Topological Landscapes: A Terrain Metaphor for Scientific Data

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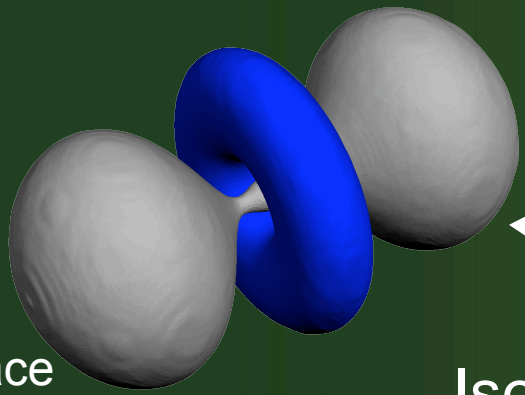
DOE SciDAC Visualization and Analytics Center for Enabling Technologies

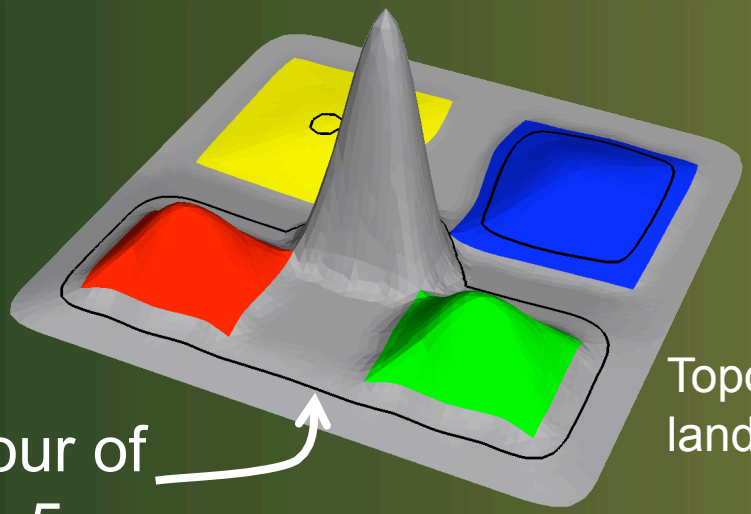
VACET

Visualization of the Electron Density Distribution of a Hydrogen Atom

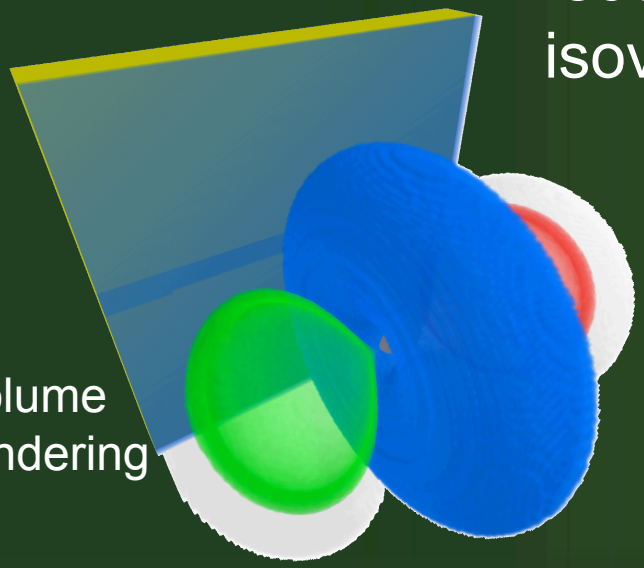


Isosurface

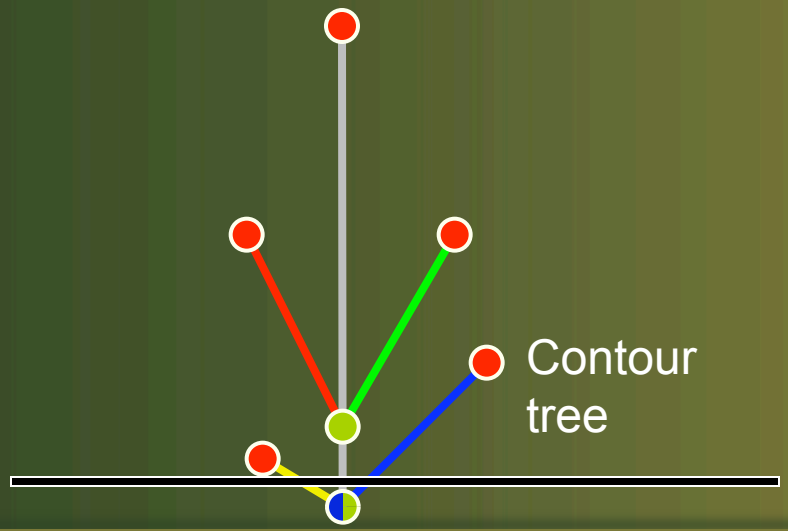
Isocontour of isovalue 5



Topological landscape

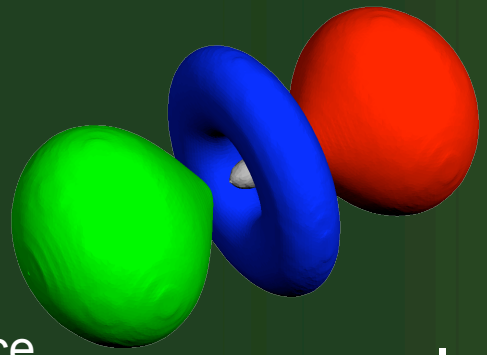


Volume rendering



Contour tree

Visualization of the Electron Density Distribution of a Hydrogen Atom



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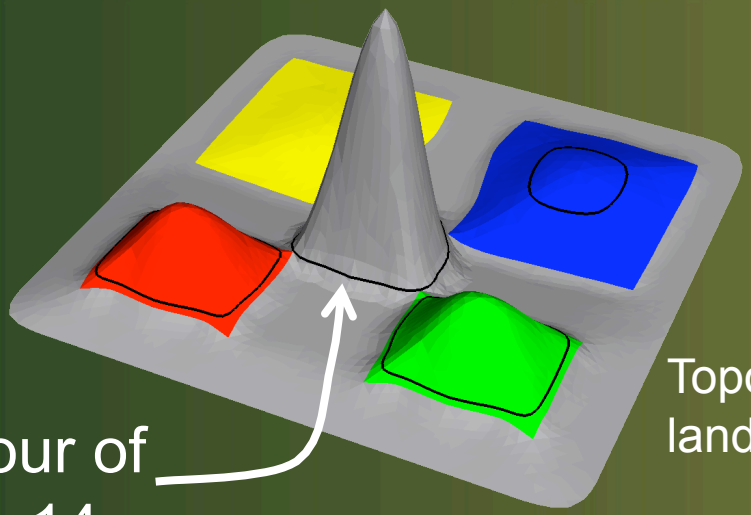
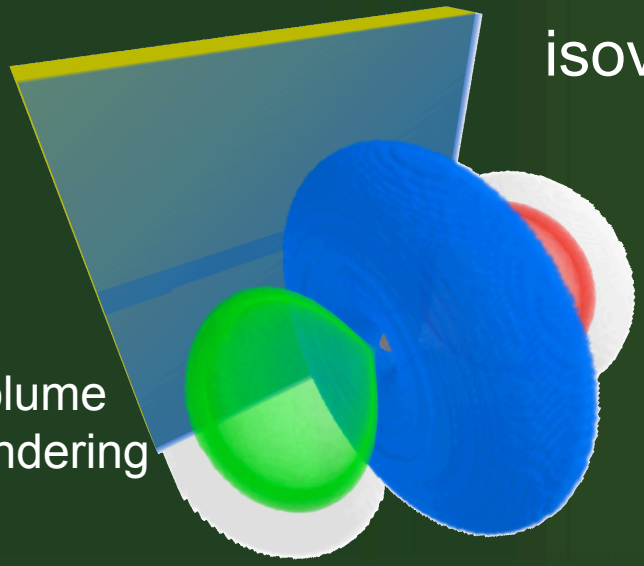


Topological landscape

Isocontour of isovalue 14



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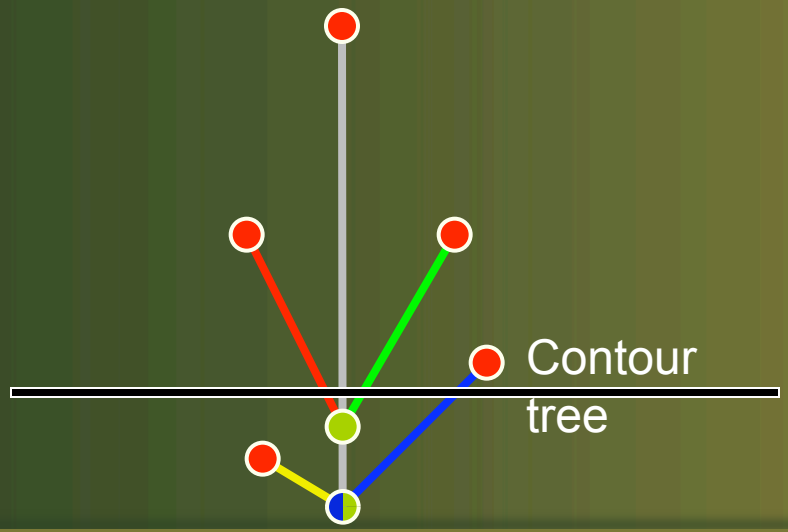

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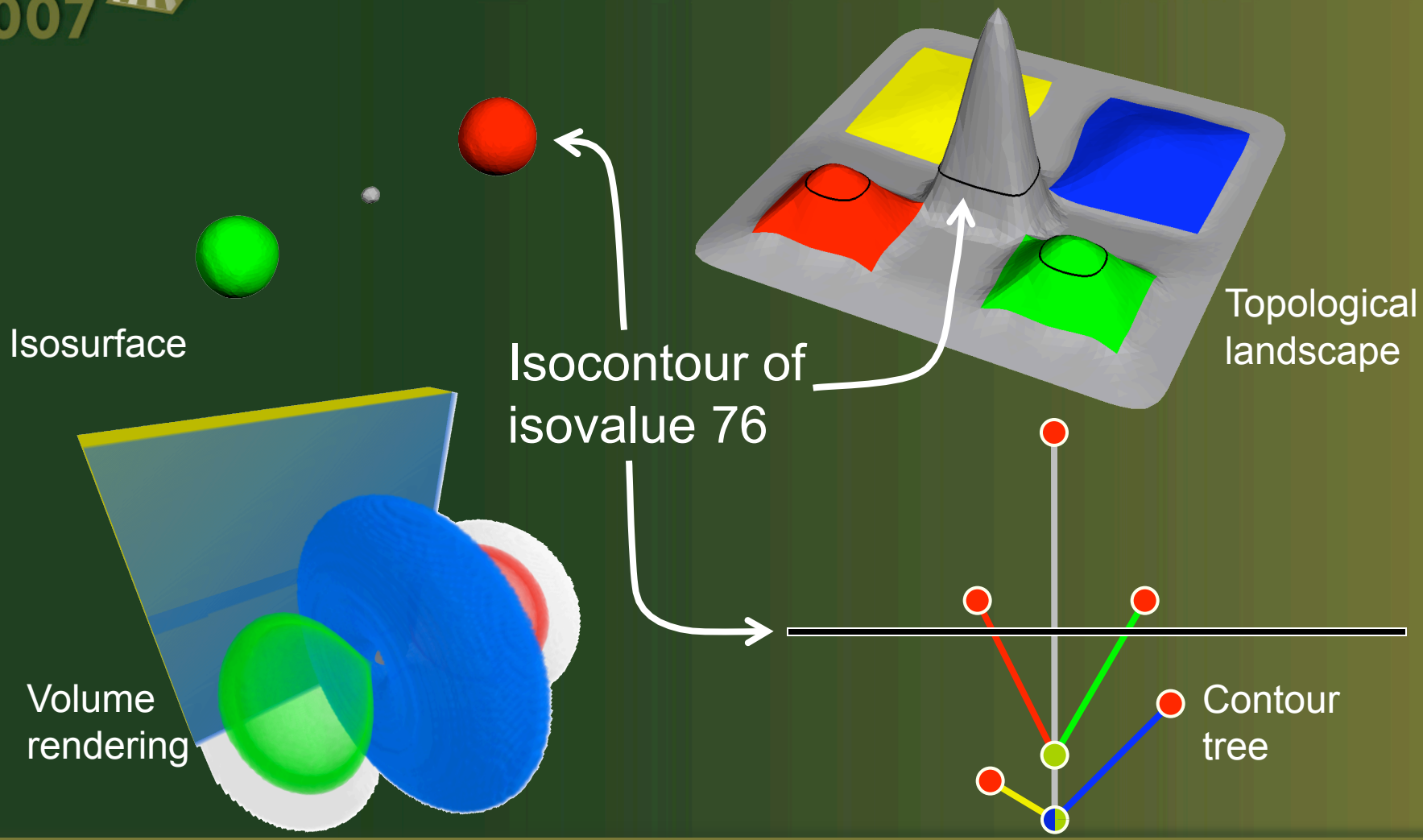

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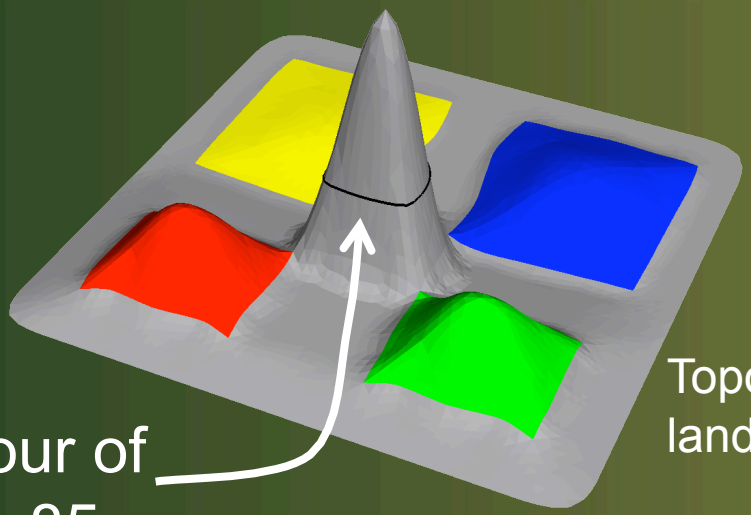
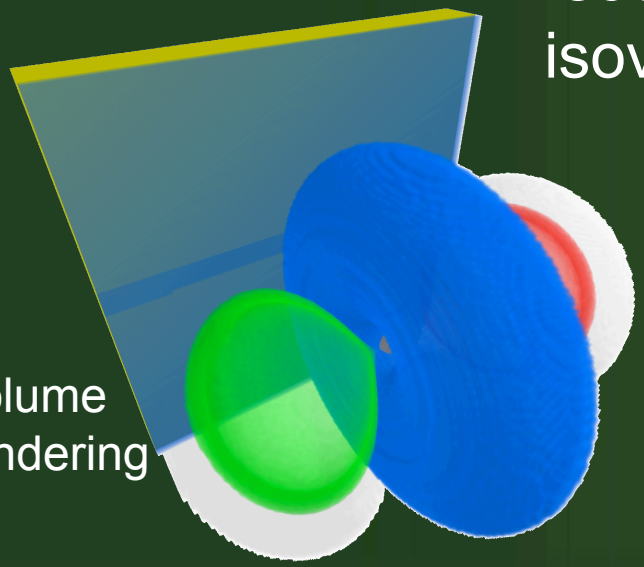


