CSE 621: Physics-based Modeling, Simulation, and Computing

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The Main Theme of CSE621

- Physics-based modeling, dynamic simulation, and scientific computing for computer science, information science, and engineering
- Their widespread applications in the entire spectrum of visual computing discipline

- Our course objective is to demonstrate that physics-based modeling and computing is a fundamental and enabling computational framework that can facilitate visual information processing in general.

Our Approach is Unique!

- The Physics-based approach is unique, natural, and integrative!
- We are driven by and are focusing on various visual computing fields such as graphics (image synthesis), visualization, computer-aided geometric design, biomedical image processing, vision (image analysis), human-computer interaction, and virtual environments
- Our research topics are centered on physics-based modeling, simulation, and scientific computing methodology and associated computational (computer science and engineering) methods for tackling theoretical and practical problems in widespread areas of visual computing

Key Theory, Algorithms, and Techniques

- The rich theory of mathematical physics
- Geometric and solid modeling based on PDEs and energy optimization
- Deformation-centered geometric design techniques
- Deformable models for shape estimation and reverse engineering
- Variational analysis, optimization methods, level-set methods
- Numerical techniques with finite-difference and finite-element algorithms
- Differential equations for initial-value and boundary-value problems
- Force-driven haptic interaction
- Dynamic sculpting system
- Animation of flexible objects and there interactions
- Simulation of physical worlds and natural phenomena
- Energy, PDE, and optimization methods for graphics applications (including texture synthesis, texture mapping, surface parameterization and mapping, shape comparison, object retrieval, etc.)
- Novel theory for new types of splines
- Many many more topics beyond the above mentioned list

Motivation

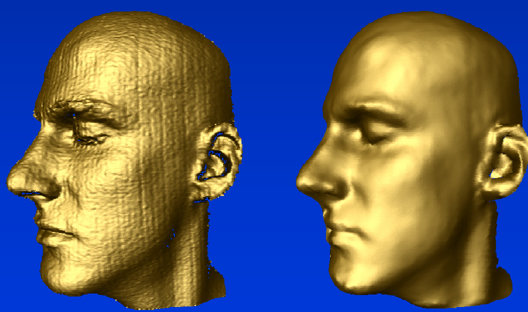
- Natural phenomena are characterized by physical laws
- Deformation (as well as time-varying events) is ubiquitous ranging from macro-scale to nano-scale
- Graphics and visual computing aim to model and simulate physical worlds including objects, phenomena, behaviors, etc.
- Every components of graphics (including modeling, rendering, animation, and interactive techniques) and the entire visual computing field is relevant to physical laws
- Many geometric problems can be formulated by and transformed to physical problems (PDEs, energy optimization)
- Geometric design requirements are naturally represented by using optimization techniques
- Graphical display mimics what is happening in real-world (projection, photorealistic appearance, etc. are based on physics, especially, optics)
- For animation and interactive techniques, physical laws are also utmost significant
- Physics-based modeling gives rise to a large variety of applications in graphics, geometric design, dynamic simulation, visualization, medical image processing, etc.
- Physics-based modeling has been a very powerful tool for us to tackle many real problems in many real applications

Application Areas

- Geometric representation by means of physics and energy
- Interactive and dynamic editing for geometric design
- Digital geometric processing (meshes, points), denoising, smoothing, fairing, hole-filling, etc.
- Virtual surgery simulation using finite element methods for surgery training
- Physics-based haptic interface
- Animation such as morphing, smoking, firing, etc.
- You will see more applications later…

Geometric Processing

- **A**pplying signal and image processing algorithms to geometry



De-noising

Enhancement

Shape Smoothing/Denoising

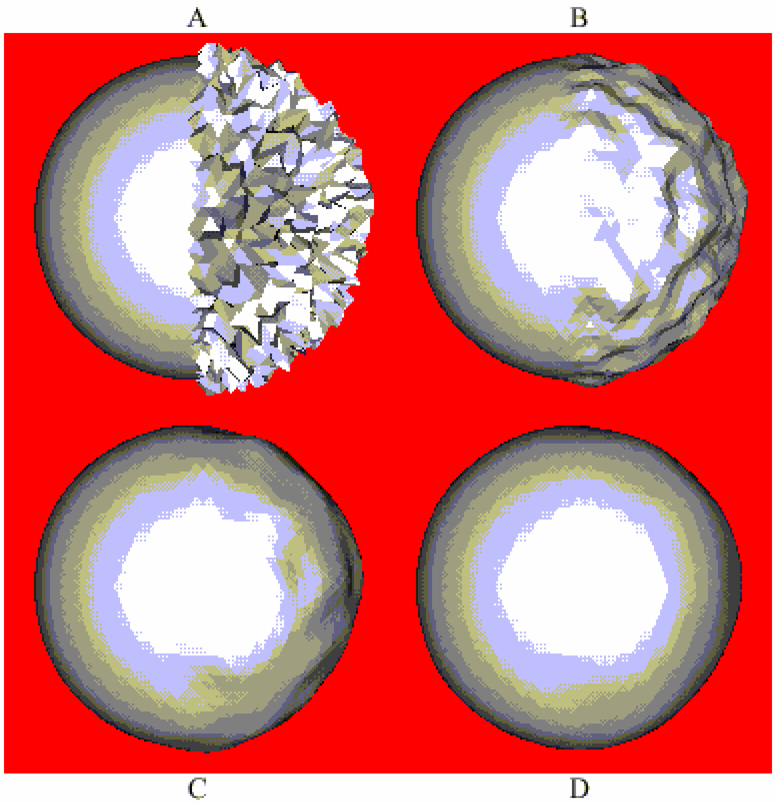


Figure 3: (A) Sphere partially corrupted by normal noise. (B) Sphere (A) after 10 non-shrinking smoothing steps. (C) Sphere (A) after 50 non-shrinking smoothing steps. (D) Sphere (A) after 200 non-shrinking smoothing steps. Surfaces are flat-shaded to enhance the faceting effect.

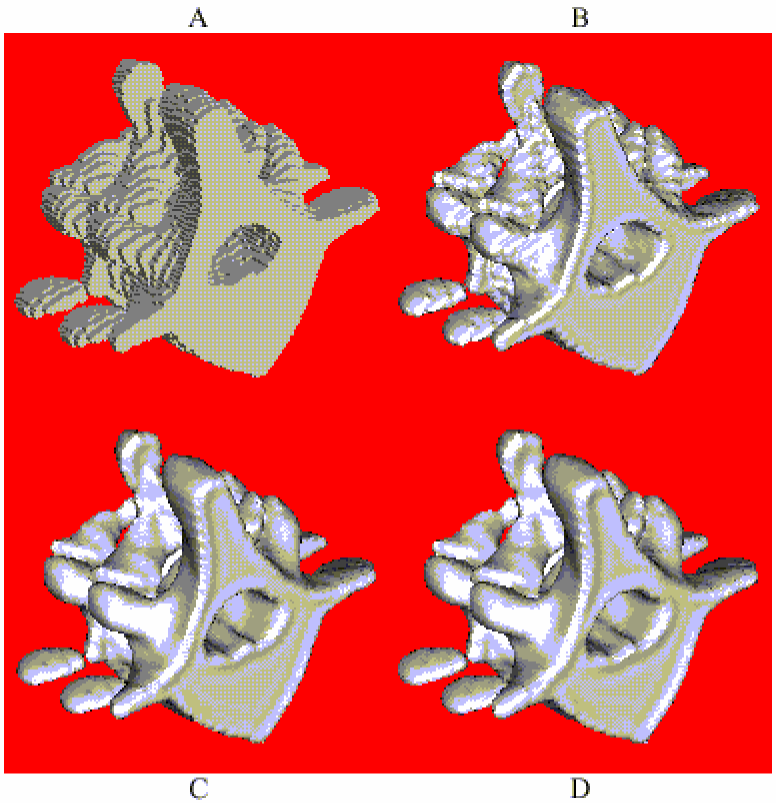


Figure 4: (A) Boundary surface of voxels from a CT scan. (B) Surface (A) after 10 non-shrinking smoothing steps. (C) Surface (A) after 50 non-shrinking smoothing steps. (D) Surface (A) after 100 non-shrinking smoothing steps. $k_{PB} = 0.1$ and $\lambda = 0.6307$ in (B), (C), and (D). Surfaces are flat-shaded to enhance the faceting effect.

Another Example on Smoothing

- Smoothing with volumetric constraints

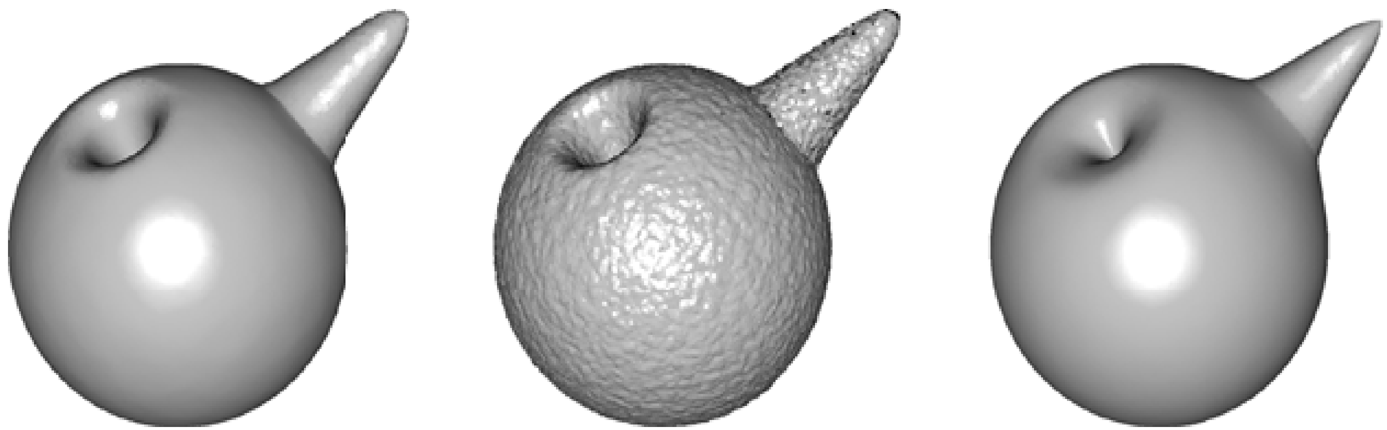
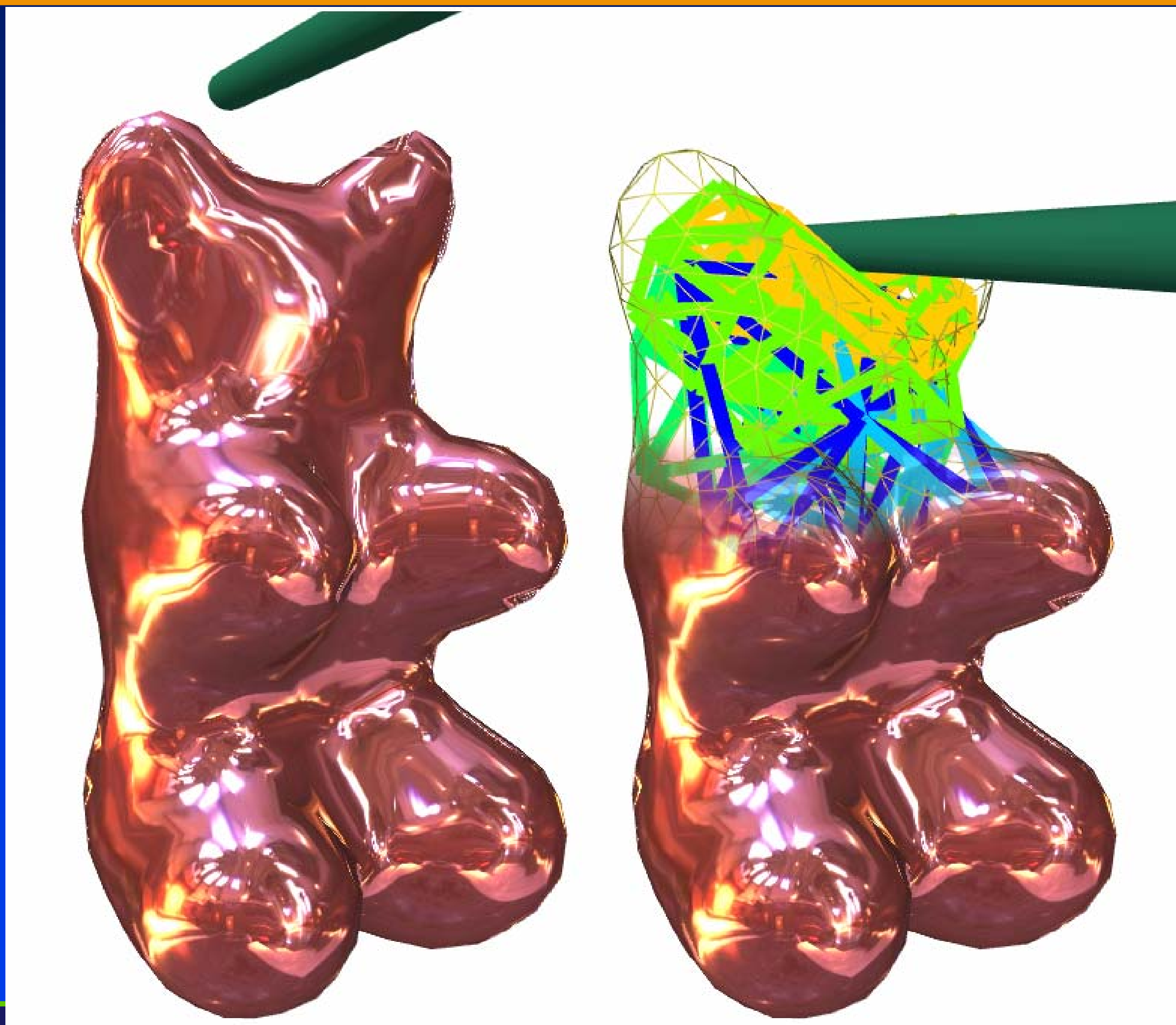
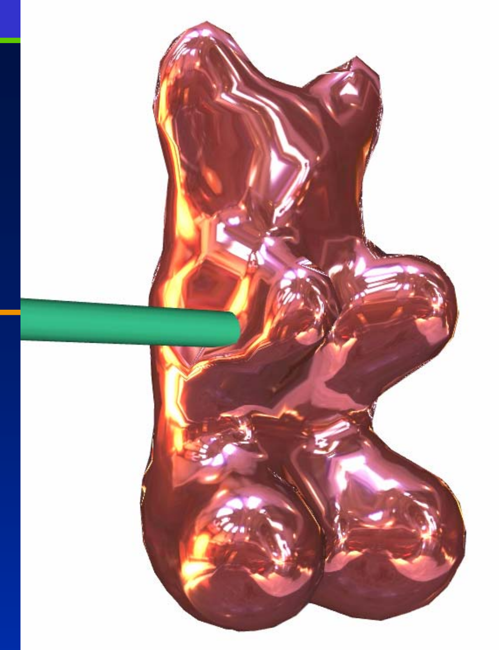
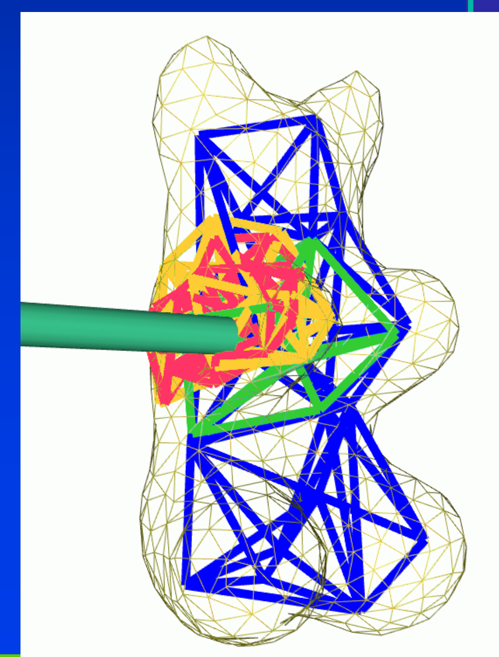


