Mesh Segmentation

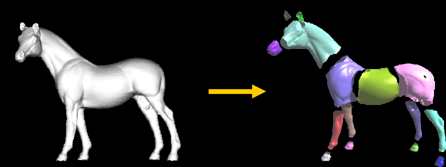
Thomas Funkhouser

(most slides by Arik Shamir)

Introduction

Goal:

- Given: a mesh M = {V,E,F}
- Create: a set S of submeshes M_i that partition the faces of M into disjoint subsets.



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Motivation

Applications:

- Analysis
- Representation
- Recognition
- Collision detection
- Animation
- Modeling
- etc.

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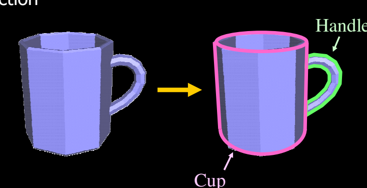

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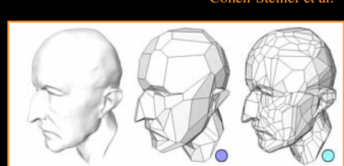
Cohen-Steiner et al.



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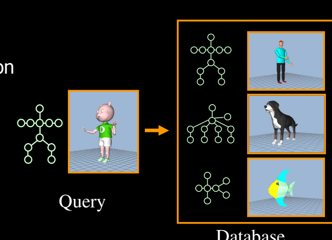

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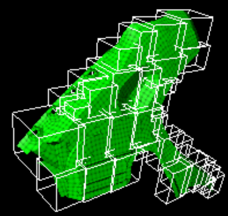

Tal & Frisch

Motivation

Applications:
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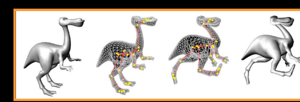
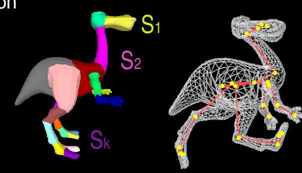




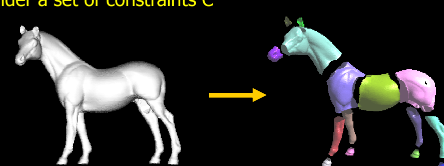
Katz & Tal

Motivation

Applications:
- Analysis
- Representation
- Recognition
- Collision detection
- Animation
- Ø Modeling
- etc.

Problem Statement

Optimization formulation:
- Given: a mesh M = {V,E,F}
- Create: a set S of submeshes M_i that partition the faces of M into disjoint subsets that minimize an objective function J under a set of constraints C



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Outline

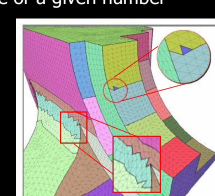
Constraints
Objective function
Algorithmic strategies
Some results

Constraints

Cardinality
- Not too small and not too large or a given number (of segment or elements)
- Overall balanced partition

Geometry
- Size: area, diameter, radius
- Convexity, Roundness
- Boundary smoothness

Topology
- Connectivity (single component)
- Disk topology



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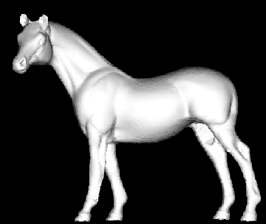
Objective Function

Object function J says how "good" a segmentation is …

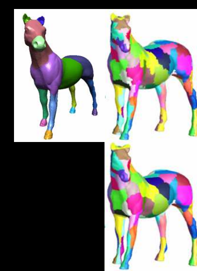


What properties define a good segmentation of this horse?

Objective Function

Object function J says how "good" a segmentation is …

- Number of segments?
- Surface properties?
- Boundary properties?
- Global shape properties?
- Semantics?
- etc.



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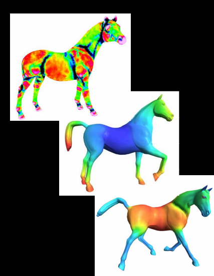
Objective Function

Mesh attributes to consider:

- Distances
- Normal directions
- Smoothness, curvature
- Shape diameter
- Distance to proxies
- Symmetry
- Motion
- etc.



