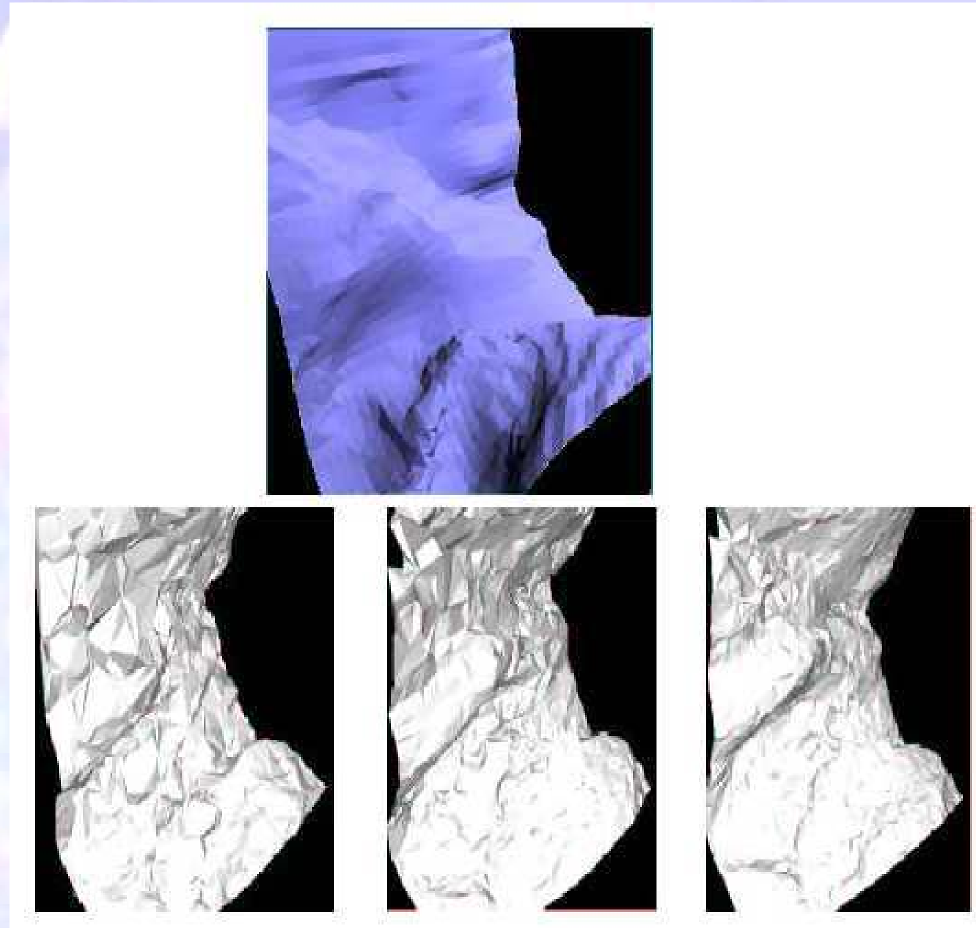
As expected:
Mesh requires large storage space



Data-set	Data-set size(bytes)	# vertices	# pentatopes	Pentamesh size(bytes)	mesh/data-set size.
JetStreamChunk	1,048,576	72,035	1,719,999	69,160,135	65.96
Oil&Water	280,000	19,018	435,771	17,525,930	62.6
Cubic	2,825,761	17,271	430,883	17,321,675	6.13

Results

- Severe aliasing for sections of low-resoution penta-meshes
- Iso-surface from the *JetDataChunk* data-set at iso-value = 128, time = 12



Iso-surfaces at three stages of refinement

vertices:	16K	45K	72K
pentatopes:	0.4M	1.0M	1.7M

Sphere-based Delaunay

- The fast Delaunay implementation is interesting:
  - Sphere-based
  - Exact, handling all degeneracies
  - To be released this summer.