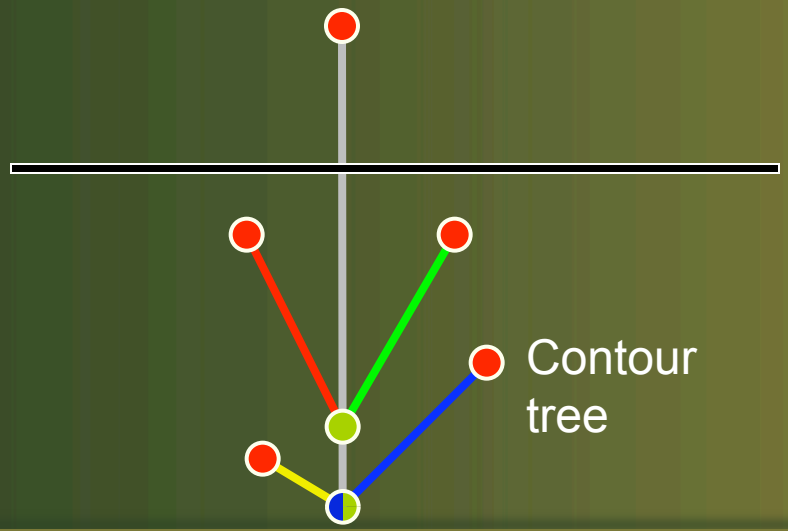
Topological landscape

Isosurface

Isocontour of isovalue 85



Volume rendering



Contour tree

Utilization and Presentation of Topological Information

- Branch of mathematics, developed before advent of visualization (Morse, 1925; Reeb, 1946; Milnor, 1963)
- Topological information used for more than 15 years in visualization (Shingawa et al., 1991; van Gelder & Wilhelms, 1994)
- Utilization
  - Transfer function design, rendering translucent isosurfaces (Fujishiro et al., 2000)
  - Interval volumes (Takahashi et al., 2005)
  - Acceleration of isosurface extraction (Bajaj et al., 1998)
  - Flexible isosurfaces (Carr et al., 2003) and volume rendering (Weber et al., 2007)
- Presentation
  - Contour spectrum (Bajaj et al., 1997) and Safari (Kettner et al., 2003)
  - Multiresolution topology and Toporerry (Pascucci et al., 2004)
  - Nested rectangle representation of contour trees (Mizuta et al., 2004)
- … and many more (refer to paper)

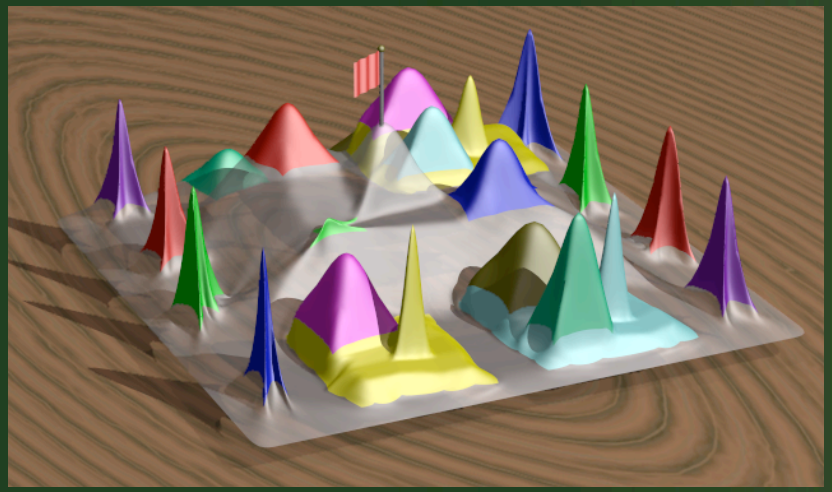
Presentation of Topological Information

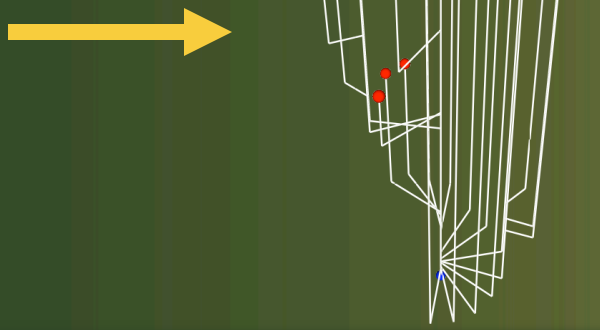
- Topological analysis powerful tool for identifying features in scientific data
- Contour tree summarizes isosurface behavior
- Valuable for identifying relevant isovalues

- Drawbacks:
  - Not intuitive for novice users
  - Clutter / layout problems for complicated contour trees
  - Little degree of freedom for display of additional quantities

Using a Terrain Metaphor

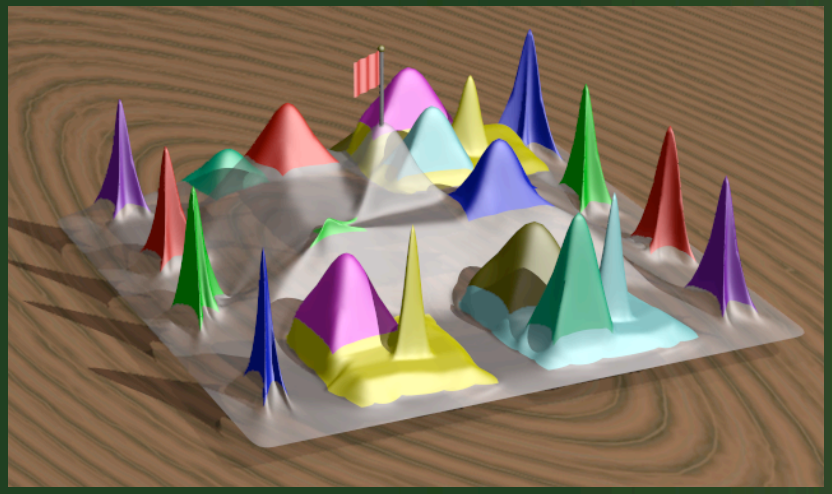
- Contour trees originally defined on terrains (Boyell & Ruston, 1963)

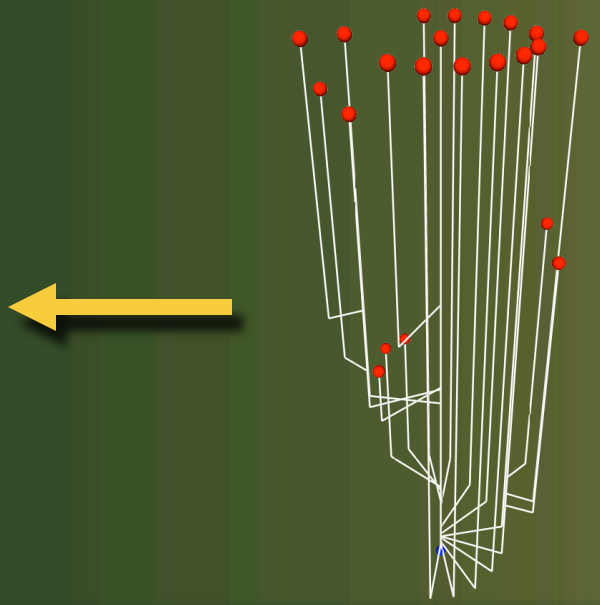




Inverse Mapping: Creating a Terrain for a Contour Tree

- Contour trees originally defined on terrains (Boyell & Ruston, 1963)
- Idea: Construct a 2D terrain with the same topology as a contour tree





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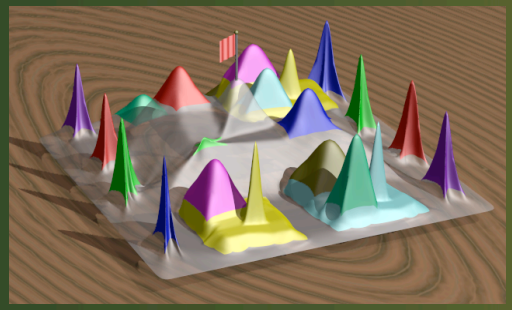
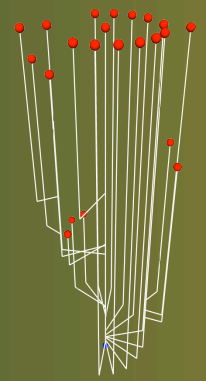




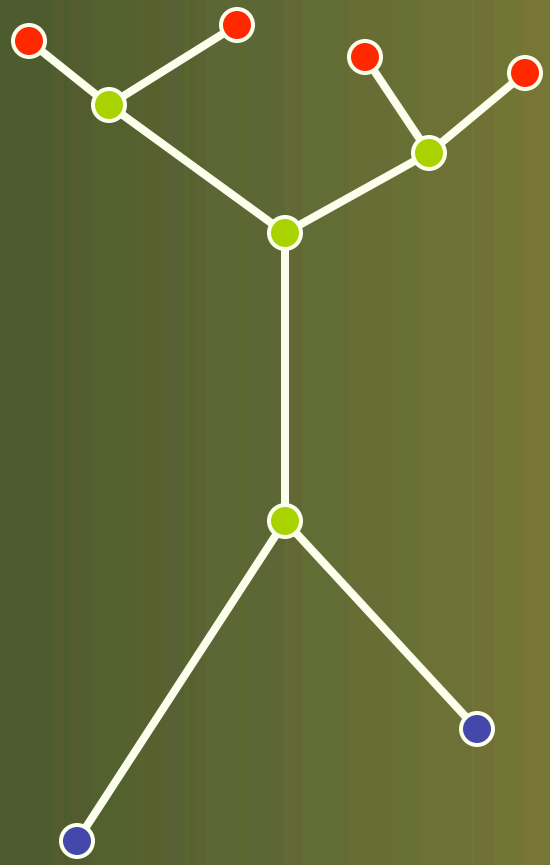
- Advantages:
  - Intuitive: humans trained to understand landscapes
  - Dimension independent
  - Topology + metric properties
  - Use efficient rendering techniques

Contour Trees

- Definitions:
  - Isosurface := $f^{-1}(\{isoval\})$
  - Contour := Connected component of isosurface

- Contour tree:
  - Collapse each contour at given level to point
  - Results in graph structure
    - Node: Critical point that changes number of contours
    - Edge: Evolving contour between contour creation/ merge/split/destruction events

Contour Tree – Example



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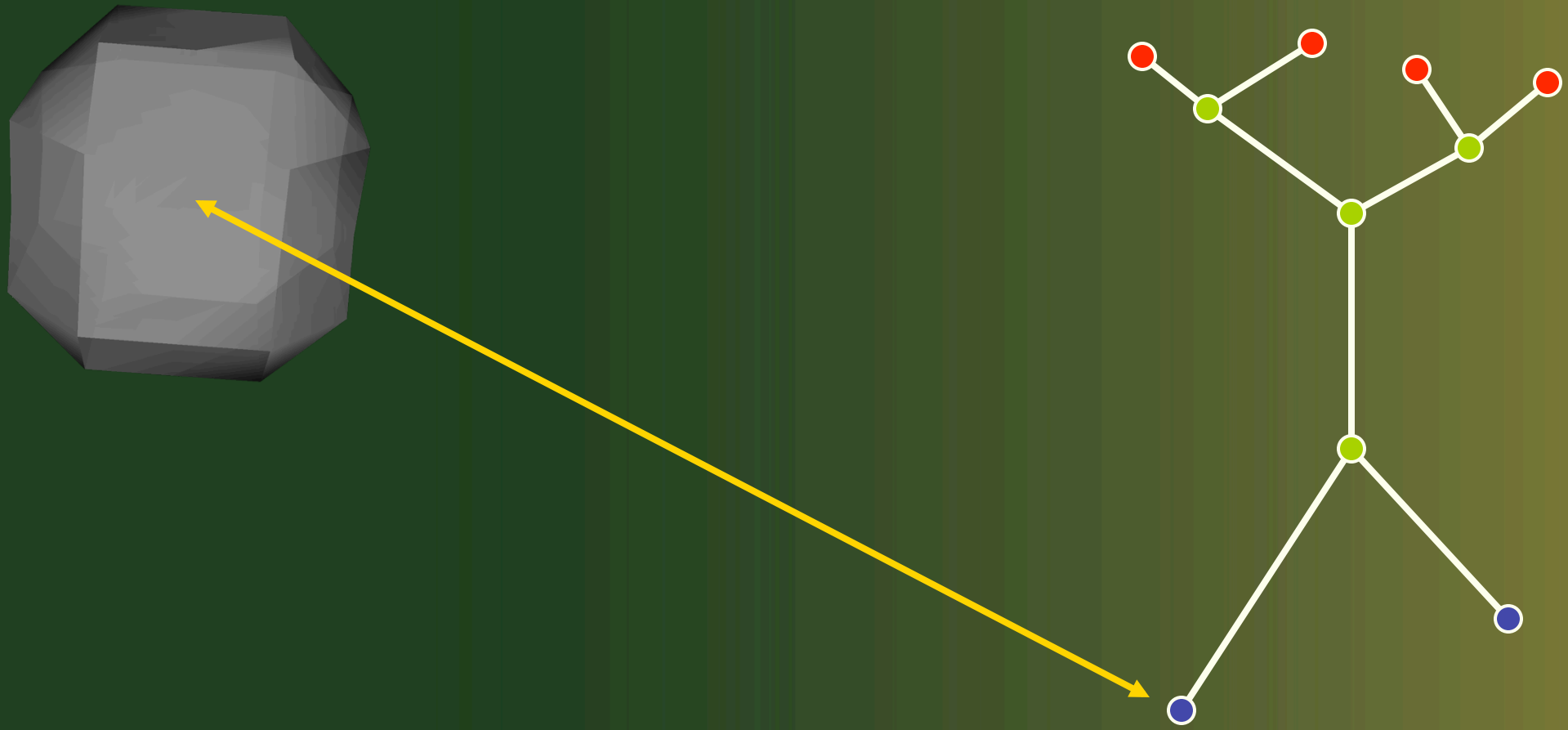

