CSE 530: Geometric Foundations for Graphics and Visualization

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Main Foci

- Mathematical concepts, geometry theory, algorithmic techniques, and computational tools
- Fundamental concepts and algorithms in data representation, geometric modeling and physics-based simulation
- Geometric (and graphical and visual) modeling and simulation techniques, and geometric processing and analysis tools
- A large variety of applications in graphics and visualization as well as other visual computing areas
- Several advanced topics and they are all research-oriented, representing the most sophisticated ones

The Course Objectives

- Provide (entry-level) graduate students a comprehensive knowledge on geometric concepts and techniques for modeling and simulation
- Demonstrate the significance of these mathematical and computational tools and geometric algorithms in graphics and relevant areas
- Emphasize a ``hands-on" approach to both the better understanding of geometric theory/algorithms and the effective use of geometric techniques

Course Topics

- Geometric algorithms for both polygonal and curved objects
- Theory of parametric and implicit representations
- Modeling methods of curves, surfaces, and solids
- Subdivision algorithms and techniques
- In-depth spline theory, wavelet theory and multi-resolution shape representations
- Differential geometry fundamentals
- Real-world application problems

Course Topics

- If time permits
- General data and material modeling/simulation techniques
- Novel spline/subdivision schemes and their effective computation
- Reverse engineering
- Shape deformation, as well as
- Other sophisticated topics and latest advances in the field

Key Theory, Algorithms, and Techniques

- Throughout the course, we will emphasize the application relevance in graphics, visualization, simulation/animation, digital geometric processing and analysis, medical imaging analysis, human-computer interface, etc.

Our Course

- A subset of key theory, algorithms, techniques, and applications
- Extensive topics with main concentrations on our unique course mission
- Comprehensive lectures (focusing on geometric 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

- This is an entry-level graduate course!!!
- Mathematical skills: calculus, linear algebra, analytic geometry
- Computer Science background: programming, basic graphics/visualization courses at the undergraduate level or 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

My Contact Information

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How to Get a “A”?

- NO midterm tests!
- NO final exams!
- PAPER READING/PRESENTATION and COURSE PROJECT only, 100% on paper reading and course project !!!

How to Get a "A"?

- In particular, throughout this semester, each student is expected to study 10 papers!!!
- Among them, each should present two papers in class (paper presentation), and work on a course project which is based on one paper (from your paper pool of 10 papers).
- Please note that, the course project paper should be different from the two papers that you are presenting in the class !!!
- Once again, reading/presentation and course project !!!

Lecture Information

- WHEN: Monday & Wednesday 4:00pm - 5:20pm
- WHERE: Frey Hall Rm.317
- OFFICE HOURS: MONDAYS 1:00pm – 2:10pm, or by appointment!
- CREDITs: 3

Course Facts

- This is an entry-level graduate course for both MS and PhD students!!!
- Can I take this course? YES, if YOU
  - are a graduate student with CS background, have skills in calculus and linear algebra, have BASIC knowledge on graphics and visualization, or talk to the instructor
- You do NOT need to take CSE328 prior to this course
- However, you need to have taken CSE328, or CSE332, or equivalent courses elsewhere
- No required textbooks, several suggested references
- Lecture notes are important!!! Class attendance in critical!!!

Course Facts

- Students are expected to
  - Read 10 papers and present two papers in the class
  - Complete one course project, present your project in the class, and submit the final report
- What projects are appropriate?
  - Talk to the instructor and suggest possible topics of interest
  - Projects also available from the instructor

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)
- Study geometric fundamentals and applications!
- Learn geometric modeling and its significance for visual computer applications
- Course projects lead to MS thesis (project) or Ph.D dissertation topics

Papers, Projects, and Assignments

- Paper reading and literature review report (10 papers total, throughout the semester, technical report as a survey paper due November 21, Friday, 11:59pm, 8-10 pages): 20%
- Paper presentation on two papers (November 18 & 19, Tu+W): 20%
- Class attendance and asking questions during office hours: 10%
- Course project: 50%
- Basic project requirements
  - Interactive interface (graphics-based)
  - Intuitive and easy to understand
  - Efficient (fast, high-performance)
  - Basic functionalities
  - Examples
  - Flexible and easy to generalize

If You are Serious

- Study my on-line, electronic course notes
- Paper reading (10 papers) and literature review technical report (due November 21, Friday, 11:59pm)
- Two paper presentations in our class
- Think about your course project right away
- Write a proposal on your project and start to work on it
- 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, call me, or come to meet with me in my office!

Paper Reading and Literature Review

- 10 papers total, throughout the semester
- Paper review technical report due: November 21, Friday, 11:59pm
- 8-10 pages

Project Plan and Deadlines

- Multiple check-points and phases, so please pay attention to the deadlines!!!
- Study a set of relevant papers (10 papers, throughout the semester), submit your literature review report on November 21 Friday, 8-10 pages long for your report.
- Submit your own one-page proposal (October 1, Wednesday)
- Implement basic functionalities and user interface before the mid-term check point (November 5, Wednesday)
- Paper presentation week (November 18 & 19, Tu+W)
- Class presentation & final project demonstration (at the end of the semester, December 7-8, Sun+Mon)
- Final project report (at the end of the semester, December 5, 11:59pm)
- Individual project or group project!
- Office hours / individual meetings (on Mondays and Wednesdays, or by appointments!!!)
- Penalty for late submission (25% per day)

Course Project (50%)

- One-page project proposal: 5%
- Mid-term demo with preliminary results: 10%
- A working system + software codes: 20%
- Final project report: 7%
- Oral presentation and final demo: 8%

Grading Requirements

1. Meet with Hong for (at least) 30-45 minutes to decide your study plan for this course, review your research experiences in the past, and plan for the future
2. Upon the individual meeting with Hong, select 10 research papers and start to read them immediately
3. Write and submit an one-page technical proposal on what you are planning to do during the next 2-3 months (programming-driven research projects, re-implementation of at least one paper, etc.)
4. Finish a 8-10 page technical report on literature review for the 10 papers you are reading (due November 21, Friday, 11:59pm)
5. Give two paper presentations in class (Nov. 18-19, total 30 minutes)
6. Finish all the course requirements for all check points
7. Give a final presentation (total 30 minutes) based on your technical report for your project (8-10 pages)

Course 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, and your studying plan
5. Other important issues that you can think of

How to Get a "A"?

- Finish all the course requirements, and I will issue a "A" grade

Course Synopsis

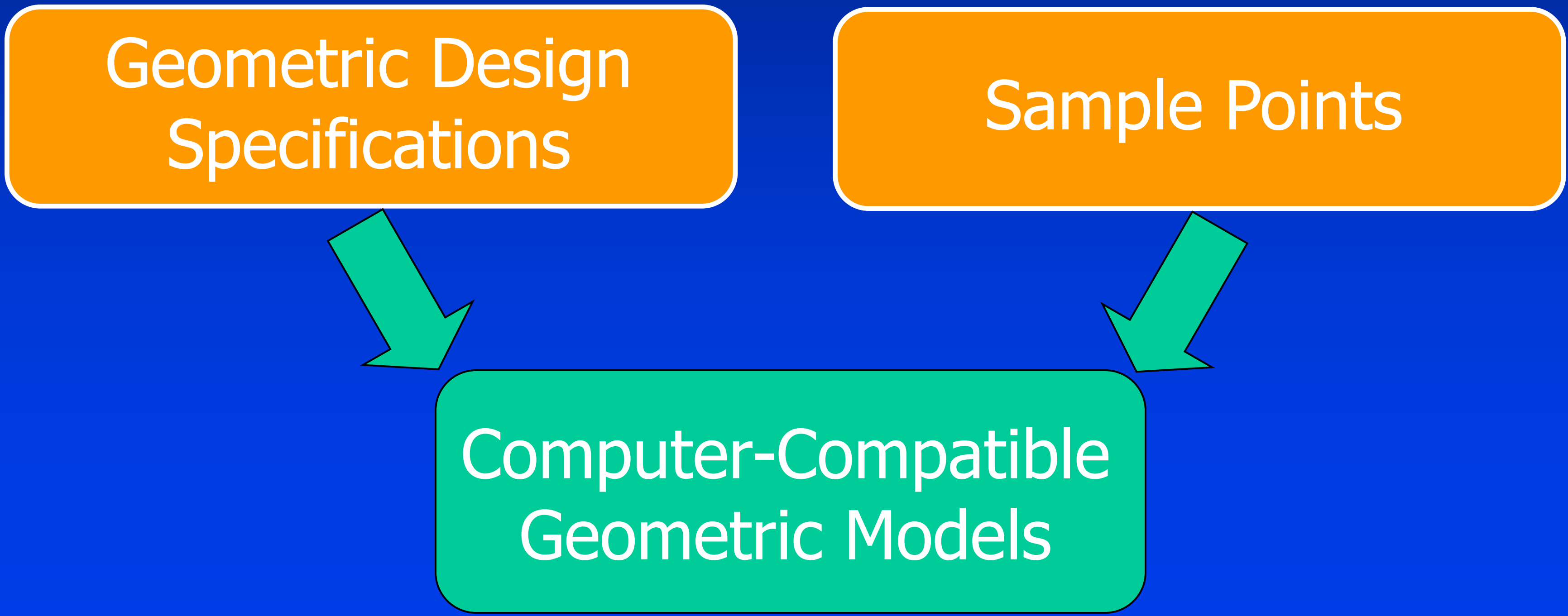
- Our goals
  - Geometric concepts, mathematical tools, geometric modeling techniques, fundamental algorithms, graphics and visualization relevance
- Technical coverage
  - Polygonal and curved objects, parametric and implicit representations, modeling of curves, surfaces, and solids, spline theory, wavelet theory, multi-resolution synthesis and analysis, differential geometry, more advanced topics

Course Scopes

- Geometry is ubiquitous
- But if time permits, we will go beyond the traditional boundary of geometric modeling and simulation
- We will be covering the topics of general data and material modeling as well

Geometric Processing

- Geometric Models
- Geometric Design
- Geometric Reconstruction



Geometric Models

- The geometric models are approximations of real-world geometric objects by a finite set of shape parameters
- By manipulating this set of shape parameters, modelers can design a large variety of geometric shapes

Continuous Real-World Objects → Abstraction & Approximation → Finite Set of Shape Parameters

Bridge the Shape Parameters with Geometric Modeling Specifications

- Geometric modeling techniques translate the geometric modeling requirements to appropriate shape parameter values

