Modeling and processing of topologically complex 3D shapes

Denis Zorin, NYU

Peter Schröder, Caltech

Mathieu Desbrun, USC

new york university
mrl

Goals of the project

Tools for handling topologically complex objects

- exisiting tools good for complex geometry, simple topology
- new representations and algorithms are needed

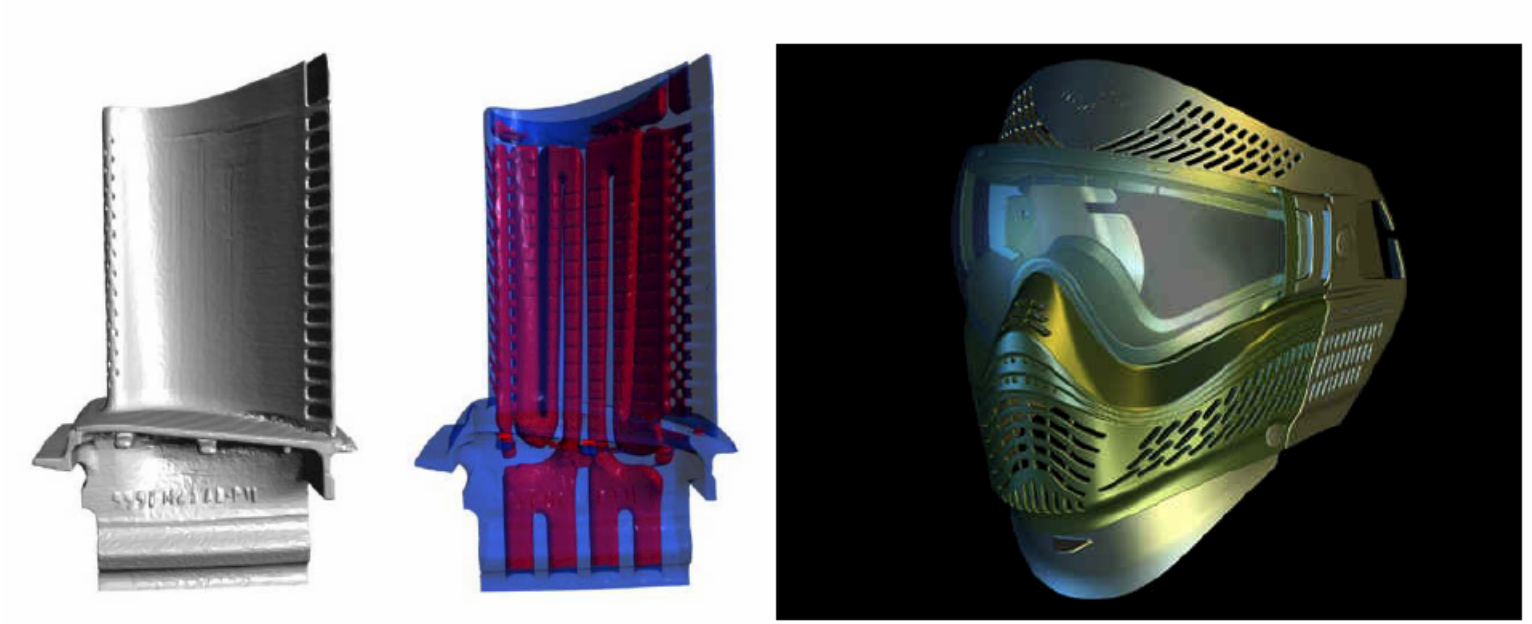
Students: Zoë Wood (Caltech), Jianbo Peng (NYU)

Collaboration: I. Guskov (U. Mich.), H. Hoppe (Microsoft)

new york university mrl

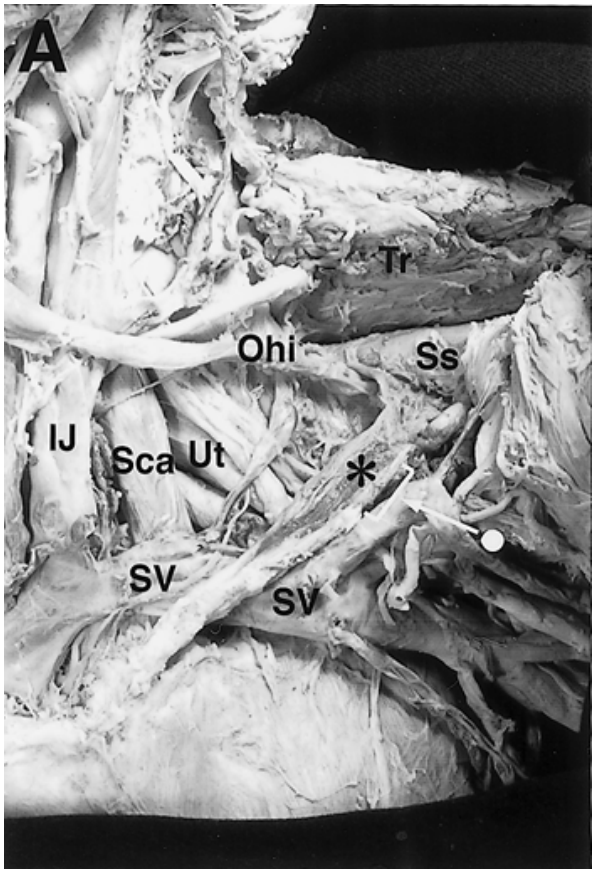
Motivation

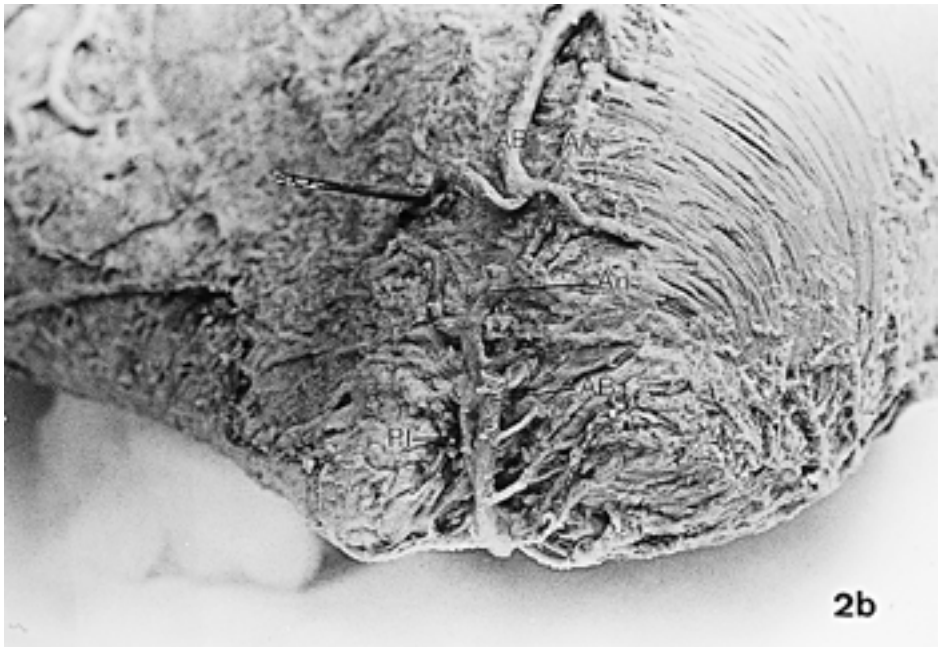
CAD applications



Motivation

Bio and medical applications





new york university mrl

Main directions

Extraction and processing

- assume existing acquisition techniques: range scanning, CT, MRI
- introduce topology control into the reconstruction process
- eliminate topological noise in already constructed models