Figure 1: Local vs. global volume preservation: The middle image shows the original noisy surface. On the left 100 smoothing iterations with the local strategy, on the right 100 iterations with global rescaling.

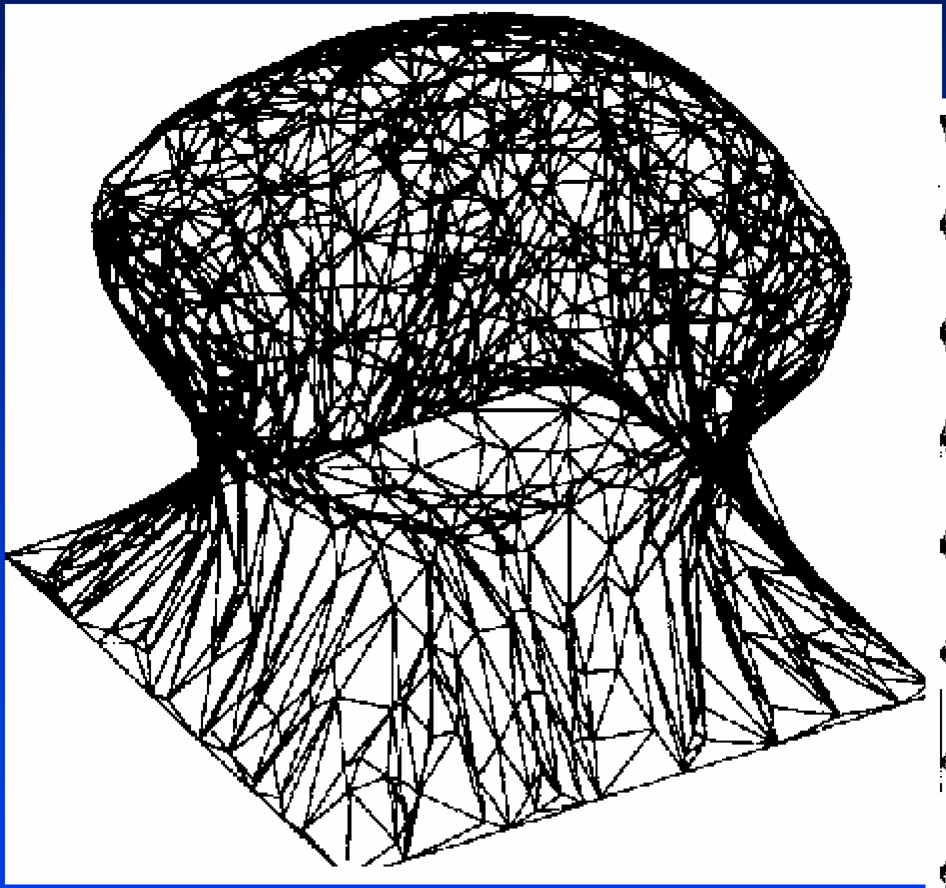
Real-time Simulation

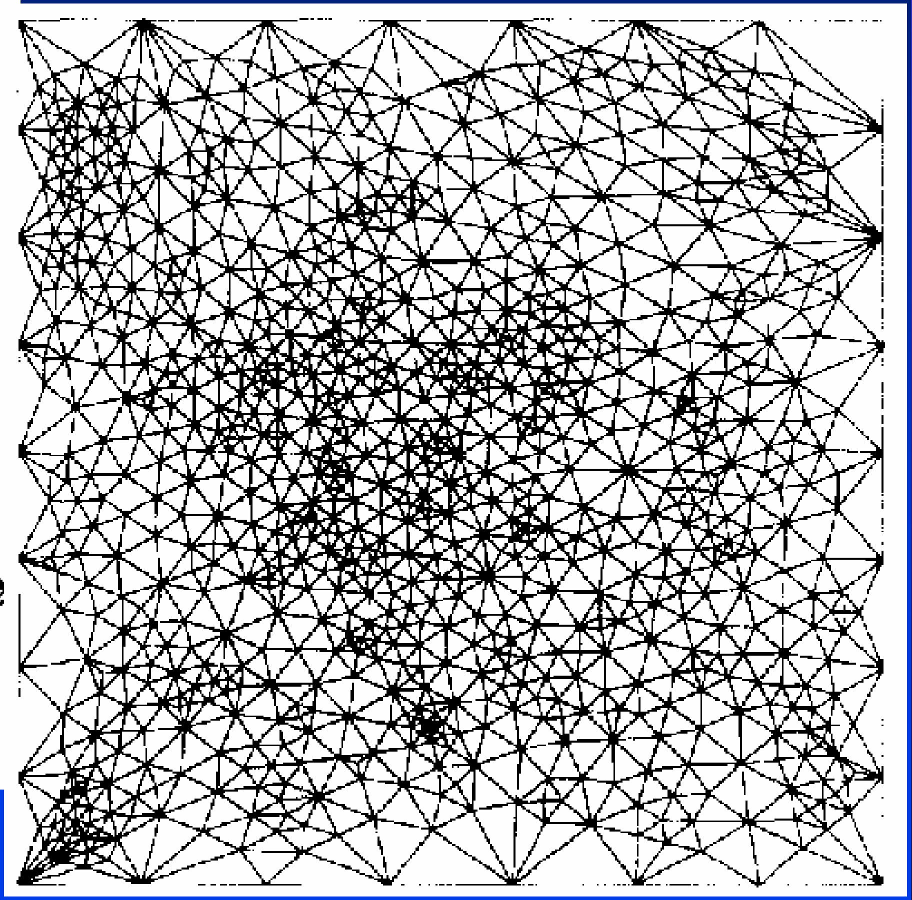




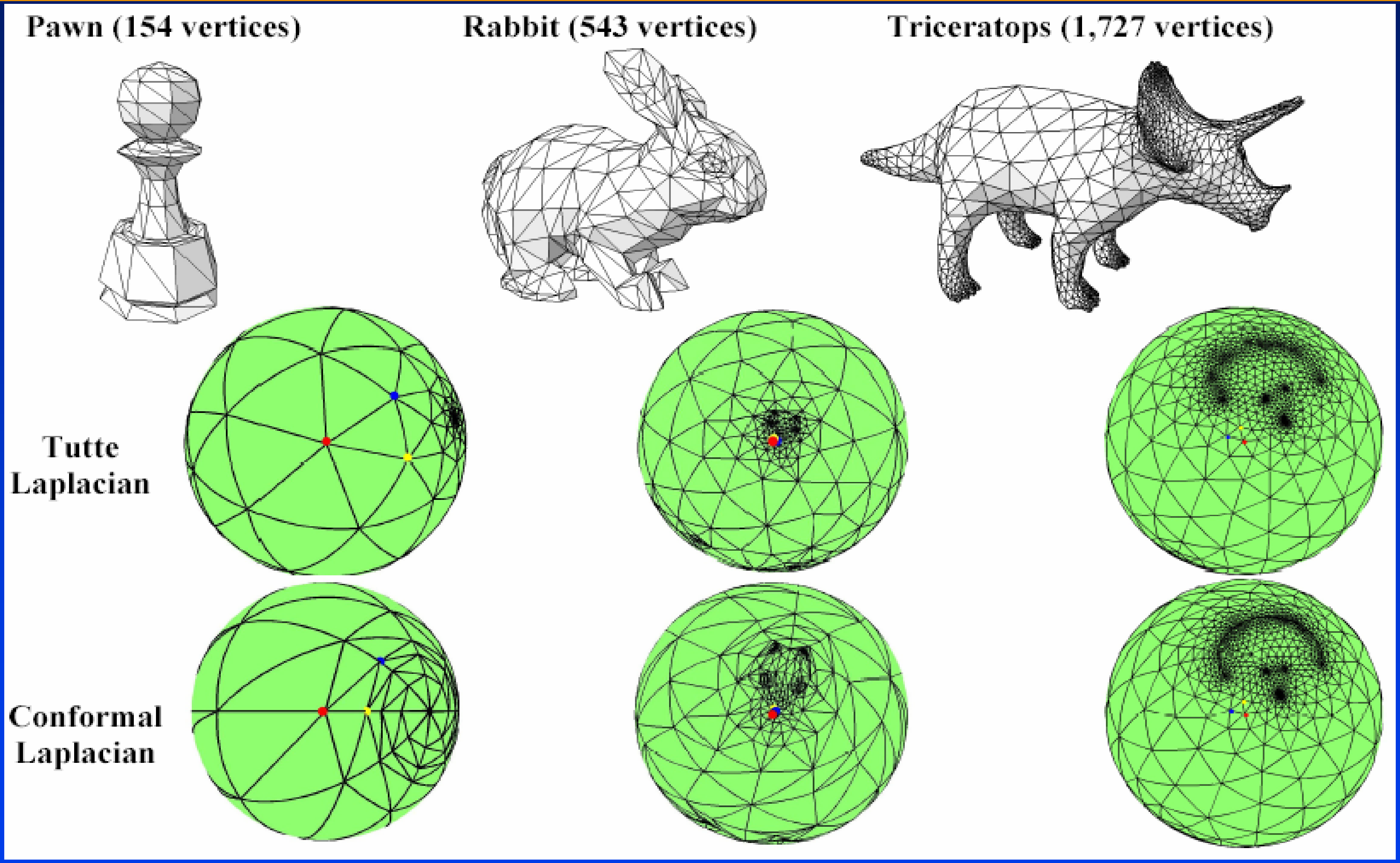


Parameterization based on PDEs

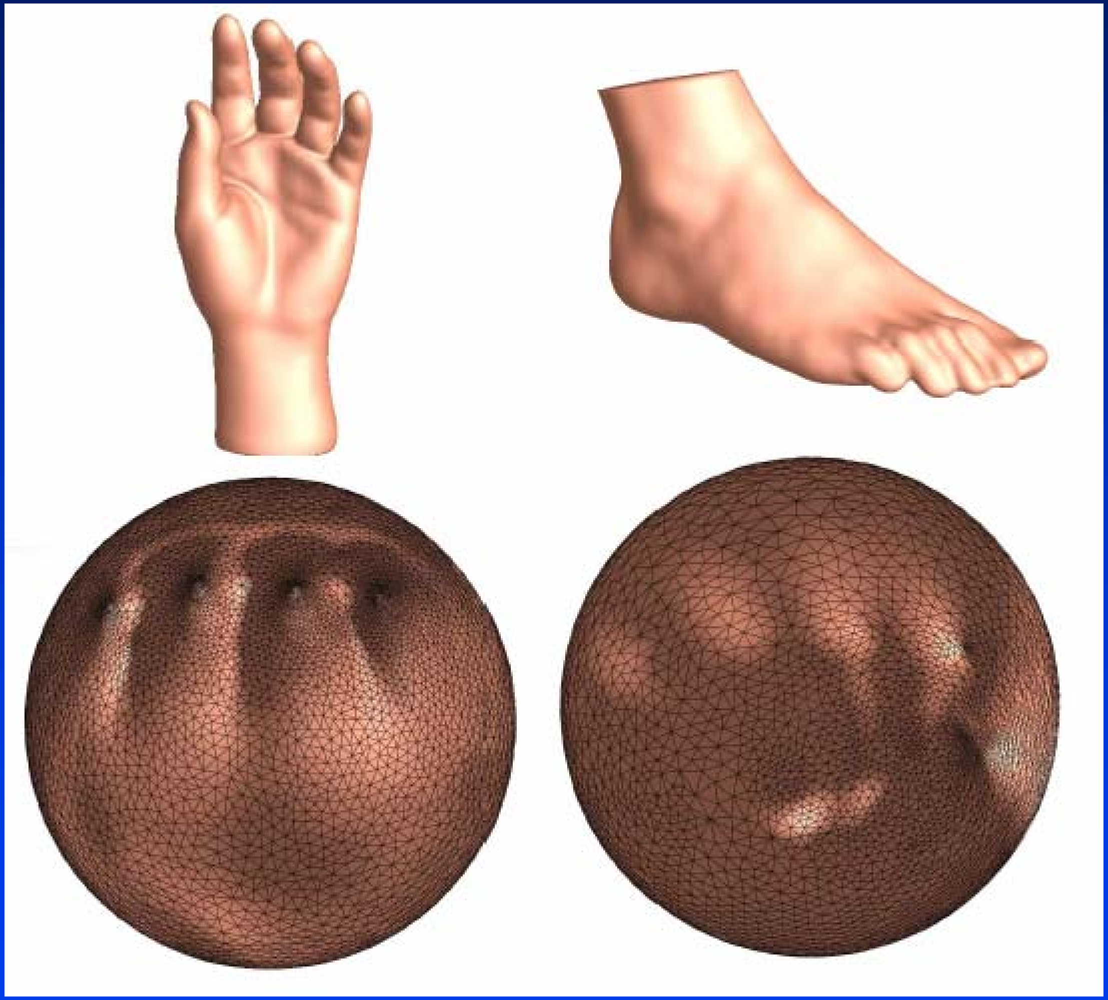




Spherical Parameterization

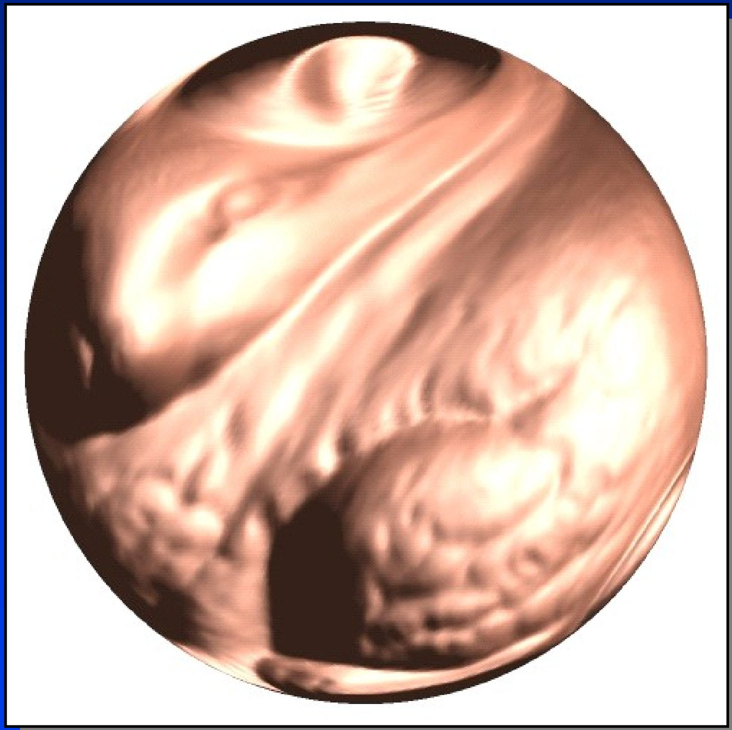


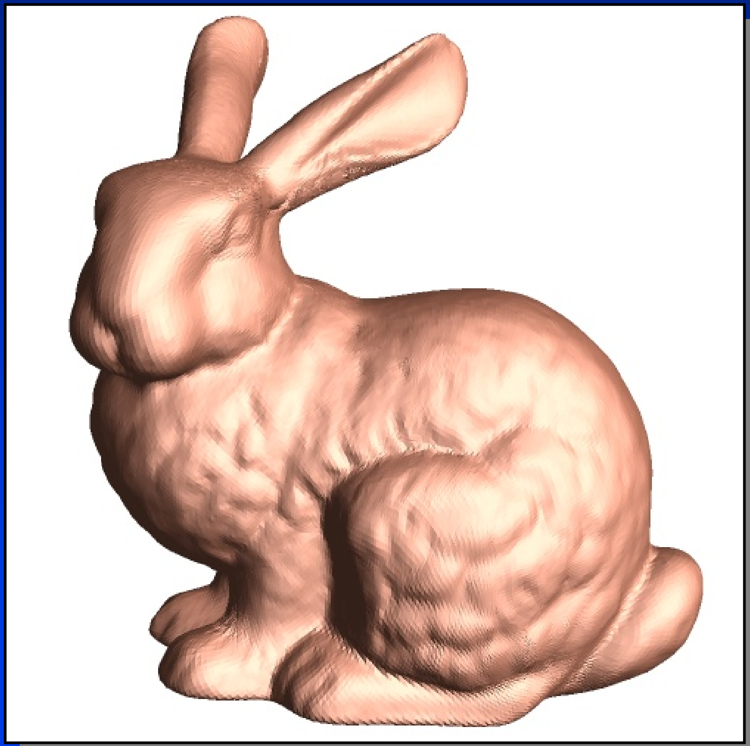
More Parameterization Examples



Spherical parameterization (closed genus-0 surface)

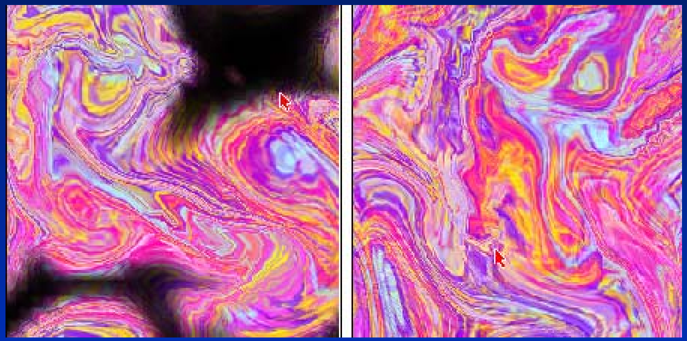
- For closed genus-0 surface, the natural domain is the sphere

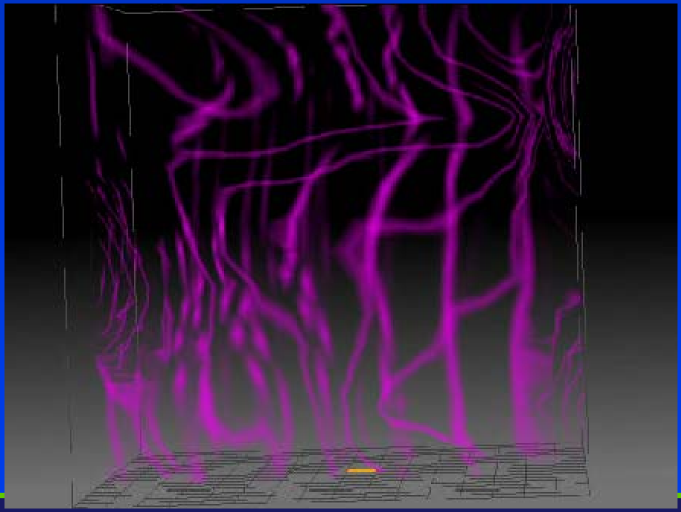




(courtesy of Hugues Hoppe)