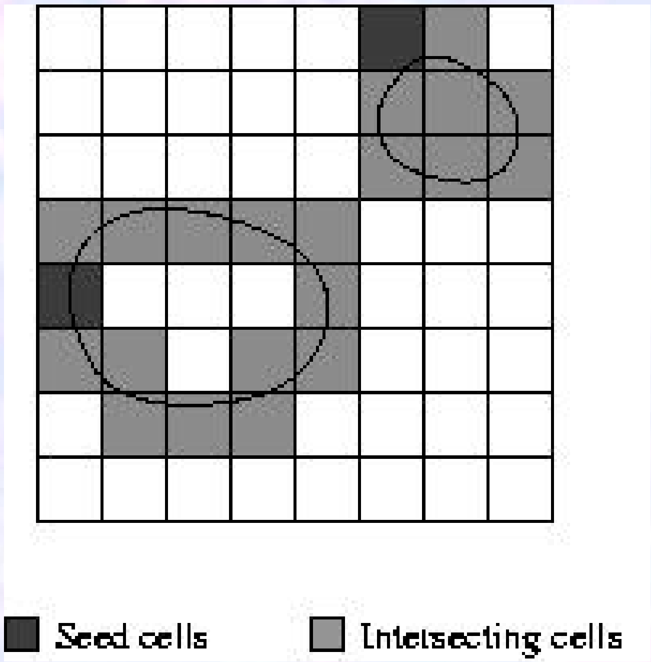
Seed Set Computation for Iso-surface Extraction in Time-varying Volumetric Data

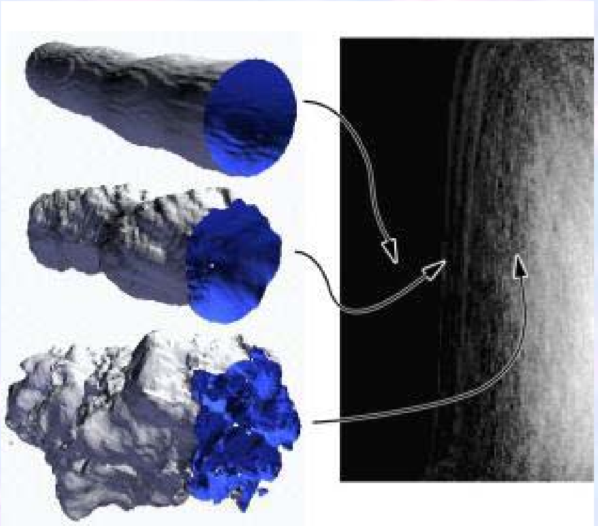
student:

Ajith Mascarenhas (UNC)

Extract iso-surfce component

- Volume data is often visualized by extracting iso-surfaces.
- Efficient iso-surface extraction.
  - Start at cell known to intersect iso-surface - seed cell.
  - Extract iso-surface component by visitingneighboring cells recursively

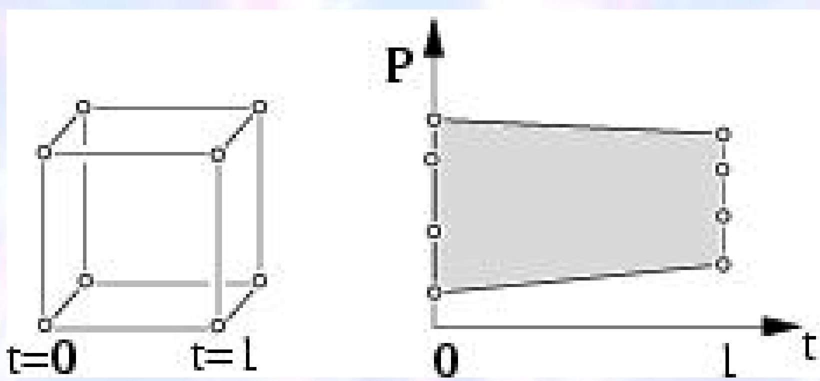




Iso-surfaces of Jet Stream simulation data.