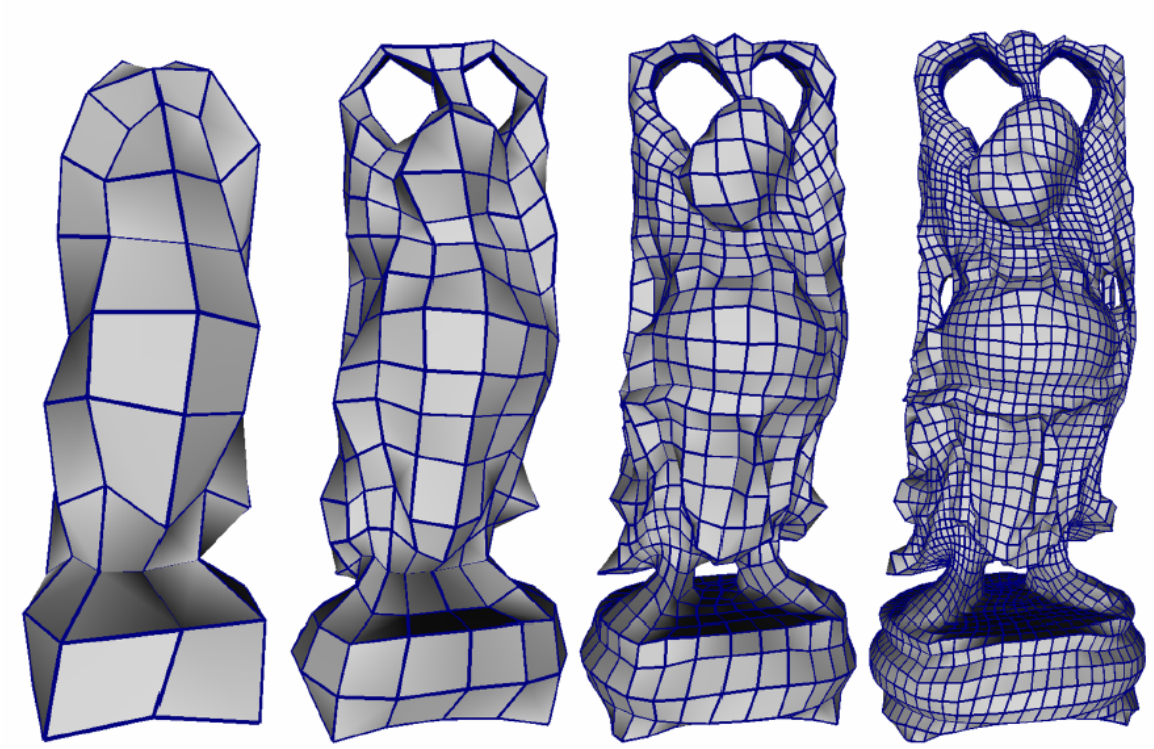
Main directions

Multiscale representations

- efficient algorithms for rendering, modification and simulation
- hierarchical
- as regular as possible
- coarse scale: relatively low genus, features close in scale to the model
- small scale: high genus, feature scale small compared to the model

Efficient representation

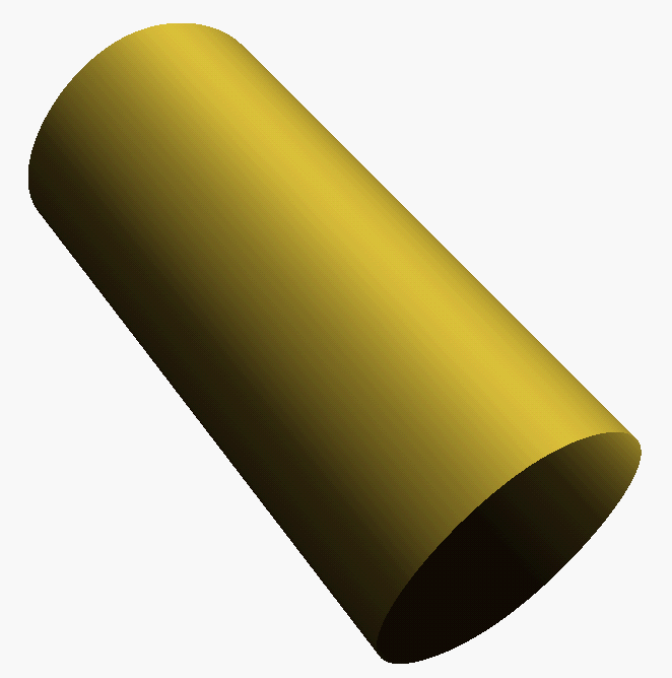
Example: coarse-scale



Caltech

Efficient representation

Example: fine-scale



NYU

Theory

Several fundamental questions

- what is feature size for different feature types
- effects on size of properties of embedding vs. intrinsic properties
- features and topological scale definition for stratified complexes

Topology processing

Different starting points

- existing mesh models
  - eliminate topological noise, i.e. small-scale features
- volume data (distance function, densities)
  - simplify level-sets indirectly
- raw data
  - figure out ways to get more information on topology

Previous work

Geometry from point sets

- Amenta et al, Bernardini and Bajaj, Edelsbrunner
- only topology guarantees: Amenta

Geometry from range data

- Hoppe et al, Turk and Levoy, Curless and Levoy

Simplification

Lack of guarantees results in artifacts

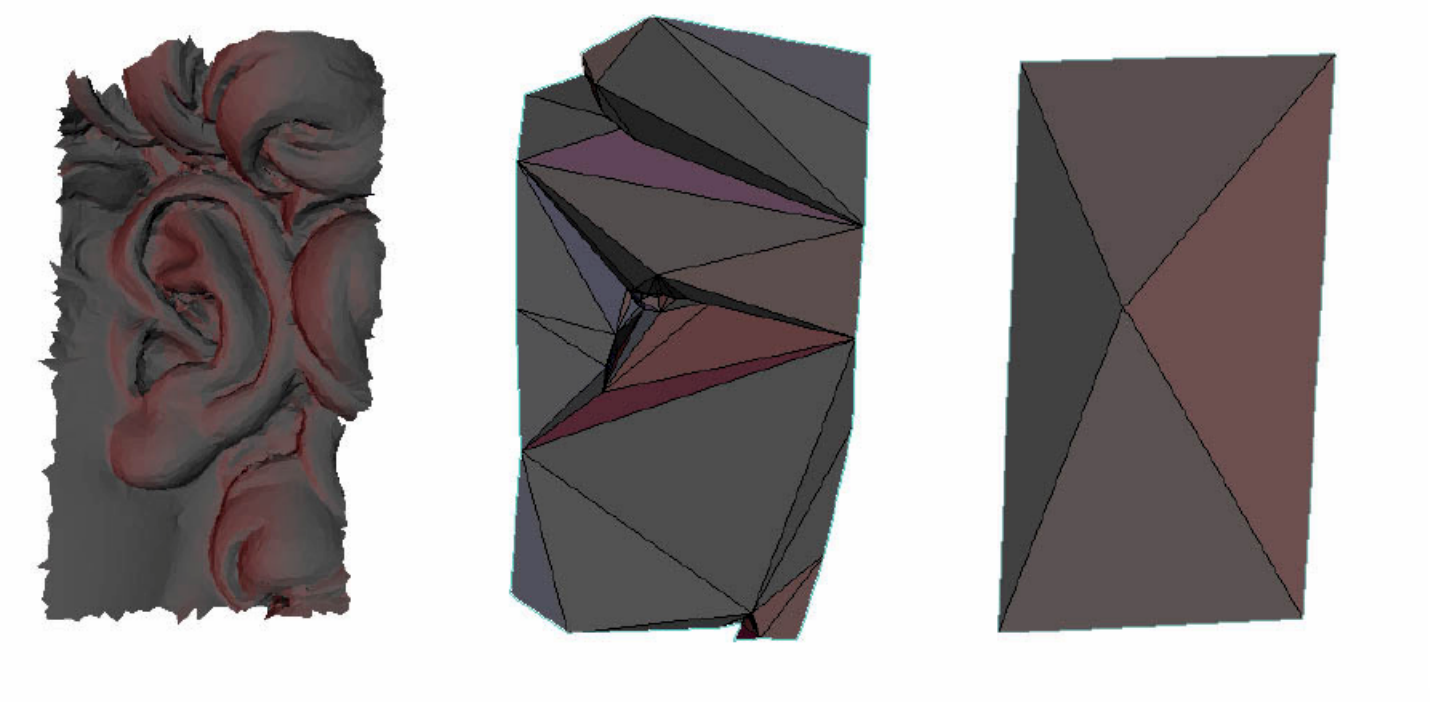
genus 104

genus 46

genus 340

Topological simplification

Mesh simplification before and after:



Previous work

Marching cubes and variations

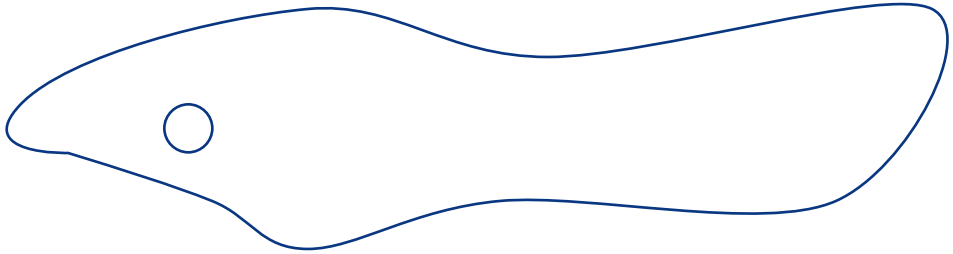
- surface constructed as isosurface
- noisy volume data result in topological noise

Snake-type methods

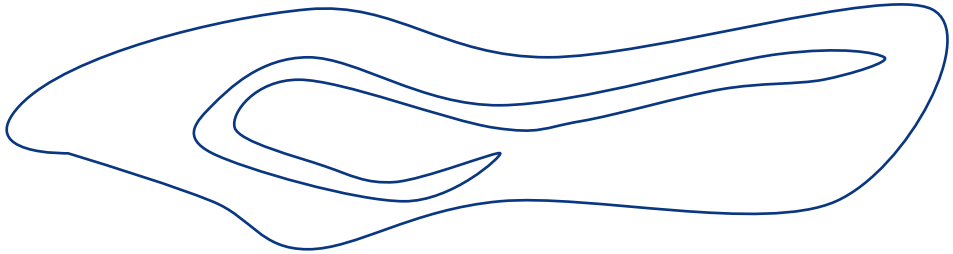
- given surface evolve to fit the data
- topological structure defined by user