Geometric Modeling Specifications

↓

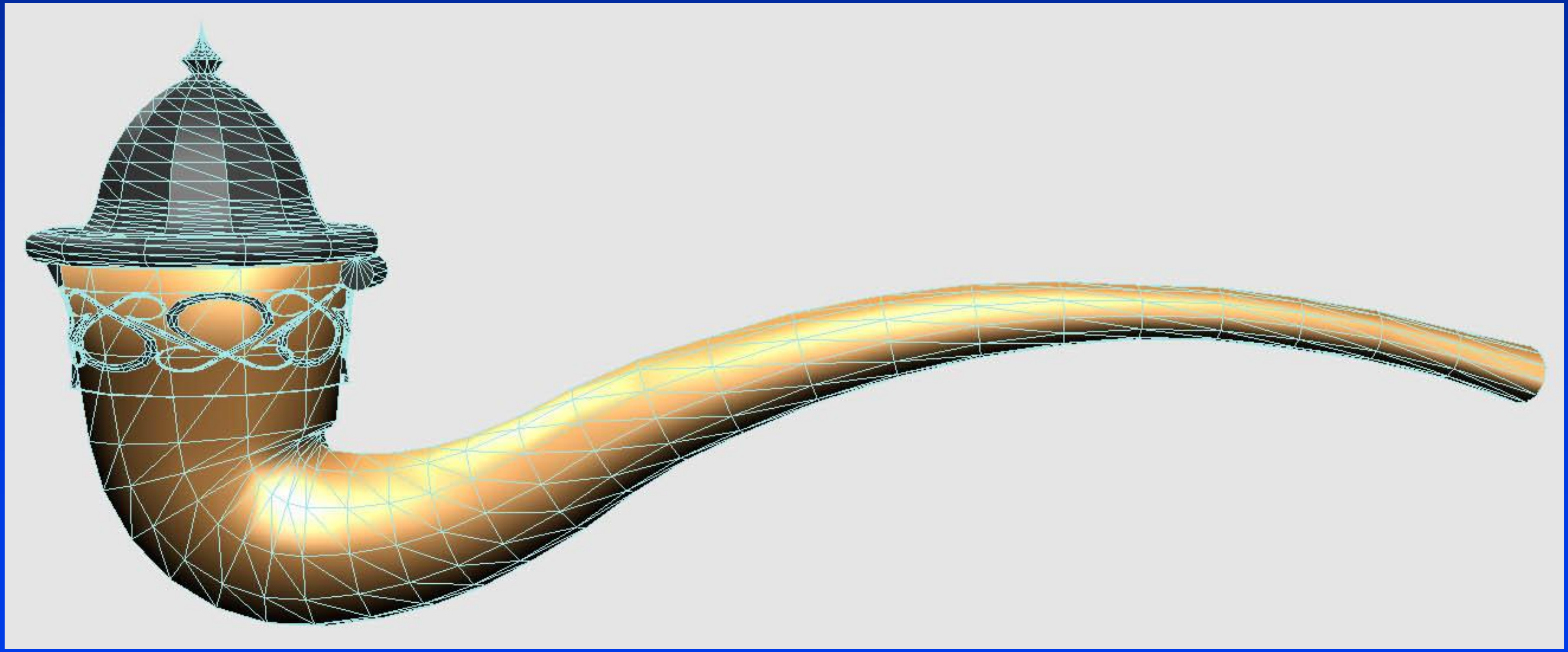
Geometric Modeling Techniques

↓

Shape Parameters of Models

Polygonal Meshes

- Shaded model



Parametric Representation

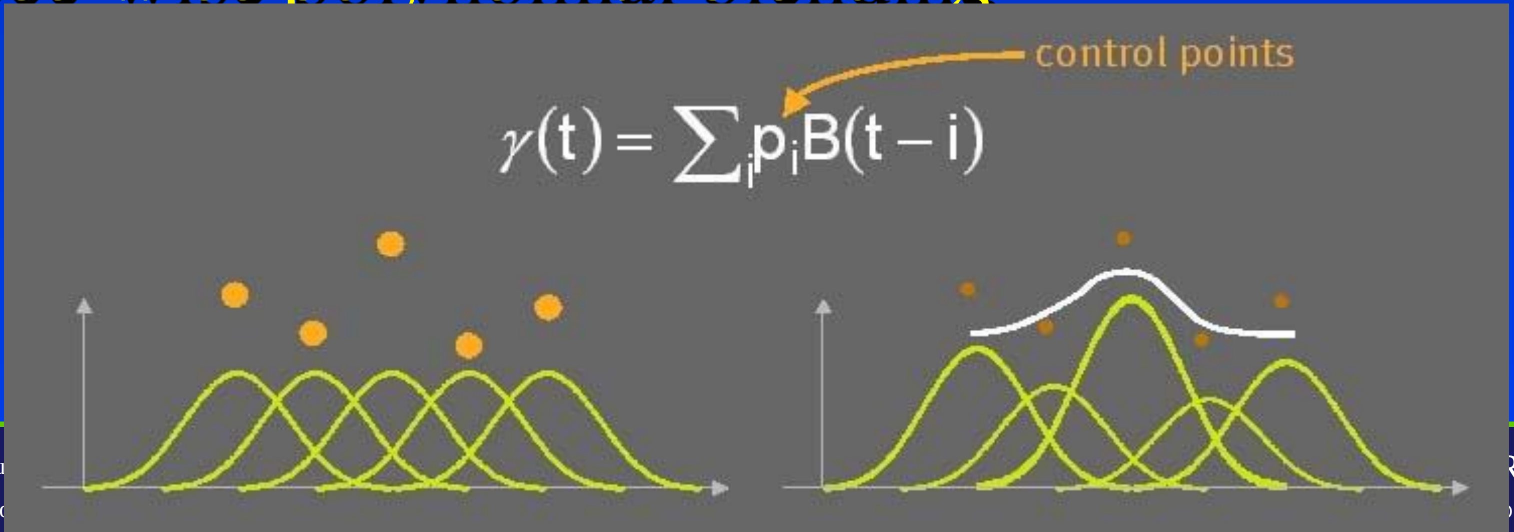
- Parametric curve functions

$$x = x(u), y = y(u), z = z(u)$$

- Parametric surface functions

$$x = x(u,v), y = y(u,v), z = z(u,v)$$

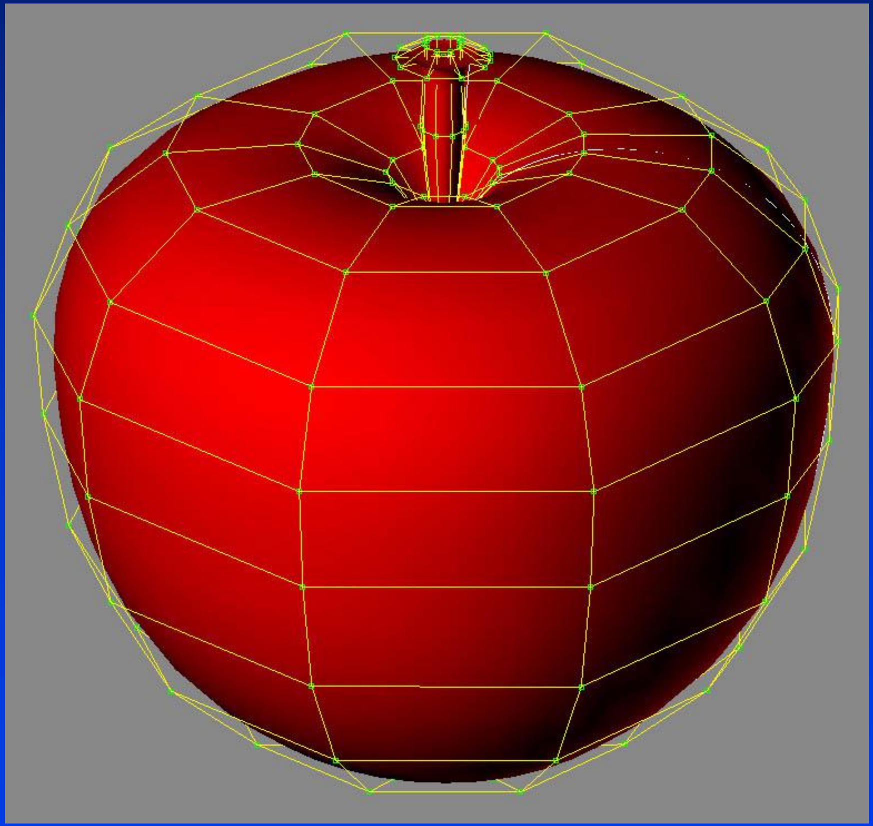
- Piece-wise polynomial blending



NURBS Curves and Surfaces

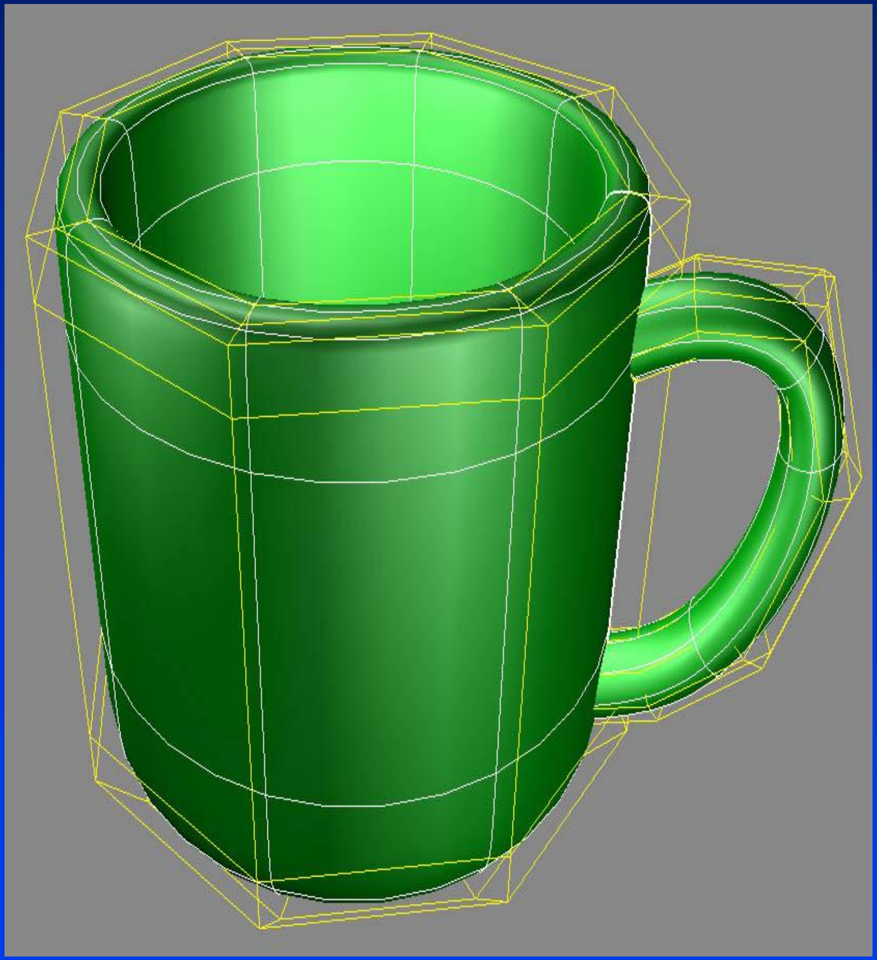
$$C(u) = \frac{\sum_{i=1}^{n} p_i w_i B_{i,k}(u)}{\sum_{i=1}^{n} w_i B_{i,k}(u)}$$

$$S(u,v) = \frac{\sum_{i,j=1}^{n} p_{ij} w_{ij} B_{i,k}(u) B_{j,l}(v)}{\sum_{i,j=1}^{n} w_{ij} B_{i,k}(u) B_{j,l}(v)}$$