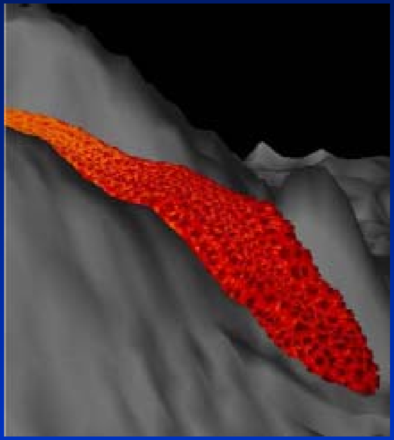
Flow Simulation (Navier-Stokes Equation)



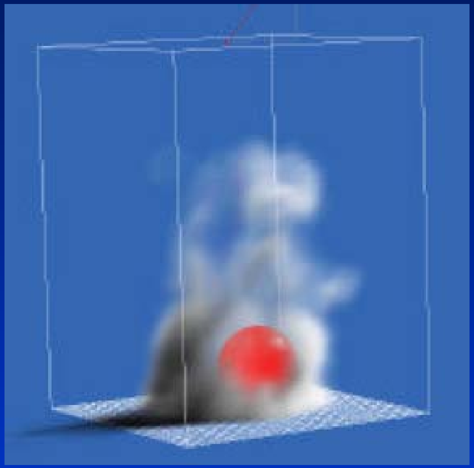


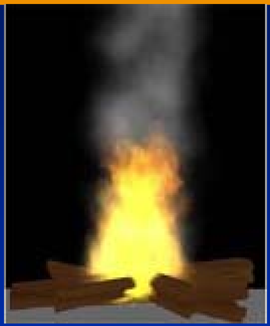
Natural Phenomena

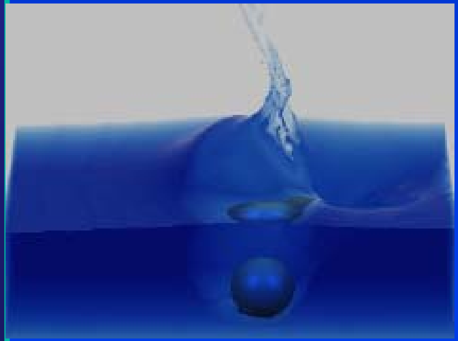





Fluid Simulation







Cloud Animation

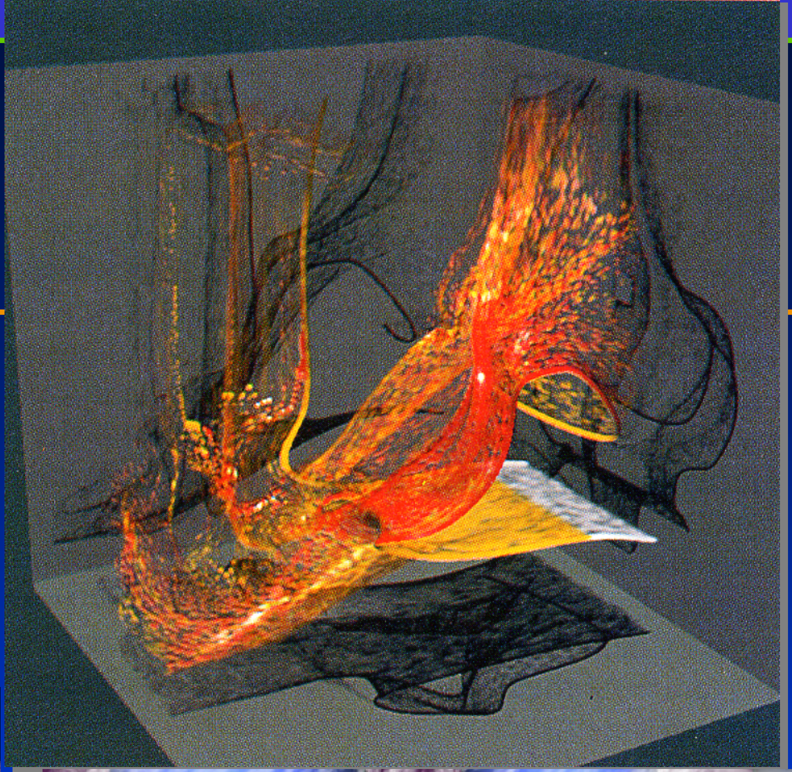
- No heat involved
  - Ebert et al. 1990, 1996, 1997, 2003
    - Procedural modeling
  - Dobashi et al. 2002
    - CA model with humidity
- Simple linear relation between buoyancy force and temperature
  - Kajiya and Herzen 1984
  - Overby et al. 2000
- Completely physical based
  - Harris et al. 2003
    - Grid-based method with Euler's equation
    - Based on heat transfer equation, experimental equations on buoyant force, phase transition, saturation, pressure lapse rate
    - Fully implemented on GPU