Topological feature size

Localized features



Non-localized features



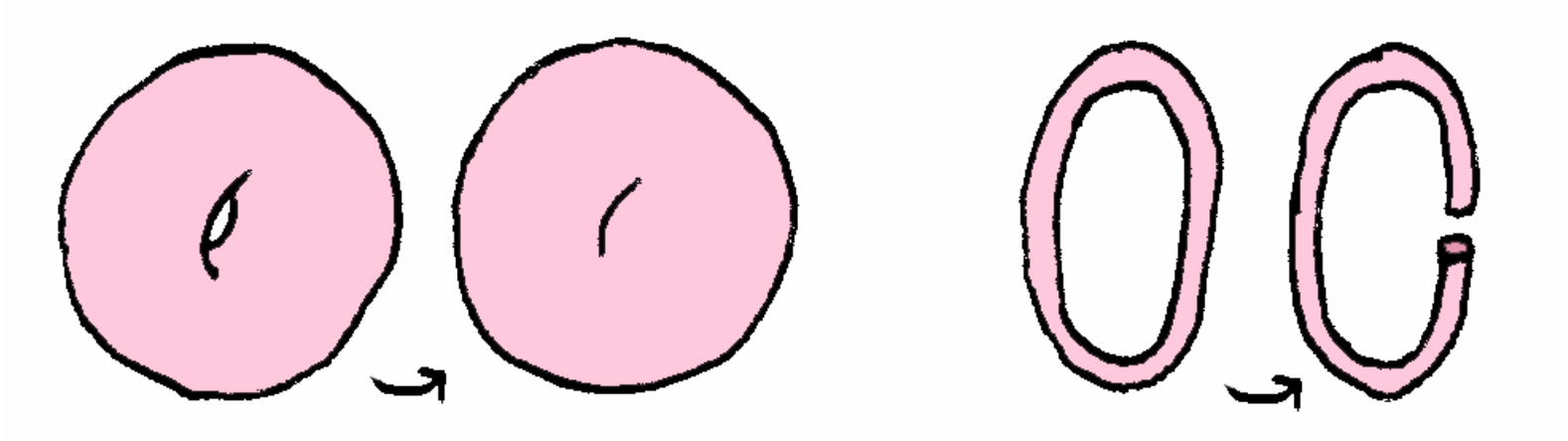
Geodesic disc measure

A geodesic disk of radius r impossible to flatten

- convenient for surfaces specified as embeddings (meshes, parametric)
- localized features
- not suitable for non-localized features

Shortest loop measure

Cut along a loop eliminates a handle



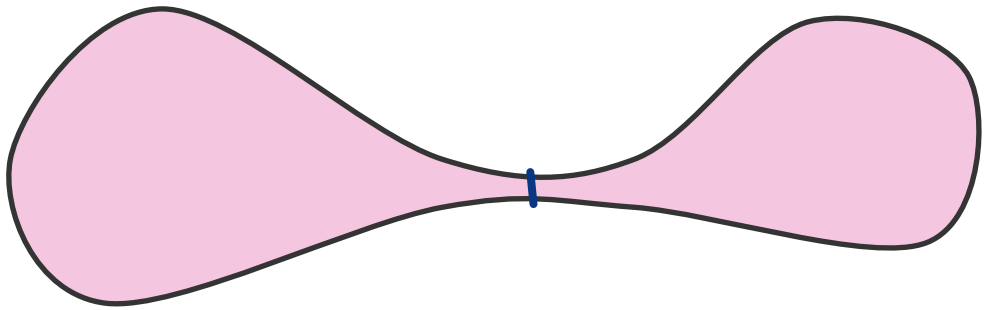
collapse

pinch

Shortest loop measure

Use shortest loop length as measure

- works for long skinny features
- may not work well for features with complicated shape



Persistence

Based on Morse theory

- introduced by Edelsbrunner et al.
- general, not entirely clear how well it measures feature scale in specific cases
- based on characterizing topological features as pairs of critical points of a Morse function

Morse functions

Reduce topology to local analysis

- Morse functions: either $M \rightarrow R$ (surface) or $R^3 \rightarrow R$ (solid)
- surface: simplest example is height
- solid: distance function
- under assumptions, surface reduces to standard form near critical points
- critical point = topological event (start a feature, end a feature)

Persistence

"Natural" measure if distance function is used as 3D Morse. BUT:

- long skinny features are likely not to be persistent

Persistence

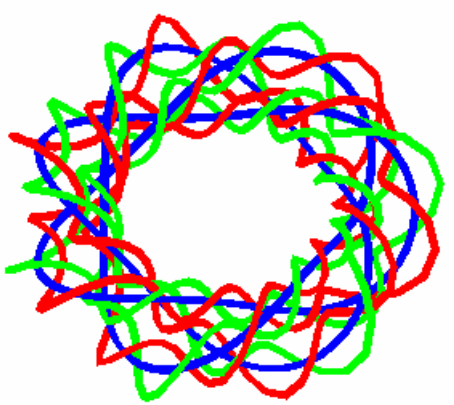
Canonical pairing of critical points defines features

- persistence = difference of Morse function values at critical points
- if Morse function = distance function, appears to be a natural measure
- geometrically continuous tunnel is not necessarily a single feature

Knots

How convoluted embedding is

- topology of a surface is intrinsic, has nothing to do with embedding
- embedding also can be simple or complex
- 3D Morse functions also characterize embedding
- algorithms may exist for tracking when embedding changes



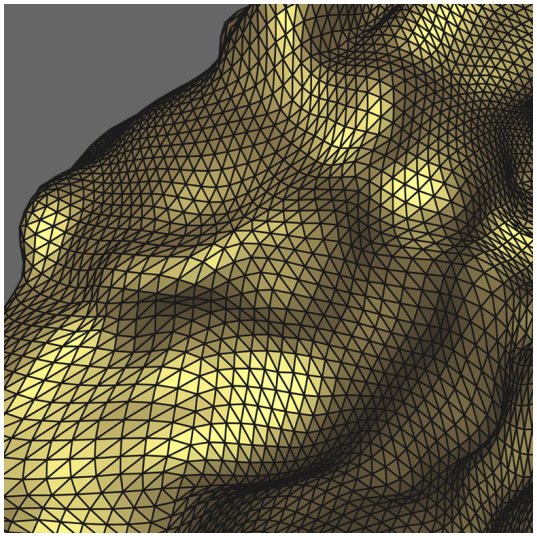
Multires representations

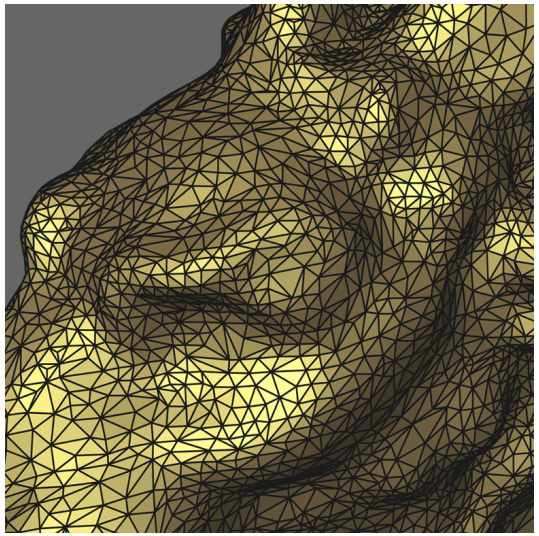
Efficiency

- rendering
  - Level of detail, fast approximate rendering
- modification
  - can manipulate object on different scales for editing and animation
- simulation
  - hierarchical algorithms (also useful for modification)

Semiregular meshes

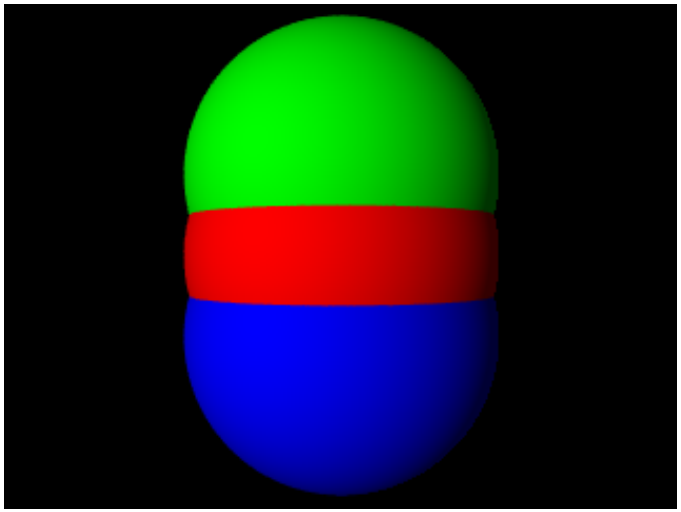
Different connectivity, identical appearance