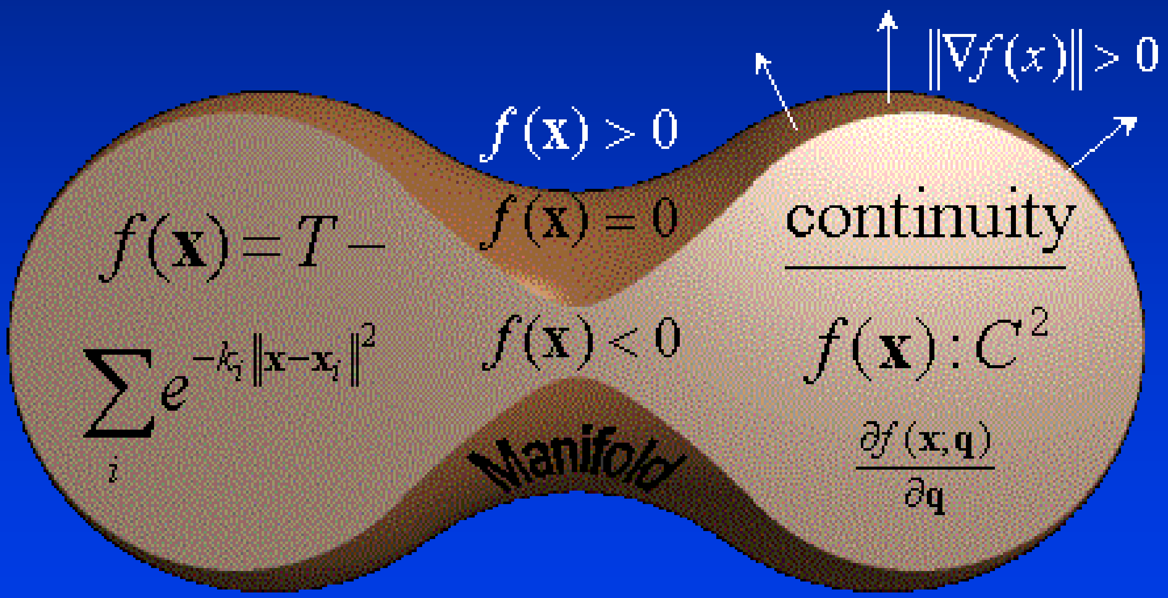
NURBS Surfaces

- Good for
  - Mechanical parts
  - Smooth free-form surface representation
- Bad for
  - Non-genus-0 surfaces
  - Interactive design of free-form surfaces