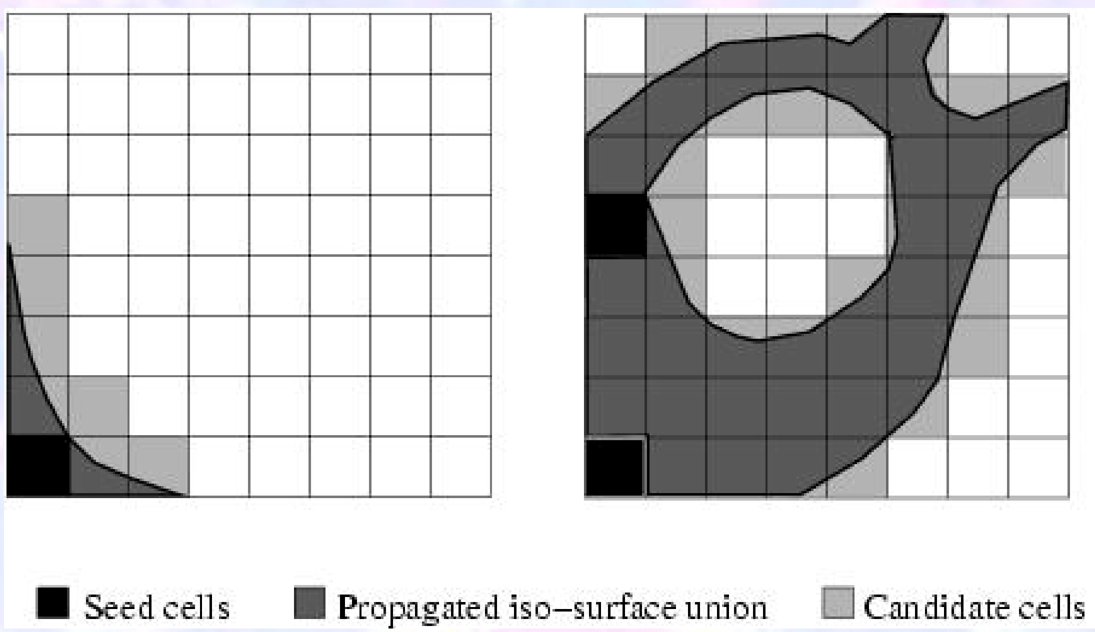
Seed set computation

- AIM
  - Compute seed set for time-varying volumetric data (4-d).
- Range of a cell.
  - Set of iso-values for which the cell intersects an iso-surface.
  - For volumetric data in 3D, range is an interval on the real line.
  - For time-varying volumetric data, the iso-value is a *(Value, time)* pair => the range is a convex set on the plane.



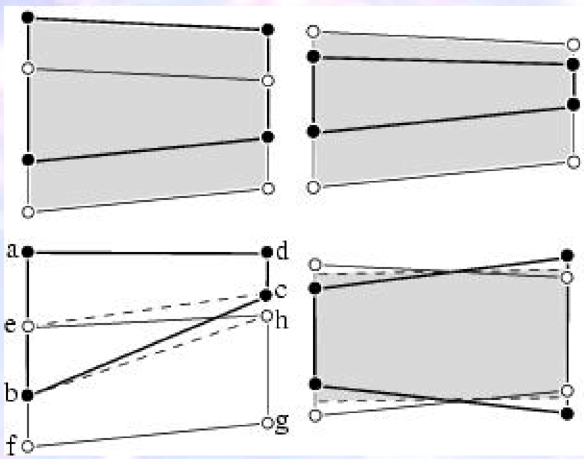
Seed set computation in 3-d

- Greedy Algorithm (Bajaj et al.)
  - Propagate union of iso-surfaces starting from arbitrary cell.
  - While more seeds can be chosen
    - Choose candidate cell with largest uncovered range as next seed.
    - Propagate residual range.

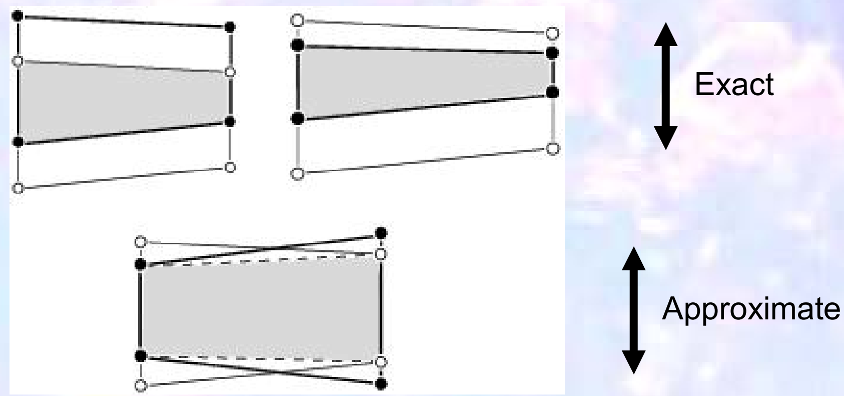


Range Operations in 4-d

– Union, Intersection, Difference
  - Exact for some cases.
  - Approximation for others.