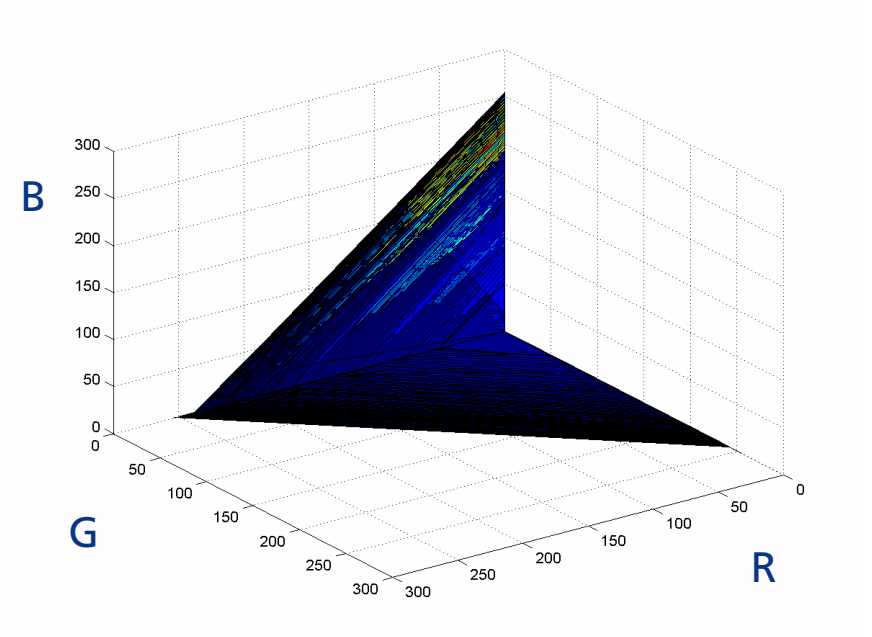


images by I. Guskov et al

Images as geometry



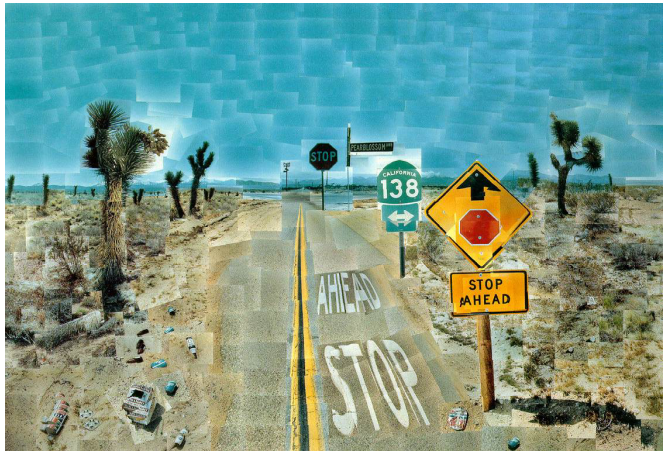
image



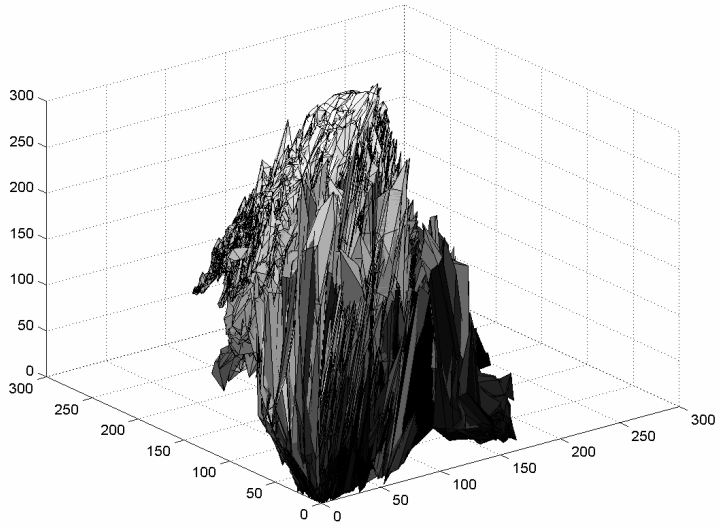
corresponding surface

new york university mrl

Images as geometry



Pearblossom highway, D. Hockney

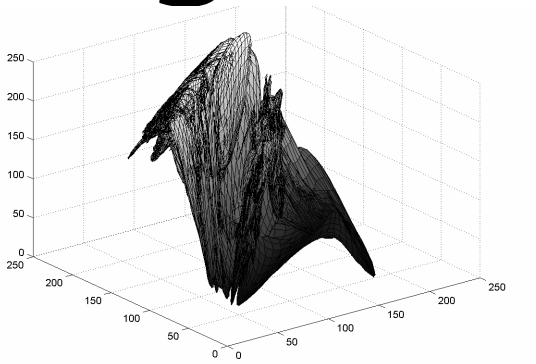


image

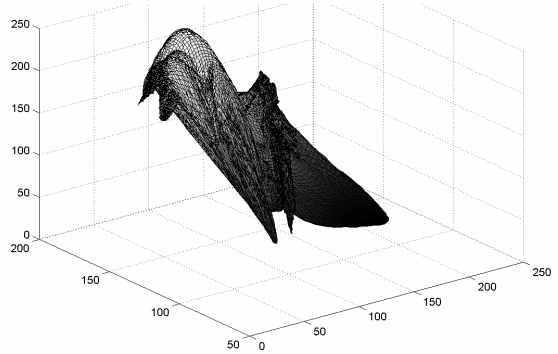
corresponding surface

For realistic images, the surface is very complex

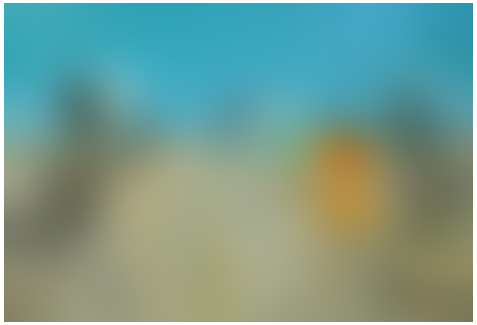
Images as geometry

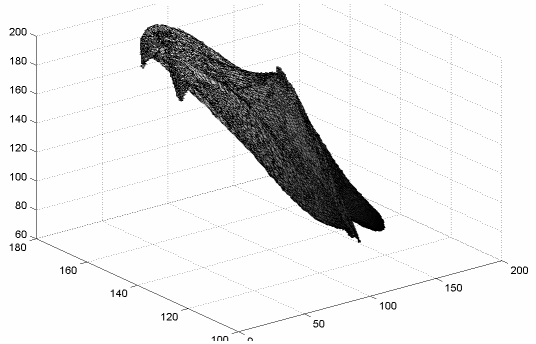


original: 320x240