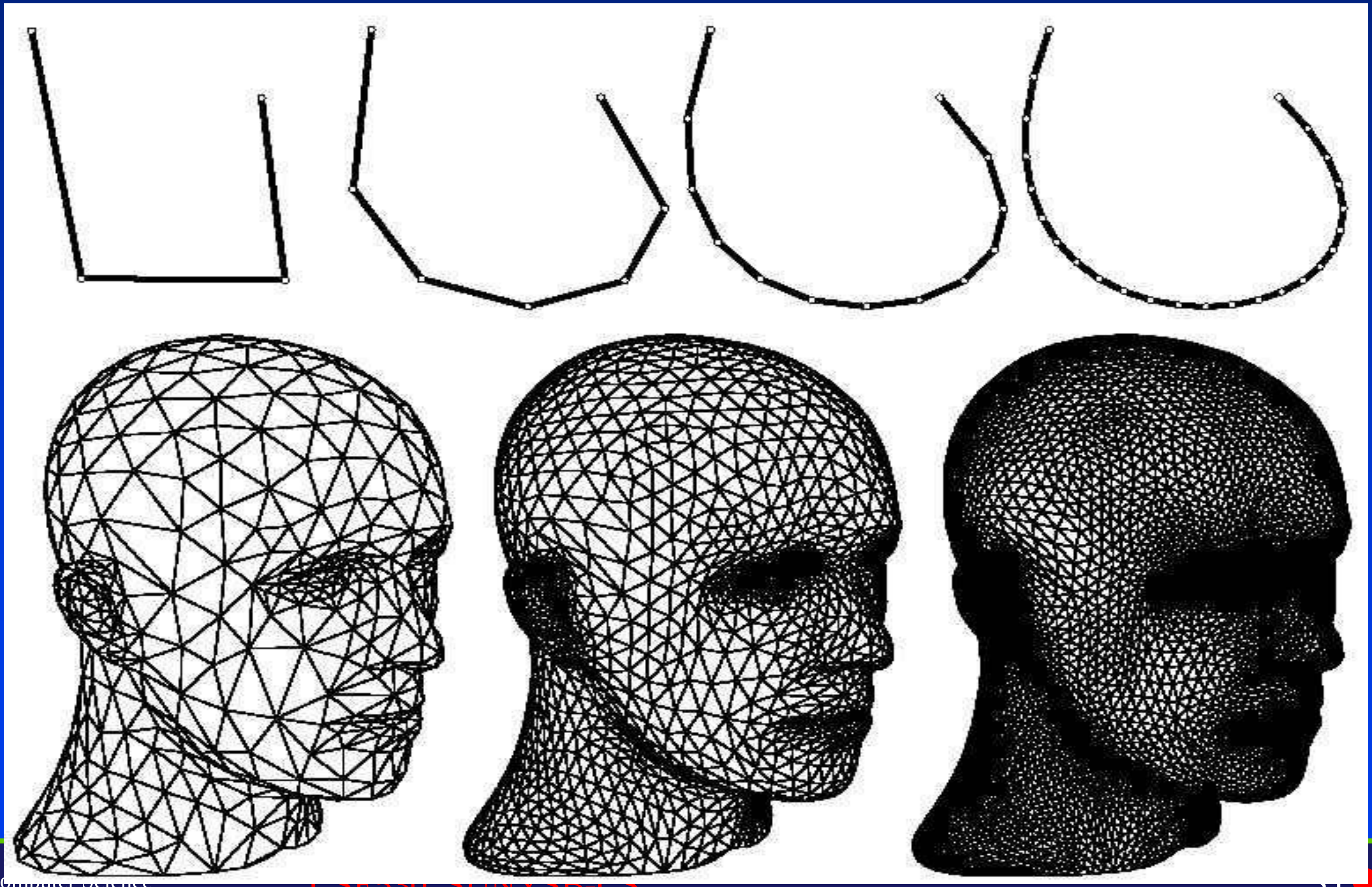
Implicit Functions

$$f(x, y, z) = 0$$



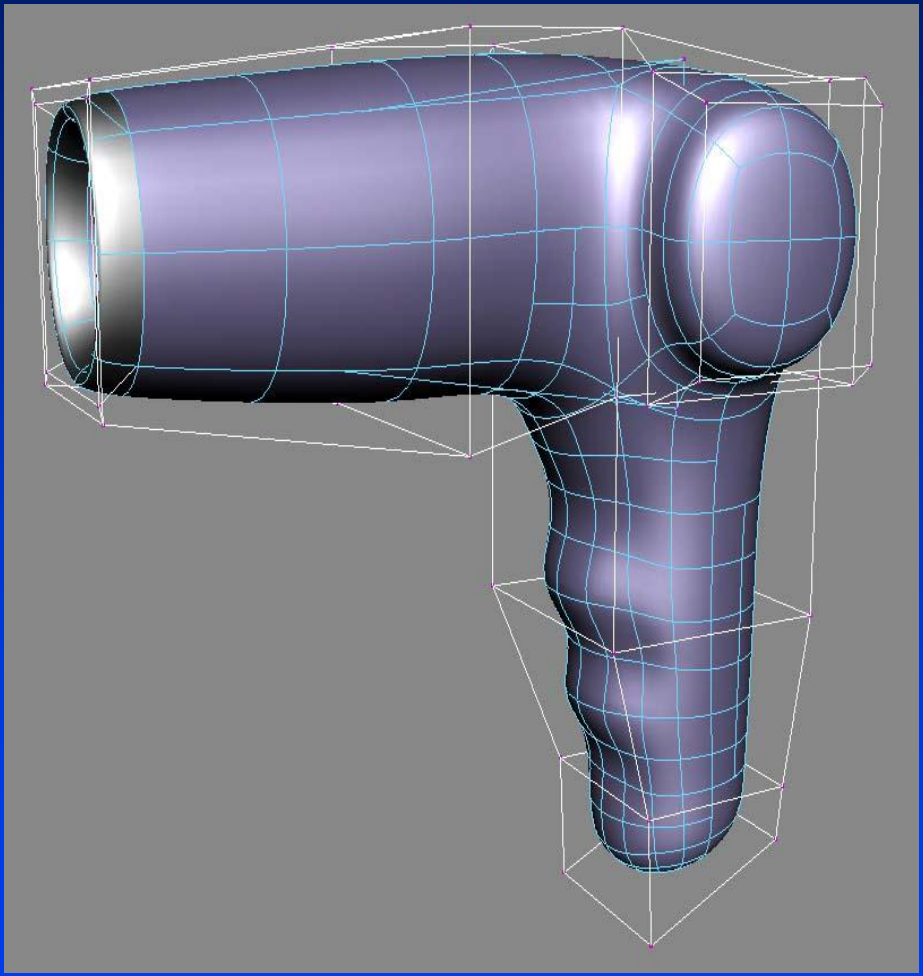
Subdivision Techniques

- Recursively smoothing of a polygon

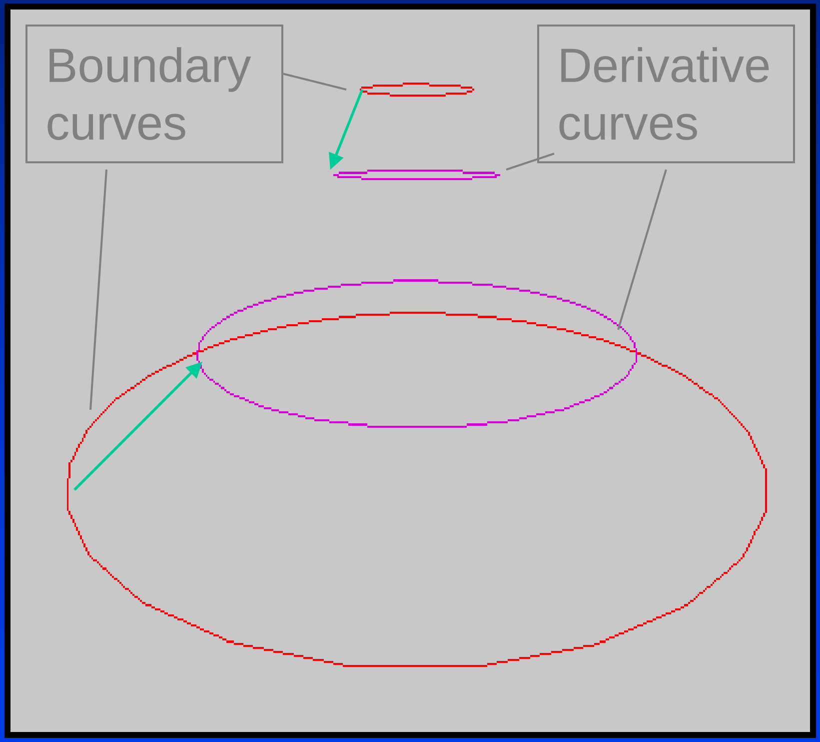


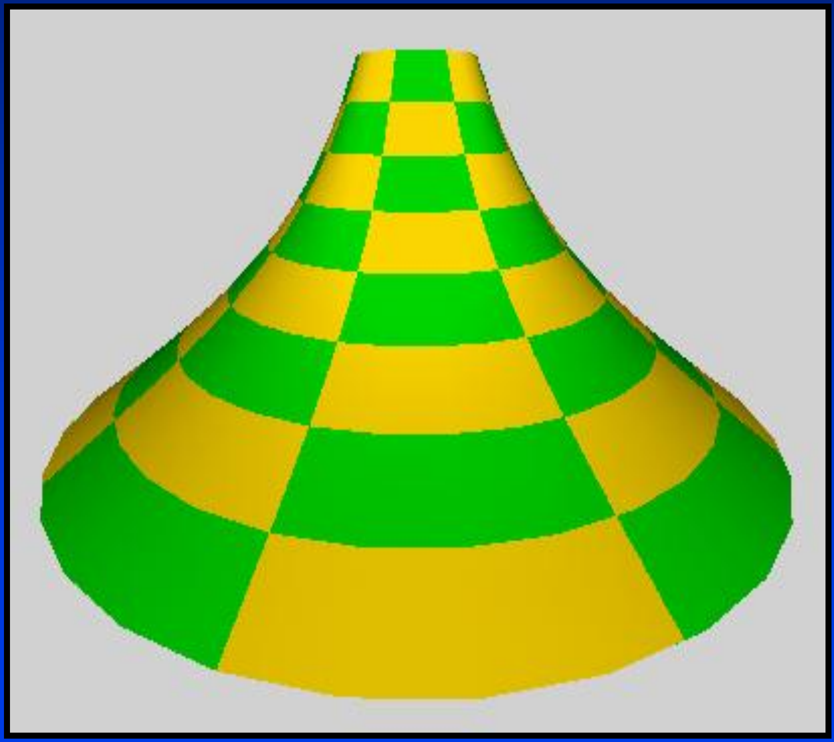
Subdivision Methods

- Good for
  - Smooth surfaces of arbitrary topology
  - Multi-resolution modeling and rendering
- Bad for
  - Mathematical analysis
  - Set operations

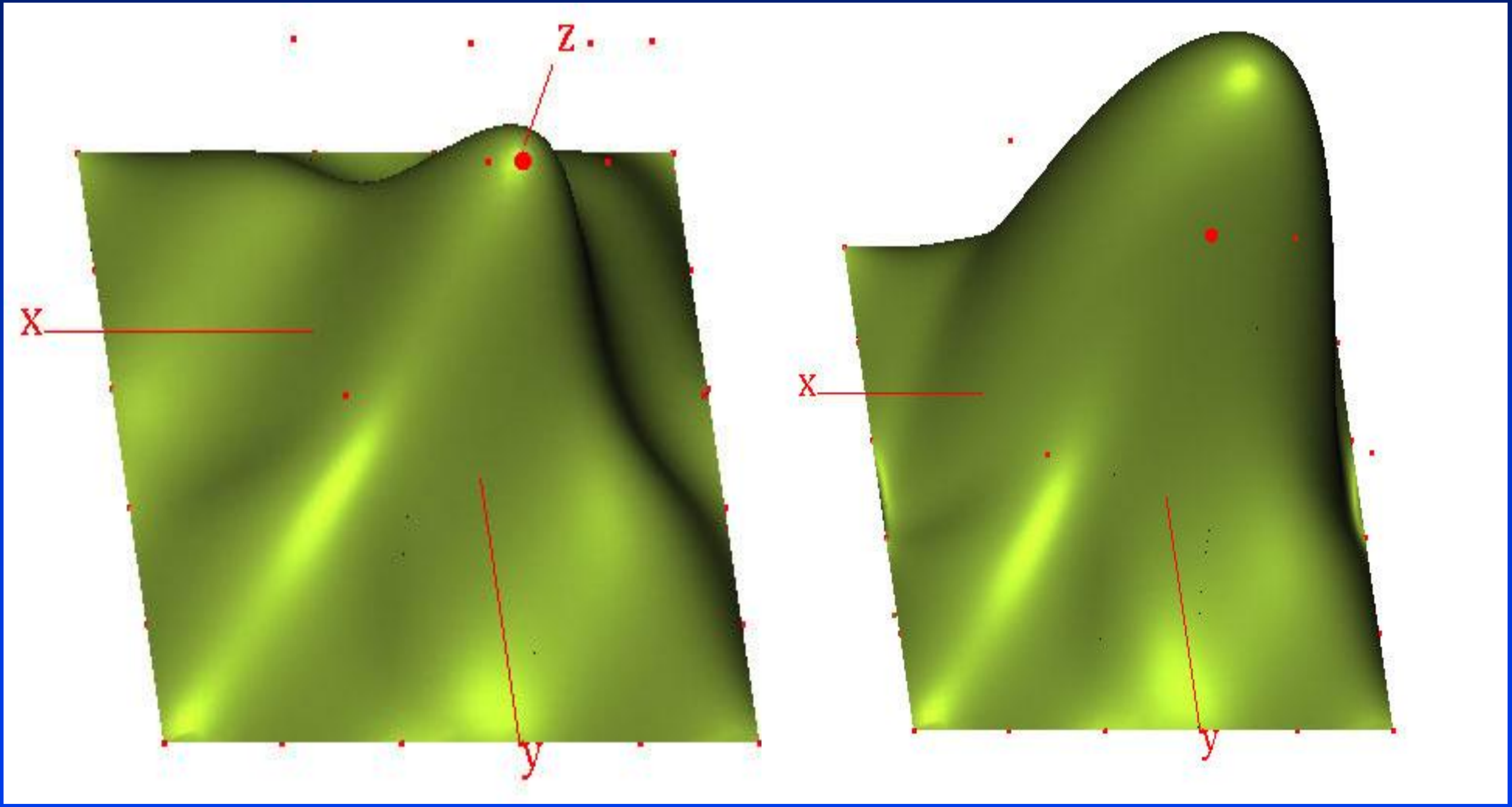


PDE Surface Example

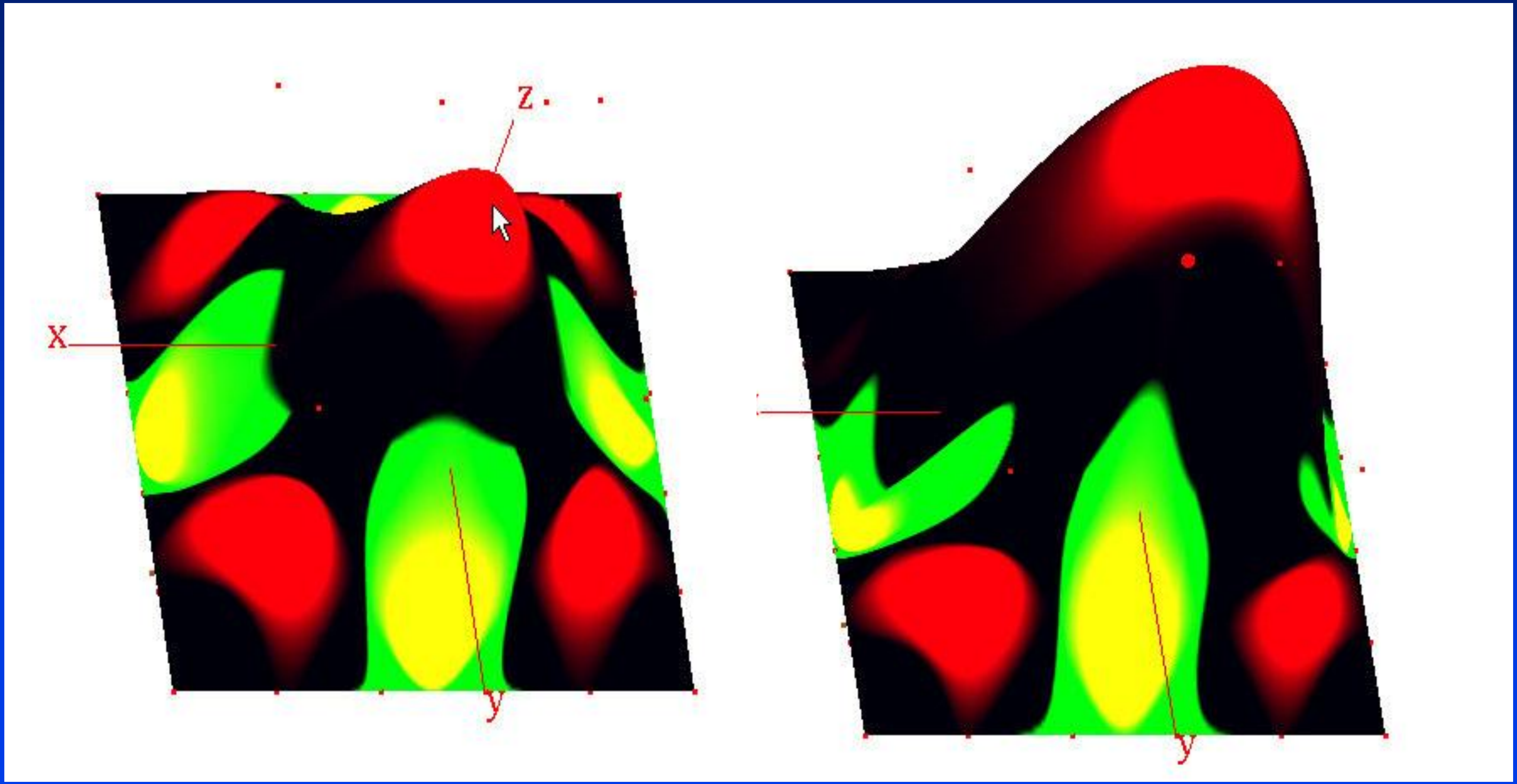




Geometric Manipulation (Curvature)



Result (Curvature at a Point)