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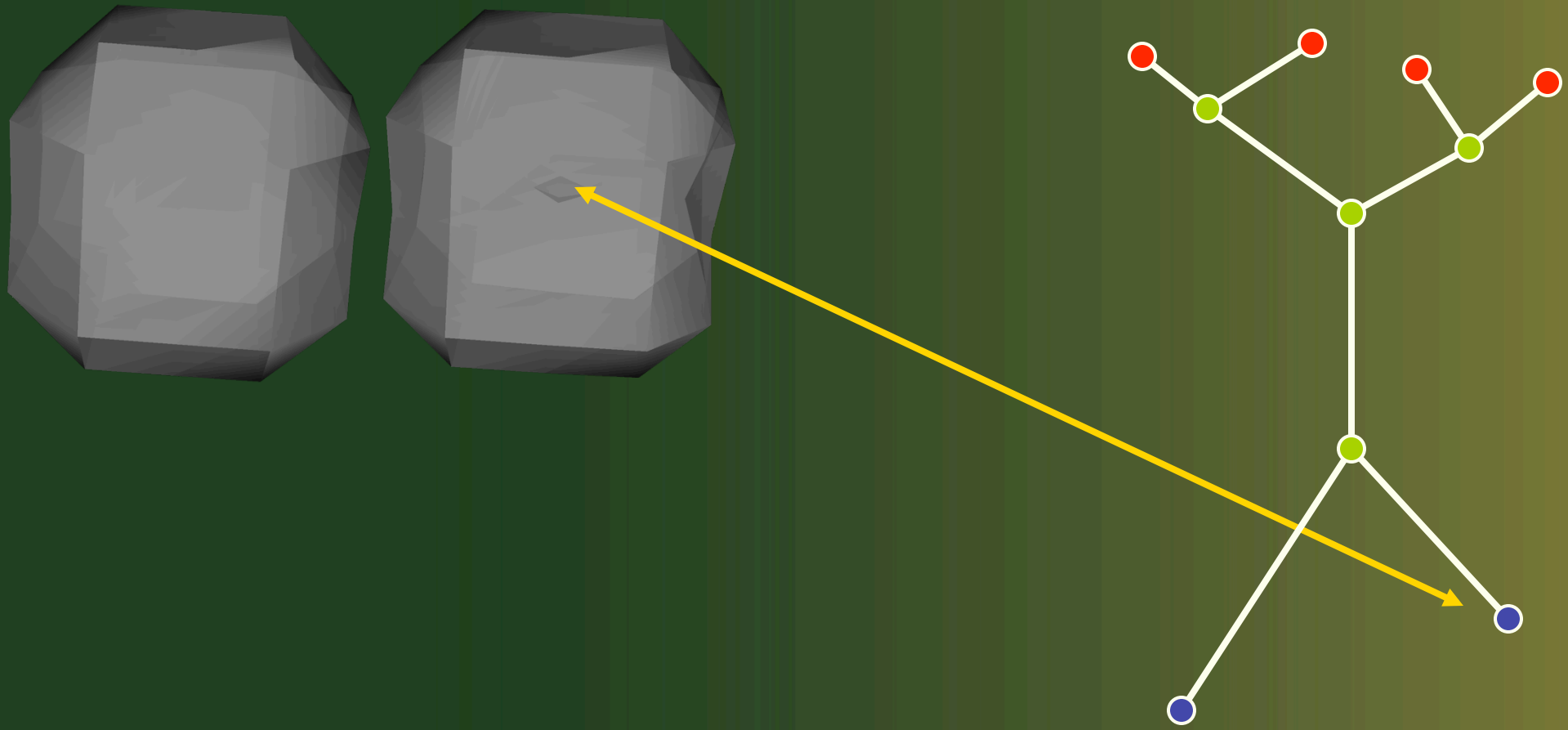

Contour Tree – Example

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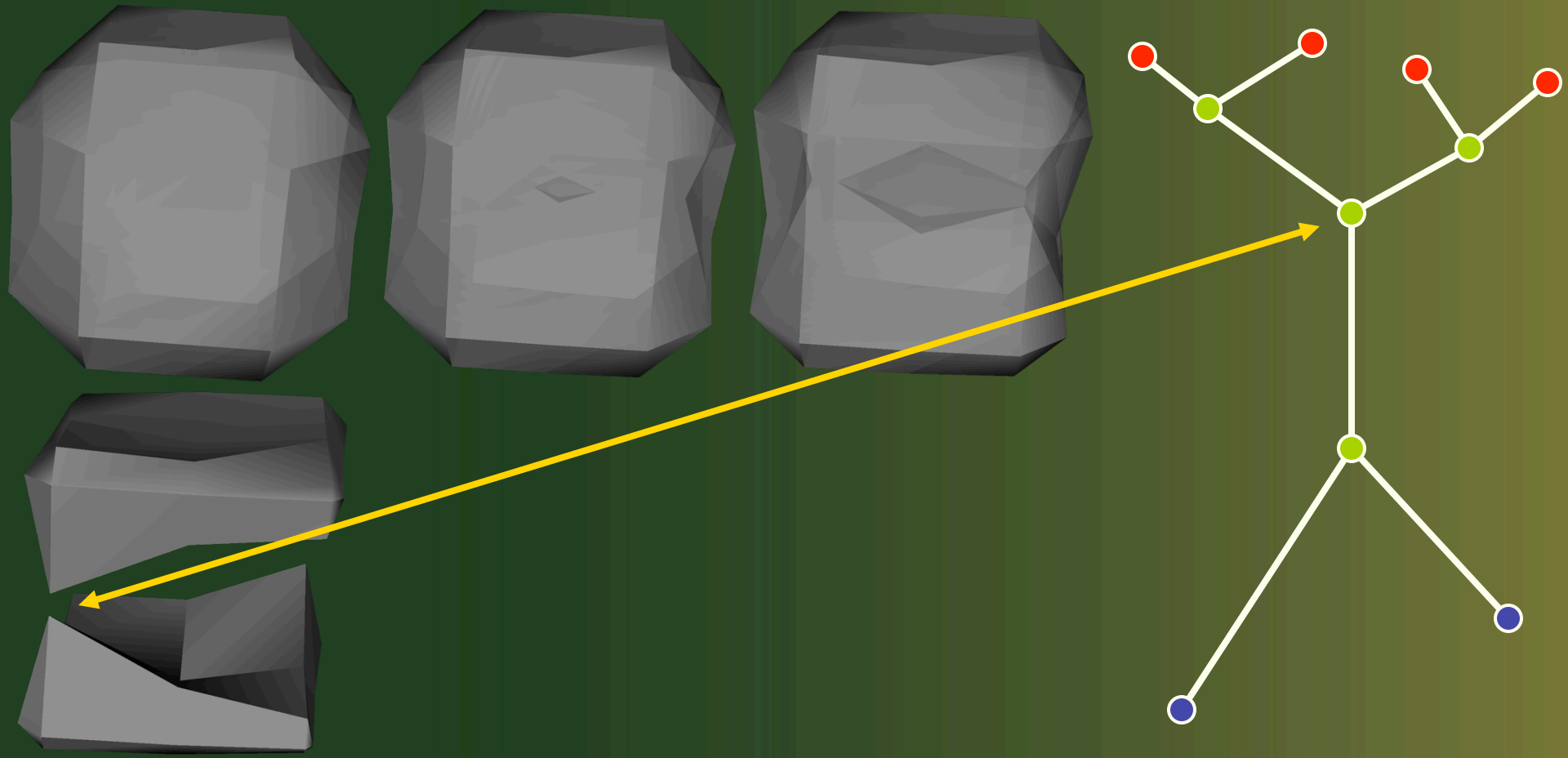

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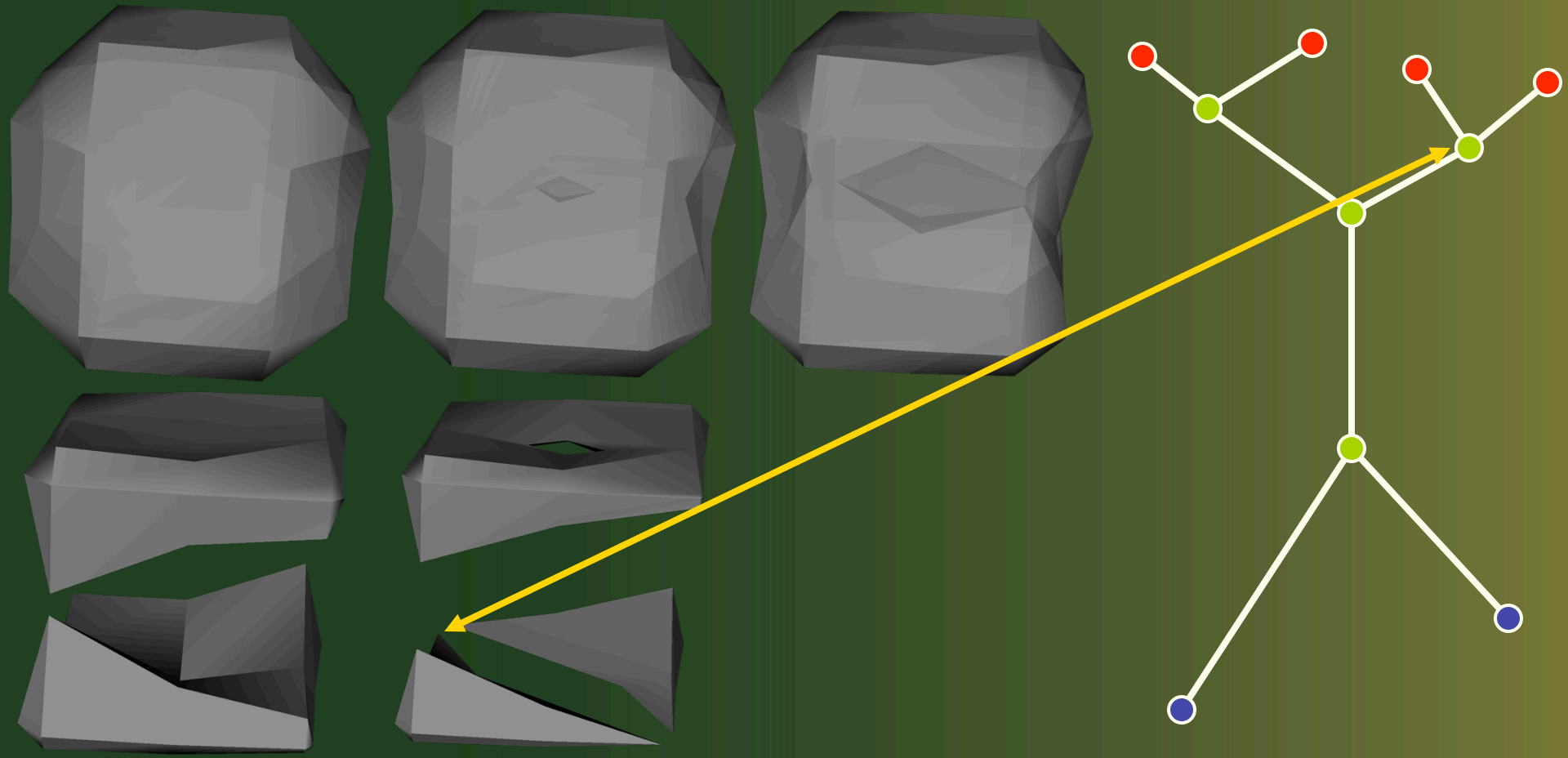

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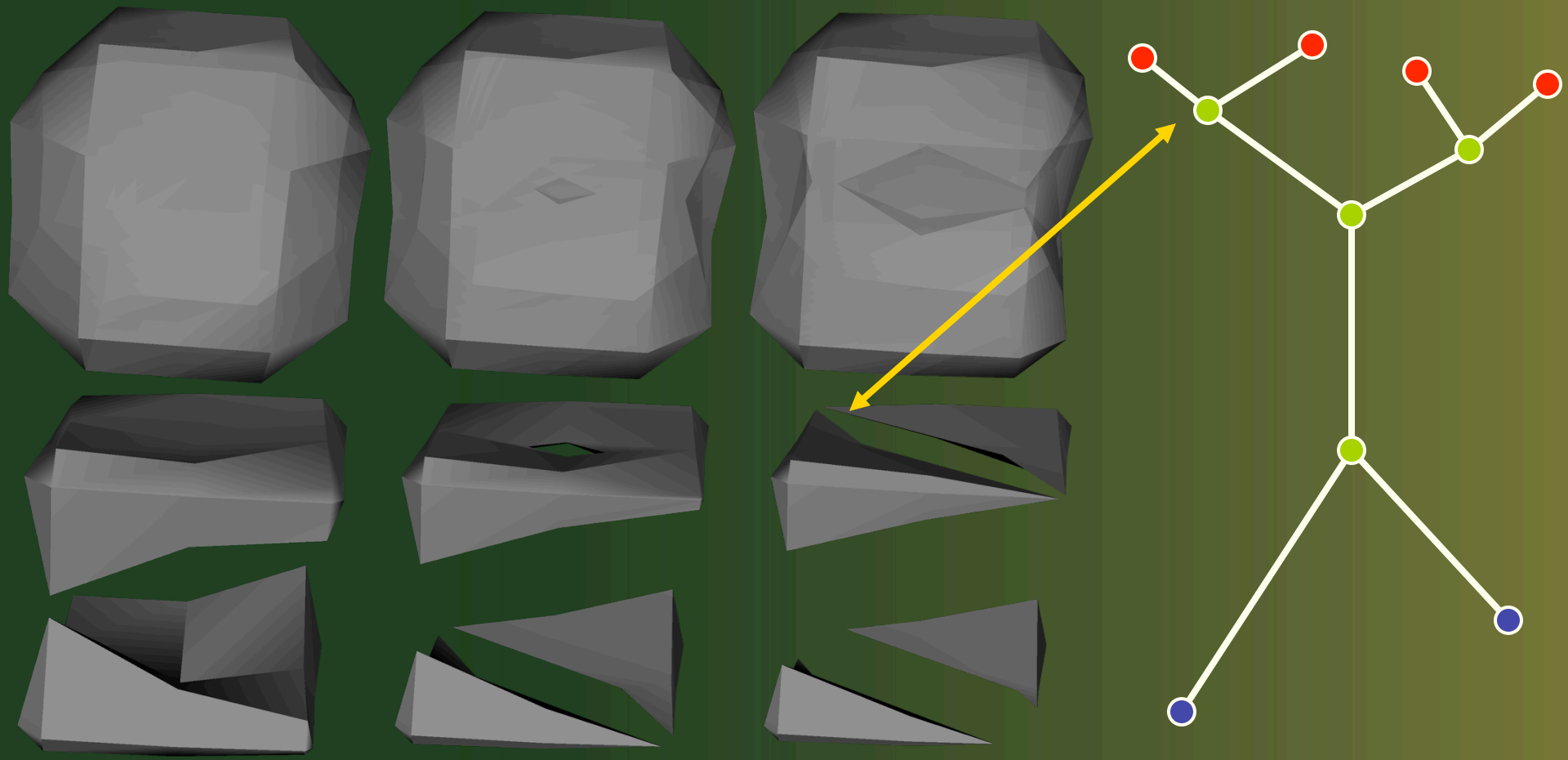
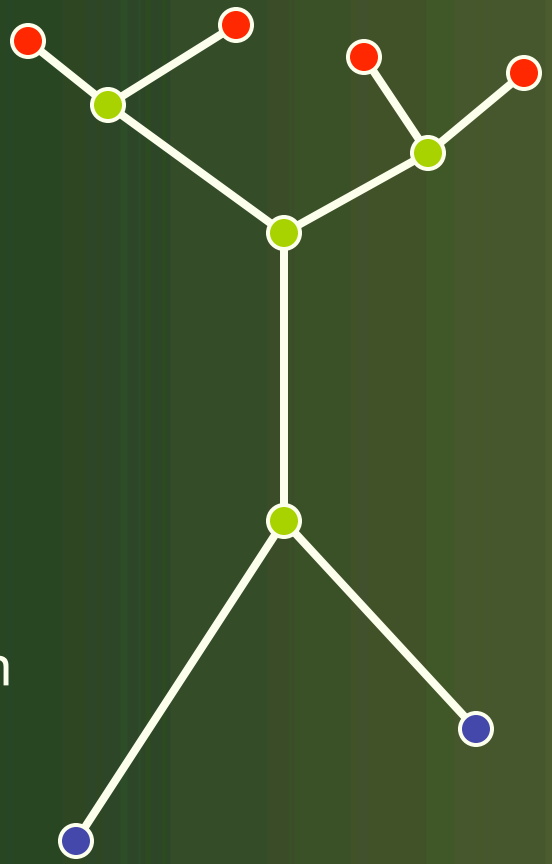