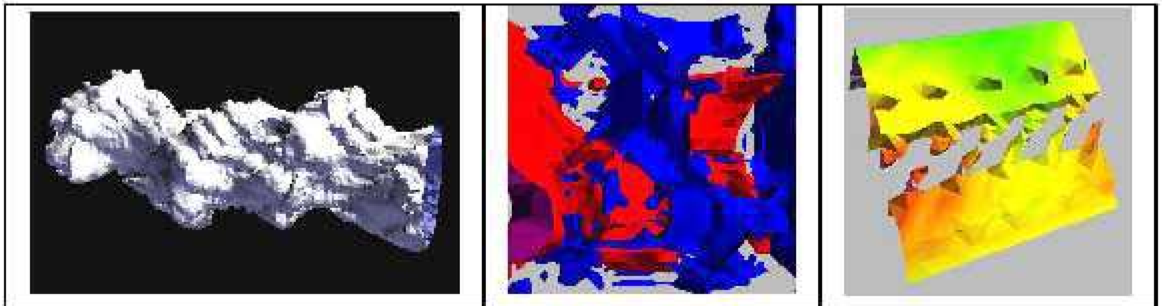
Union



Intersection

Seed set computation in 4-d

– Results



JetData | *Oil&Water* | *Combustion*

Table 1. Iso-surfaces of Data-sets

Data-set	Dimensions($x \times y \times z \times t$)	no. cells	seed-set size	% seed-set./cells
JetData_4	$64 \times 64 \times 64 \times 100$	24,754,653	57,928	0.23
Oil&Water	$28 \times 25 \times 25 \times 16$	233,280	2,814	1.2
Combustion	$27 \times 16 \times 20 \times 20$	140,790	10,544	7.4

Iso-surface extraction from 4D regular grids

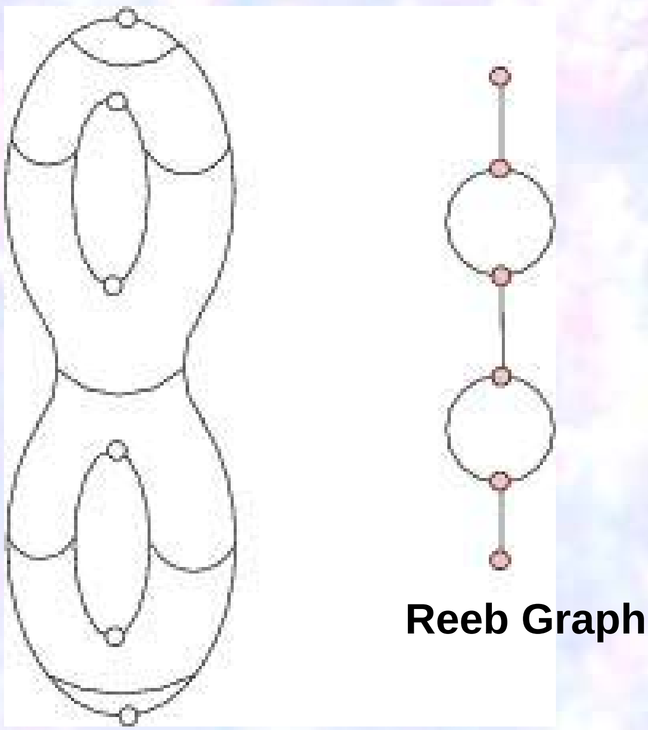
- Time-varying Reeb graphs, Jacobi sets, & the γ-curve
  - Jack Snoyink and Ajith Mascarenhas (UNC)

- Joint work with:
  - Herbert Edelsbrunner, John Harer, (Duke U.)
  - Valerio Pascucci, (LLNL)

Contour trees

Reeb Graph captures topological changes of iso-contours.