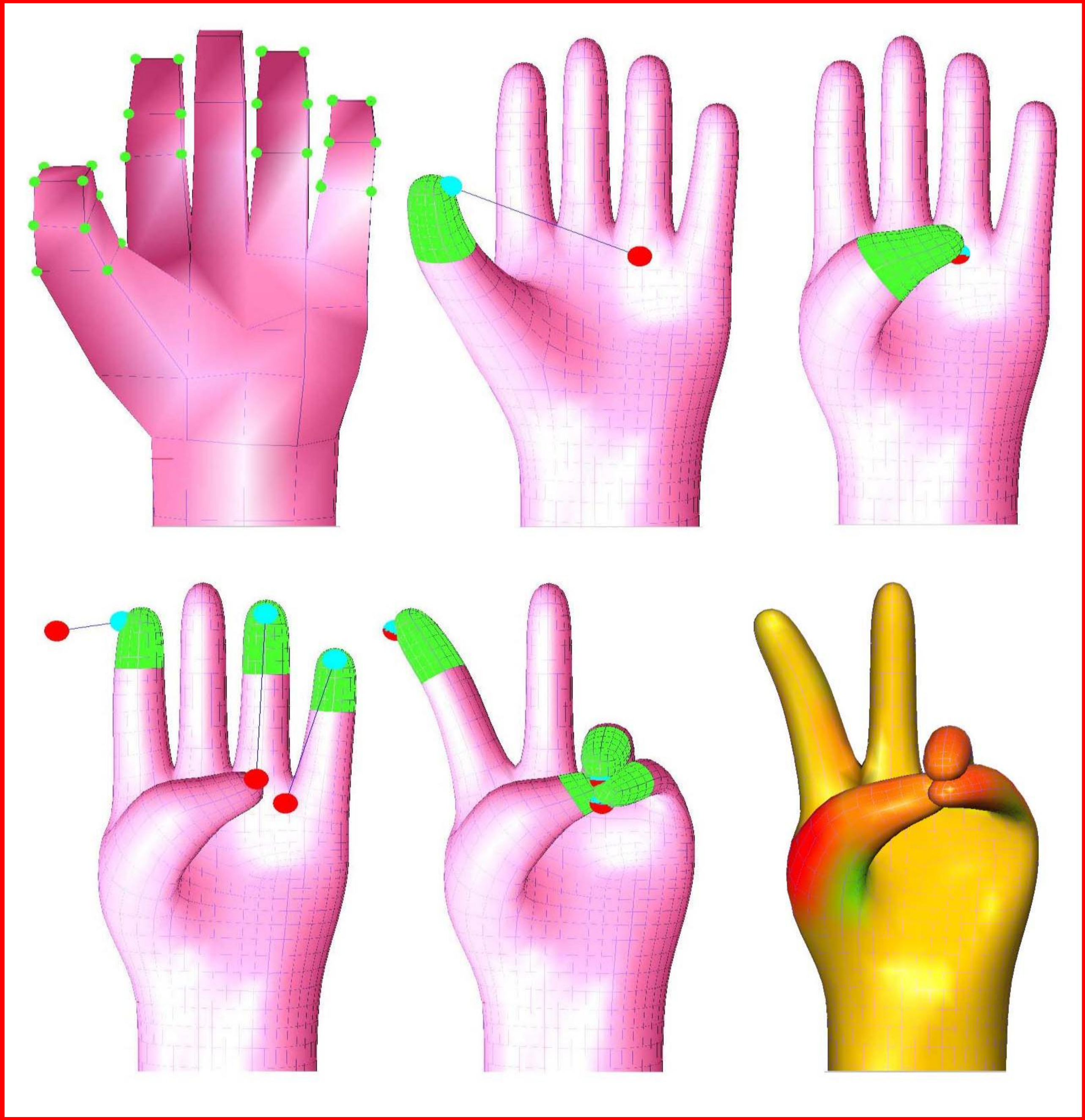


Energy-based Optimization

- Two steps to the optimization approach
  - Formulate modeling requirements of the object in terms of energy functionals
  - Seek a solution which minimizes a weighted combination of these functionals using appropriate techniques (e.g. Conjugate gradient, quasi-Newton's method, etc)

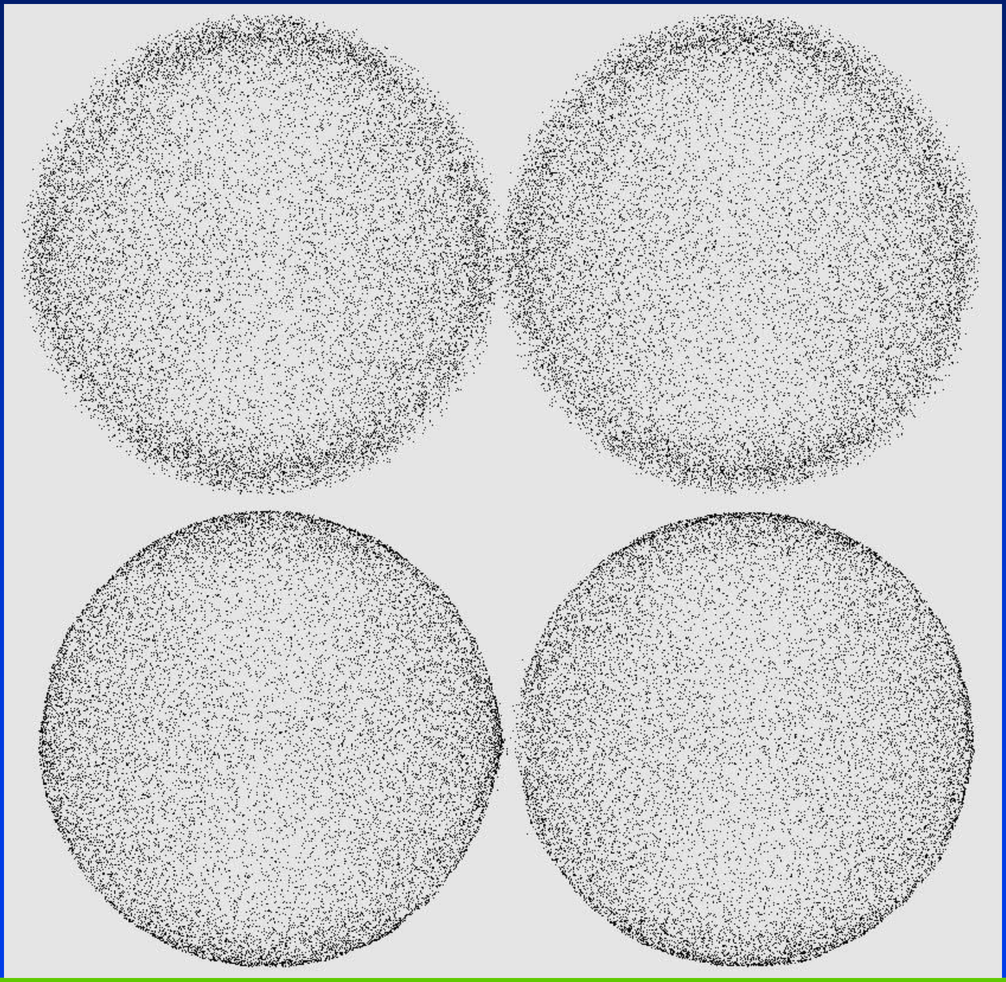
Modeling specifications → Energy Functionals → Optimized Shape Parameters