Branch Decomposition

- Complex topology
  - Inherent data complexity
  - Noise
- Need to consider topology at various scales

➔ Hierarchical contour tree representation

- Order based on simplification measure, e.g., **persistence**



(Pascucci et al., 2004)

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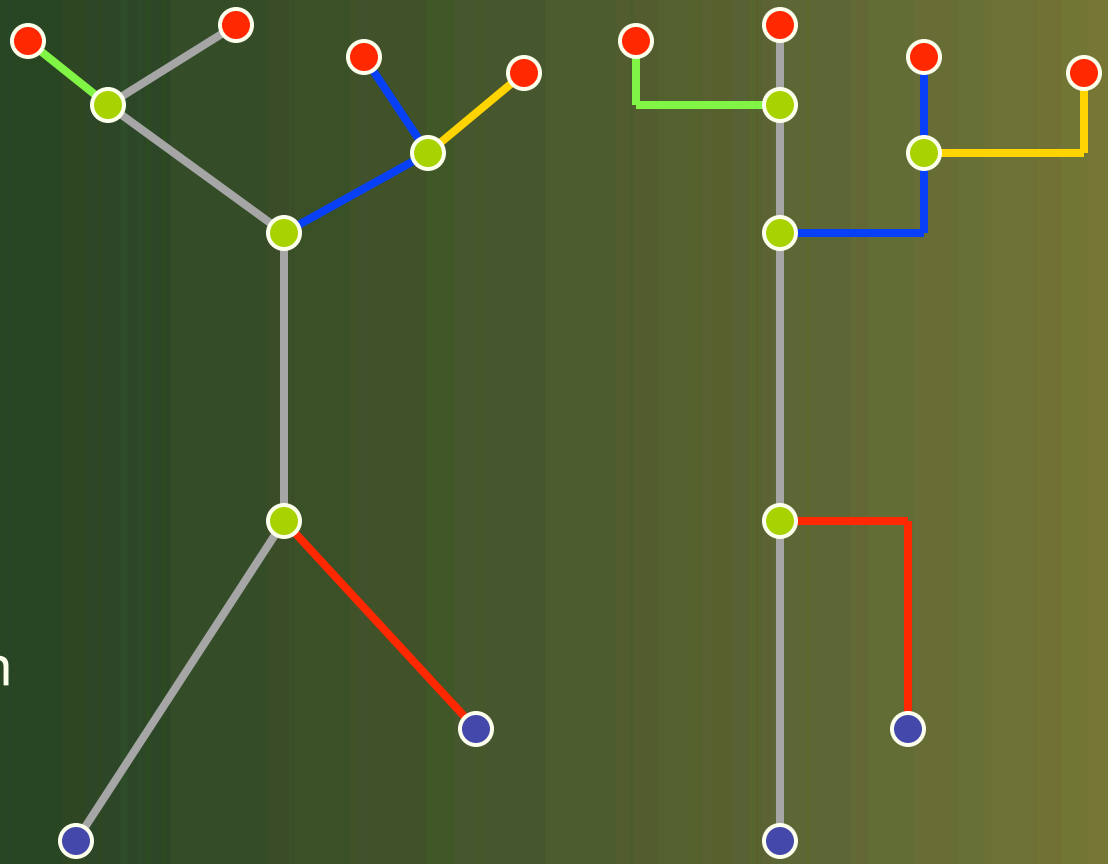
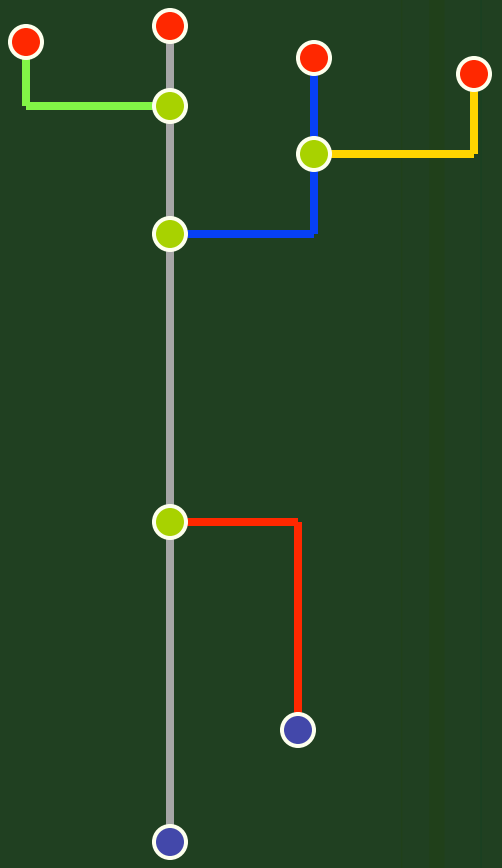
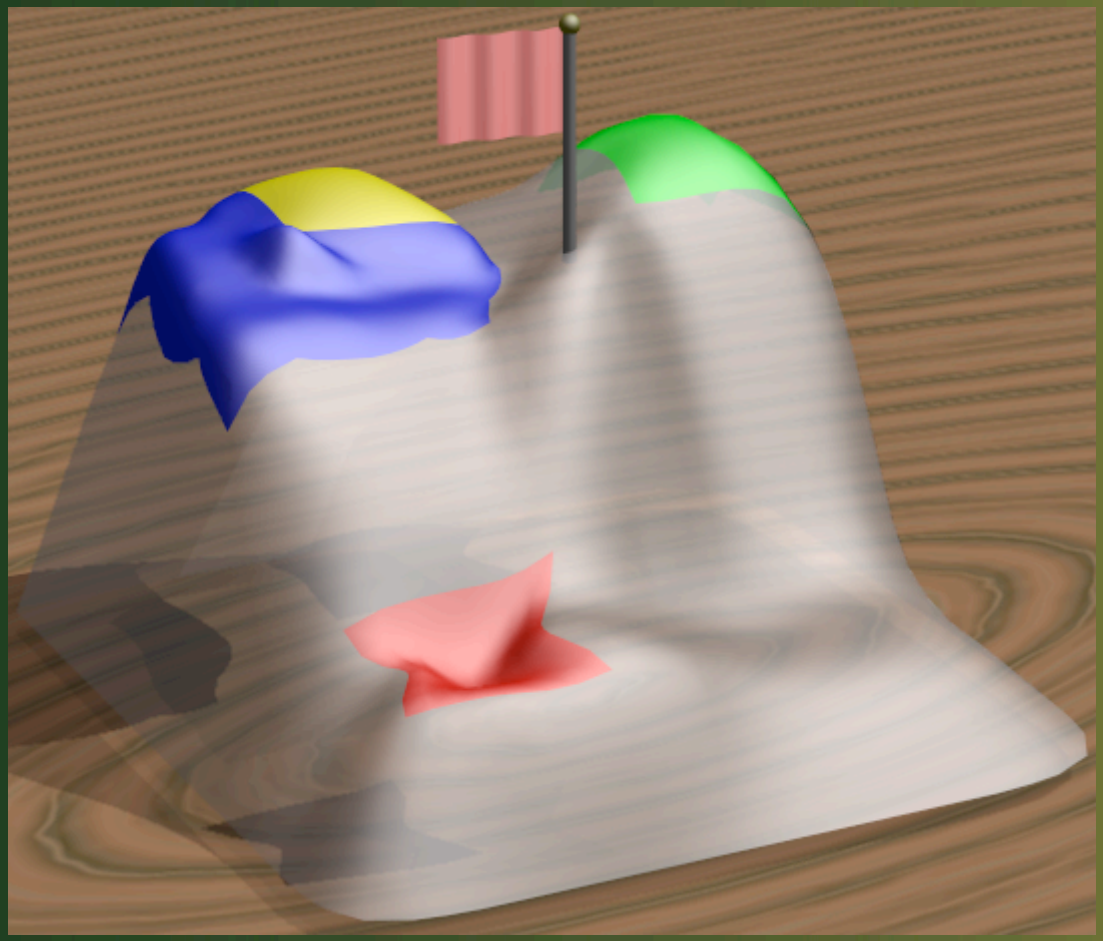


(Pascucci et al., 2004)

Topological Landscapes

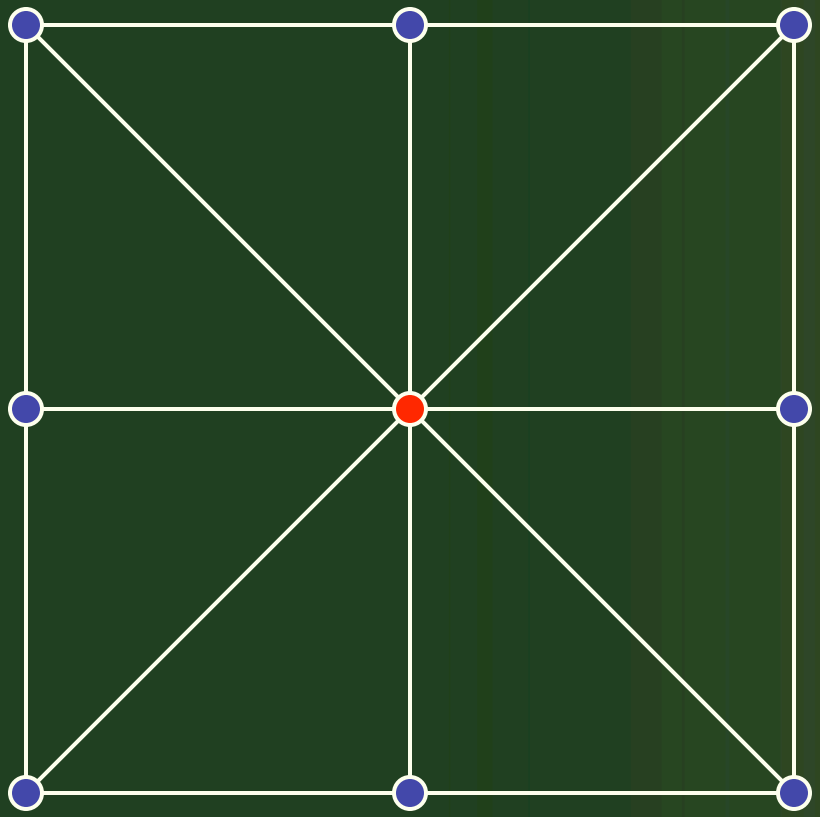




Branch Decompositon

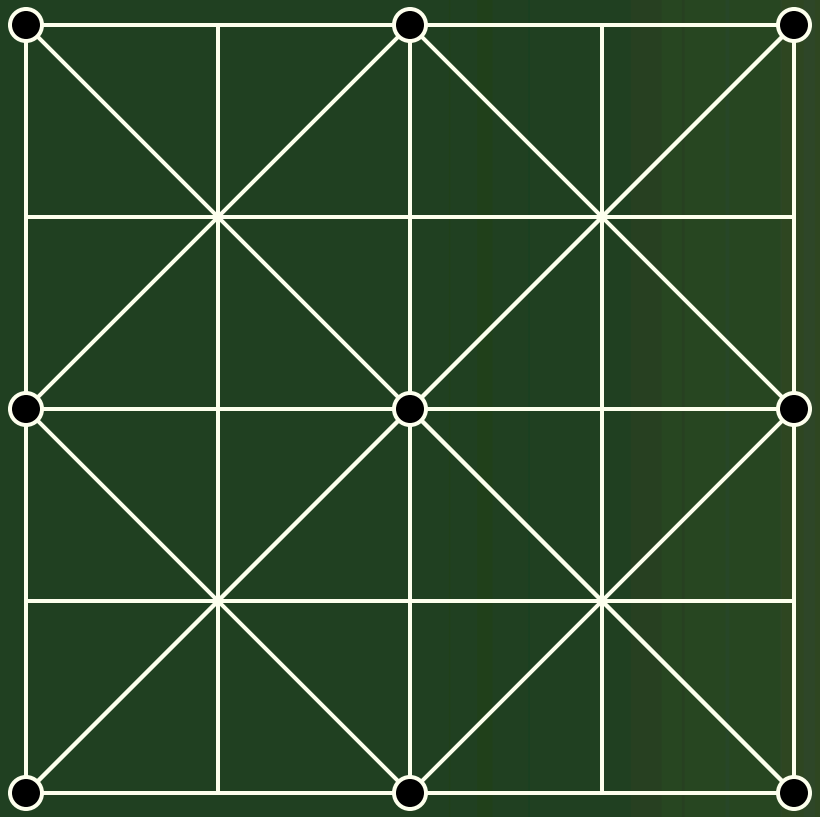
Topological Landscape

Terrain Construction – Root Branch



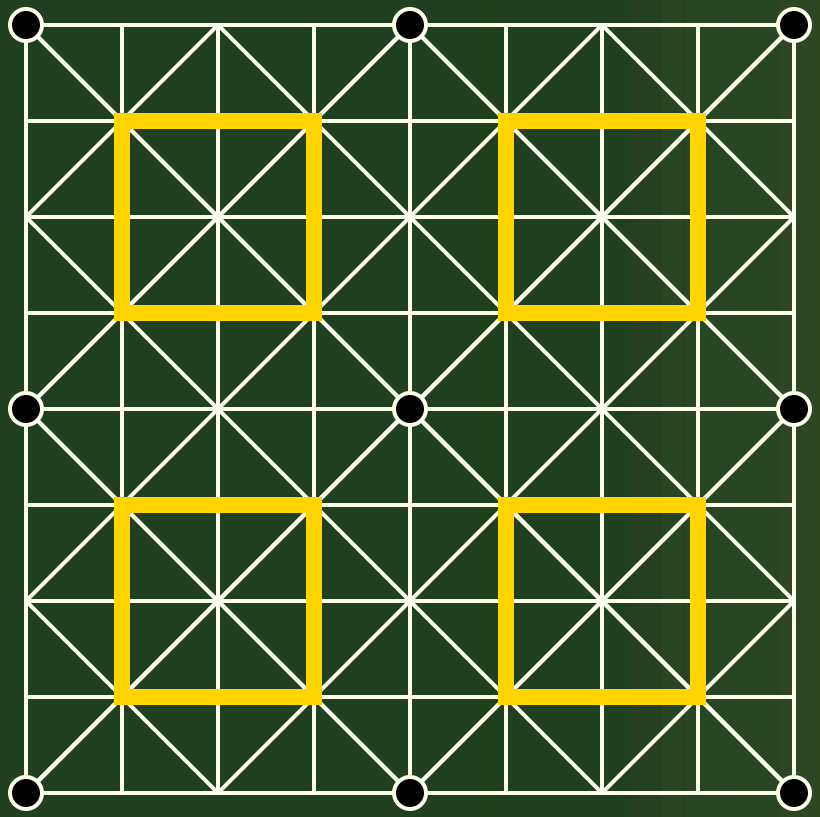
- Start with root branch of branch decomposition
- Use two levels 4-8 subdivision hierarchy
- Assign value of “branch minimum” to center vertex
- Assign value of “branch maximum” to boundary vertices