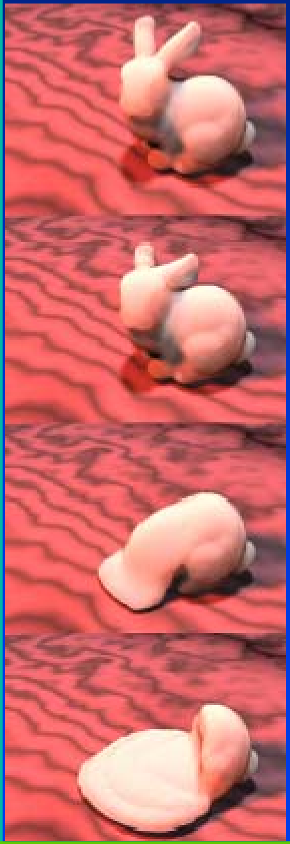
Dobashi et al. 2003

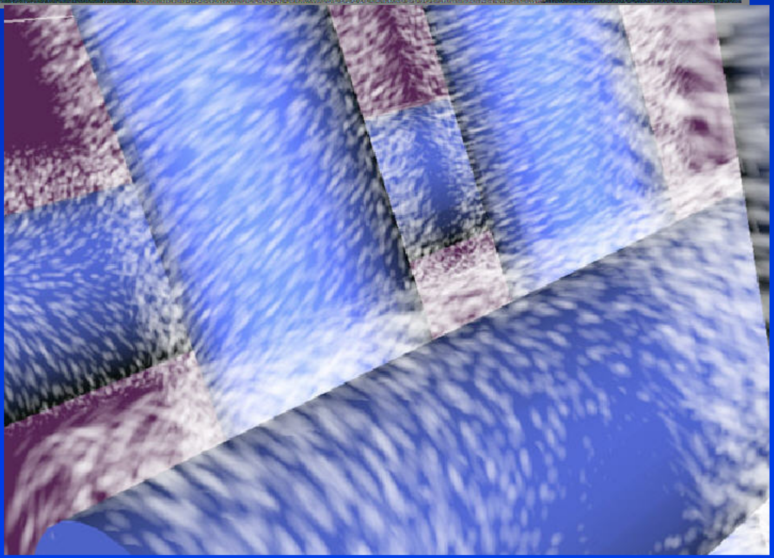
Ebert et al. 2003

Harris et al. 2003

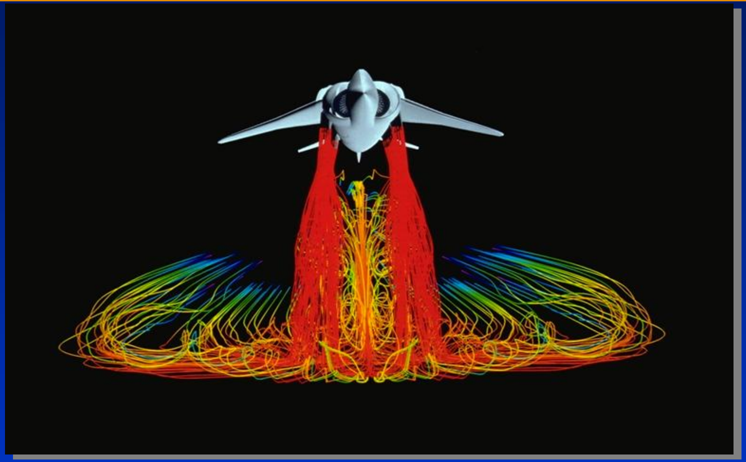
Particles

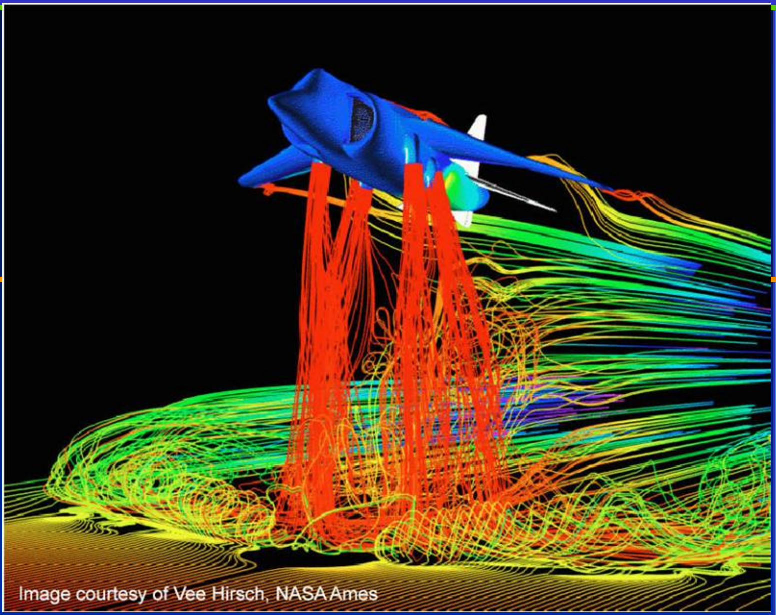


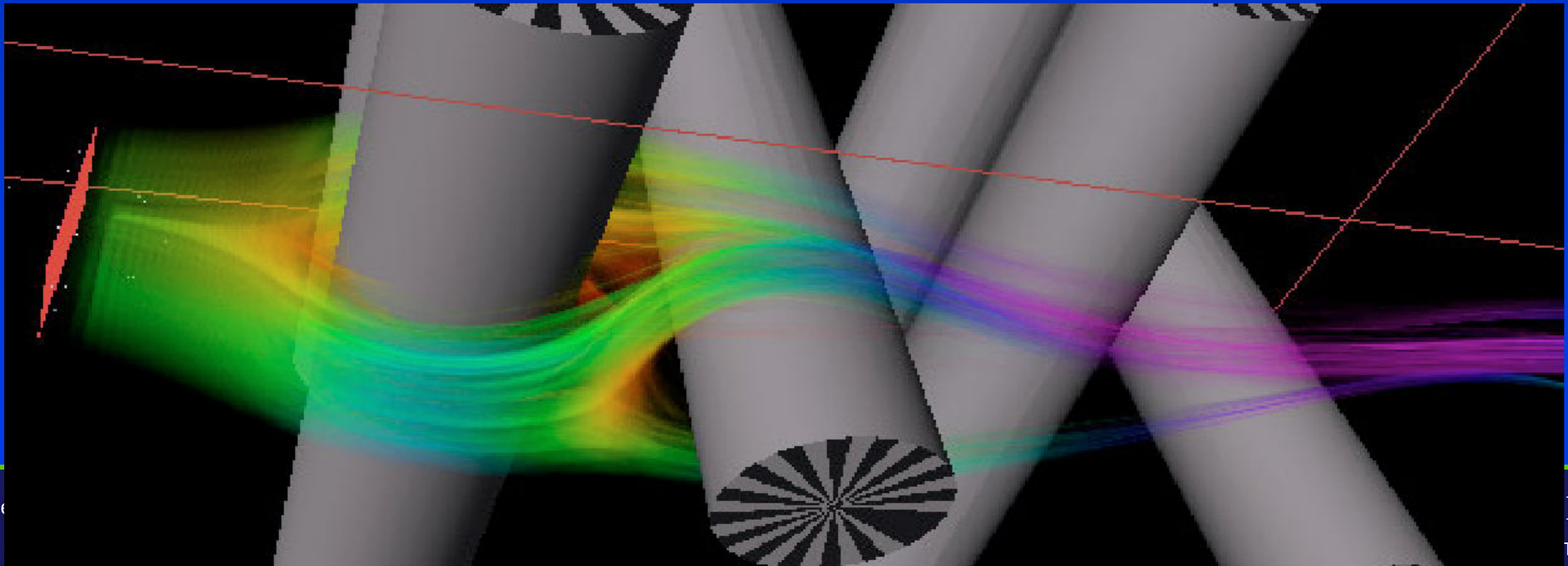




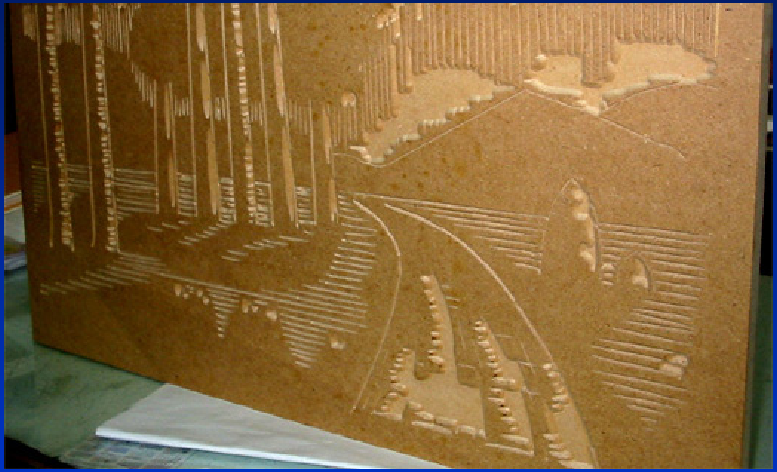
Flow Simulation

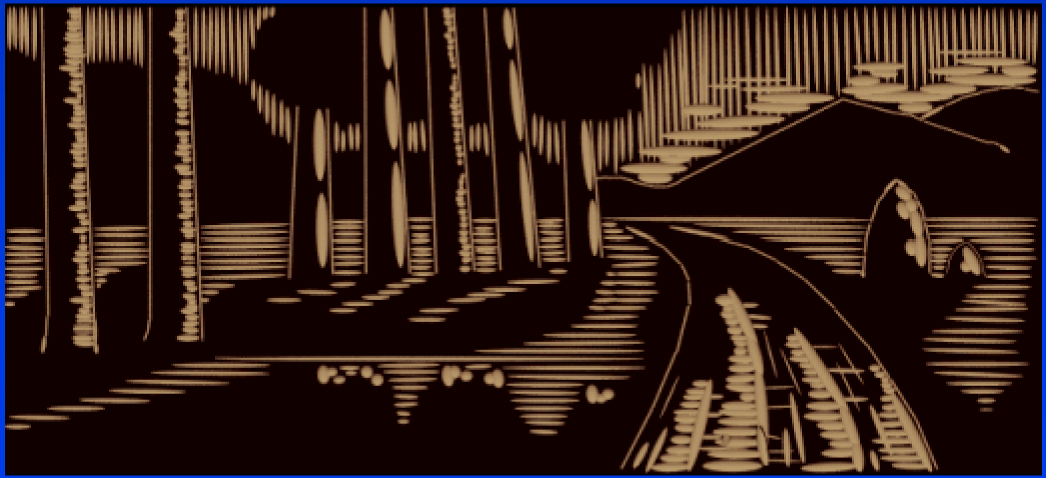






Computer Art with Physical Interface

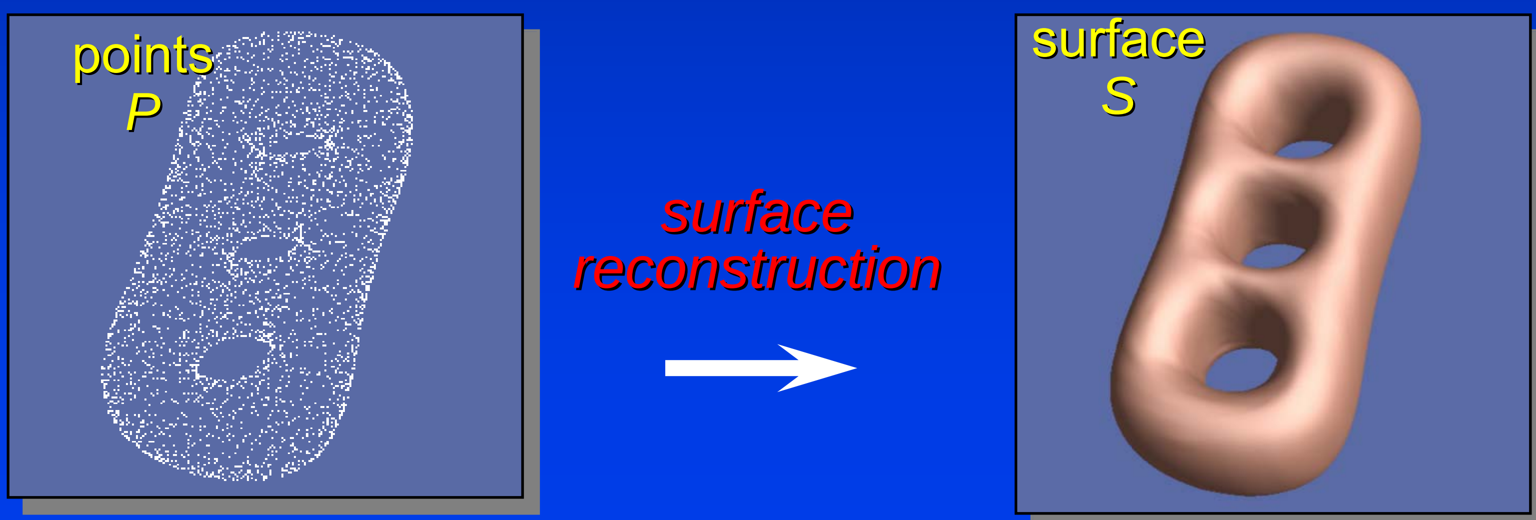




Scattered Data Fitting