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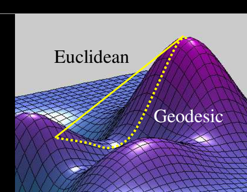
Distances

Triangles in same segment ought to be close

Geodesic distance to point



Geodesic vs. Euclidean distance

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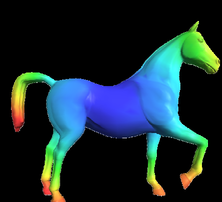
Distances

Triangles in same segment ought to be close

Discontinuities in functions of distance indicate possible boundaries



Average geodesic distance to other points

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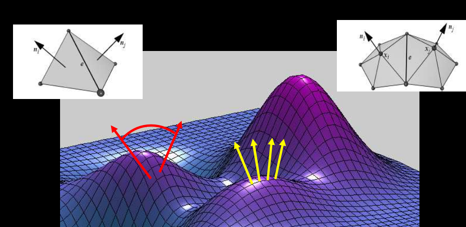
Normal direction, Dihedral Angles

Triangles in same segment ought to have normals that are: similar (planar)?, continuous (no creases)?



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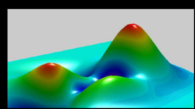
Smoothness, Curvature

Concave creases indicate good segmentation boundaries



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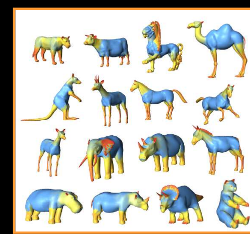
Diameter

Distinguish between thin and thick parts in a model



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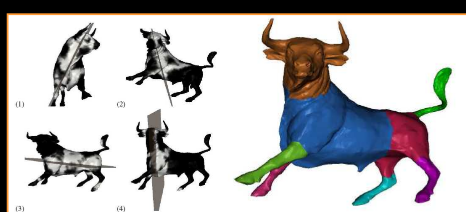
Symmetry

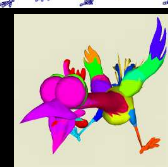
Segments should be locally symmetric



Podolak

Motion

Cluster parts which move in a similar manner



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Outline

Constraints

Objective function

Algorithmic strategies ←

Some results

Algorithmic Strategies

Segmentation problem:

- Given: a mesh M = {V,E,F}
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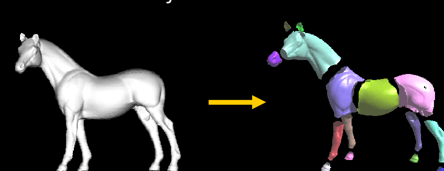

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Algorithmic Strategies

If |M| = n and |S| = k, then the search space of possible mesh decompositions is of order k^n.

- NP-complete
- Must revert to approximation algorithm

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Segmentation as Clustering

The basic segmentation problems can viewed as assigning primitive mesh elements to sub meshes

- Clustering problem
- Well-studied in machine learning

Most segmentation strategies have basis in classic clustering algorithms:

- Region growing (local greedy)
- Primitive fitting (model-based)
- Hierarchical clustering (global greedy)
- K-means (iterative)
- Graph Cut

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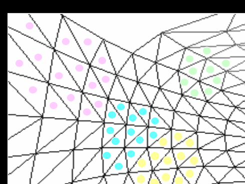
Region Growing



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Region Growing

```
Region Growing Algorithm
Initialize a priority queue Q of elements
Loop until all elements are clustered
   Choose a seed element and insert to Q
   Create a cluster C from seed
   Loop until Q is empty
      Get the next element s from Q
      If s can be clustered into C
         Cluster s into C
         Insert s neighbors to Q
Merge small clusters into neighboring ones
```

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Multiple Region Growing Algorithm

```
Multiple Source Region Grow
Initialize a priority queue Q of pairs
Choose a set of seed elements {s_i}
Create a cluster C_i from each seed s_i
Insert the pairs <s_i,C_i> to Q
Loop until until Q is empty
   Get the next pair <s_k,C_k> from Q
   If s_k is not clustered already and
   s_k can be clustered into C_k
      Cluster s_k into C_k
      For all un-clustered neighbors s_i of s_k
         insert <s_i,C_k> to Q
Merge small clusters into neighboring ones
```