Terrain Construction – Refinement (1/2)



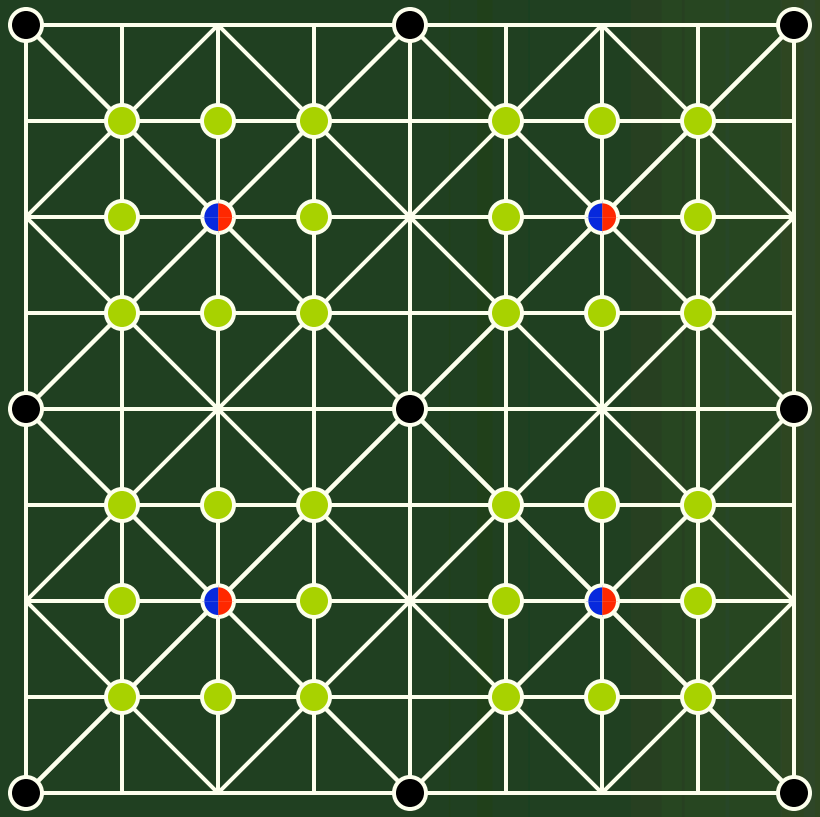
- Adding two levels is insufficient for placing children

Terrain Construction – Refinement (2/2)



- Adding four levels of refinement creates space for four children

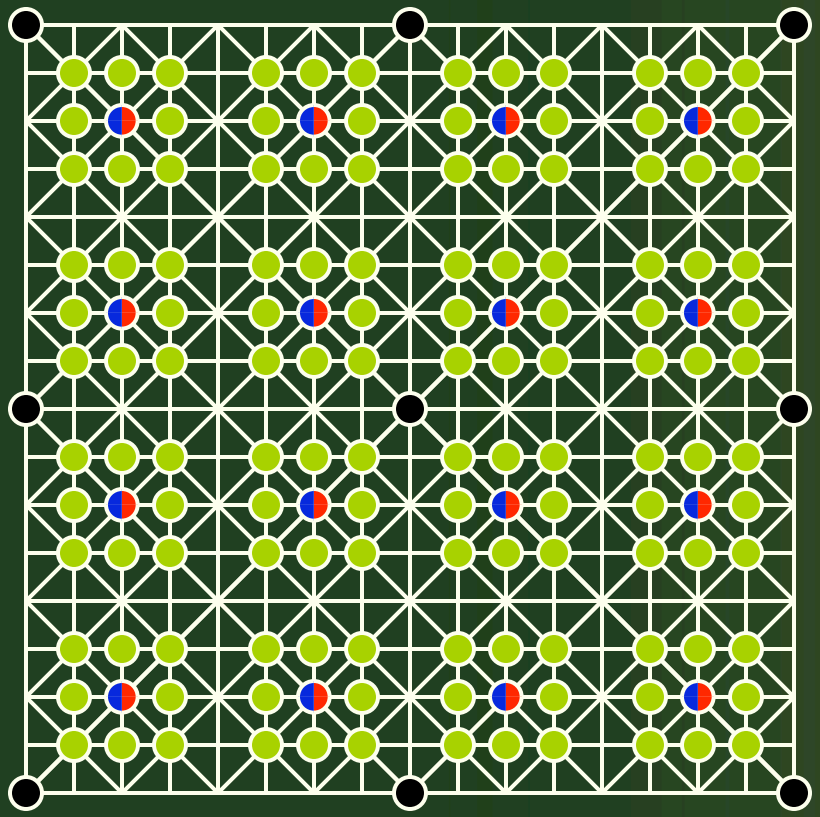
Terrain Construction – Placing Child Branches



- Assign branch maximum (or minimum) value to center vertex
- Assign branch saddle value to “boundary” vertices
- Space for children has same configuration as root level

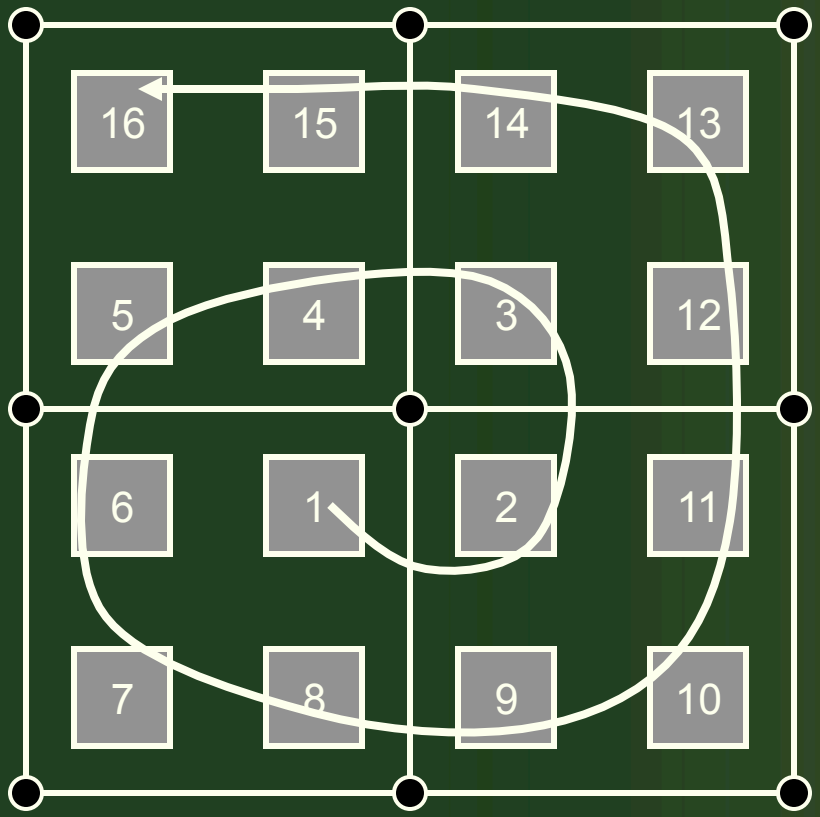
➔ Recursive construction scheme

Terrain Construction – Placing More Child Branches



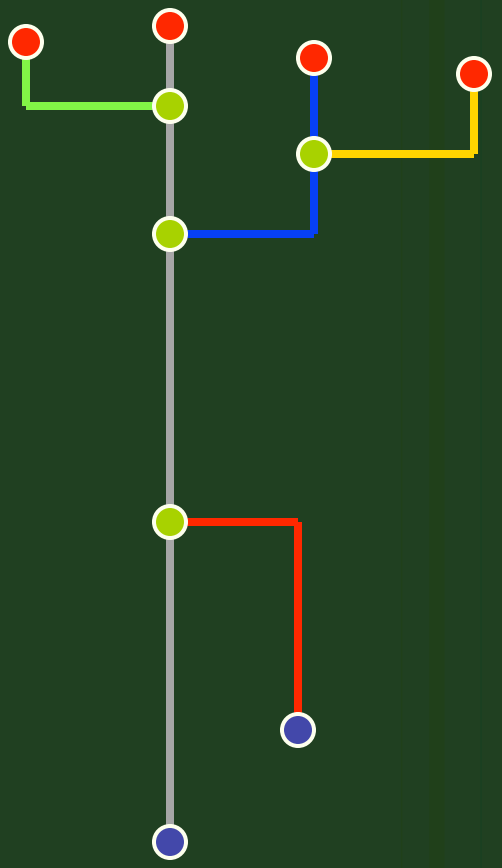
- Each two levels of additional refinement quadruple the number of spots for children
- Refine until sufficient number of locations for all child branches

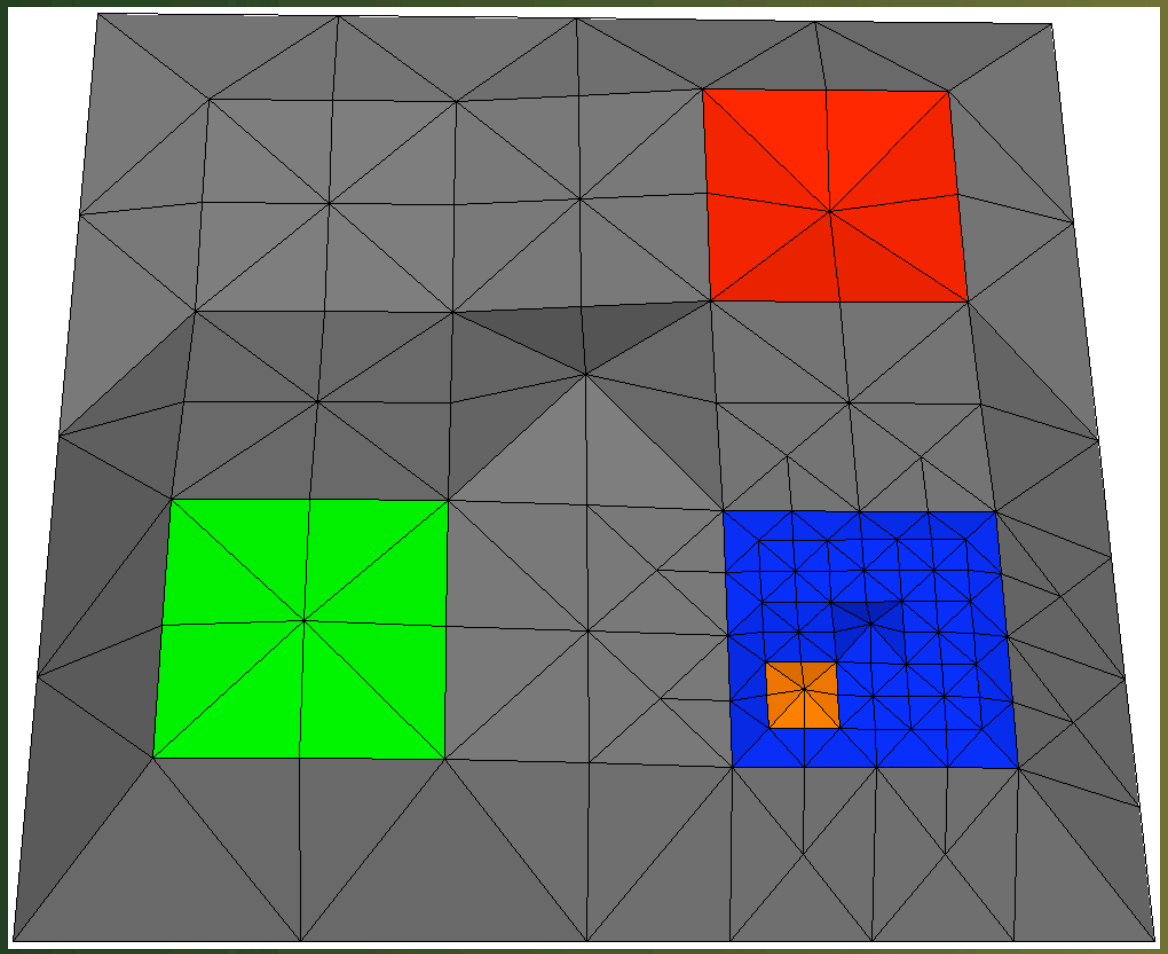
Terrain Construction – Child Branch Layout



- Arrange child branches in spiral layout
- Avoids new maxima, minima and thus new saddles
- Create “flat” regions for vacant spots

Terrain Construction – Example





Branch Decompositon

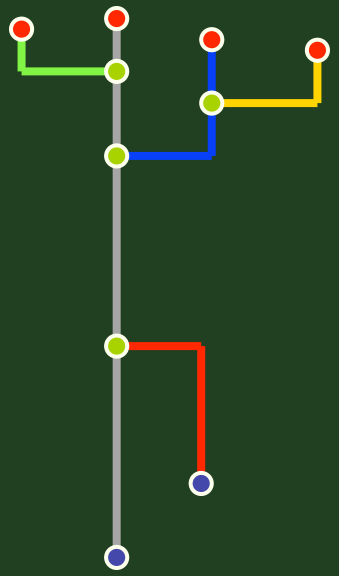
Topological Landscape

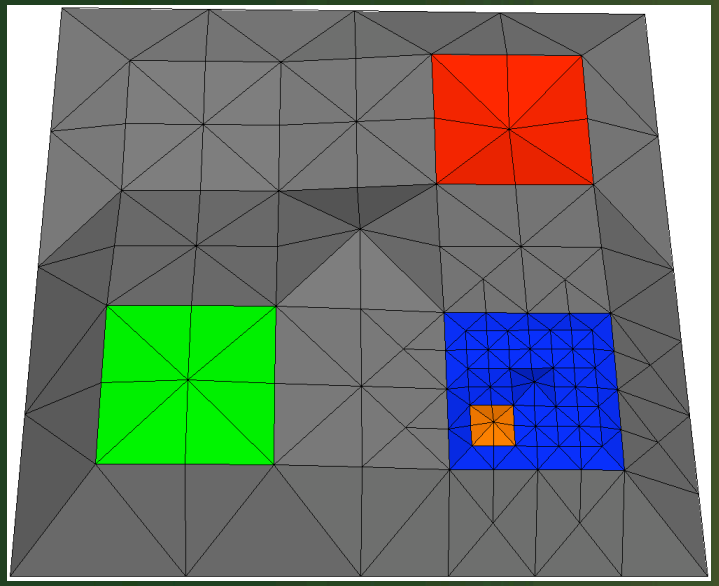
Metric-based Distortion – Motivation

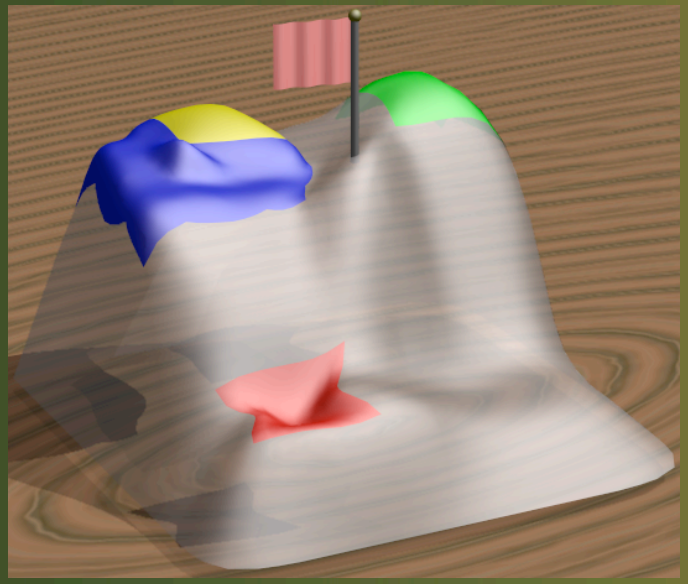
- Problem: Area assigned to a branch depends on hierarchy level, not necessarily on importance
- Can result in “spikes” (small patches with high persistence)
  - Difficult to see
  - Perceptual problem (interpretation as noise / outliers)
- Solution:
  Map additional property, such as feature volume, to area