32x24 pixels





10x8 pixels

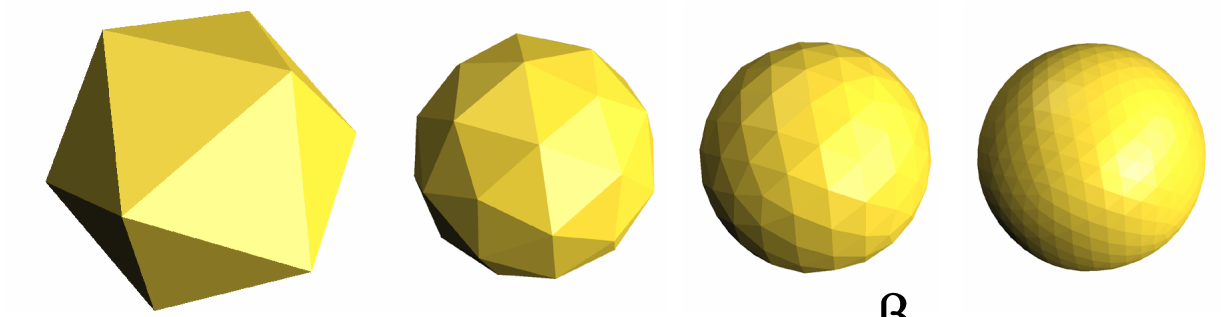
5x4 pixels

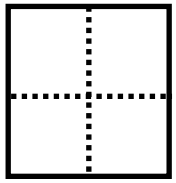
new york university mrl

Subdivision surfaces

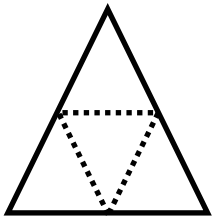
One subdivision step

- refine
- smooth

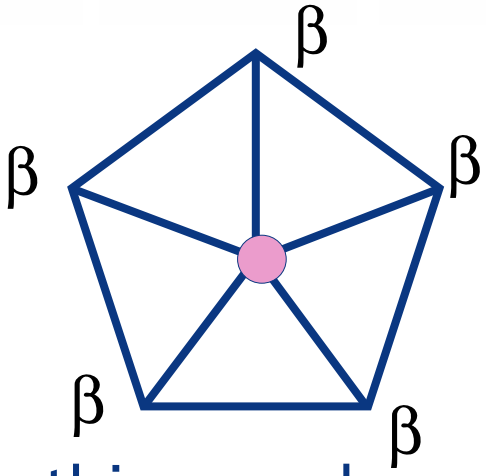




Catmull-Clark



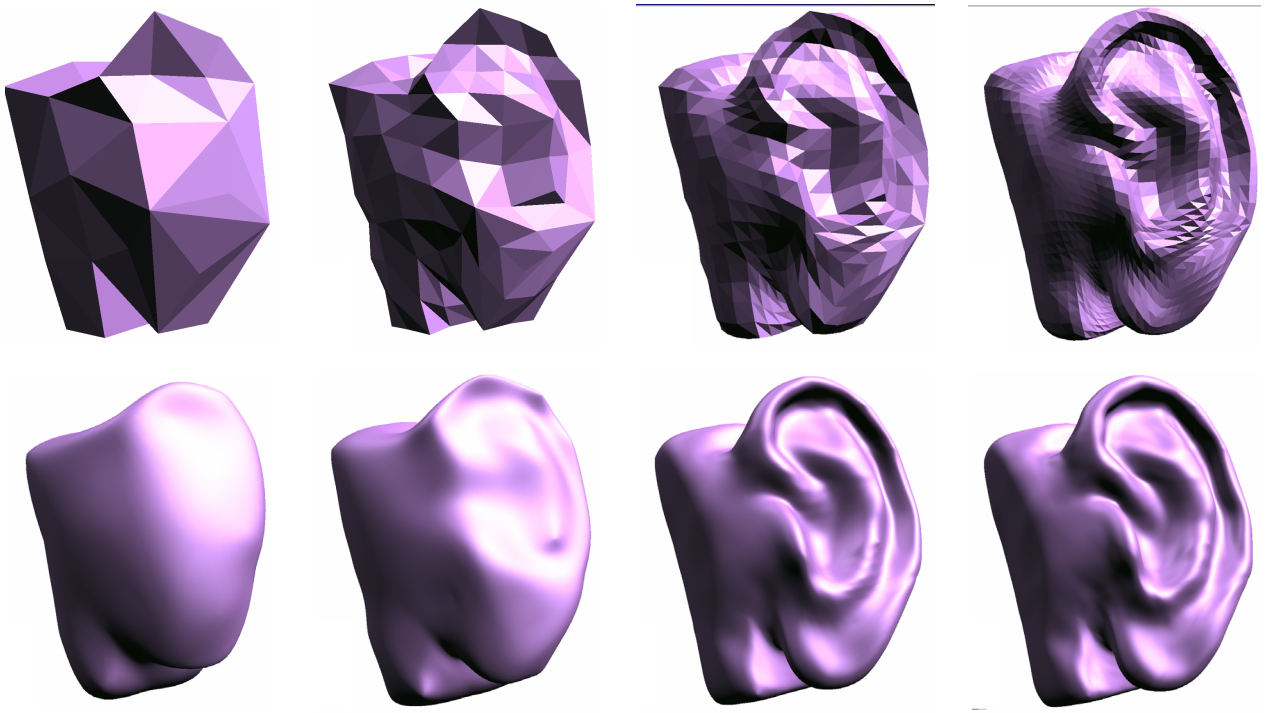
Loop

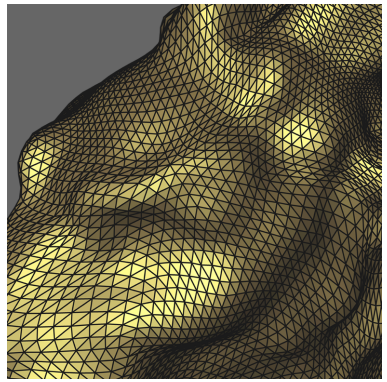


smoothing mask

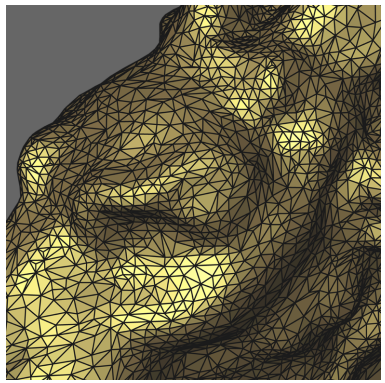
Multiresolution

Add details at any level





semiregular

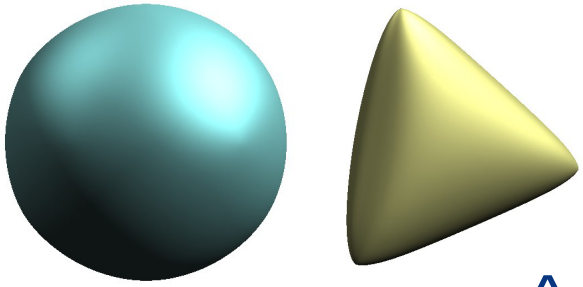


irregular

Boolean operations