Examples

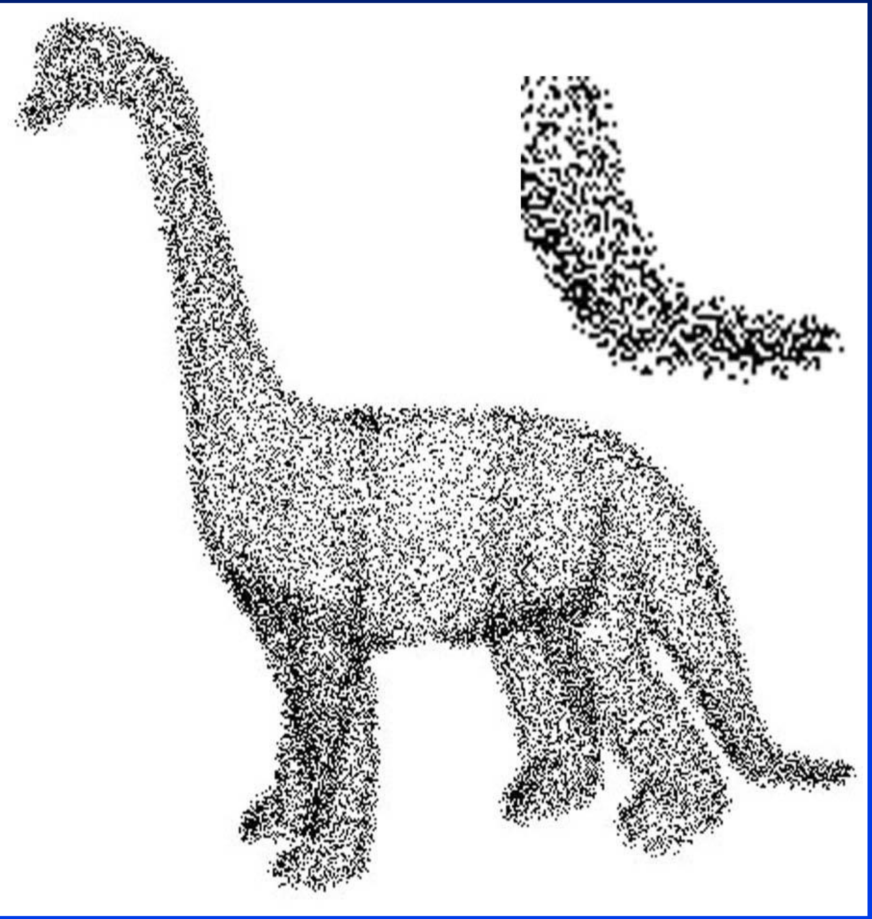


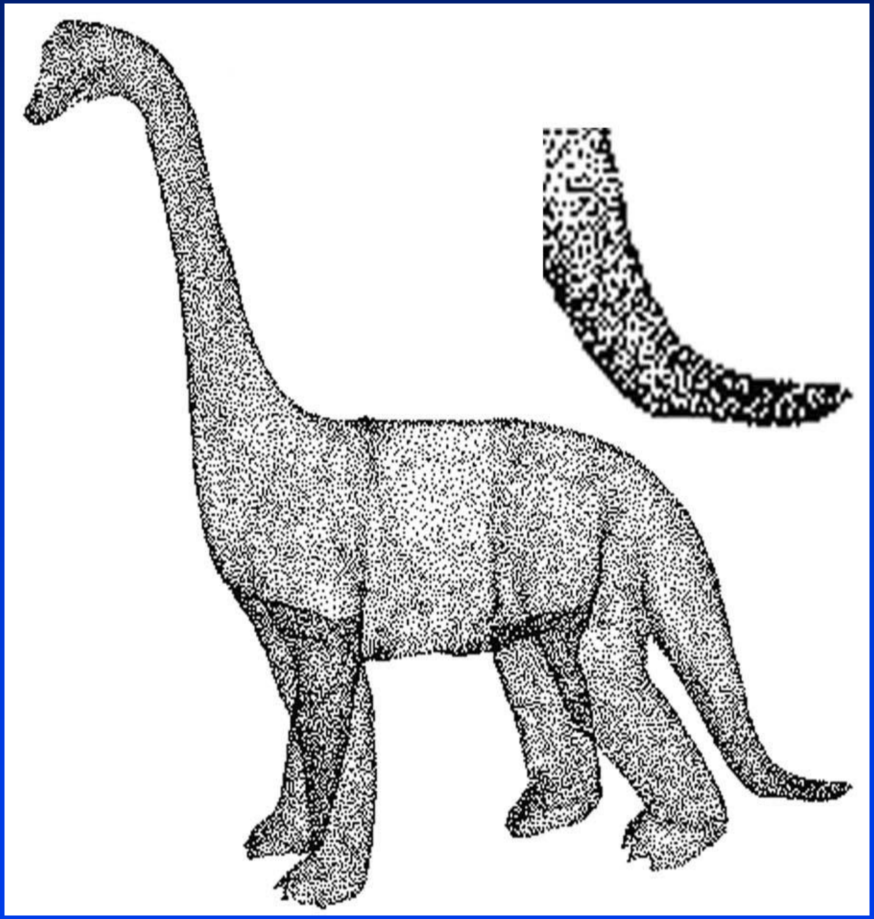
Geometric Processing

- Point-set surfaces and denoising

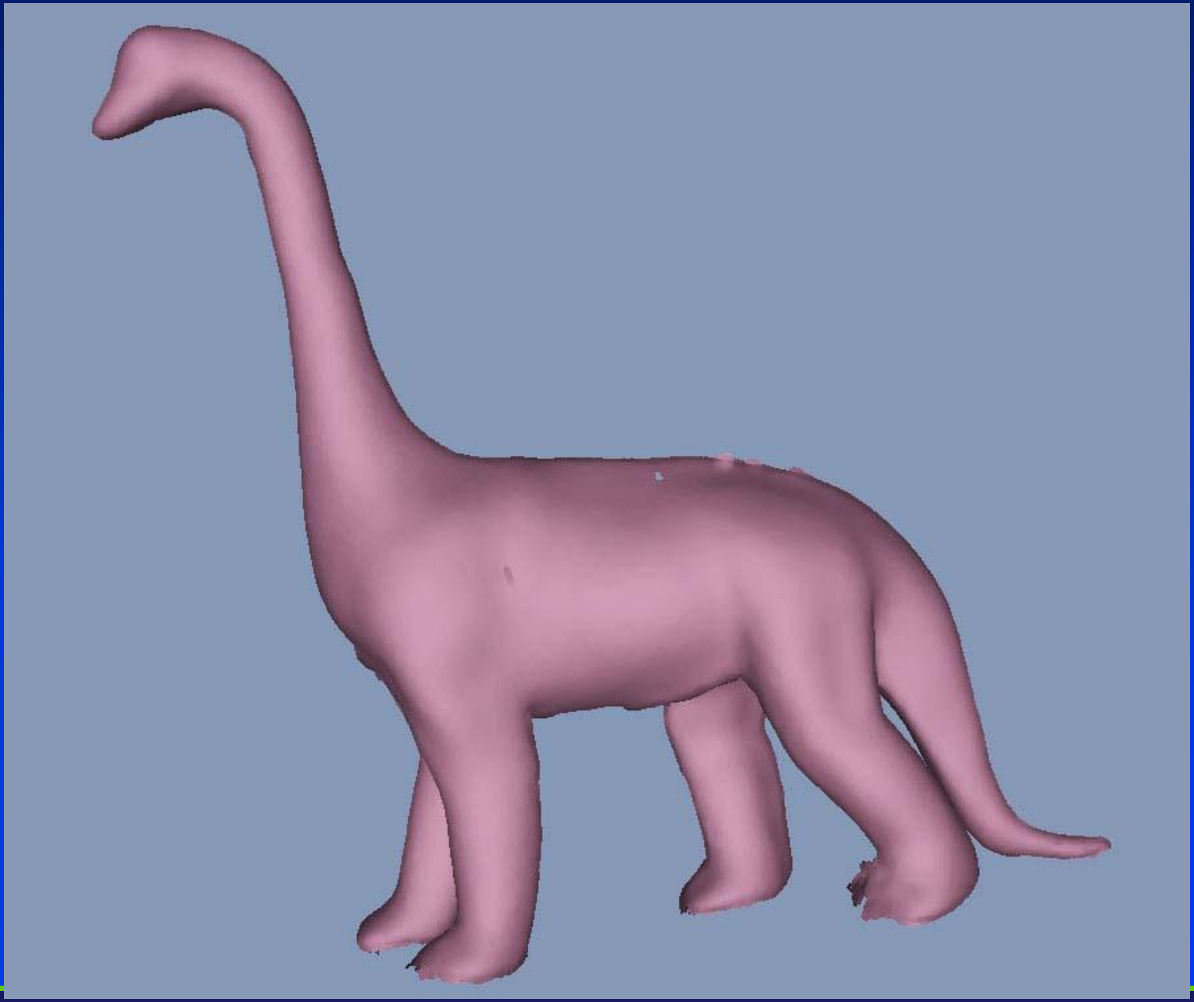


Point Processing

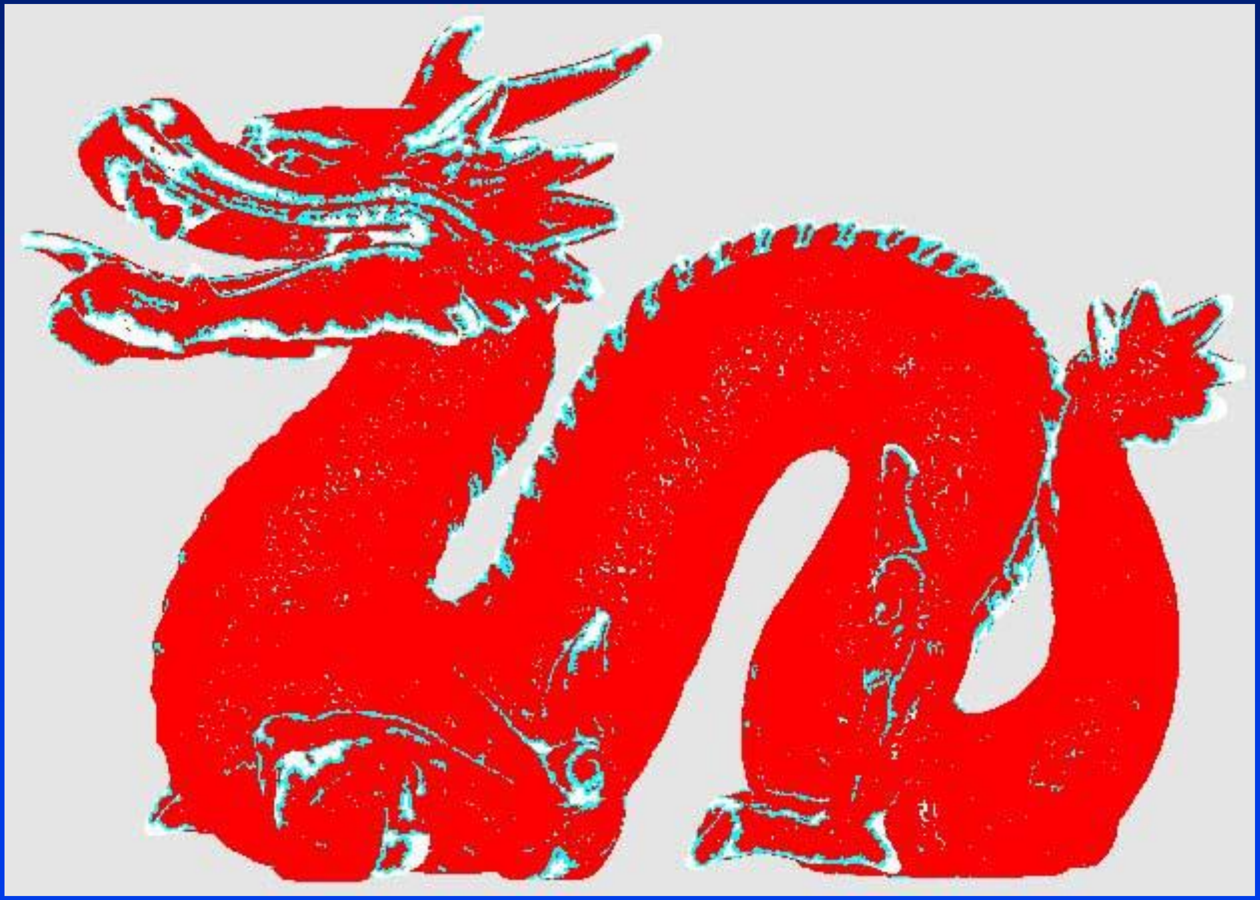




Result



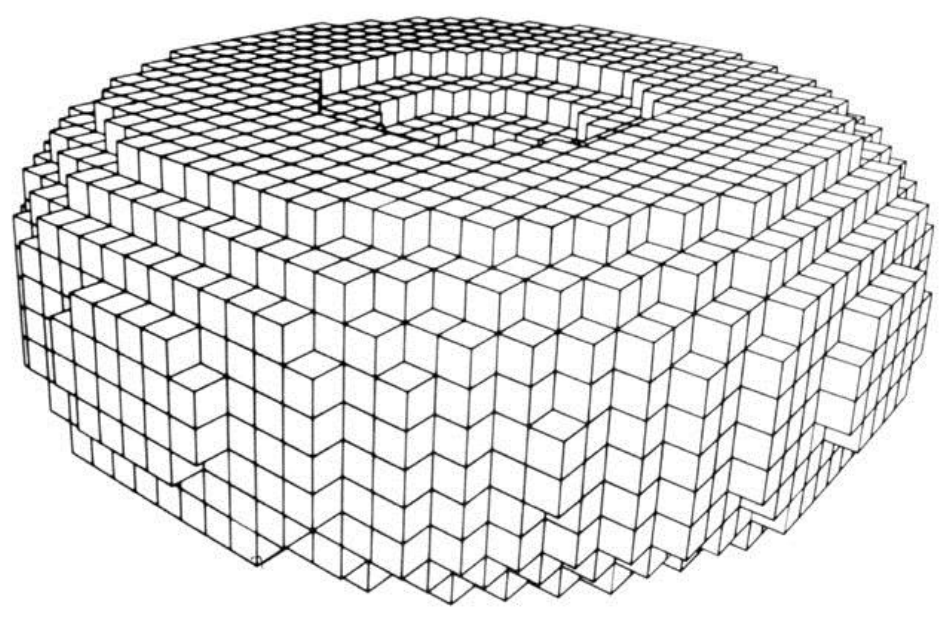
Feature Detection

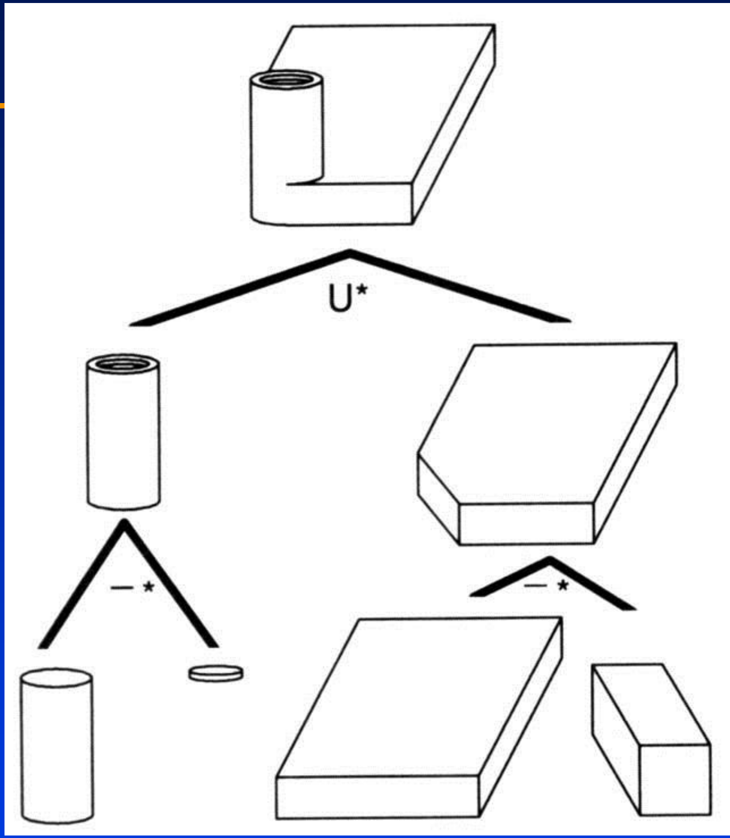


Solid Modeling

Volumetric modeling

can describe interior properties such as density, color, tension, etc.