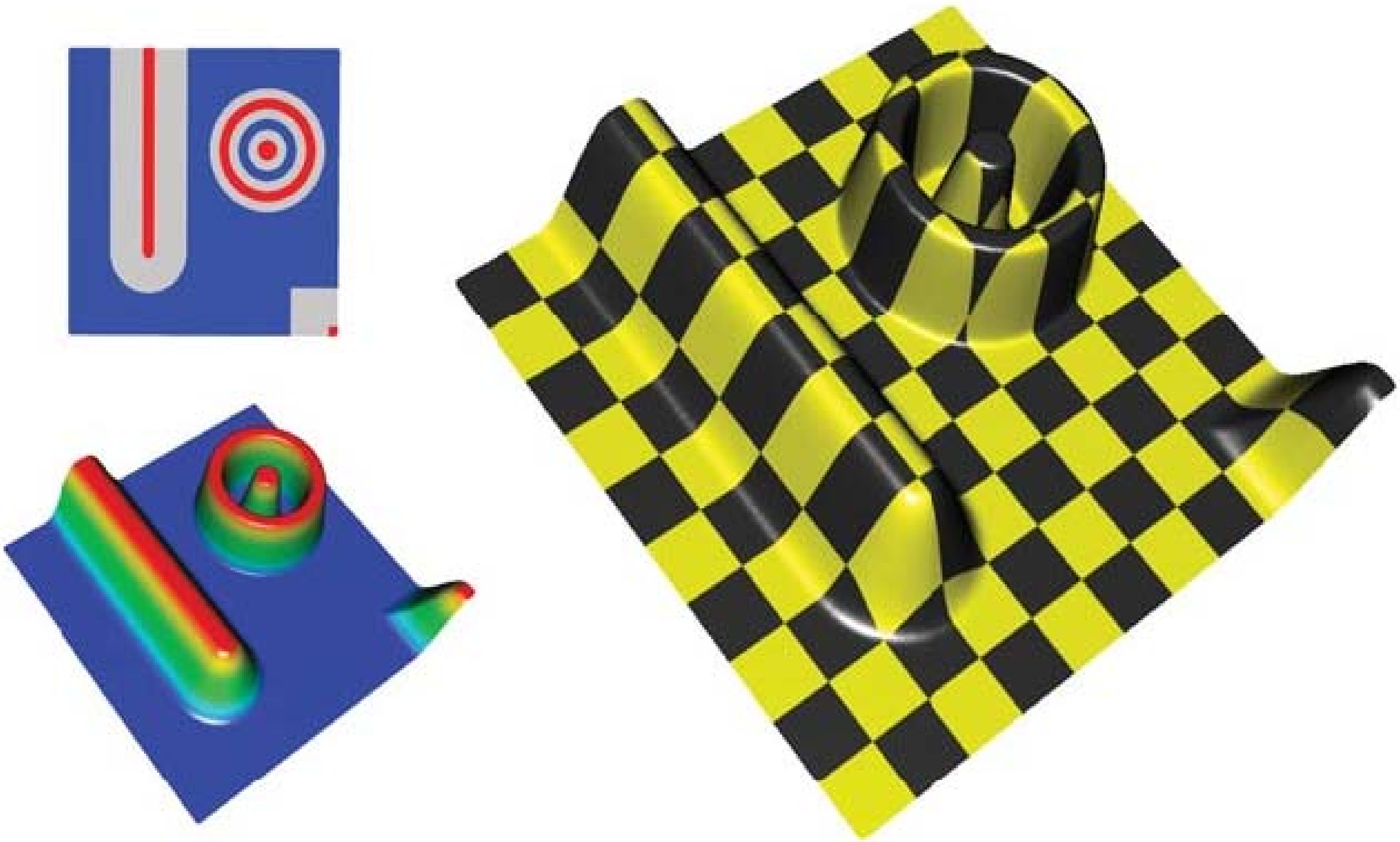
From points to splines

- Reverse engineering
- Geometric modeling and processing



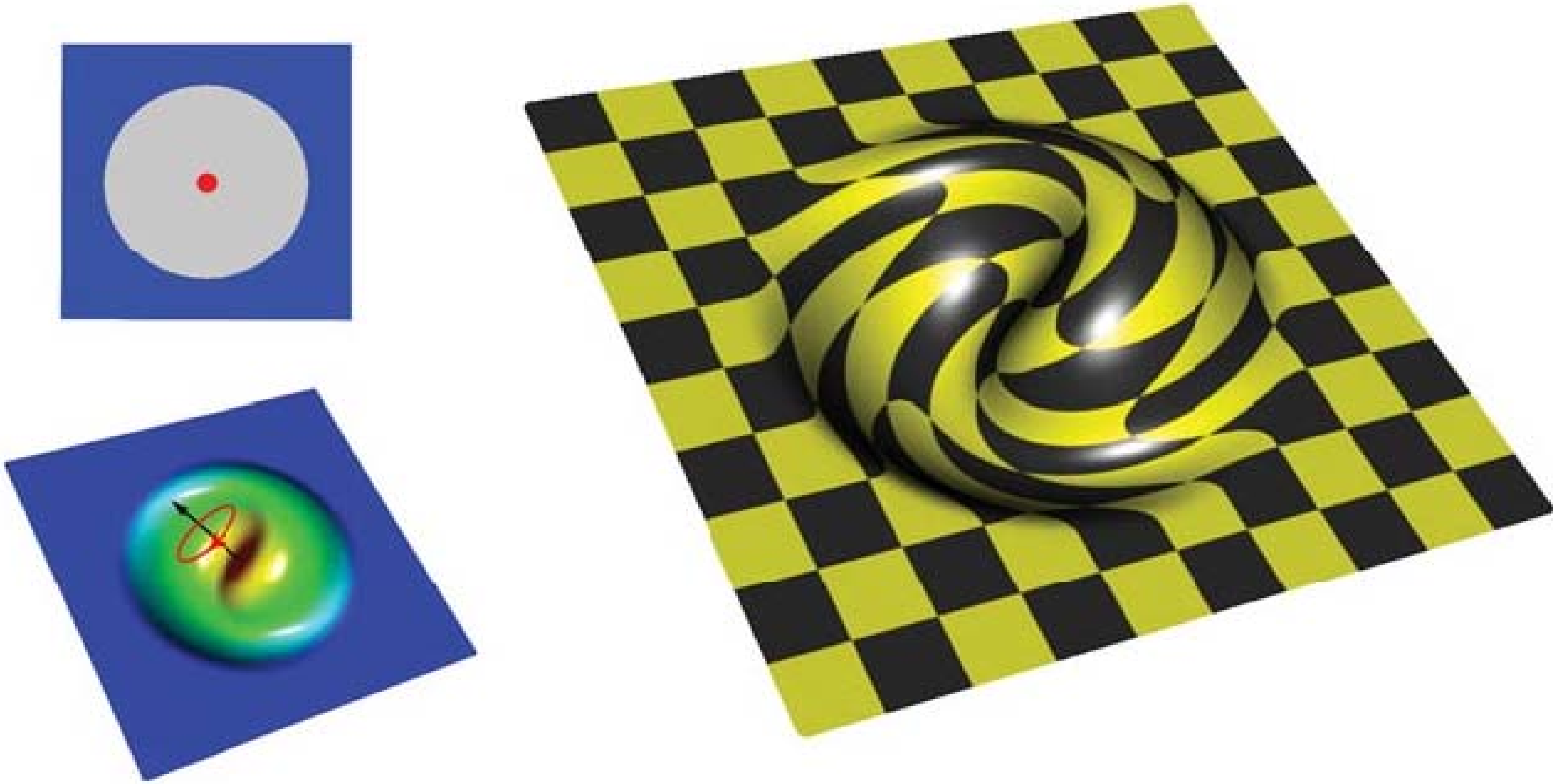
(courtesy of Hugues Hoppe)

Sketch-based Shape Editing



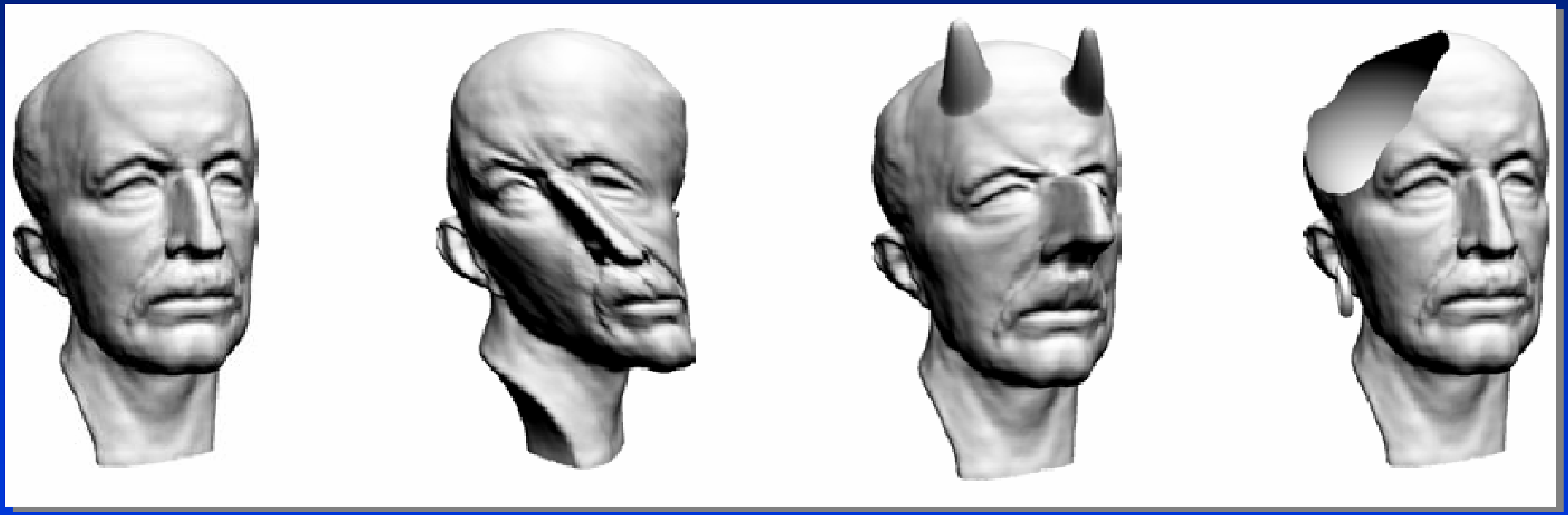
(b) Translation in the direction of the plane normal

Interactive Manipulation

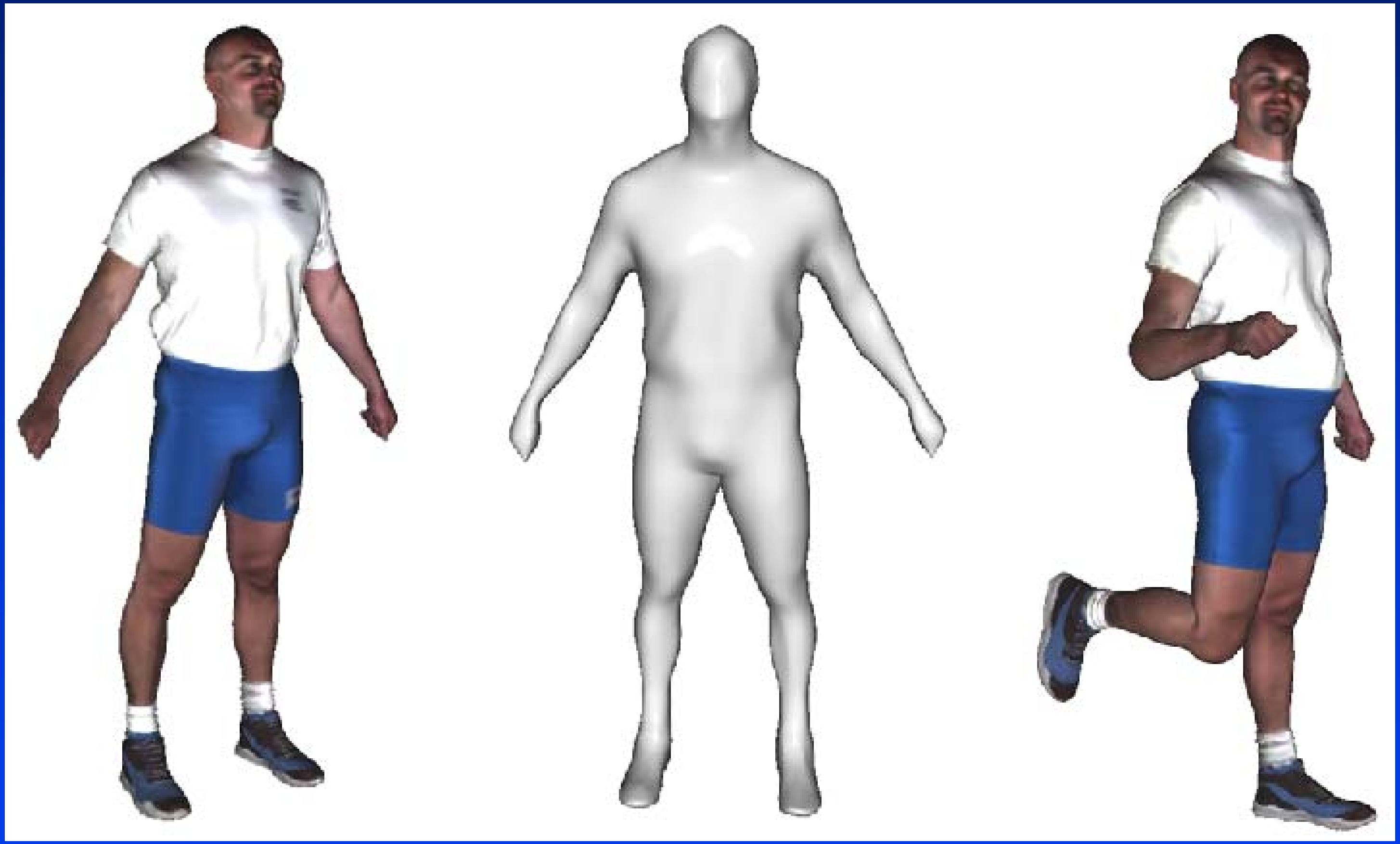


(a) 90 degree rotation around an axis through the plane center that spans an angle of 45 degrees with the plane normal