➔ Increases expressiveness of landscape

Metric-based Distortion – Area Assignment

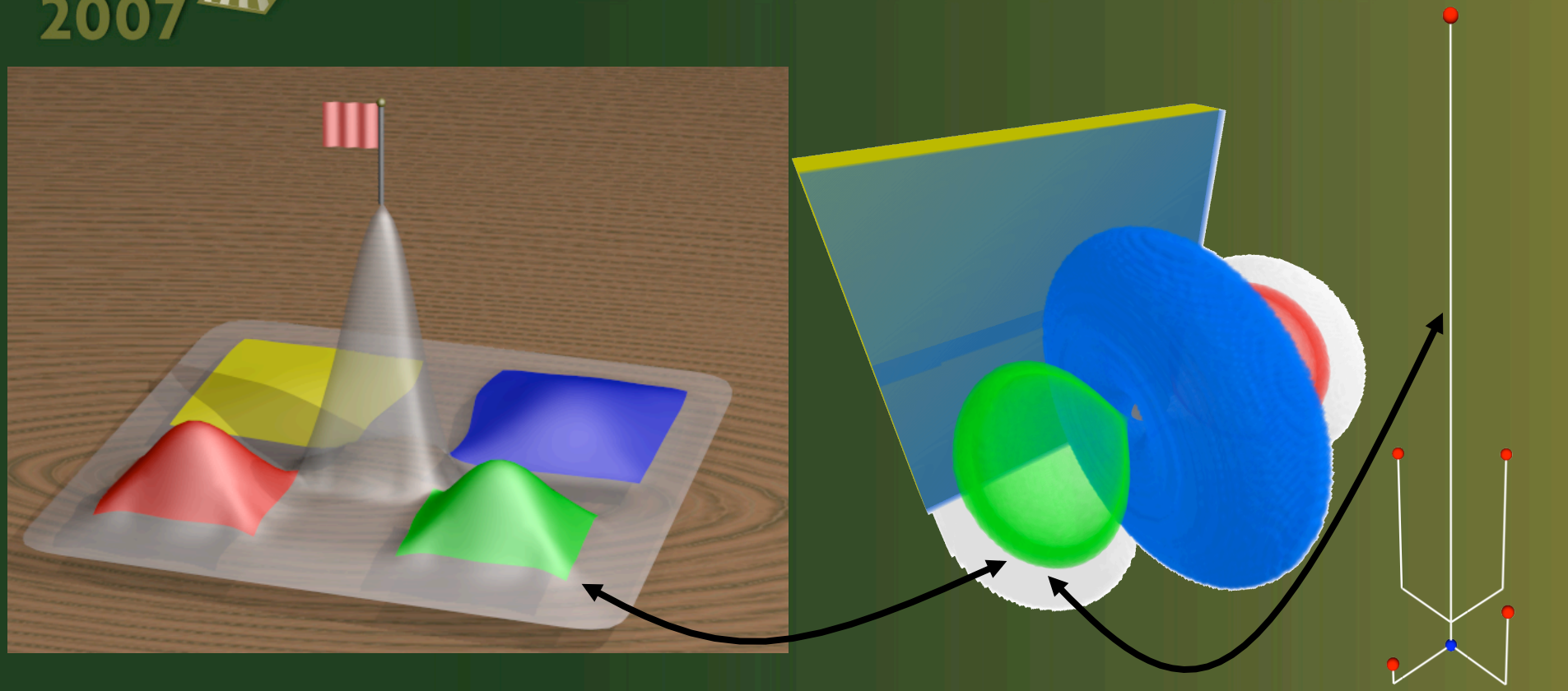






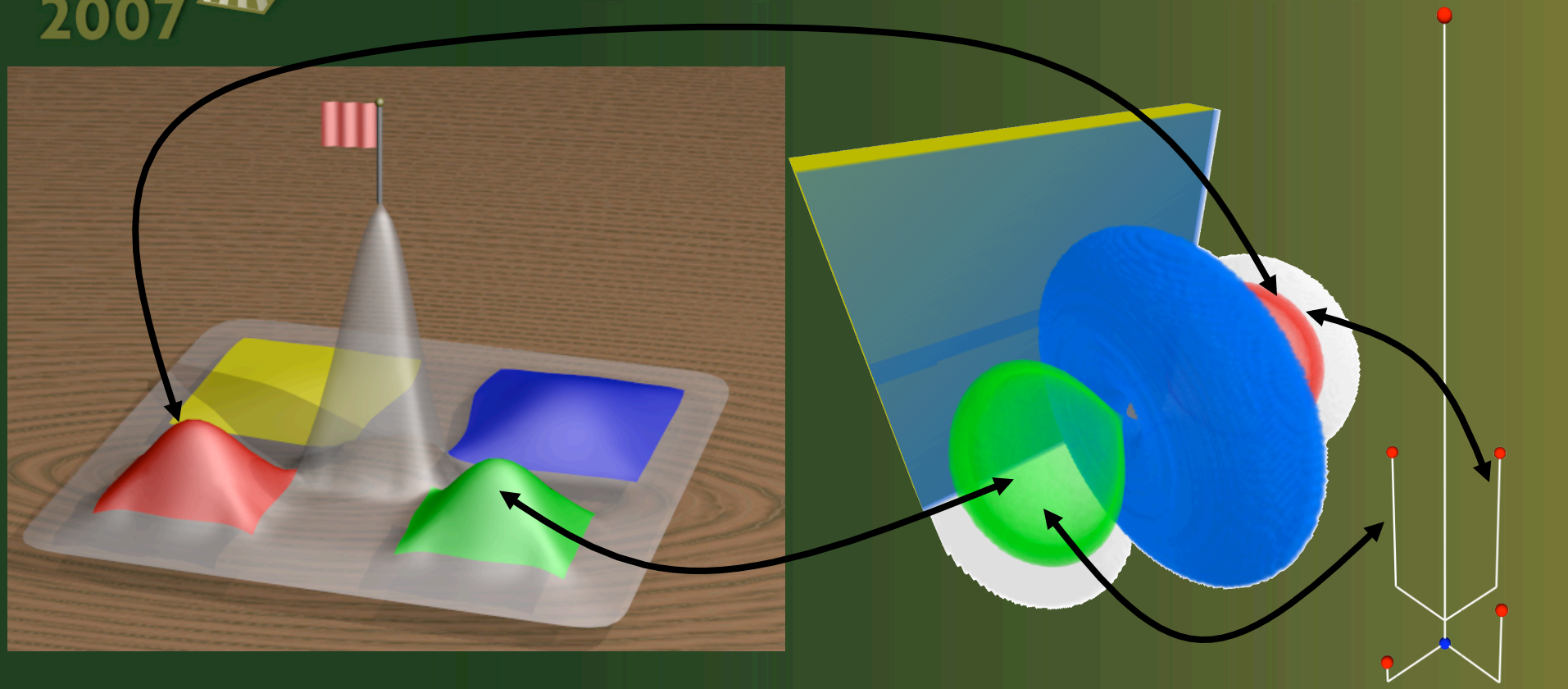
- Area = Volume$^{2/n}$, where n = dimension of data set
- Area assigned to triangles comprising patch for feature
- Use iterative reparametrization scheme

Results – Hydrogen Atom



Spatial probability distribution of the electron in an hydrogen atom in a strong magnetic field; 1.1% average volume to area error

Results – Hydrogen Atom



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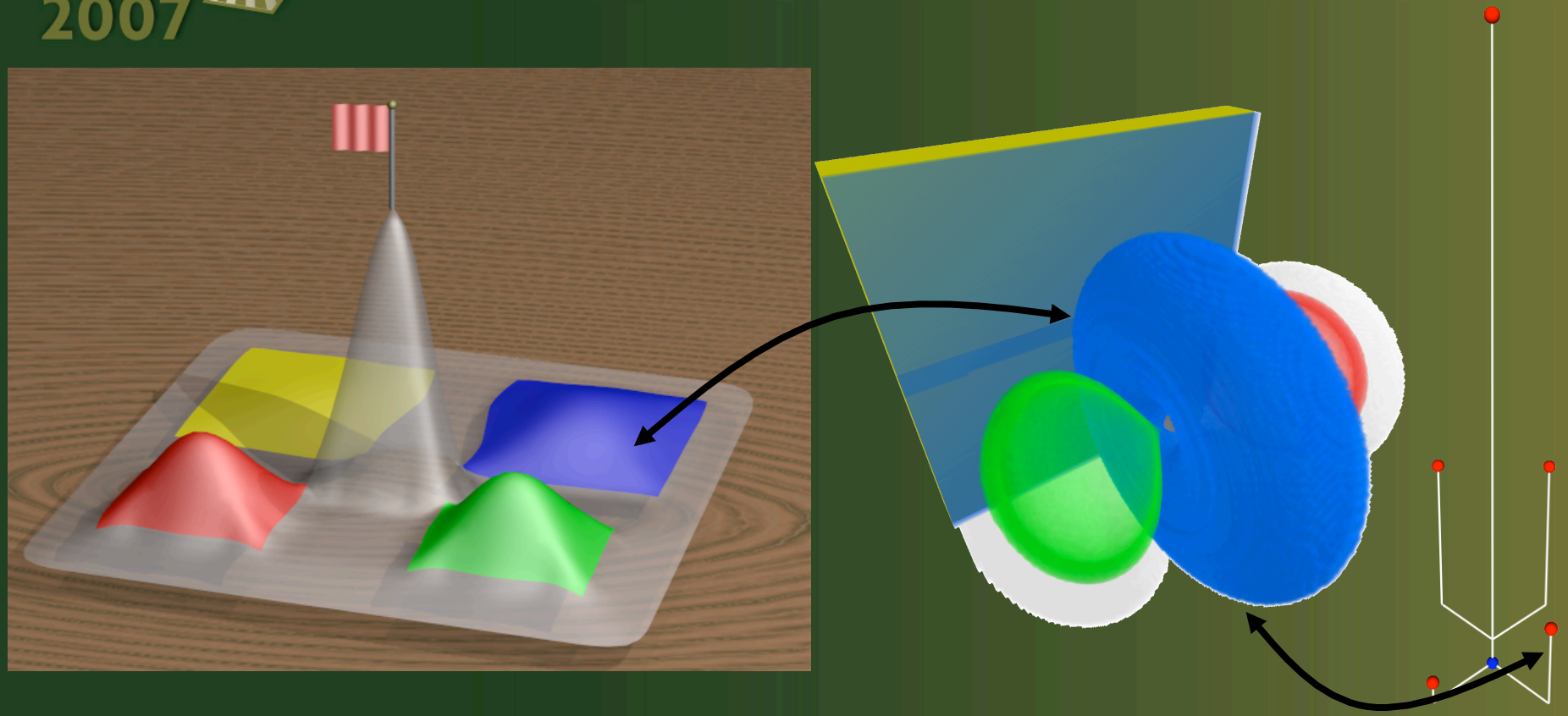