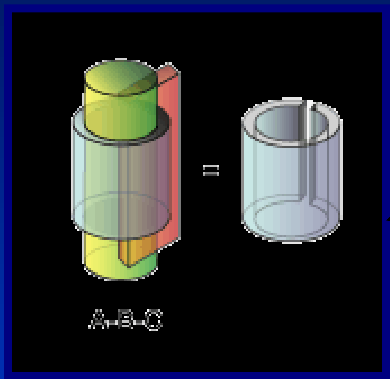


CSG modeling

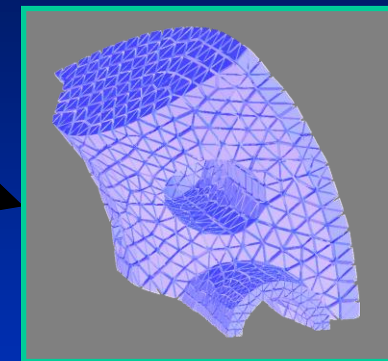
Precise representation for regular shapes

Solid Modeling Techniques

Solid Modeling



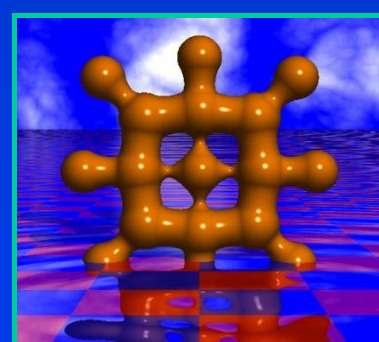
CSG



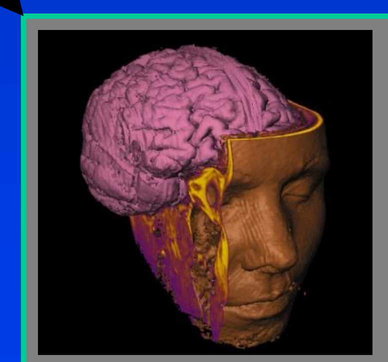
Polyhedral Mesh

B-Rep

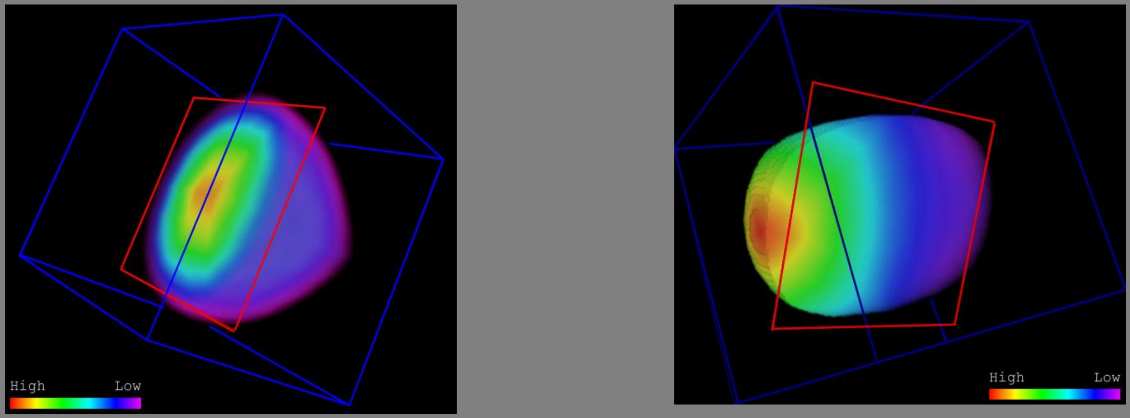
Implicit Function

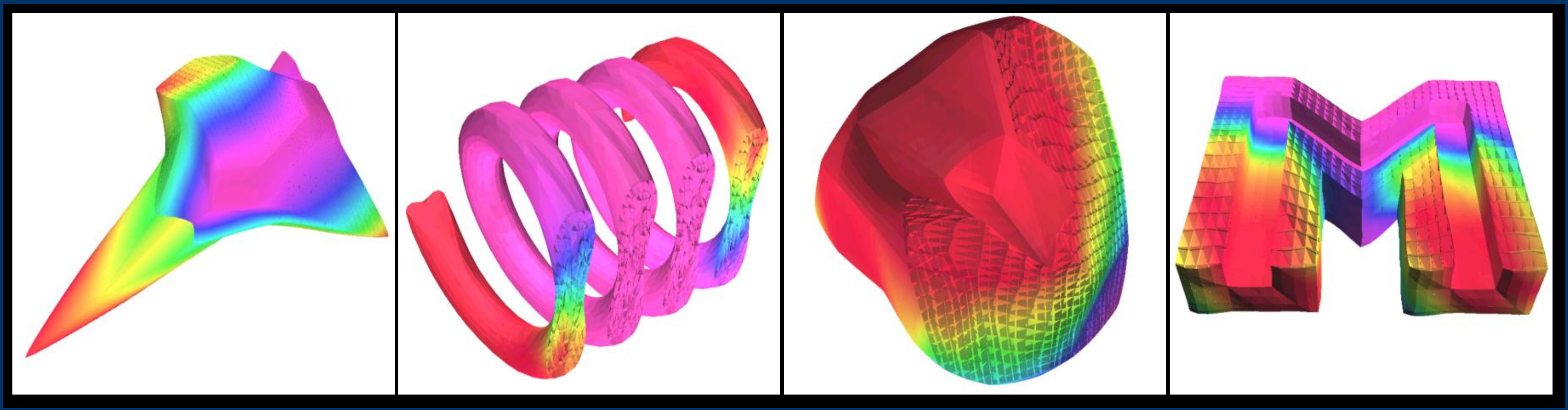


Voxel

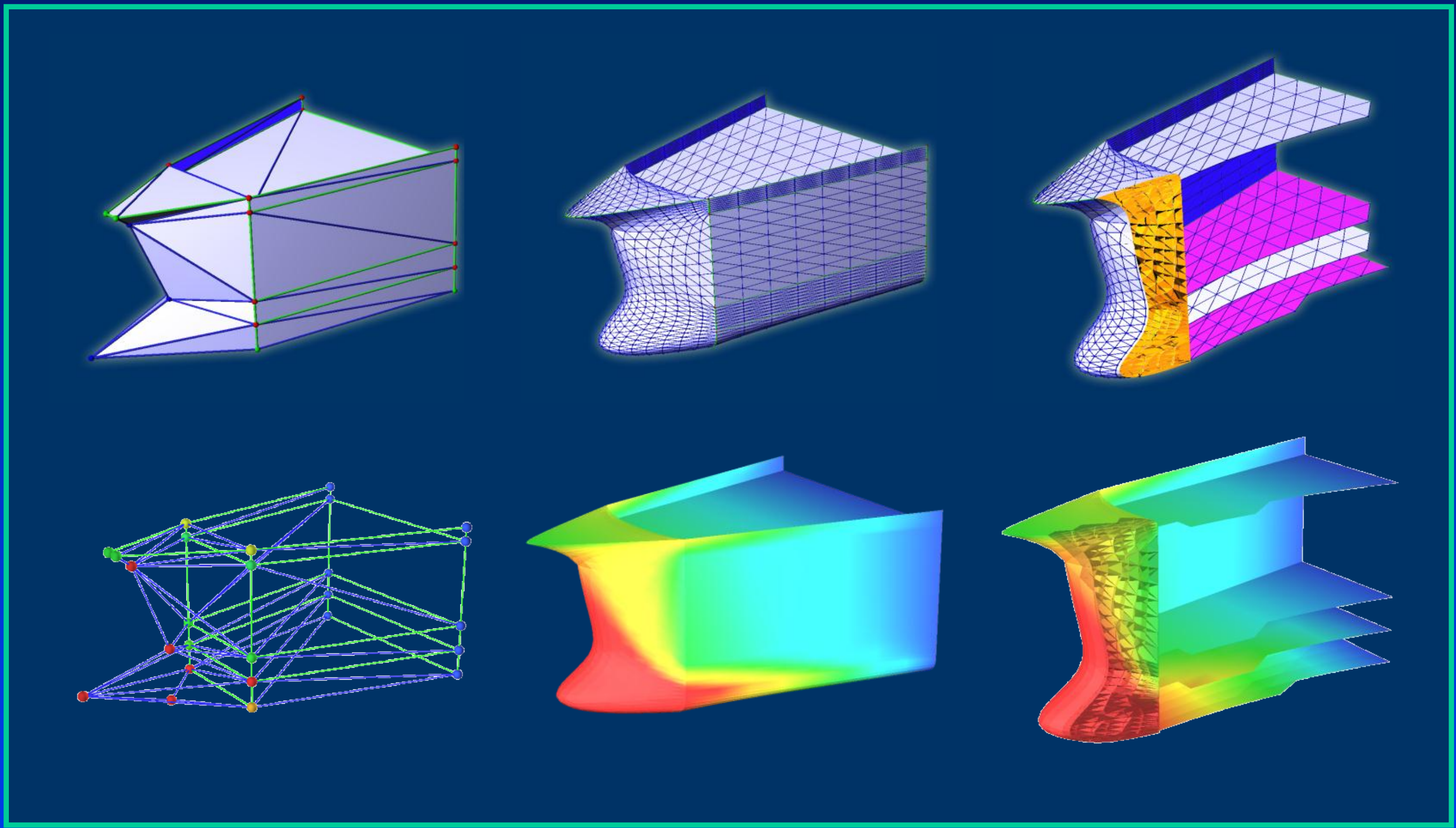