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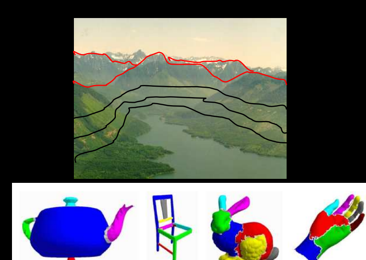
Watershed



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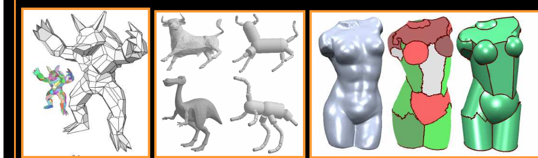
Primitive Fitting

Find set of primitives that best approximates shape and map triangles to primitives



Planes | Cylinders | Spheres, cylinders, & rolling ball surfaces

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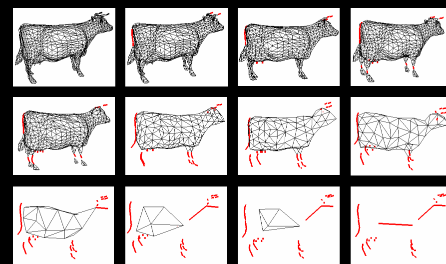
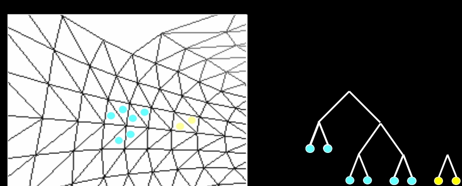
Primitive Fitting

Simplification is an example (map triangles of mesh to small set of triangles)



Li

Hierarchical Clustering



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Hierarchical Clustering

```
Hierarchical Clustering Algorithm
Initialize a priority queue Q of pairs
Insert all valid element pairs to Q
Loop until Q is empty
   Get the next pair (u,v) from Q
   If (u,v) can be merged
      Merge (u,v) into w
      Insert all valid pairs of w to Q
```

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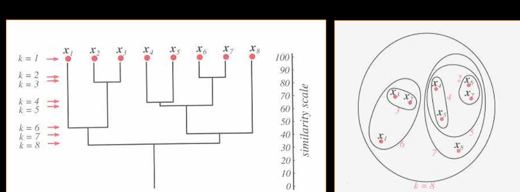
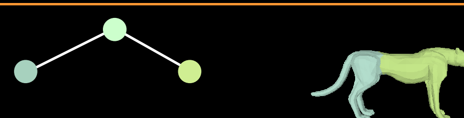
Hierarchical Clustering