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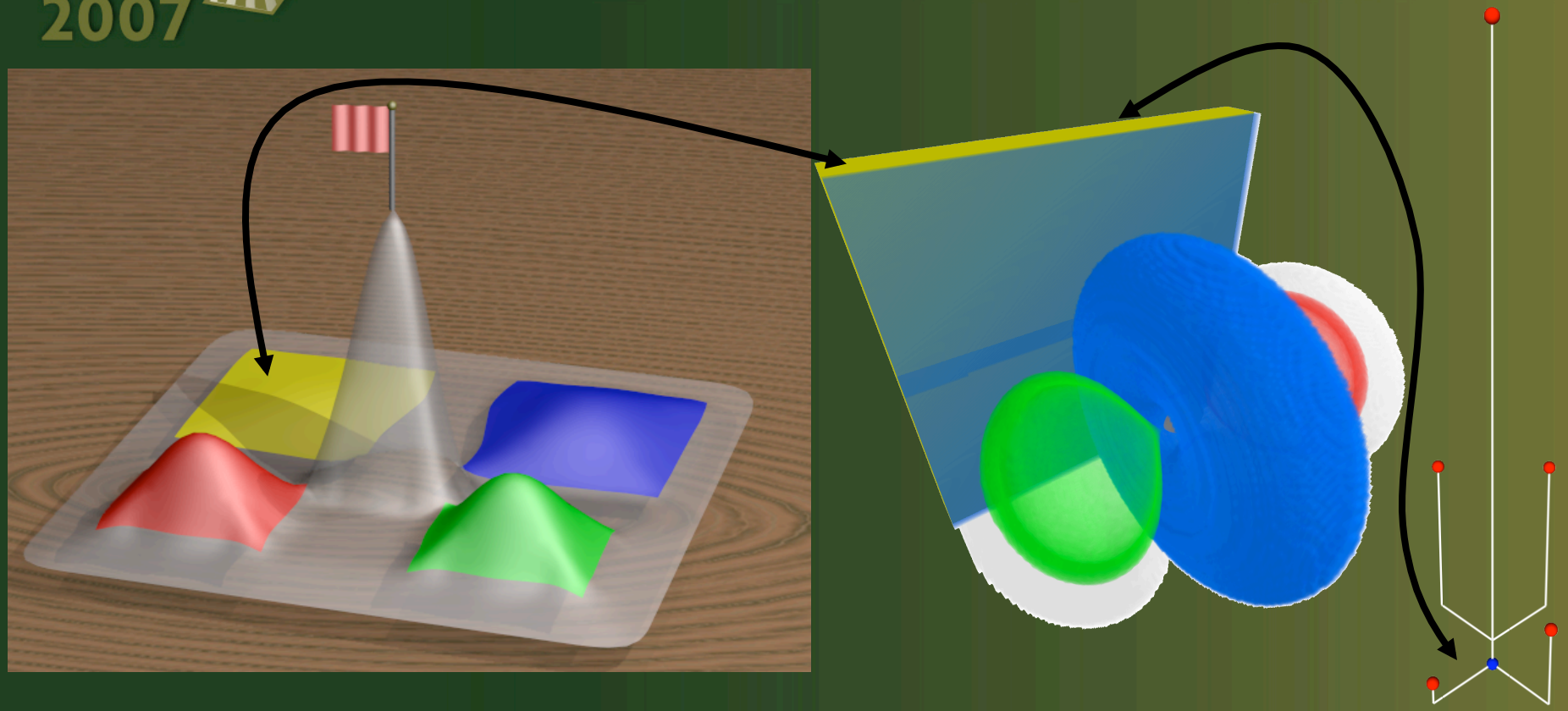
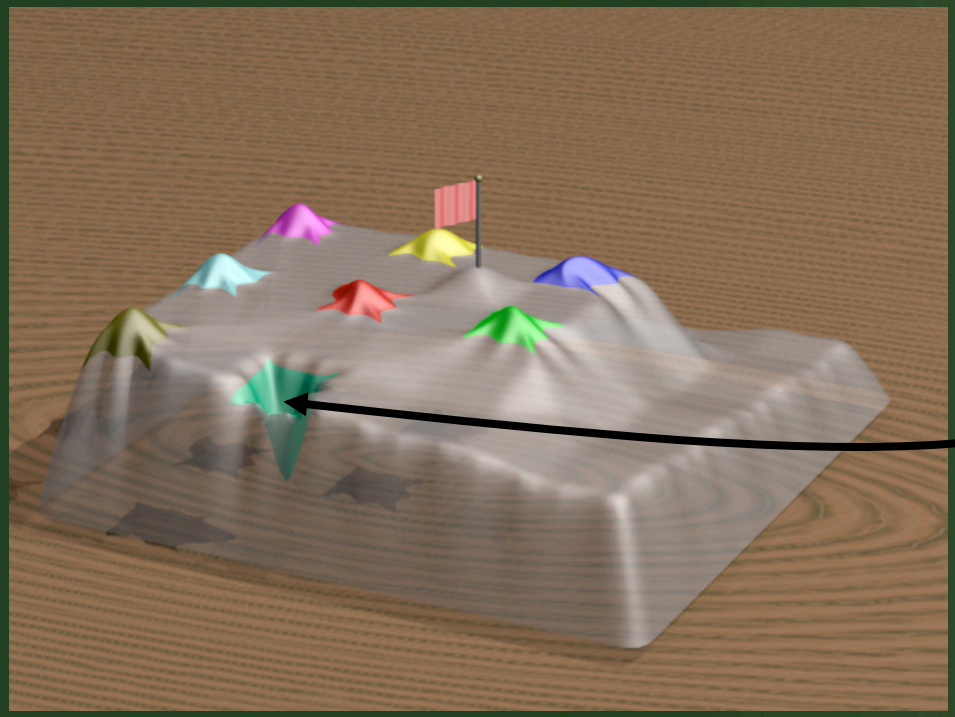
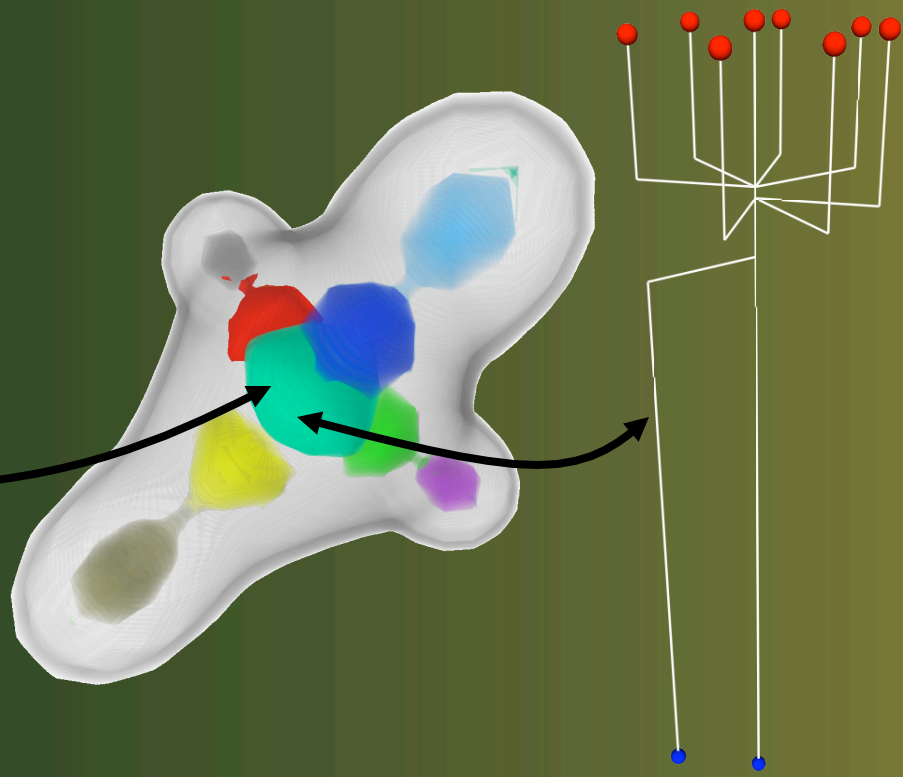


Spatial probability distribution of the electron in an hydrogen atom in a strong magnetic field; 1.1% average volume to area error

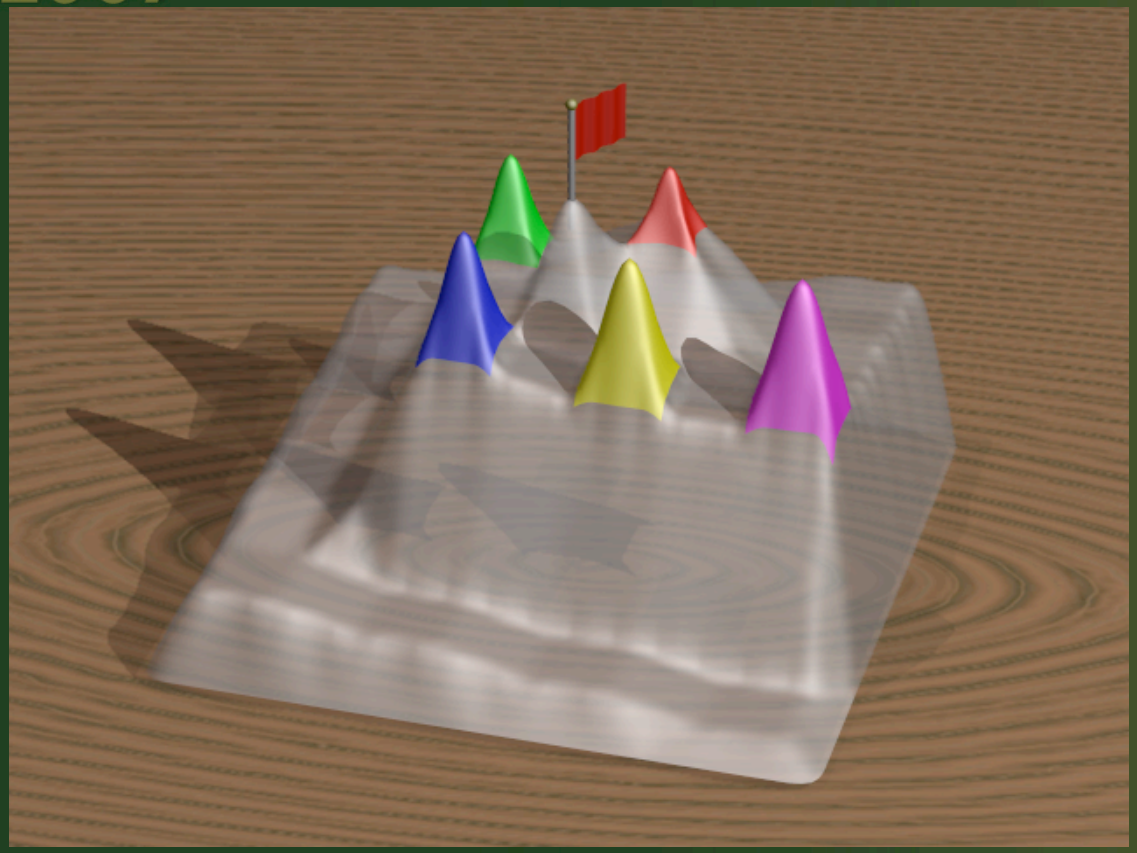
Results – Methane Molecule





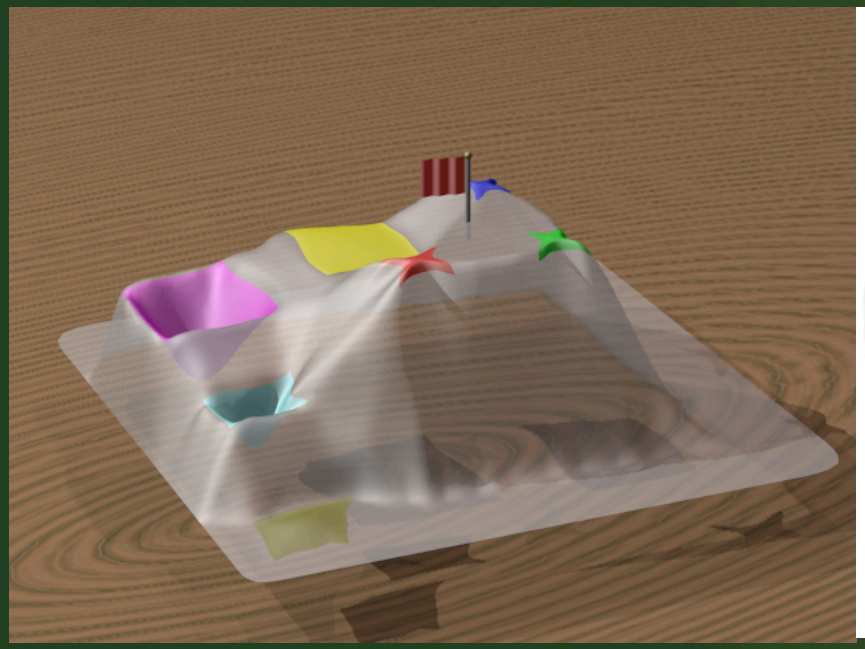
Electron distribution in methane molecule; 1.5 % average volume to area error