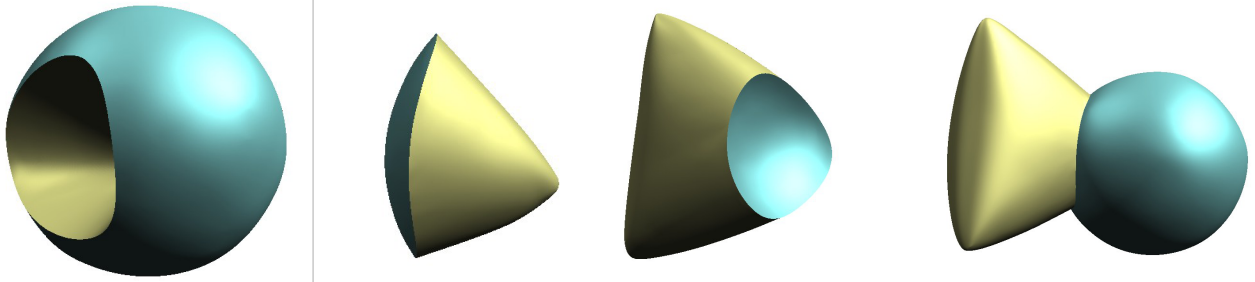
Construct objects from parts

- Combine



^

- Difference, intersection, union

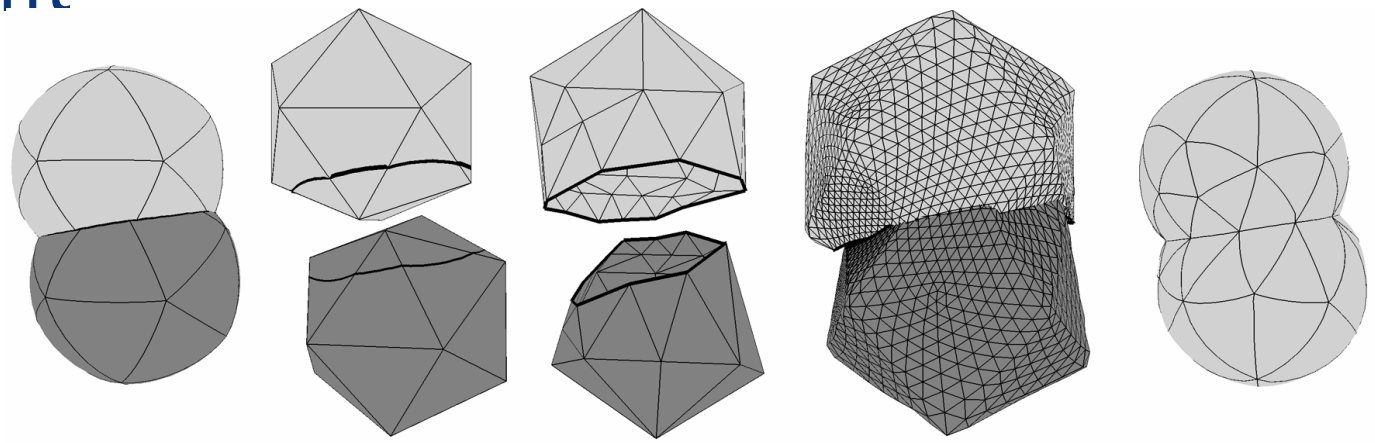


_–^ ^÷∩_ ^–_ _∪^

Boolean operations

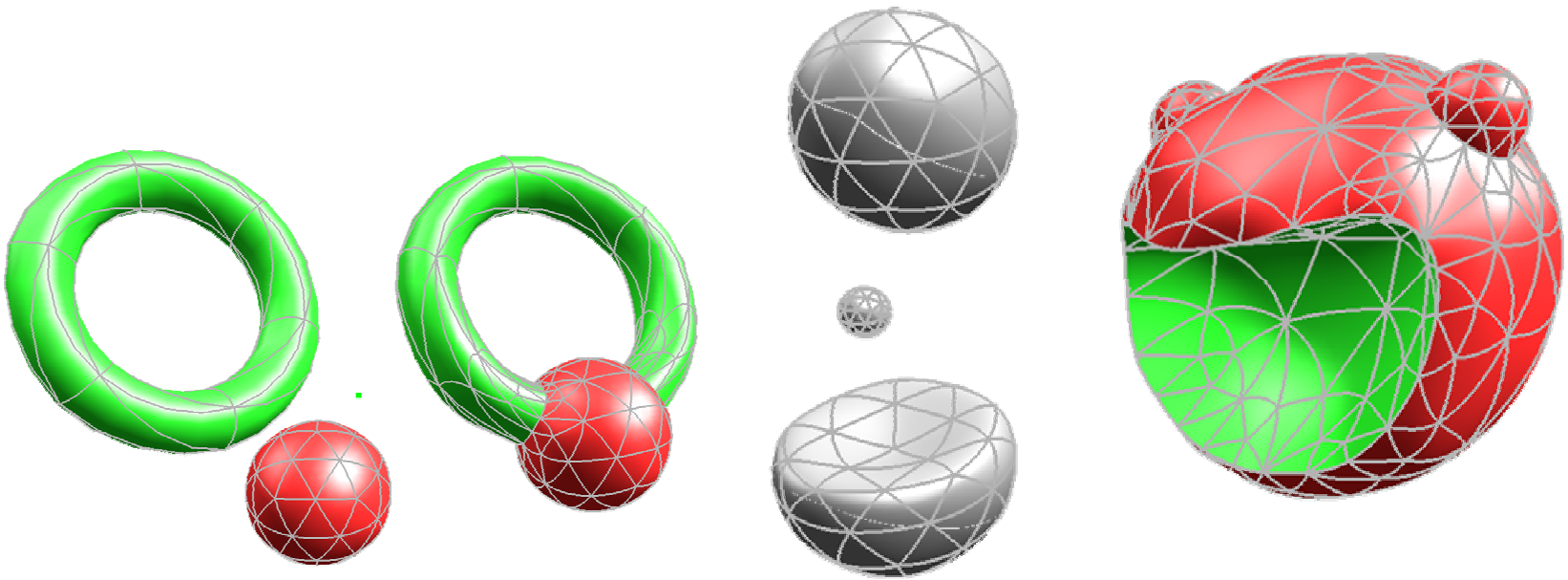
4 main steps

- approximate intersection
- cut and merge meshes
- optimize parameterization
- fit



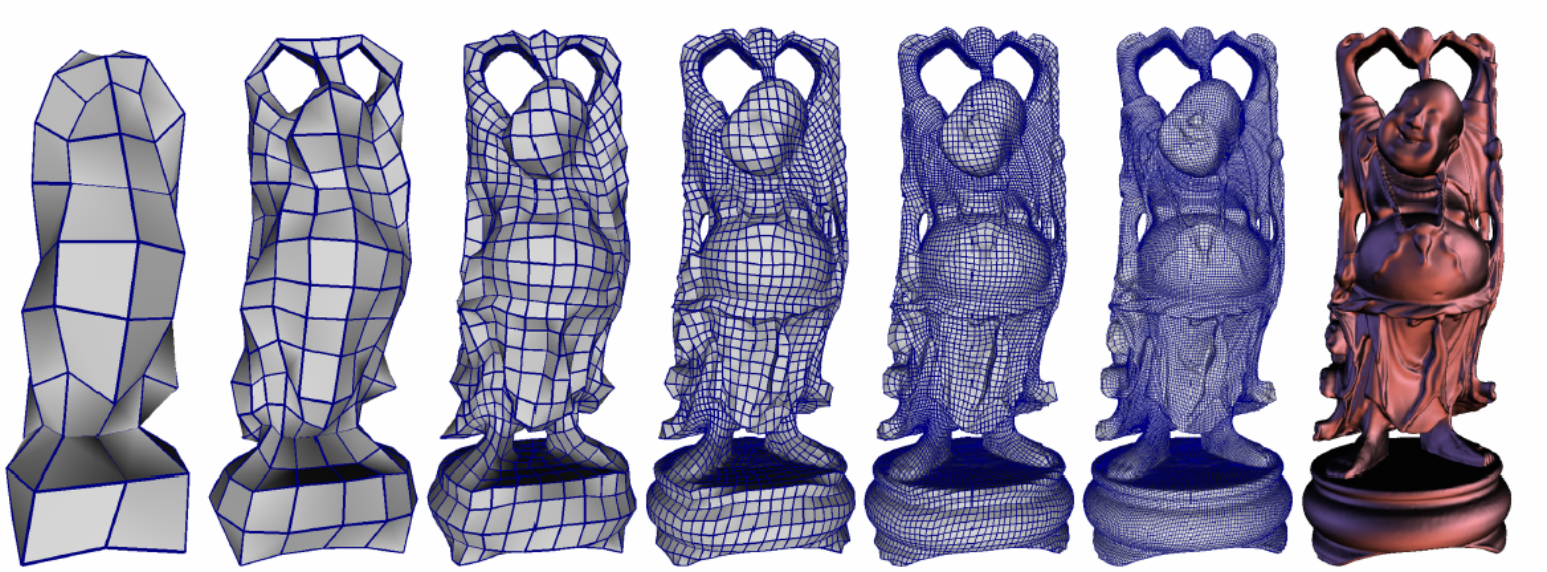
Boolean operations

Increase in the number of patches in simple cases



Hybrid meshes

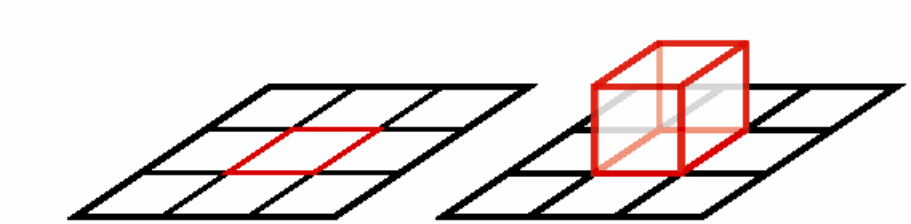
Do regular refinement, in some cases do irregular modifications