Duda

Hierarchical Clustering



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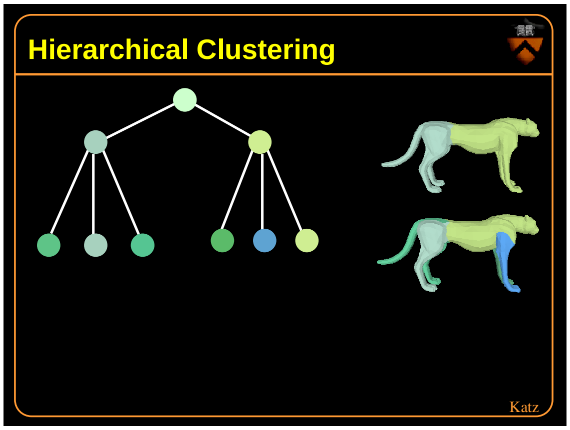
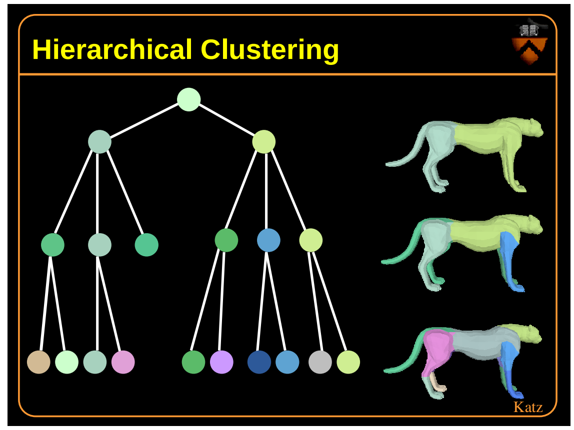
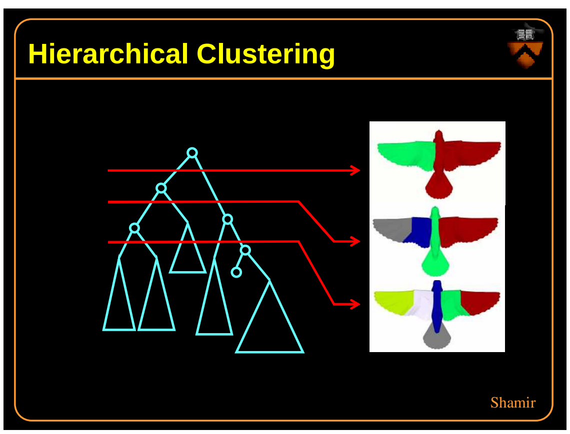
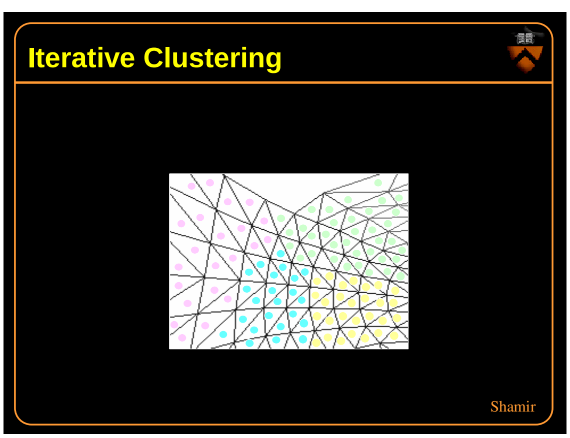

Hierarchical Clustering
Katz


Hierarchical Clustering
Katz


Hierarchical Clustering
Shamir


Hierarchical Clustering
Katz


Iterative Clustering
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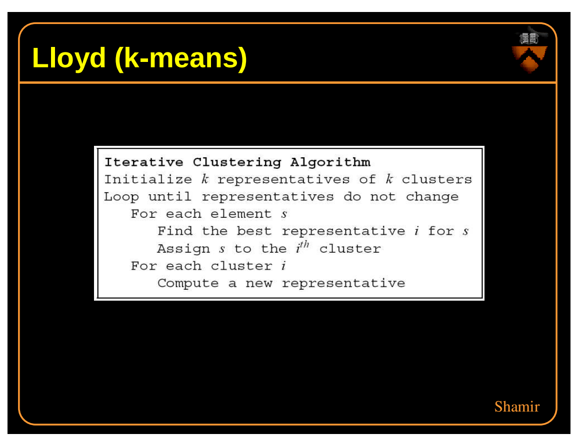
Lloyd (k-means)
Iterative Clustering Algorithm
Initialize k representatives of k clusters
Loop until representatives do not change
For each element s
Find the best representative i for s
Assign s to the i^th cluster
For each cluster i
Compute a new representative
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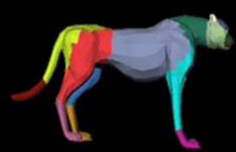
Lloyd (k-means)

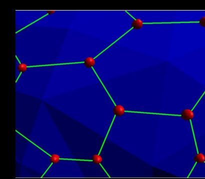


Shalfman

Graph Cuts

Define a graph where each node is an element and the edges hold weights according to the distances between the elements.

Example: dual graph and the weight is the dihedral angle.