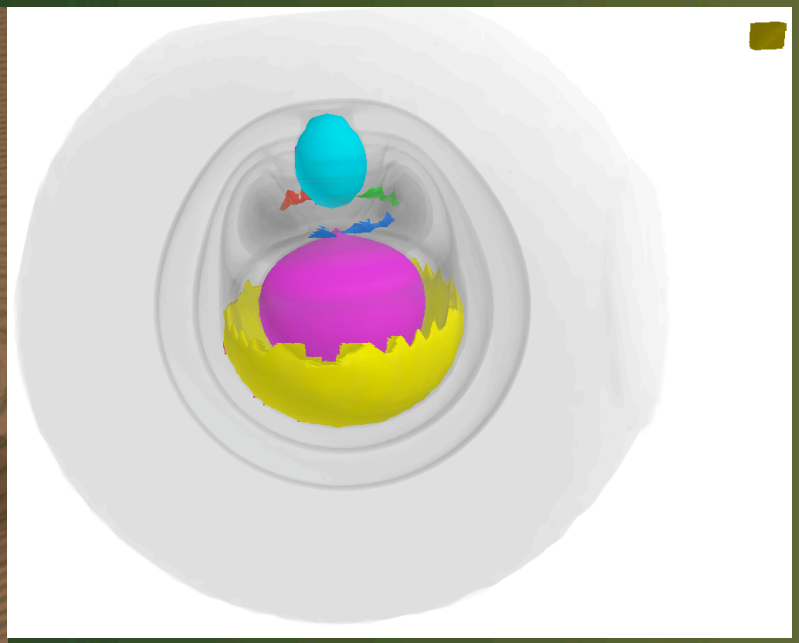
Results – Engine

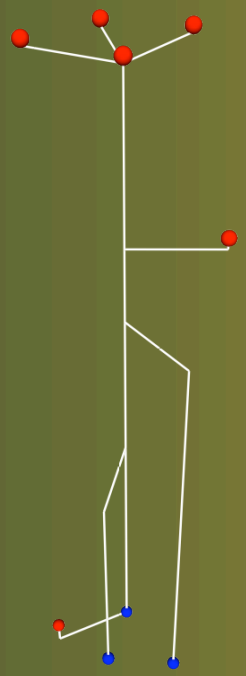


CT scan of two cylinders of an engine block; 1.3 % average volume to area error

Results – Nucleon

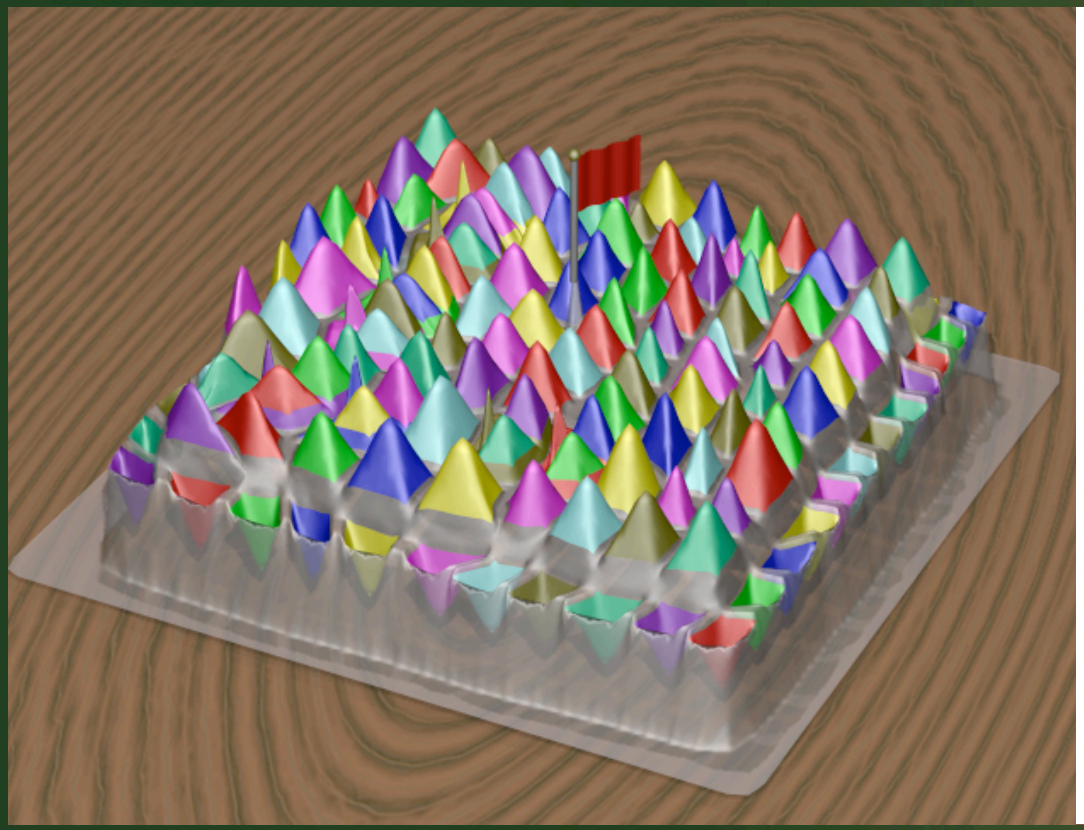


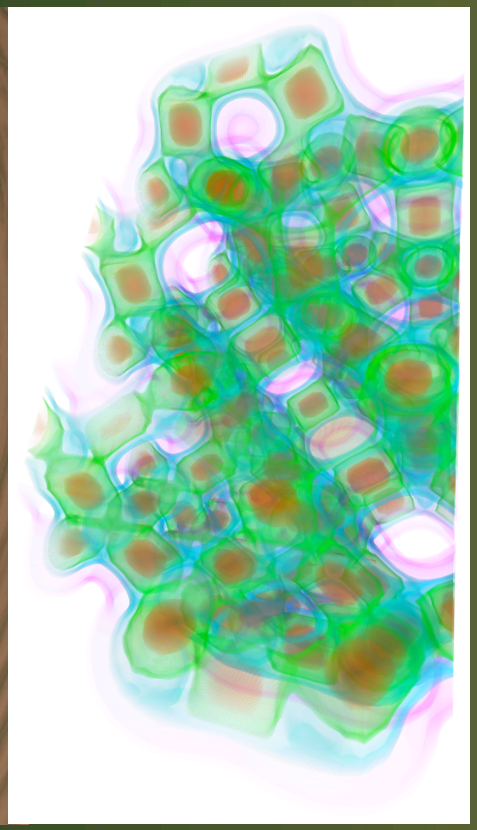


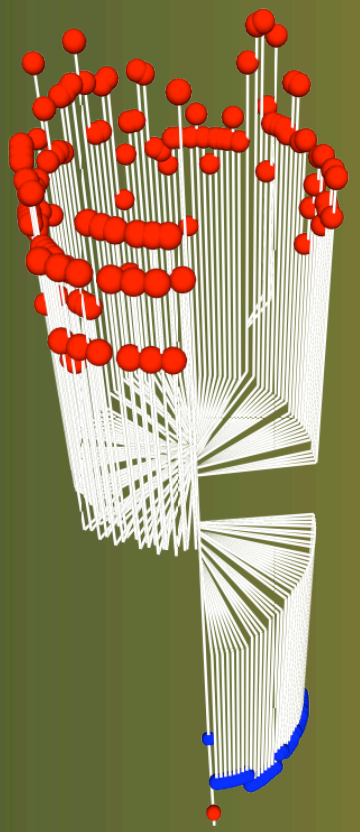


Two-body distribution probability of a nucleon in the atomic nucleus 16O if a second nucleon is positioned in a distance of 2 fm; 0.6 % average volume to area error

Results – Silicium

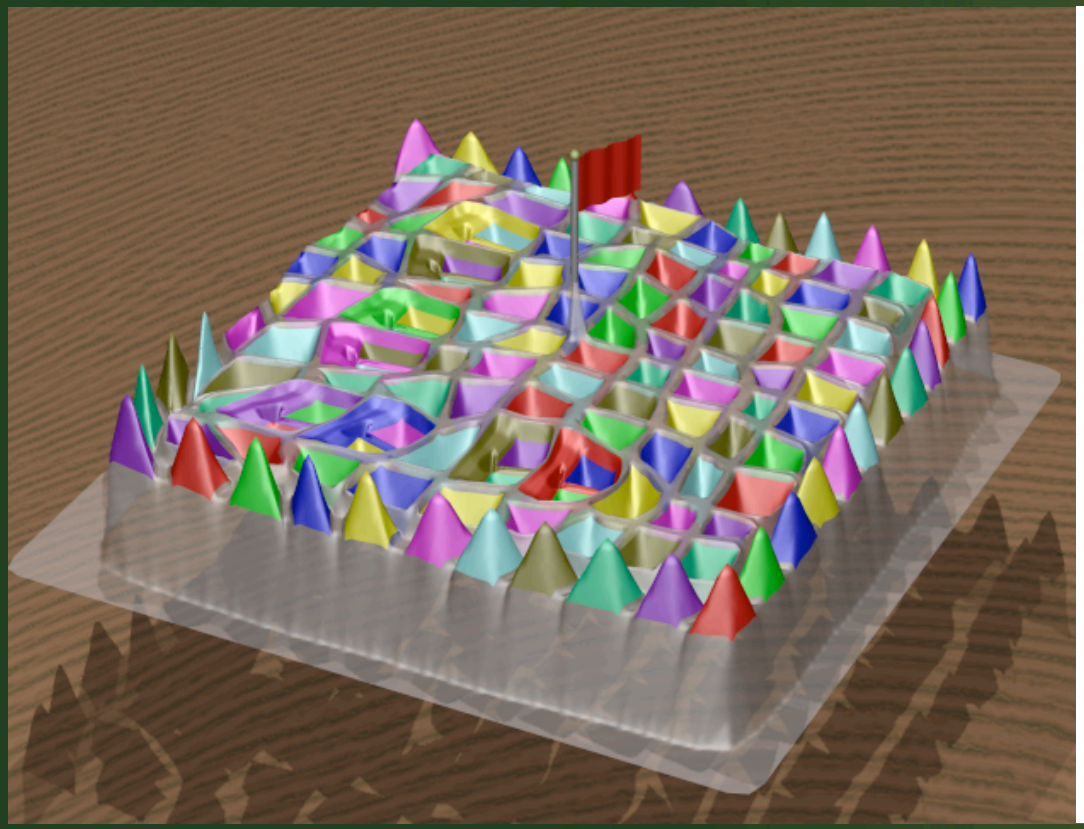


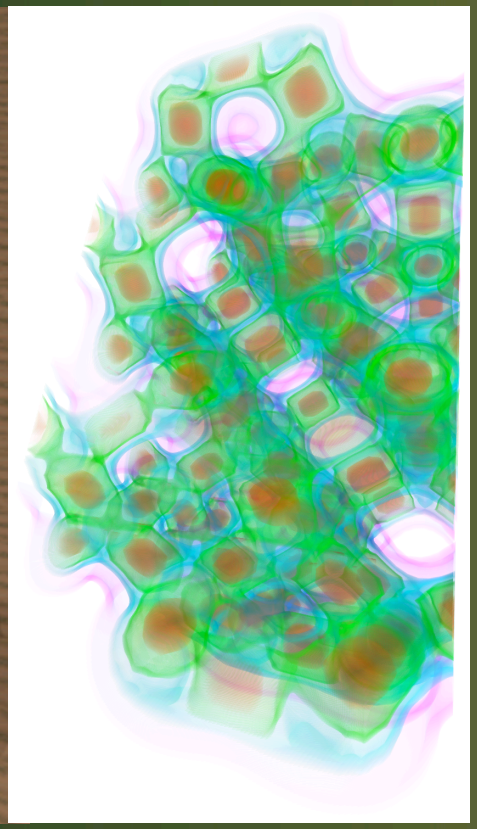


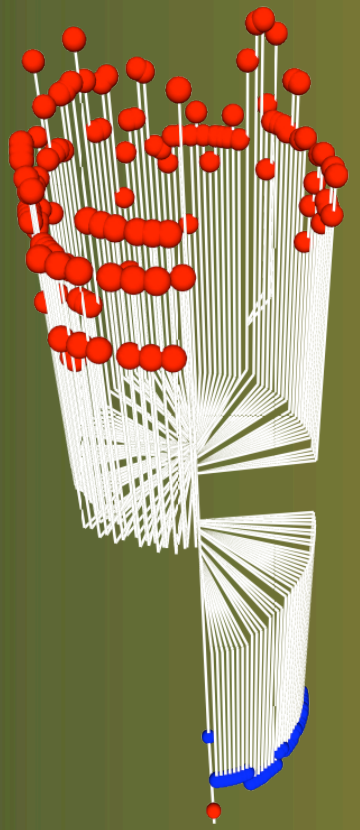


Simulation of a silicium grid; 1.0 % average volume to area error

Results – Silicium (Flipped)

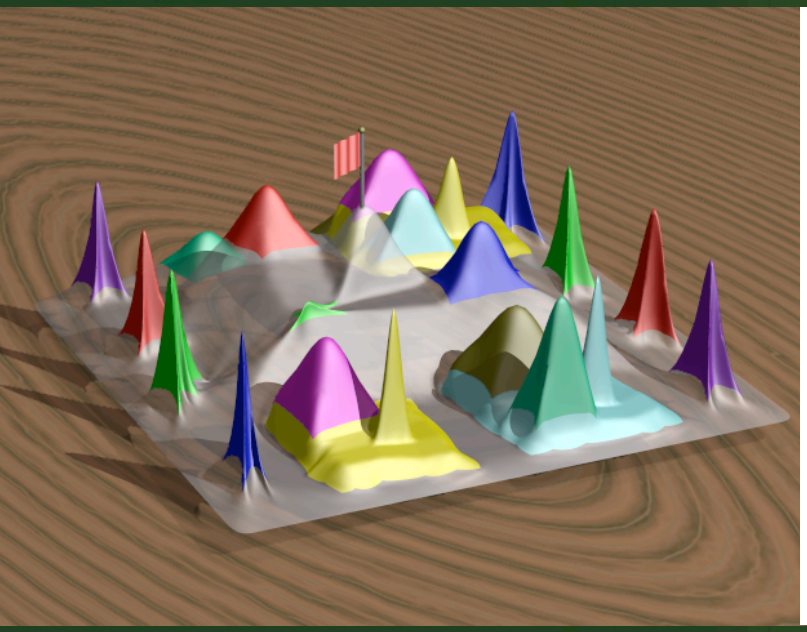


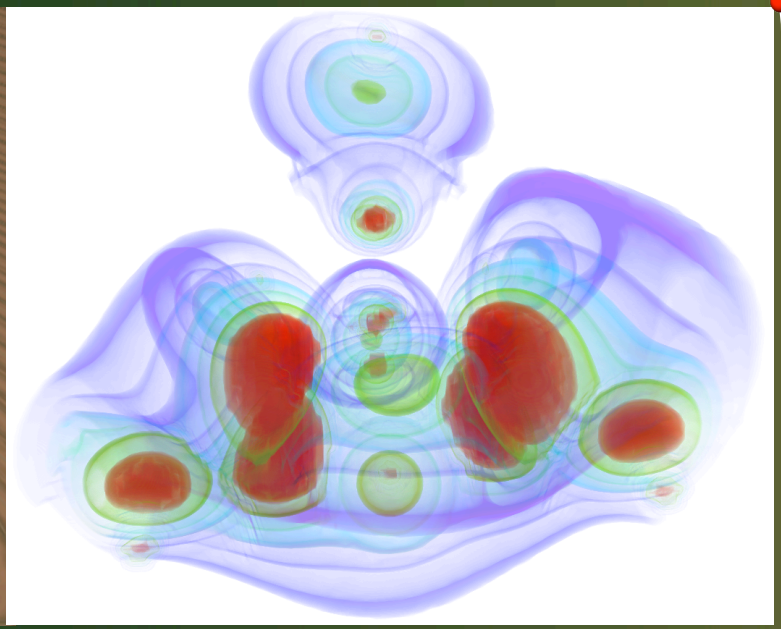


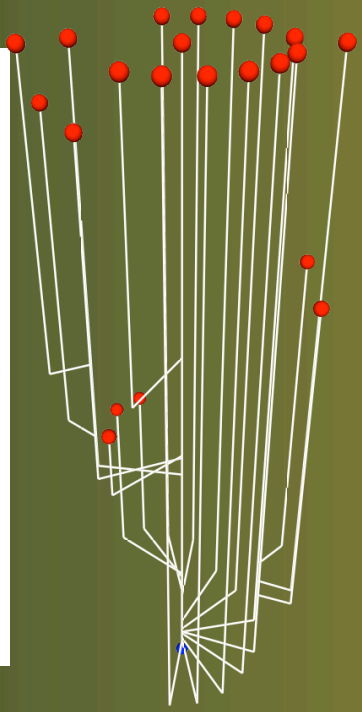


Simulation of a silicium grid; 1.0 % average volume to area error

Results – Neghip

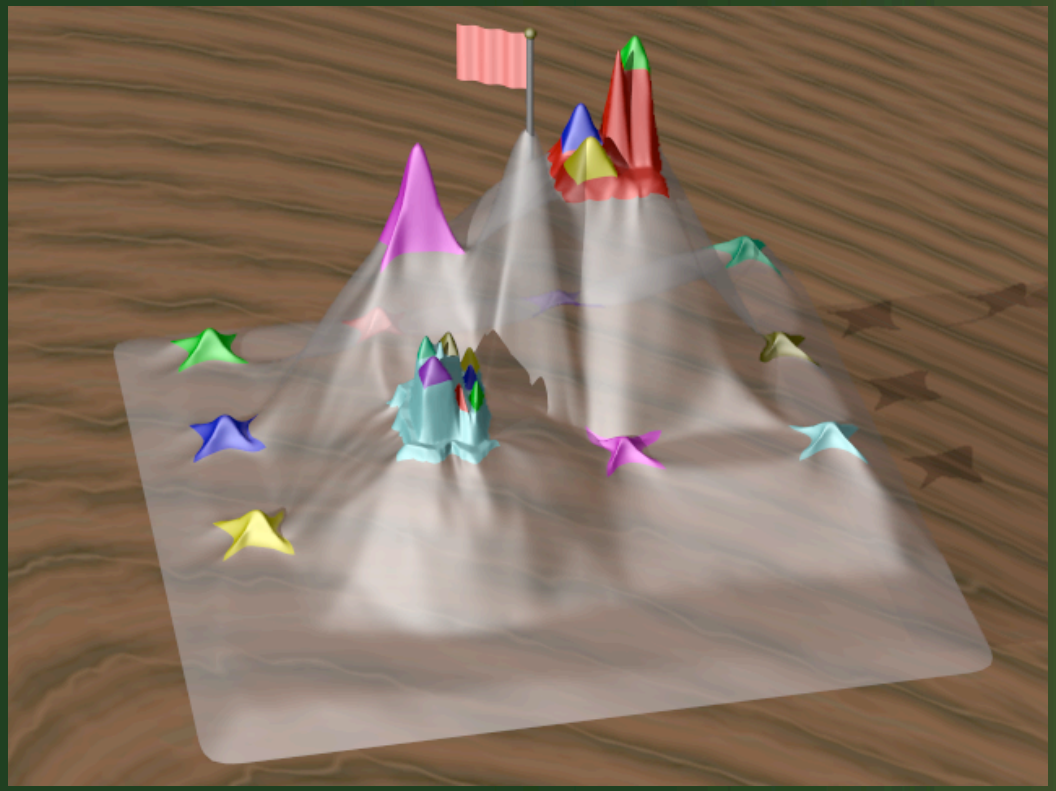






Spatial probability distribution of the electrons in a high potential protein molecule; 1.9 % average volume to area error

Results – Fuel



Simulation of fuel injection into a combustion chamber;
4.1 % average volume to area error

Conclusions

- Introduced Topological Landscape as metaphor for translating a scalar function *f* to two dimensions
- Preserve topological structure
- Preserve additional metric
- Promising results on commonly used example data sets
- Can be rendered as hierarchy corresponding to persistence-based simplification
- Examples are 3D data sets, but concept applies to higher dimensions

Future Work

- Apply to real world large-scale data and evaluate more formally
  - Improve layout
  - Experiment with additional metrics
- Apply to higher dimensional data sets
- Link with volume rendered view, Toporrery view, etc.
- Link 2D contours in Topological Landscape to 3D contours in data set

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