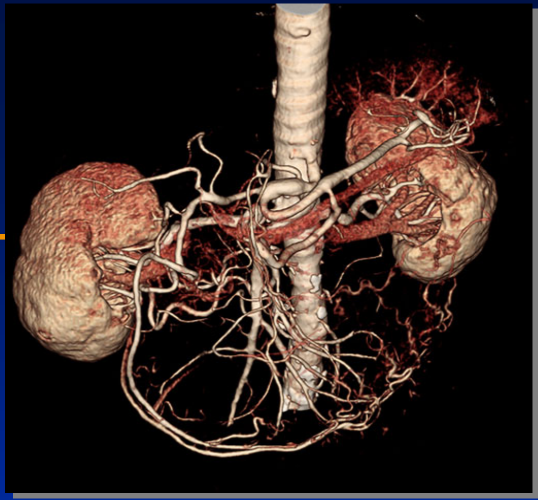
Shape Deformation and Editing

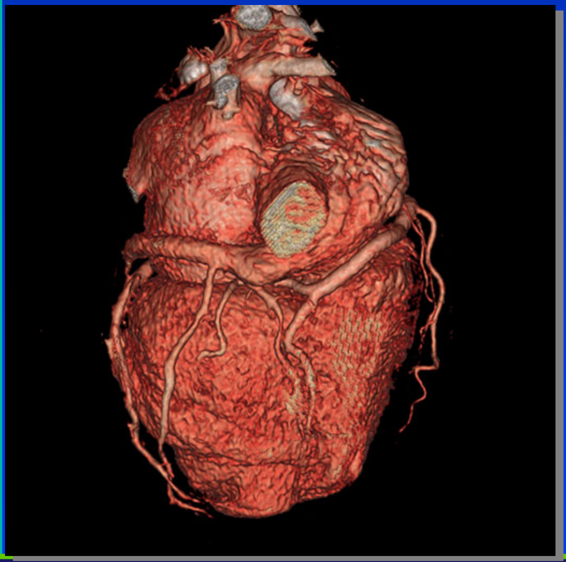


Motion Synthesis (Animation)



Bio-applications

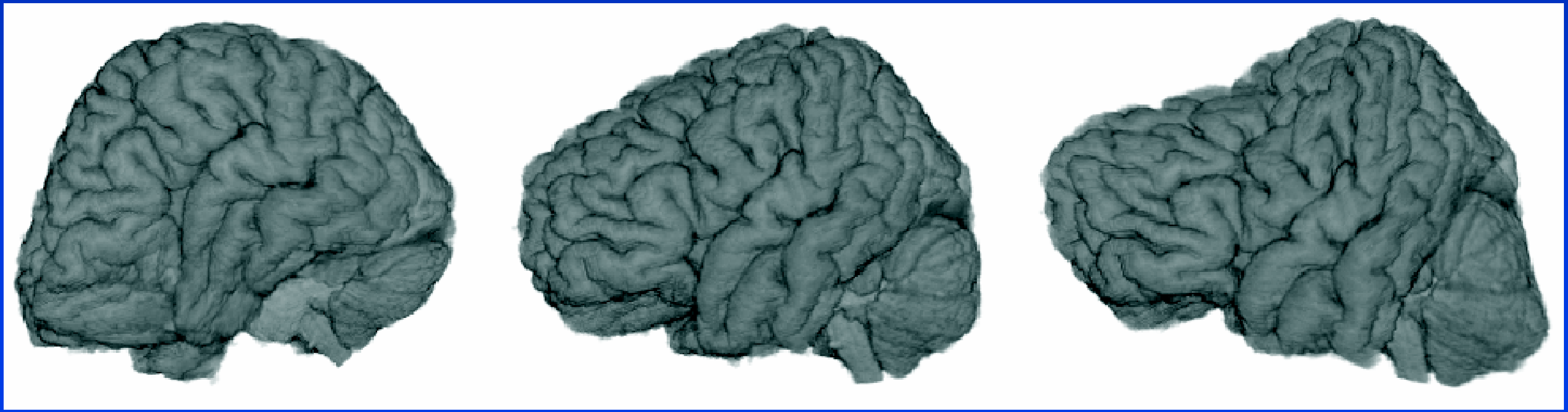




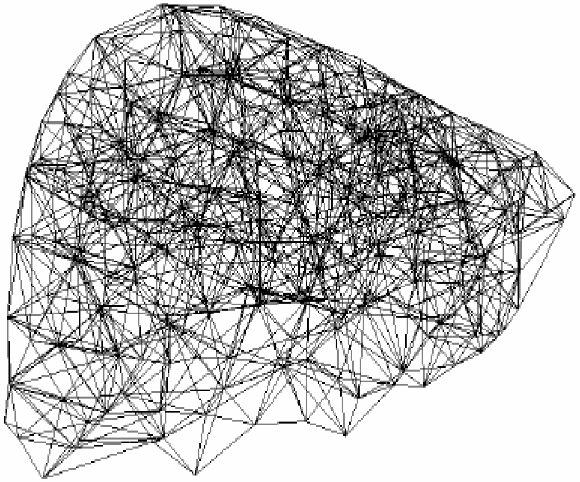
Virtual Surgery

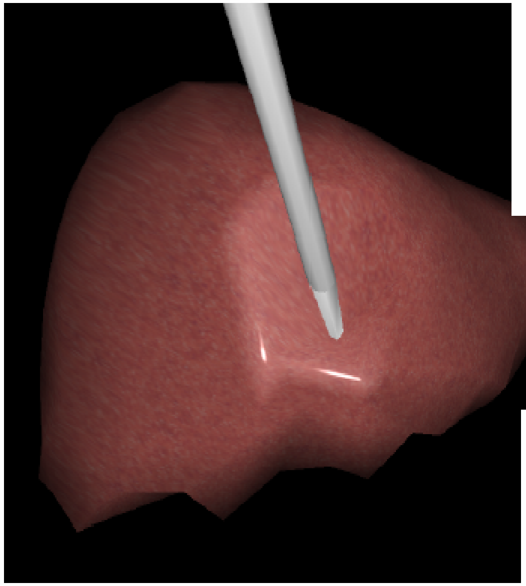
Brain Deformation

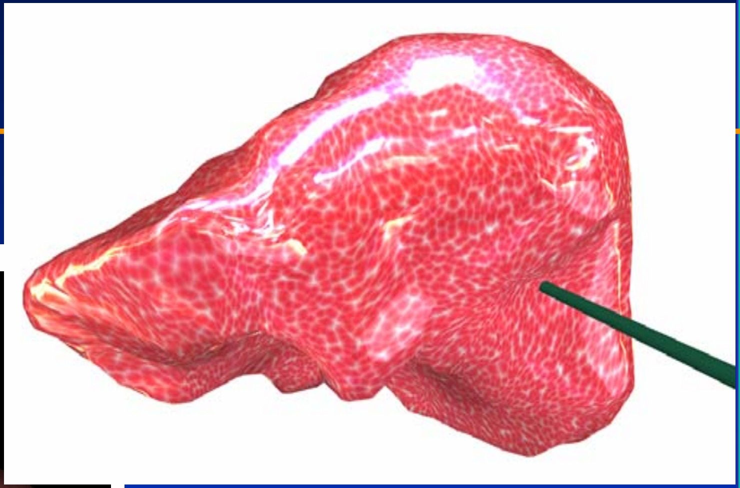
- Medicine
- Simulation
- Modeling
- Entertainment

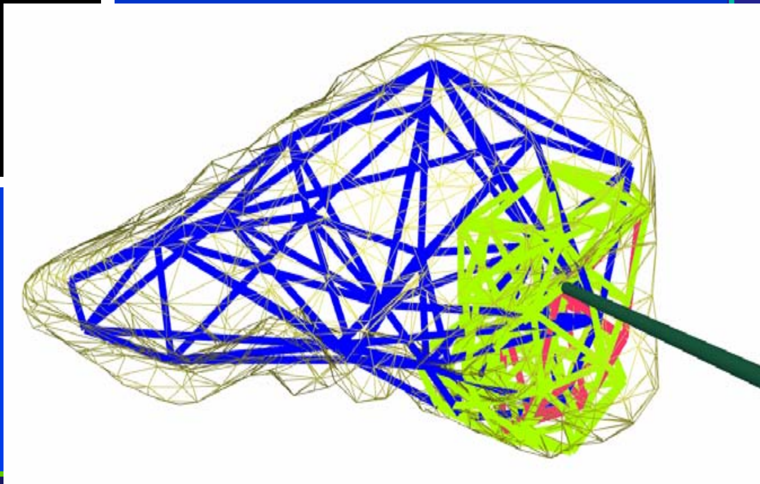


Organ Deformation









Finite Element Simulation

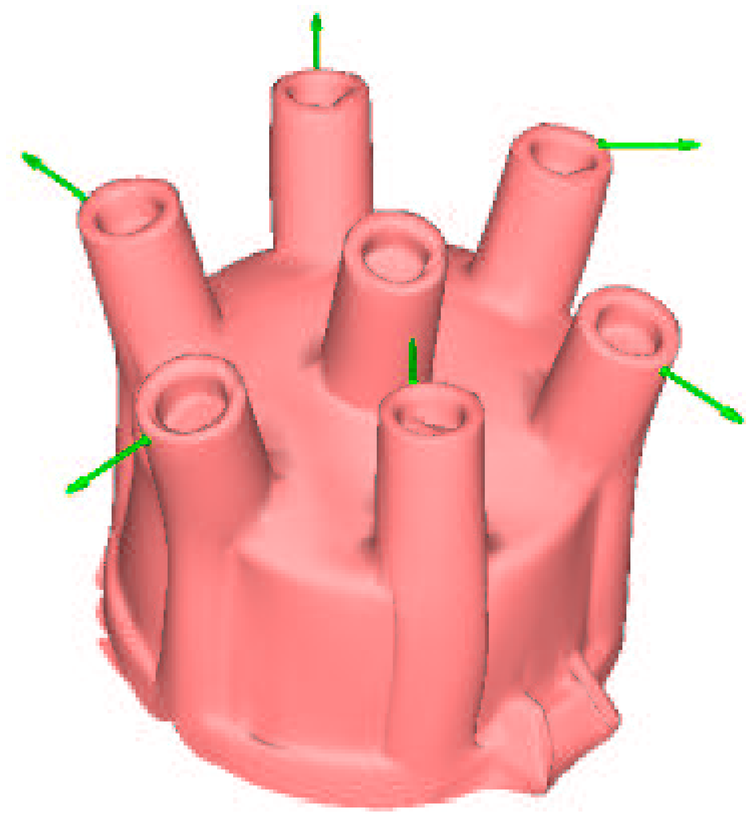
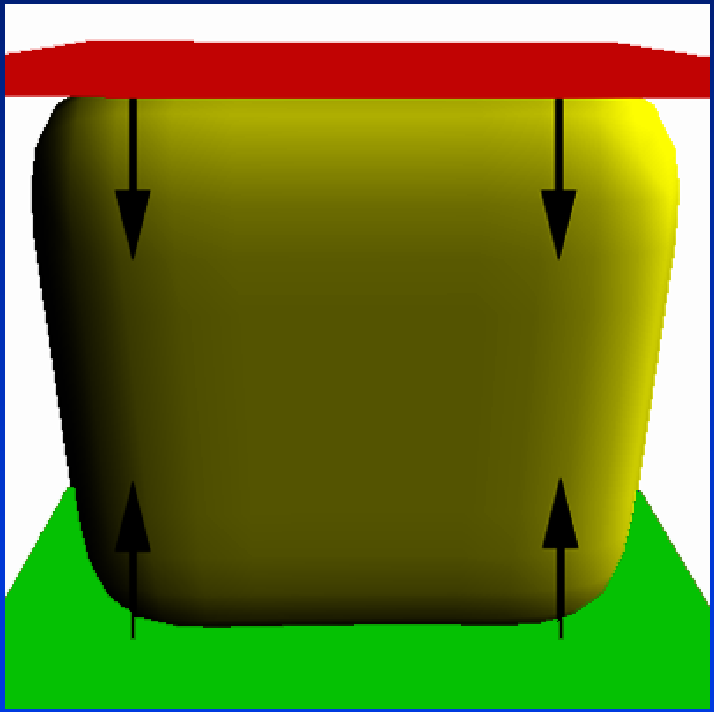
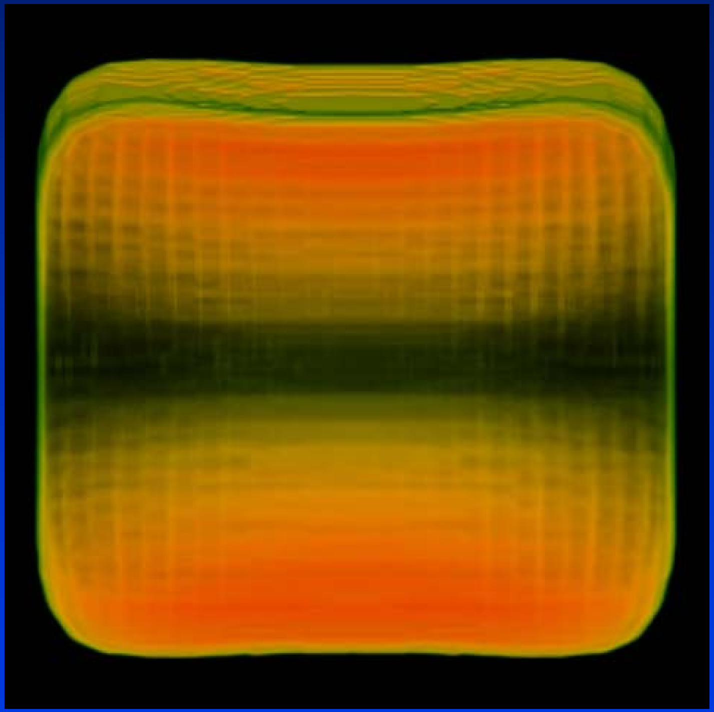


Figure 1: Distributor Cap

Material Analysis (Virtual Prototyping)