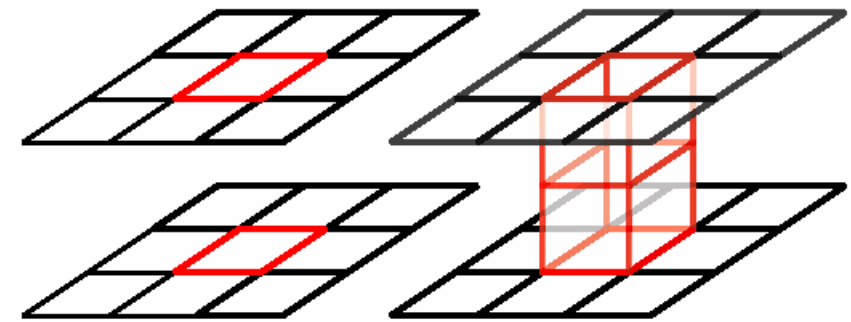
new york university mrl

Hybrid meshes

Typical operations



add cube

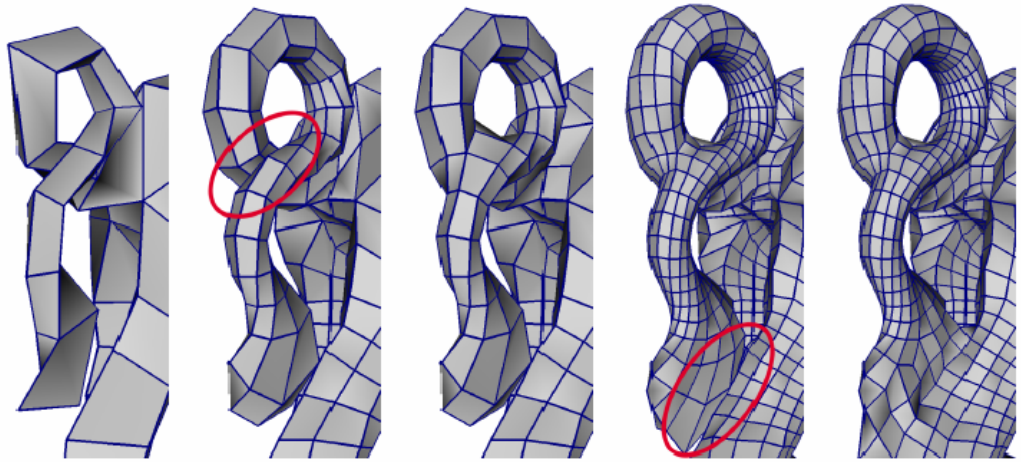


connect

Hybrid meshes

Problems

- a lot of flexibility, but hard to build



- current method is not automatic
- taking advantage of regularity is difficult

Fine-scale topology

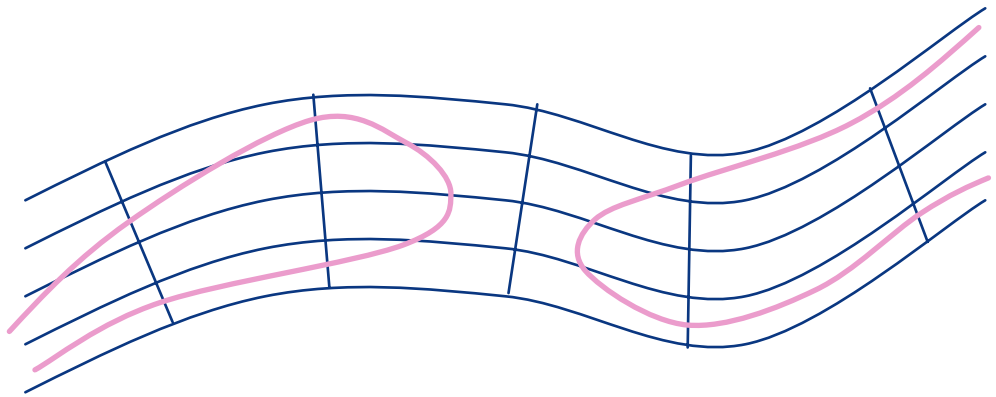
Small scale compared to model scale

- number of features can be large
- hybrid mesh degenerates into irregular hierarchy
- expensive analysis is required to build a mesh-based rep.
- alternative: combine implicit and parametric

Topological texture

3D scalar or vector texture associated with a surface

- define actual surface as isosurface inside a layer



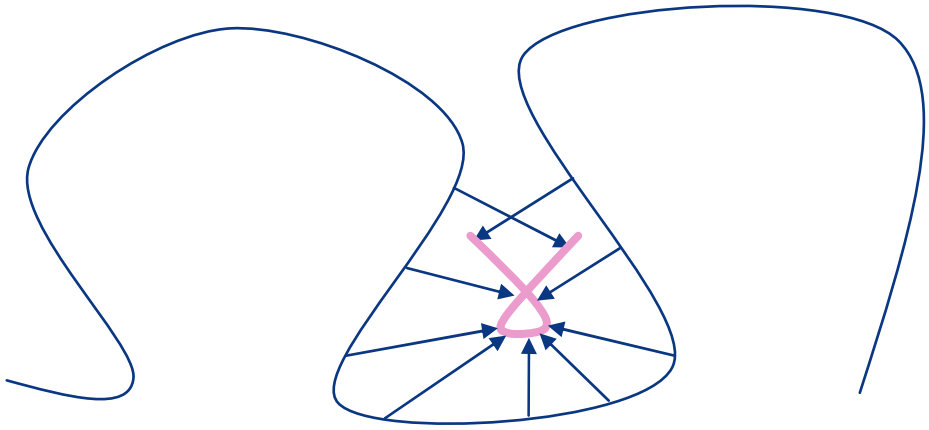
Previous work

Several similar techniques

- interactive fur (Leguel et al)
- hypertexture (Perlin)
- slabs for material weathering
- volume textures (F. Neyret)

Construction

Given a surface construct a shell of thickness as close as possible to prescribed



Construction

Additional constraints

- keep the mesh structure the same for all layers
- fast enough to update interactively
- existing approaches do not help
  - Varshney (“rolling sphere”)
  - level sets (Sethian’s mesh generation)

Multiresolution

Filter the texture to create topological mipmaps

- need “smart” filtering, simple low pass is not good enough
- idea (Edelsbrunner) try to filter locally

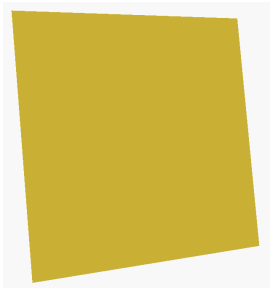
keeping track of the critical point annihilation

Rendering

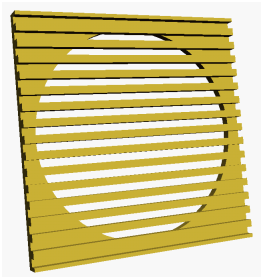
Key to interactive applications

- recent work shows that coarse isosurfaces can be extracted quickly
- why not do this in hardware?
- use texture tricks
- approximating visibility is a problem

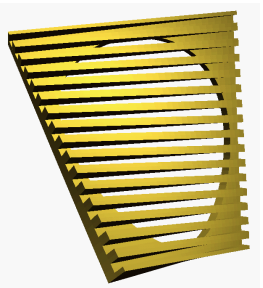
Examples



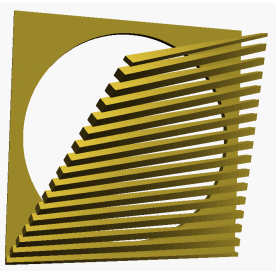
base

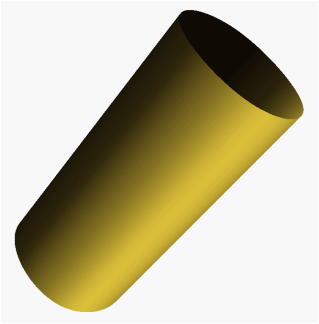


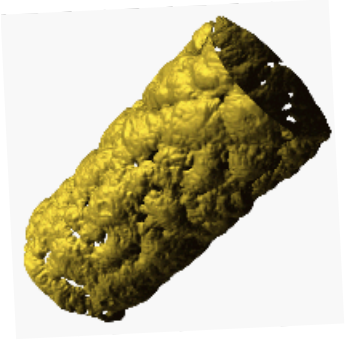
small-scale topolgy added



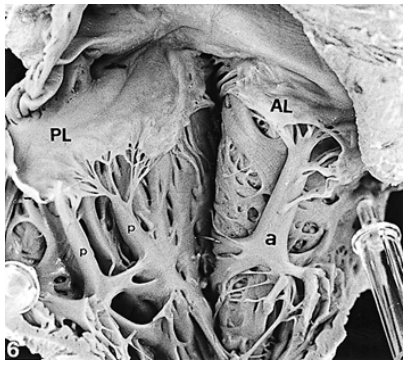
base modified







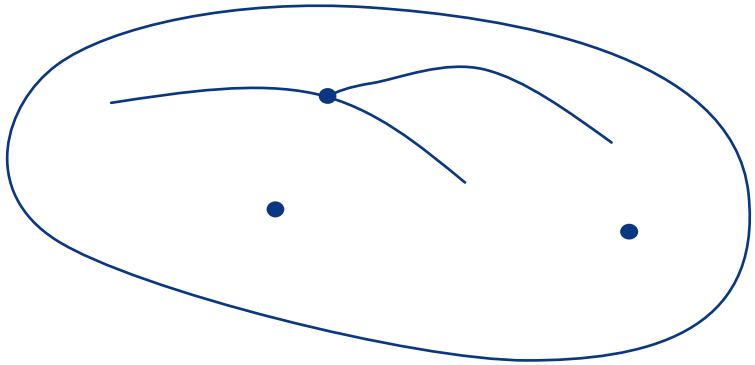
goal:



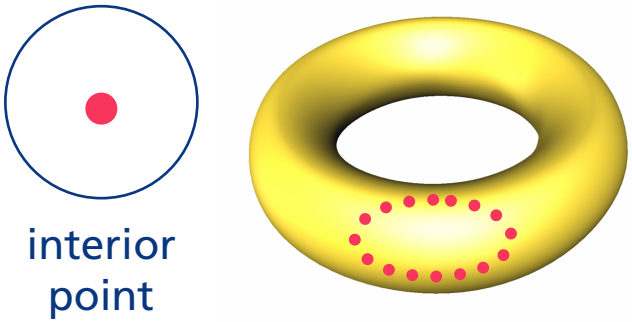
Stratified surfaces

Surfaces with one- and zero-dim complexes embedded

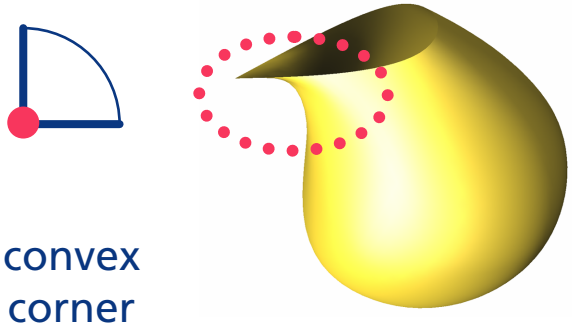
- what is the right way to characterize topology
- measures of feature size
- simplification techniques