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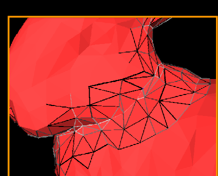

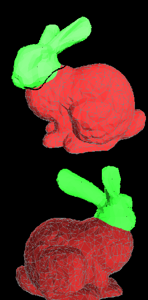

Comparison of Strategies

Strategies

- Region growing
- Hierarchical
- Iterative
- Graph cut

intensive ↓   greedier ↑

Other considerations: local control, hierarchy, convergence, parametric vs. non parametric…

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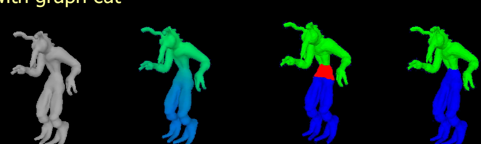
Hybrid Strategies

Construct fuzzy decomposition with Lloyd's algorithm

- Assign distances to pairs of faces
- Assign probabilities of belonging to patches
- Compute a fuzzy decomposition

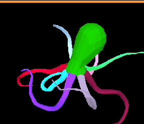
Construct exact boundaries within fuzzy regions with graph cut

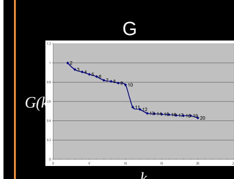


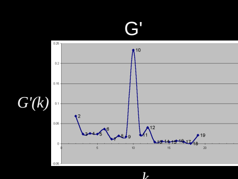
Katz

Choosing the Number of Segments

$$G(k) = \min_{i<k}(Dist(REP_k, REP_i))$$







Katz

Outline

Constraints
Objective function
Algorithmic strategies
Some results ←

Some Results

Algorithms compared:

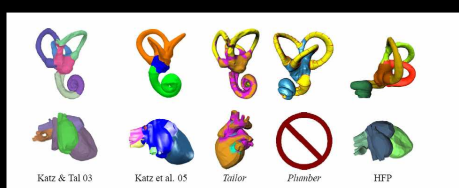
- Katz03: hybrid iterative + graph cut
- Katz05: feature detection + core extraction
- Mortara04: region growing (Plumber)
- Attene06: hierarchical primitive fitting (HPF)
- Others

Some evaluation criteria:

- Part semantics
- Boundary quality

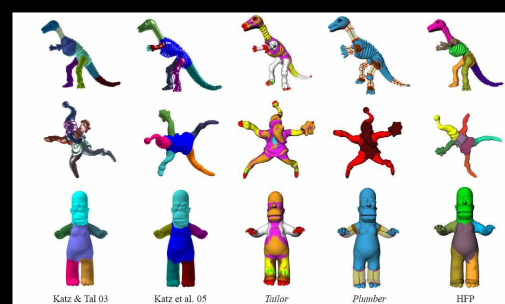
Attene06

Some Results



Attene06

Some Results

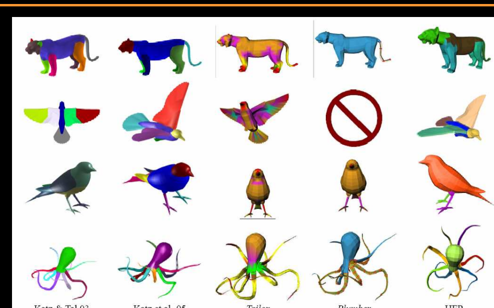


Attene06

Some Results

Attene06

Some Results



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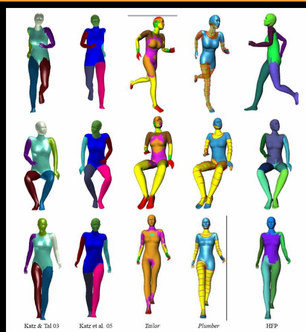
Some Results



Attene06

Final Remarks

- Many applications use mesh segmentation as a sub-stage
- Segmentation usually has more effect on the results than seem to be realized
- 3D segmentation is still a very difficult problem – and still in its infancy, e.g. compared to image segmentation (hundreds of papers).
- More advanced coherency issues should be addressed such as pose invariance, extracting similar parts and shapes over similar objects, global shape properties, and more…

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Acknowledgements

Thanks to Arik Shamir, who provided the first draft (and final draft for most) of these slides.