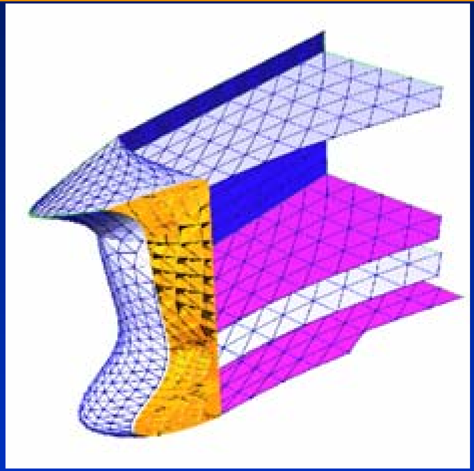


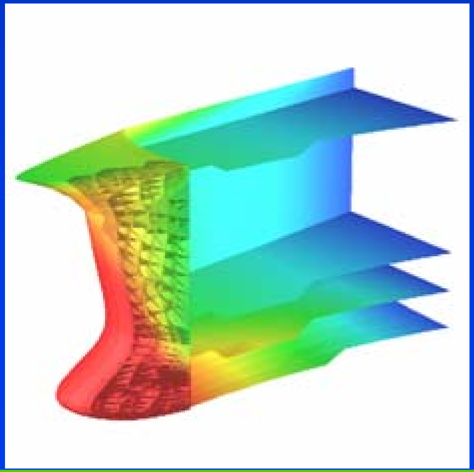
compressive forces

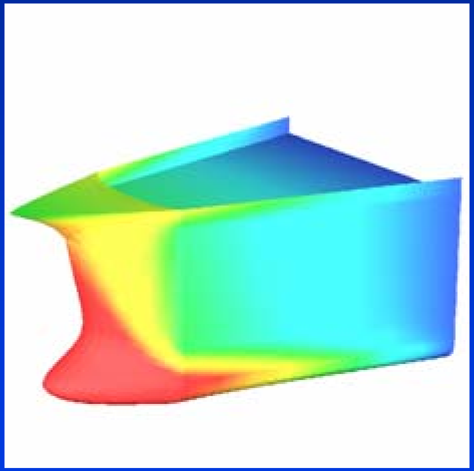


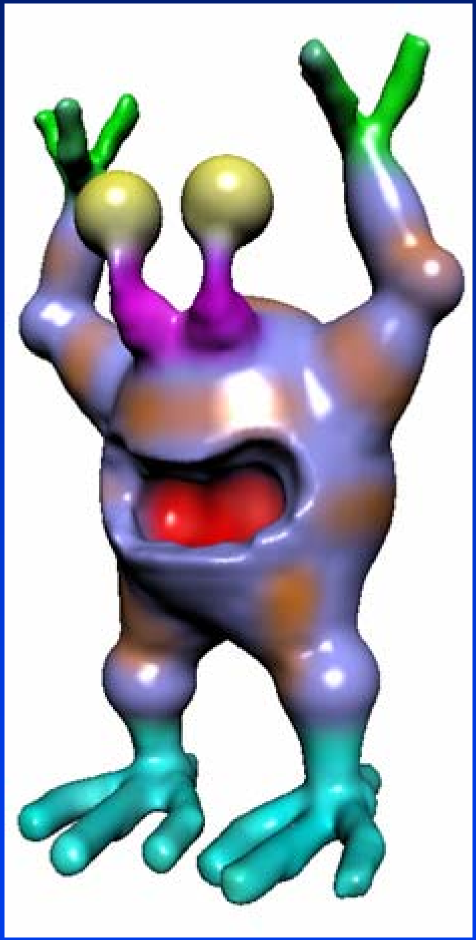
displacement mapping

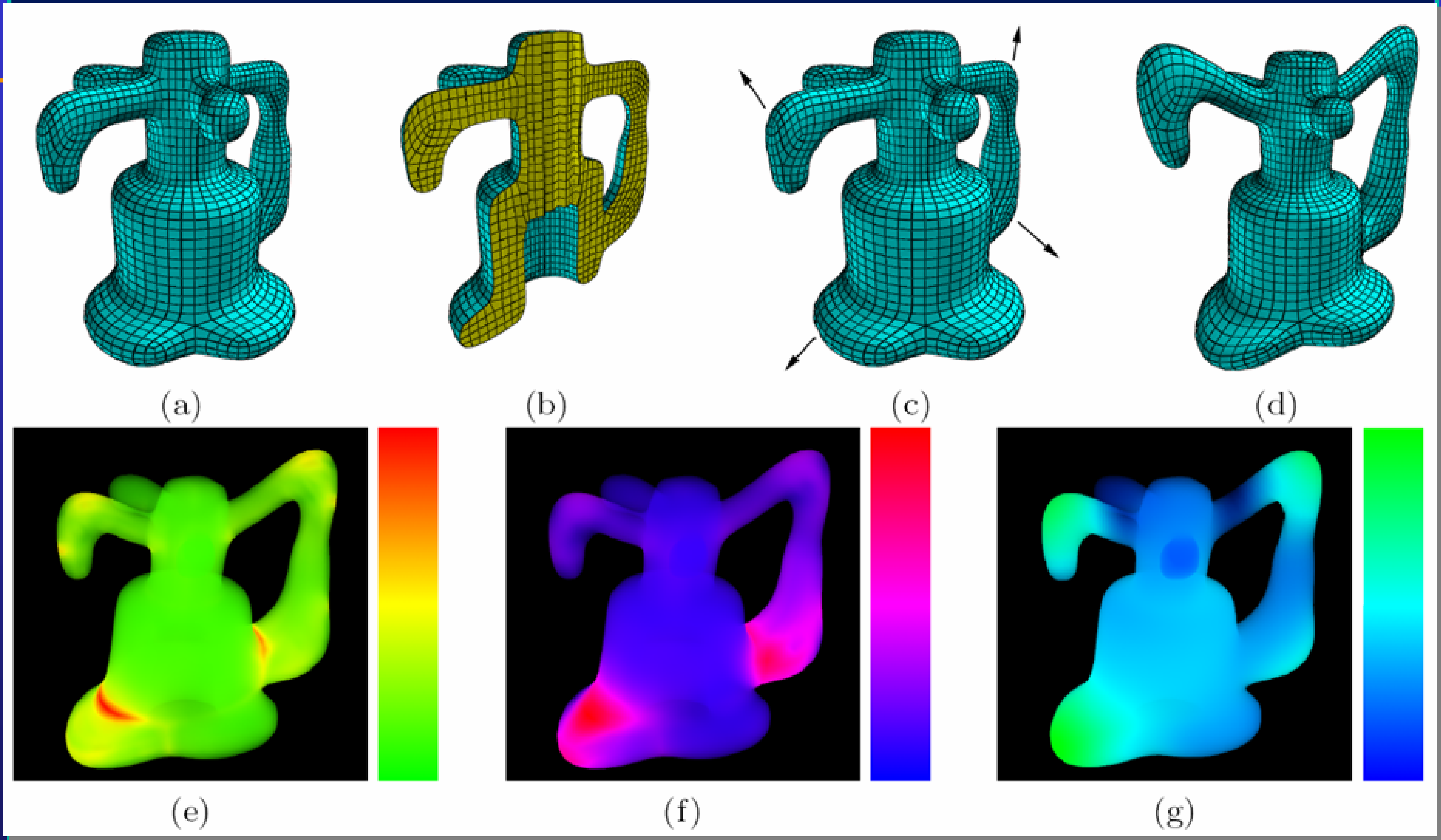
Material Modeling



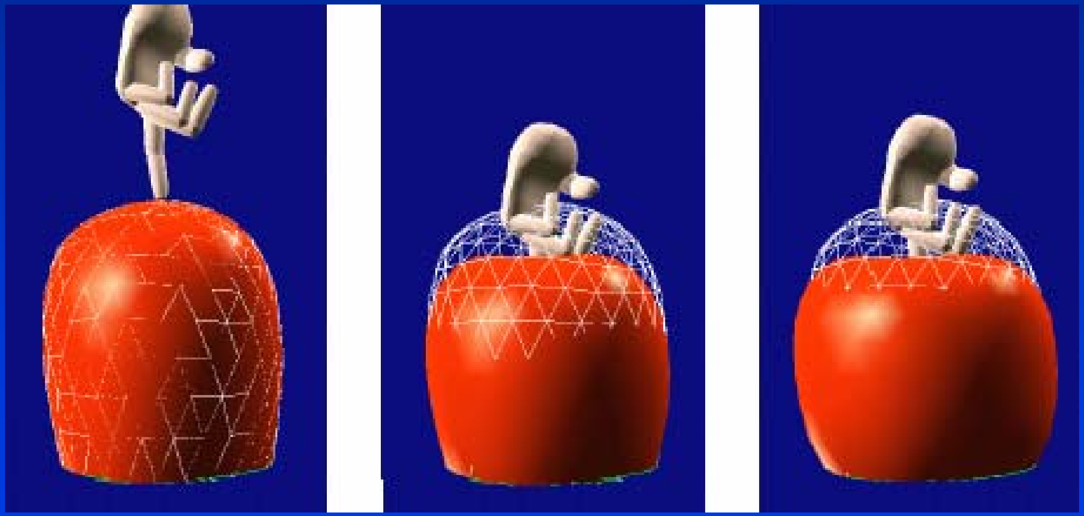




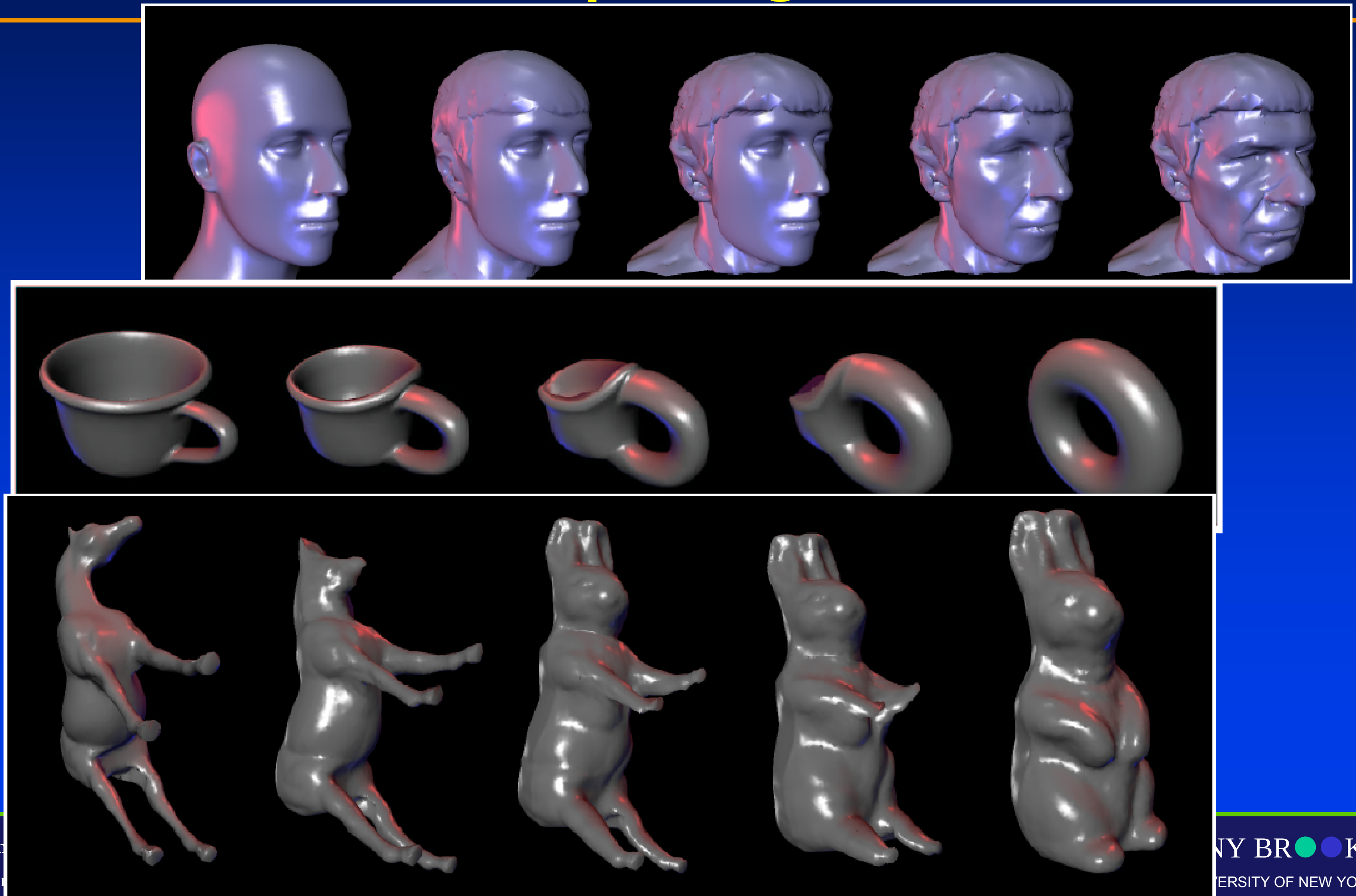



(a)
(b)
(c)
(d)
(e)
(f)
(g)