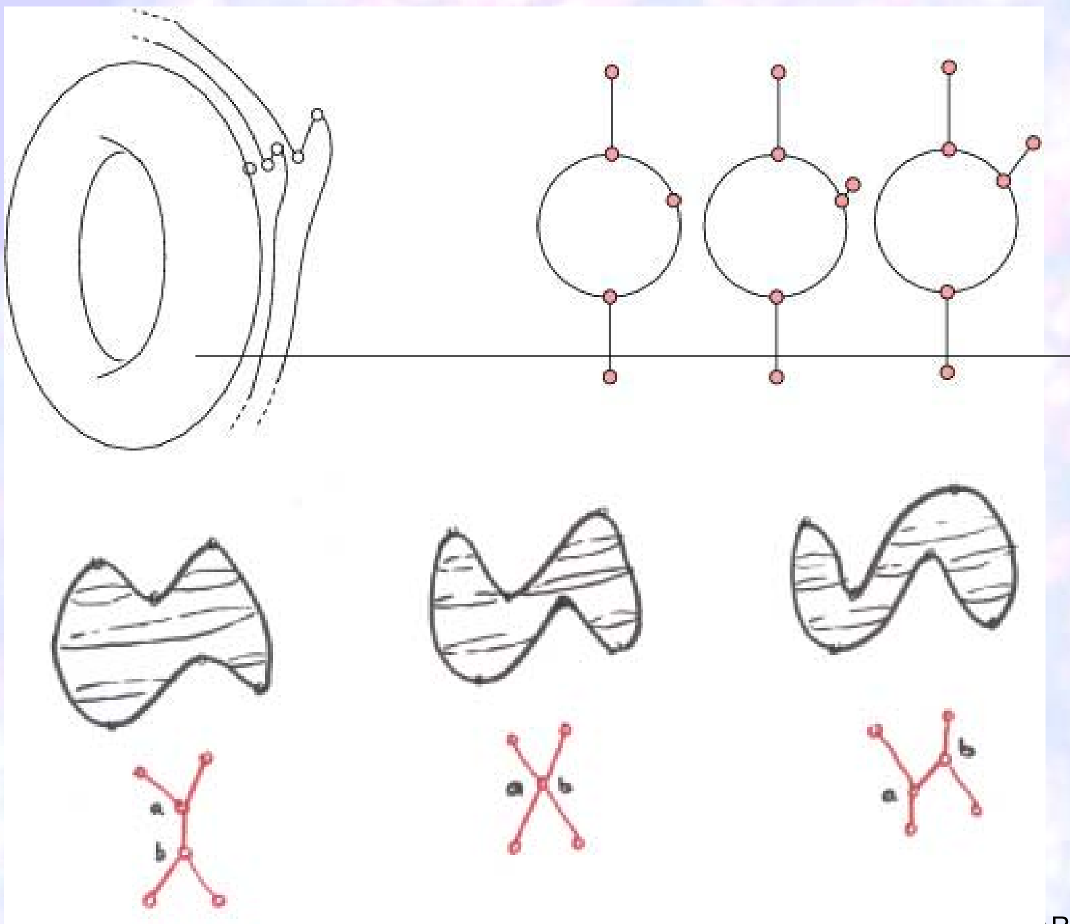
- A Contour Tree is a special kind of Reeb graph.



- Critical pts. of function map to nodes of Reeb graph
- AIM: Study changes to Reeb graph as function changes with time.
- Construct time-varying Contour Trees for time-varying volumetric data.

Evolution of contour trees?