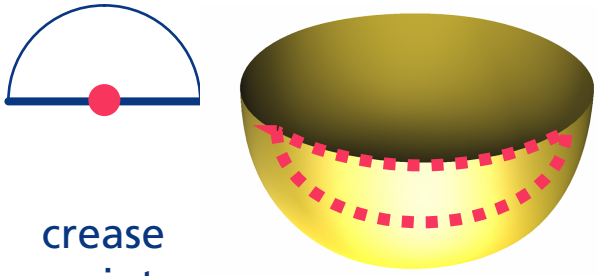
Manifolds with features



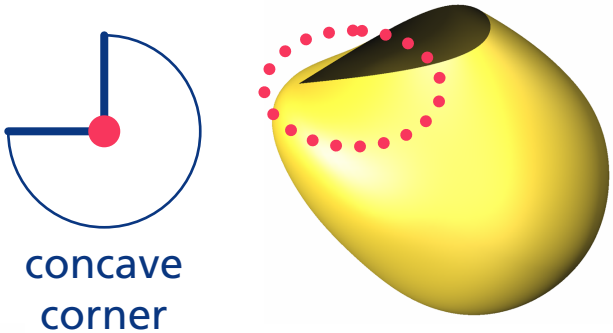
interior point



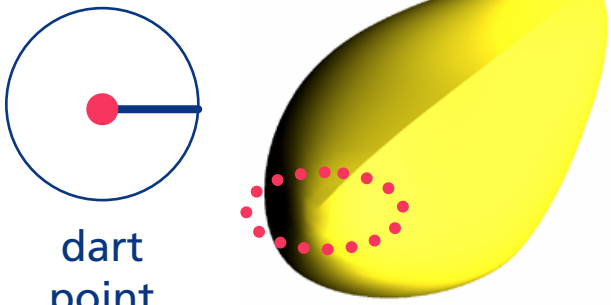
convex corner



crease point



concave corner

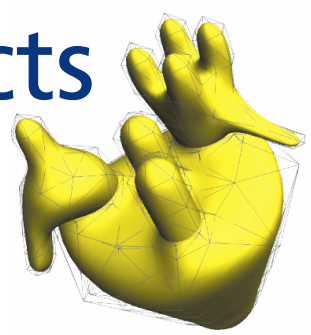


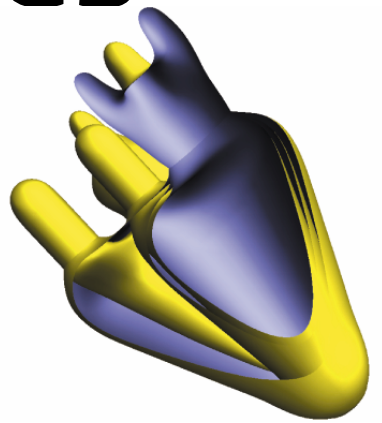
dart point

Nonmanifold surfaces

Models of real objects

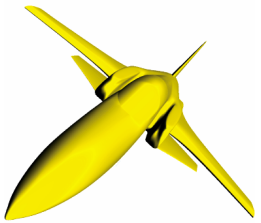
- biological
- mechanical

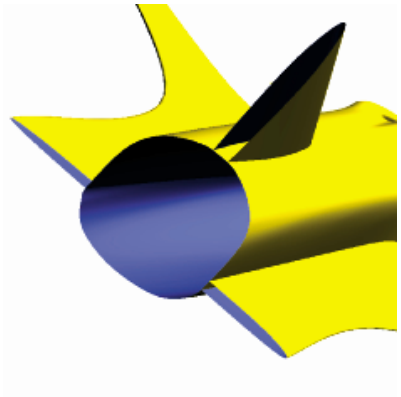




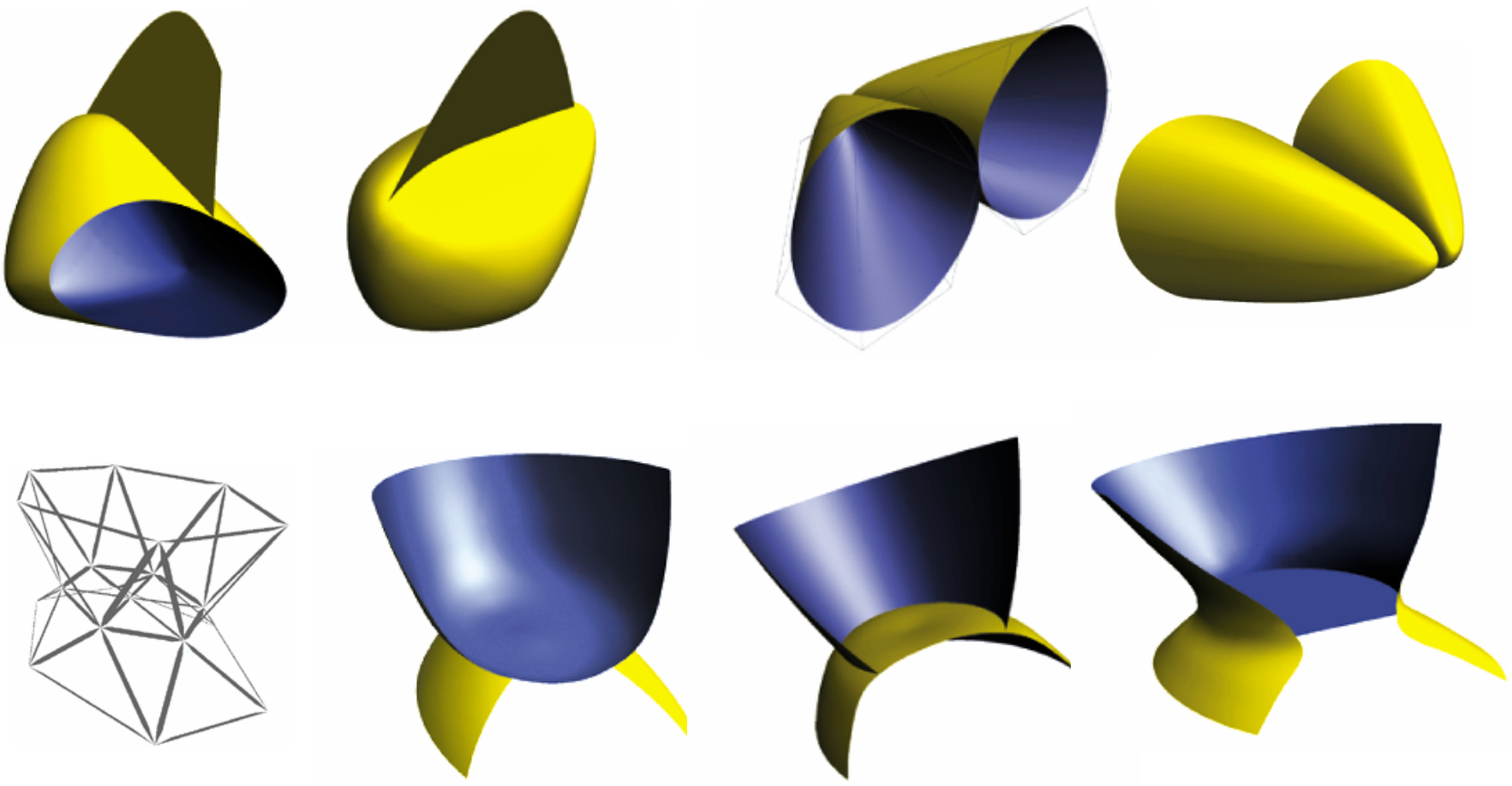
Physically based simulation

- fluid dynamics
- elasticity





Nonmanifolds

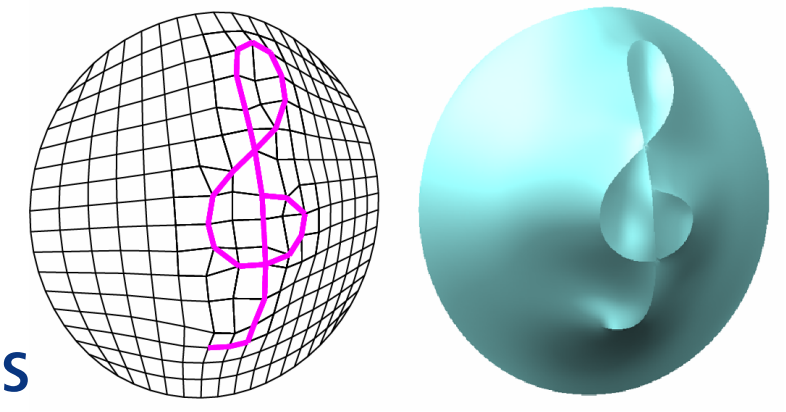


Multires representation

Semi-regular mesh aligned with sharp features

Problems

- restricted topology
- topological changes



Summary

Main directions

- topology extraction and processing
  - simplification of mesh models
  - simplification of volume data
  - enhanced distance functions
- multiscale topology representations
  - coarse-scale: hybrid meshes
  - fine-scale: topological texture
- theoretical foundations
  - scale measures, stratified surfaces