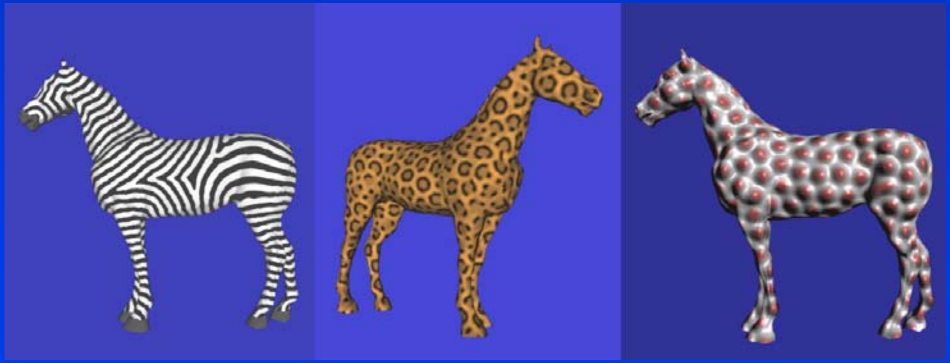
FEM-based Deformable Objects



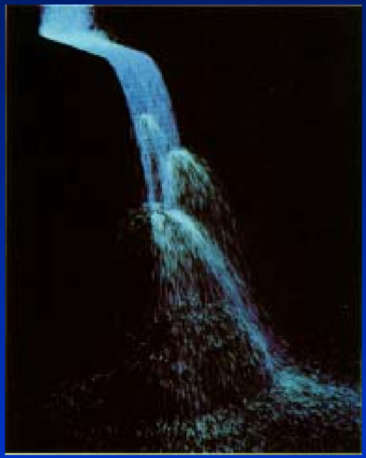
Animation: Morphing



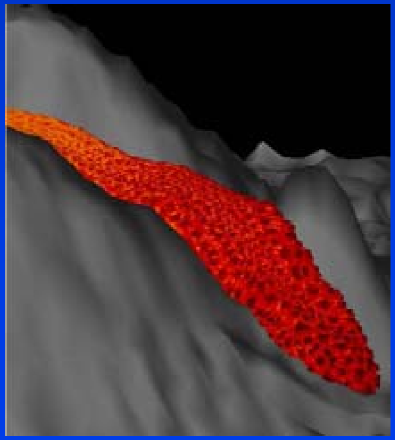
PDE-driven Texture Synthesis



Natural Phenomena



Sims 1990



Stora 1999

Our Course

- A subset of key theory, algorithms, techniques, and applications
- Extensive topics with a main focus on our unique course mission
- Comprehensive lectures (focusing on geometric and physical intuition, good ideas, and application needs)
- Numerous slides, figures, images, and videos for easy understanding (after all, this is the nature of graphics and visualization)
- Active students' involvements

Course Prerequisites

- Mathematical skills: calculus, linear algebra, analytic geometry, basic physics
- Computer science background: programming, basic graphics/visualization courses at the undergraduate level and the graduate entry-level
- Essentially, you need to have an undergraduate education in computer science or engineering with basic knowledge on graphics/visualization
- You need to speak to the instructor if you are not sure about your background knowledge

Questionnaire

1. List your background courses/knowledge/education related to graphics/visualization, your current education level
2. What is the main goal/purpose for you to take this course (e.g., learn the knowledge, pursue a career in this area)
3. How does this course help your future professional career
4. Your expectations on the course
5. Your studying plan
6. Other important issues that you can think of about the course

If You are Serious

- Study my on-line, electronic course notes
- Review programming assignments carefully and start to implement them
- Think about your course project
- Write a proposal on your project and start to work on it
- Practice on the programming assignments
- Finish your project by the end of this semester
- Try to submit a paper if your project is really really new
- You are welcome to communicate with me via emails

My Contact Information

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How to Get a “A”?

- NO midterm tests!
- NO final exams!
- ASSIGNMENTS and PROJECT only !!!

CSE 621

Important Information

- WHEN: MW 3:50pm --- 5:10pm
- WHERE: Social and Behavioral Sciences N107 (it is possible that we will move to our CS Seminar Room (Rm.1306) after the first week of our lectures).
- OFFICE HOURS: Monday 9:00am --- 12:30pm, Wednesday 9:00am --- 11:00am, 1:00pm --- 2:20pm, or by appointment!
- CREDITs: 3
- HOW CAN I GET an “A”?
  - NO midterm tests!
  - NO final exams!
  - ASSIGNMENTS and PROJECT only !!!

Important Information

- Two types of assignments/assignments
- Paper presentation
- Programming

Course Synopsis

- Objectives
  - Physics-based modeling, simulation, and scientific computing methodology
  - Integrated approach for visual computing applications
- Concepts and framework
- Mathematical techniques
- Geometric computing
- Computational physics
- Numerical techniques
- A wide spectrum of applications

CSE631 vs. CSE530

- Above entry-level graduate course
- Open to everyone!
- MS projects (thesis)
- Ph.D oriented and research driven
- Case studies through paper presentation
- Additional handouts from various books
- Pro-active involvement from students
- Different mechanism for course grade
- Group project in encouraged
- Higher standard

Course Facts

- This is an advanced graduate course!
- Can I take this course? YES, if YOU
  - Are a graduate student with CS background
  - Talk to the instructor
  - Have graphics/visualization background
  - Familiar with calculus/algebra/geometry
  - Have basic knowledge numerical analysis
  - Understand simple physical laws

Course Facts

- You do NOT need to take CSE528 or CSE530 prior to this course
- Having knowledge from CSE528 or CSE530 makes it much better
- However, you need to have taken CSE328, or CSE332, or equivalent courses elsewhere
- Lectures: paper presentation
- Class attendance is critical!
- No textbooks

Course Facts

- Students are expected to
  - Present several papers
  - Finish one course assignment
  - Complete one course project
  - Present your project in the class
  - Given system demonstration
  - Submit the final report
- What projects are appropriate?
  - Talk to Hong
  - Projects available from Hong

Pathway to Success

- Highly-motivated
- Hard-working
- Start as soon as possible
- Meet with Hong on a regular basis
- Actively interact with your fellow students
- Visit CS library frequently

Course Facts

- NOT a graphics/visualization course
- NOT a course to teach OpenGL
- Do NOT teach graphics (basic knowledge & programming skills should be acquired elsewhere)
- Learn fundamental algorithms and advanced techniques
- Study various visual computing applications
- Course projects lead to MS thesis (project) or Ph.D dissertation topics

What Will Be Covered

- Mathematics
- Geometry
- Numerics
- Physics
- Dynamics
- Algorithm
- Simulation
- Modeling
- Computer graphics
- CAGD/CAD/CAM
- Computer animation
- Visualization
- Computer vision
- Medical imaging
- Virtual environments (VR, AR)
- Artificial life

Paper Resources

- Access libraries for journals and conferences' proceedings
- Relevant journals
  - ACM TOG, IEEE TVCG, IEEE CG&A, CAG, CAGD, Graphical Models, The Visual Computer, Computer Graphics Forum, IEEE PAMI, IJCV, IEEE Transactions on Medical Imaging, etc.
- Major conferences:
  - Siggraph, Visualization, Eurographics, Pacific Graphics, Graphics Interface, Solid Modeling, Shape Modeling, ACM I3D Symposium, ICCV, CVPR, MICCAI, etc.

Grading Schemes

- No midterm, No final exam.
- 100% on Assignment/Project
- Individual project (one student), or group project (two students)
- Paper reading and presentation (other people's work, one or two papers at most): 15%
- Assignment: 5%
- Course project: 80%, plus the additional bonus
- Class attendance: 10%

Course Project

- Two-page project proposal (10%)
- Preliminary demonstration in the middle of the semester (10%)
- Oral presentation and final demonstration (20%)
- Working system + software codes (20%)
- Project report (10-15 pages) (20%)
- Target dates
  - Warm-up assignment --- preferable 3rd week, but really anytime!
  - Paper reading --- throughout the semester
  - Paper presentation --- towards the end of the semester
  - Proposal --- 4th week
  - mid-term demo --- 8th week
  - Final presentation --- at the end of the semester
  - Project report --- at the end of the semester
- Individual or group project

Project Requirements

- Interactive interface (graphics-based)
- Intuitive and easy to understand
- Efficient (fast, high-performance)
- Basic functionalities
- Examples
- Flexible and easy to generalize
- Project plan (multiple check-points and phases)
- Individual or group project
- Office hours / individual meetings
- Penalty for late submission

Outline

- Geometric and solid modeling
- Physics-based modeling
- Deformable models
- Mathematics
- Numerical solutions
- Visual computing applications
  - Graphics
  - Vision
  - Geometric design
  - Visualization
  - Virtual environments

Geometric and Solid Modeling

- Polygonal meshes
- Polynomials and splines
- Parametric curves and surfaces
- Bezier
- B-splines and NURBS
- Triangular & irregular patches
- Multisided surfaces
- Subdivision objects
- Manifold splines
- Implicit functions
- CSG and volumetric models

Geometric and Solid Modeling

- Wavelets and hierarchical models
- Special shapes
  - Ruled surface
  - Developable surface
  - Offset
  - Sweeping
  - Swung surface
  - Surface of revolution
- Solid models
  - Constructive solid geometry (CSG)
  - Boundary representation (B-rep)
  - Cell decomposition

Geometric Operations

- Trimming, Intersection
- Approximation, Fitting
- Interaction
  - Control point, weight, knot vector
- Interpolation
  - Scattered data, curve network, regular dataset
- Constraints
  - Shape-preserving, convex-preserving
- Continuity
- Optimization
- Computational geometry
- Differential geometry
- Efficient algorithm

Physical Models

- Rigid and non-rigid models
- Mass-spring lattices
- Parameterized models
- Elastic and inelastic bodies
- Dynamic B-splines & NURBS
- Dynamic subdivision models
- Particle systems and fluid models
- Superquadric geometry
- Snakes: dynamic contour models
- Symmetric models
- Finite elements

Geometric Modeling Techniques

- Interpolation
- Approximation
- Optimization
- Interaction
- Forces
- Constraints
- Dynamic sculpting
- Continuity
- Differential geometry
- Hierarchical techniques
- Level of Details (LOD)
- Simplification

Dynamic Modeling

- Mass, damping, elastic energy
- Internal and external forces
- Geometric constraints
- Optimal control of physical models
- Lagrange mechanics
- Mathematical physics
- Multi-body (rigid and non-rigid) simulation
- Local and global deformations
- Viscoelasticity, plasticity, fracture
- Thermoelasticity, heat transfer, melting
- Fluid dynamics

Numerics

- Linear algebra & matrix computation
- Linear & nonlinear systems
- Static & dynamic problems
- Initial-value & boundary-value problems
- The finite difference method
- The finite element method
- Calculus of variations
- Direct & iterative methods
- Differential equations of equilibrium
- Numerical analysis
- Multiresolution algorithms

Visual Computing Applications

- Morphing and image warping
- Surface blending and solid rounding
- Animation and simulation
- Free-form deformation
- Reverse engineering
- Shape reconstruction
- Sparse data fitting
- Interactive sculpting
- Model simplification
- Object motion tracking
- Feature extraction and segmentation

Visual Computing Applications

- Visualization
- Variational design
- Shape interrogation and control
- Biomedical imaging
- Interface and virtual environments
- Texture mapping
- Artificial life
- Plastic surgery
- Natural phenomena

Graphics

- Computer Graphics, Hearn and Baker, 2^{nd} edition, Prentice Hall, 1997.
- Computer Graphics: Principles and Practice, James D. Foley, Andries van Dam, Steven K. Feiner, and John F. Hughes, 2^{nd} edition, Addison Wesley, 1990.
- Computer Graphics, Alan Watt, 2^{nd} edition, Addison-Wesley, 1993.

Geometric Modeling

- Curves and Surfaces for Computer Aided Geometric Design A Practical Guide, 3rd edition, G. Farin, Academic Press, 1993.
- An Introduction to Splines for use in Computer Graphics and Geometric Modeling, R.H. Bartels, J.C. Beatty, and B.A. Barsky, Morgan Kaufmann Publishers, Inc., 1987.
- Computational Geometry for Design and Manufacture, I.D. Faux and M.J. Pratt, Ellis Horwood, Chichester, England, 1979.
- Geometric and Solid Modeling: An Introduction, C.M. Hoffmann, Morgan Kaufmann Publishers, Inc., San Mateo, CA, 1989.
- Differential Geometry of Curves and Surfaces, M.P. do Carmo, Prentice-Hall, Englewood Cliffs, NJ, 1976.

Mathematics

- Introduction to Applied Mathematics, G. Strang, Wellesley Cambridge Press, 1986.
- Mathematical Programming Theory and Algorithms, M. Minoux, John Wiley and Sons, 1986.
- Numerical Recipes: The Art of Scientific Computing, W.H. Press, B.P. Flannery, S.A. Teukolsky, and W.T. Vetterling, Cambridge University Press, Cambridge, UK, 1986.
- Computer-Oriented Mathematical Physics, D. Greenspan, Pergamon Press, Oxford, 1981.
- Methods of Mathematical Physics, Vol 1, R. Courant and D. Hilbert, Interscience, London, 1953.
- Classical Mechanics, 2nd edition, H. Goldstein, Addison-Wesley, Reading, MA, 1980.

Finite Element Method

- The Finite Element Method (3rd edition), O.C. Zienkiewicz, McGraw-Hill, London, 1977.
- The Finite Element Handbook, H. Kardestuncer and D.H. Norrie, McGraw-Hill, 1987.
- The Finite Element Method Displayed, G. Dhatt, Chichester (West Sussex), New York, 1984.
- Finite Element Procedures, K.-J. Bathe, Prentice Hall, 1996.

Curve and Surface Survey

- Parametric representation for curves and surfaces
- "A survey of curves and surfaces in CAGD", W. Bohm et al. Computer Aided Geometric Design, 1(1), 1-60.