Classified Reeb Graph changes as a function of time

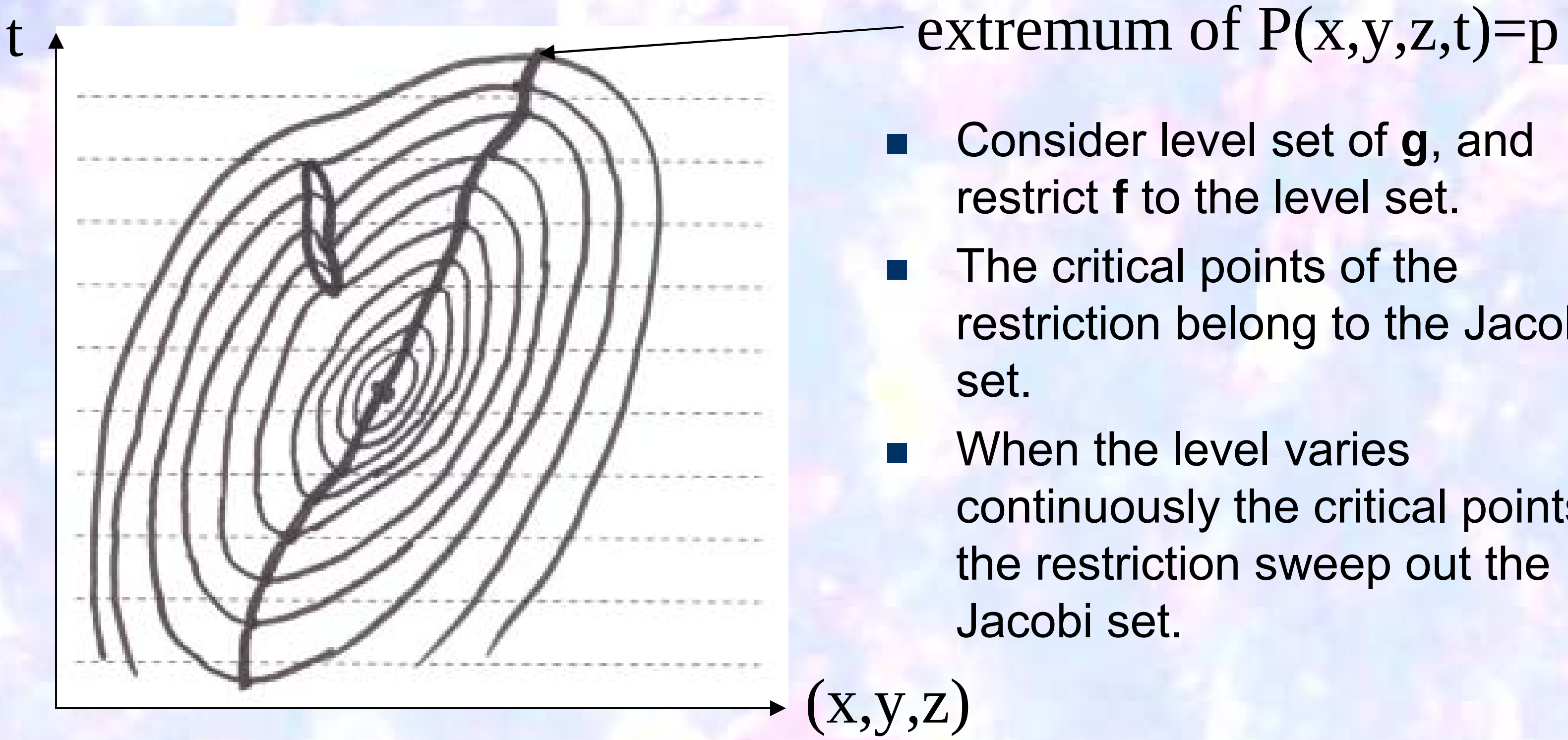


- **Contraction** of arc in Reeb graph = destruction of a pair of critical points.
- **Anti-Contraction** of arc in Reeb graph =creation of pair of critical points.
- **Critical point swap:** A pair of critical points change their order in the function value.
- **Complexity analysis:** Not suitable for large, noisy data sets…

Jacobi sets

– Jacobi sets: Simultaneous critical points of several Morse functions.

– Example with two functions f, g.
  - Jacobi set is a 1-manifold here.



- Consider level set of **g**, and restrict **f** to the level set.
- The critical points of the restriction belong to the Jacobi set.
- When the level varies continuously the critical points of the restriction sweep out the Jacobi set.

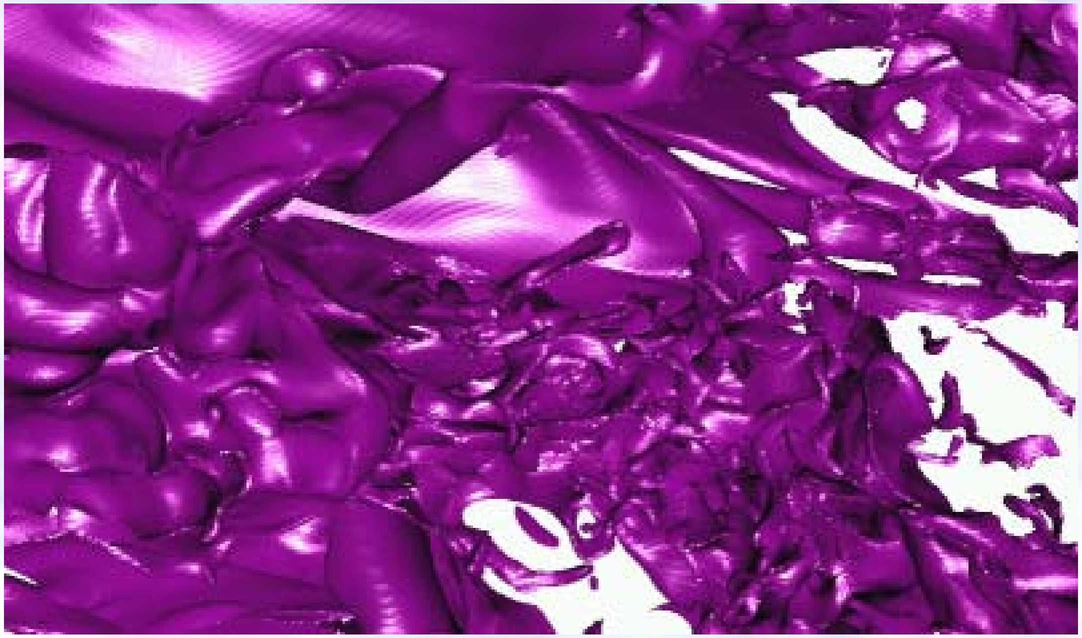
Jacobi Sets

- Used in studying time-varying Reeb graph.
  - Critical points map to nodes of Reeb graph.
  - Time-trace of critical points used to understand changes to Reeb graph.
  - Jacobi Set gives the time-trace of critical points.
- Software to compute Jacobi sets of time-varying volumetric data developed by Ajith Mascarenhas (UNC) at LLNL in Summer 02.
  - Tested on moderate data-sets.
  - Being extended to compute time-varying contour tree
  - Requires simplification for large data sets

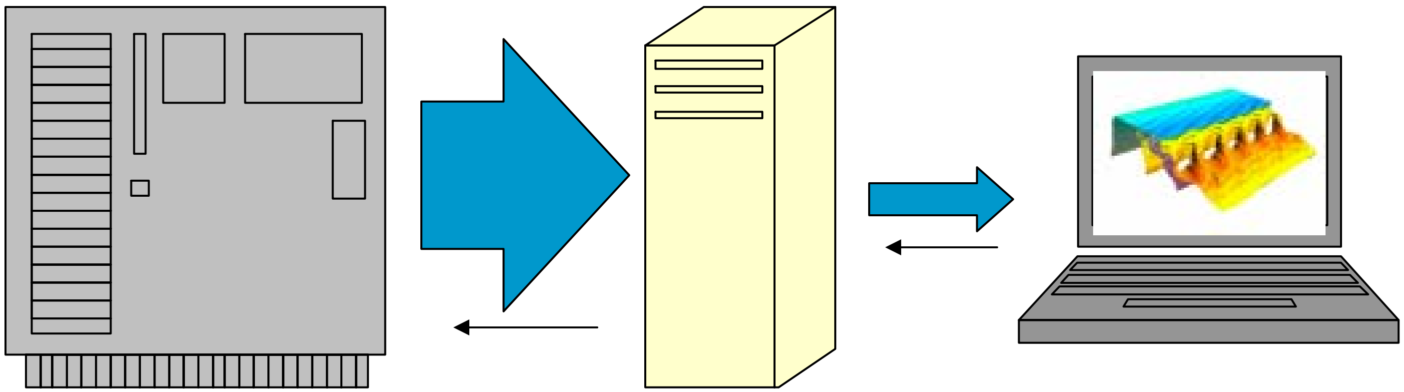
Iso-surface compression

- Out-of-core compression and simplification of iso-surfaces and geometric models
- Jack Snoyink,Martin Isenburg (UNC)
- Based on segmentation

⇨Part of a 6GB iso-surface that compresses to 640MB losslessly, & decompresses with a memory footprint of 9MB.



Tools for remote exploration



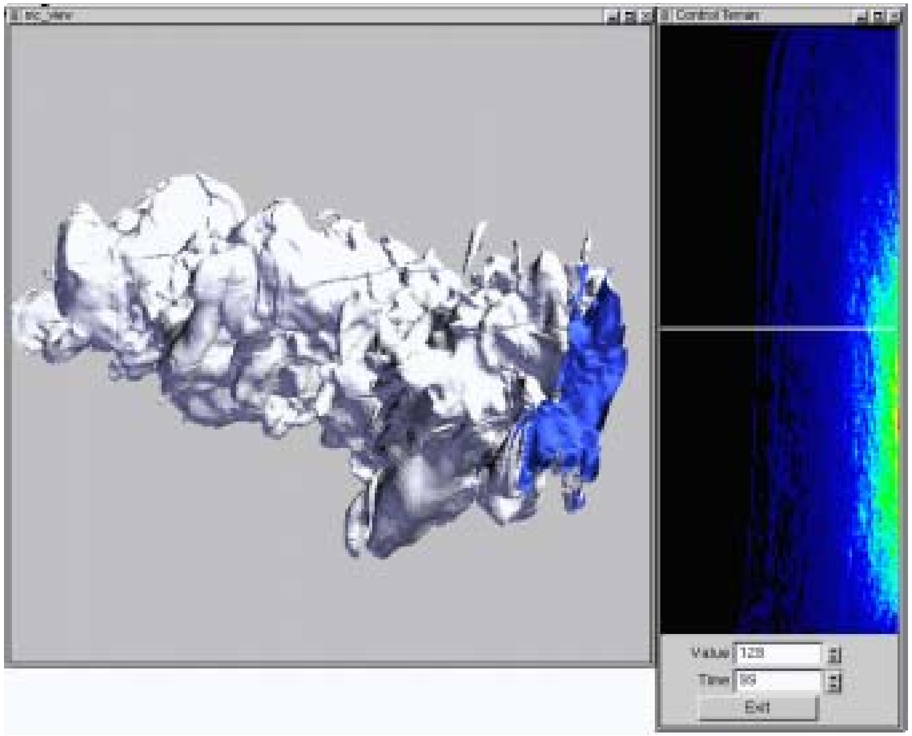
What tools can we provide to suggest
when & where to look
in large simulation data sets?

Safari on the (p,t) plane

- Samples from pressure $p = f(x,y,z,t)$.
- Level sets defined by two parameters:

$$L(P,\ T) = \{\ (x,y,z) : P = f(x,y,z,T)\ \}$$

- Partition the data dimensions
  - Viewing volume *(x, y, z)*
  - Control plane *(p, t)*



How it all will come together

- Use Lorenzo predictor to compress data on server for archival and posting
- Use contour trees analysis in 4D on server to compute image for (p,t) terrain
- Use Safari on client to plan, conduct, record, annotate exploration on the (p,t) terrain
- Use seed-set on server to quickly extract iso-surface
- Use out-of-core compression/simplification to transmit desired iso-surface
- Use Lorenzo predictor decompression to download selected portions of the original 4D data for local exploration/analysis

Publications

- **Appeared/Accepted**
  - L. Kettner, J. Rossignac, J. Snoeyink, The Safari Interface for Visualizing Time-dependent Volume Data Using Iso-Surfaces and a Control Plane, CGTA 25:1-2(2003), pages 97-116
  - H. Carr, J. Snoeyink, Path Seeds and Flexible Isosurfaces: Using Topology for Exploratory Visualization, IEEE/EG VisSym'03.
  - L. Ibarria, P. Lindstrom, J. Rossignac, A. Szymczak, Out-of-core compression and decompression of large n-dimensional scalar fields, Eurographics 2003.
- **Submitted**
  - M. Isenburg, P. Lindstrom, S. Gumhold, J. Snoeyink, Large Mesh Simplification using Processing Sequences, IEEE Vis 03.
- **In preparation**
  - A. Mascarenhas, Y. Liu, J. Snoeyink, Sphere-based Implementation of Delaunay Diagram Computation
  - A. Mascarenhas, J. Snoeyink, Seed Set Computation for Isosurface Extraction in Time-varying Volumetric Data

Conclusions of incubator project

- New solutions for out-of-core codec are effective
  - Lorenzo predictor for 4D regular grids
  - Segmentation of iso-surface for small foot print
- New methods for extracting/analysing iso-surfaces are elegant and promising
  - Time-varying contour tree
  - Greedy seed set computation in 4D
- Adaptive refinement does not look promising
  - Pentatope meshes in 4D use lots of storage
  - Delaunay refinement is expensive and difficult
  - Isosurfaces from slices of pentas show artifacts

Thanks to

- Students
  - Lawrence Ibarria (GATech)
  - Ajith Mascarenhas, Martin Isenburg (UNC)
- Lawrence Livermore National Labs
  - Valerio Pascucci
  - Peter Lindstrom
- Other Collaborators
  - Andrzej Szymczak (GATech)
  - Herbert Edelsbrunner, John Harer (Duke)
  - Lutz Kettner (MPI Saarbruecken)
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