Heterogeneous Material Modeling



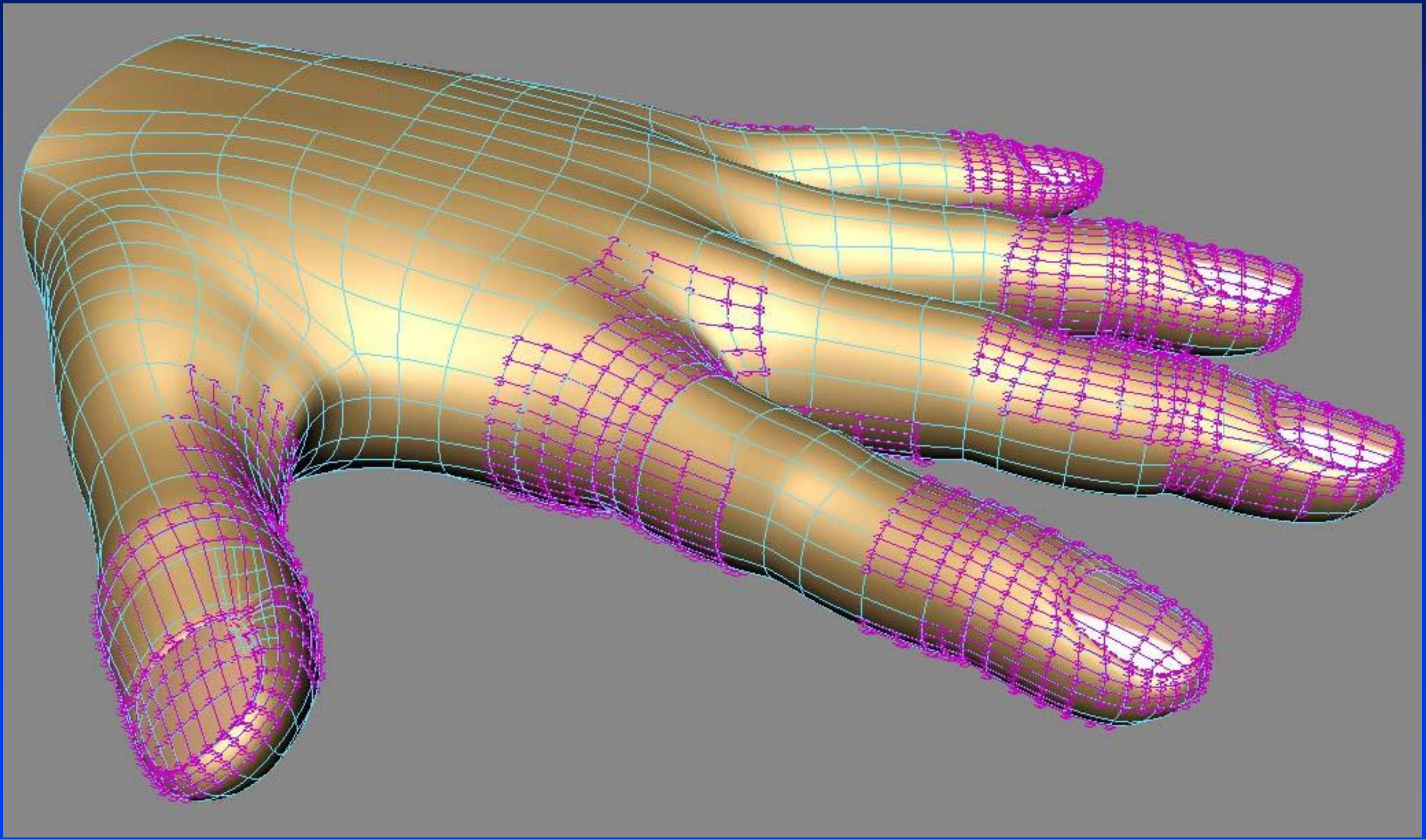


Non-manifold Heterogeneous Object



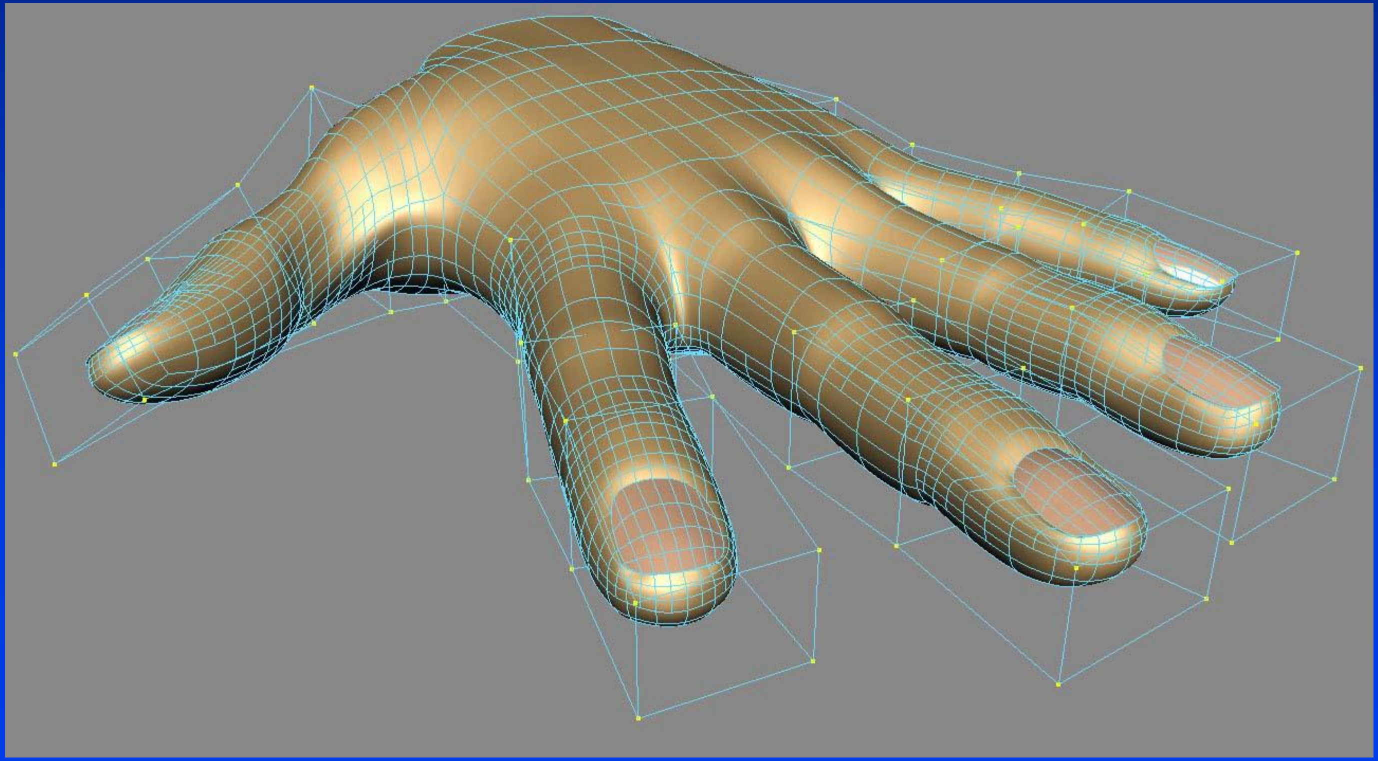
Orange: Solid Cross-section, **Purple**: Surface-only region, **Green**: Features

Hierarchical Modeling and Editing



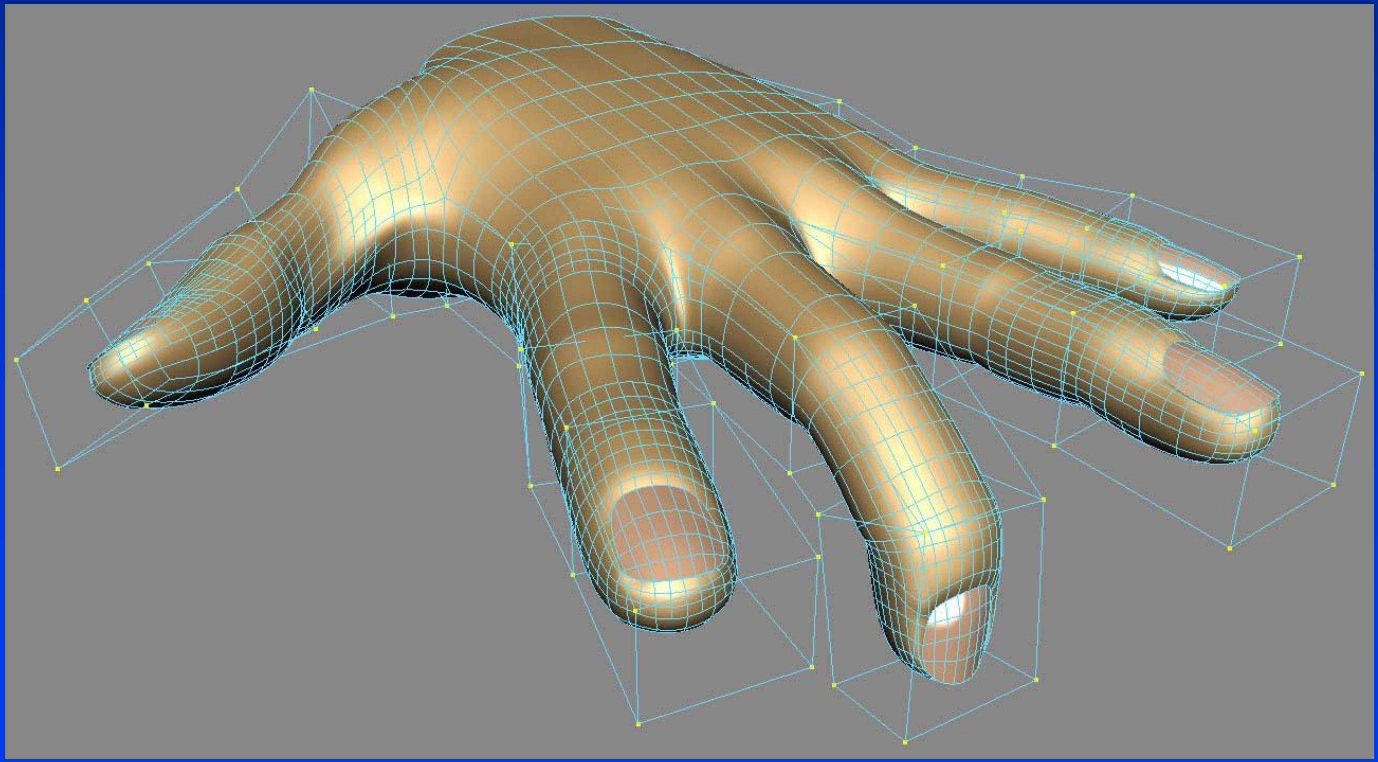
Skeleton-based Editing

- Hierarchical subdivision surface manipulation with virtual (pseudo) skeleton

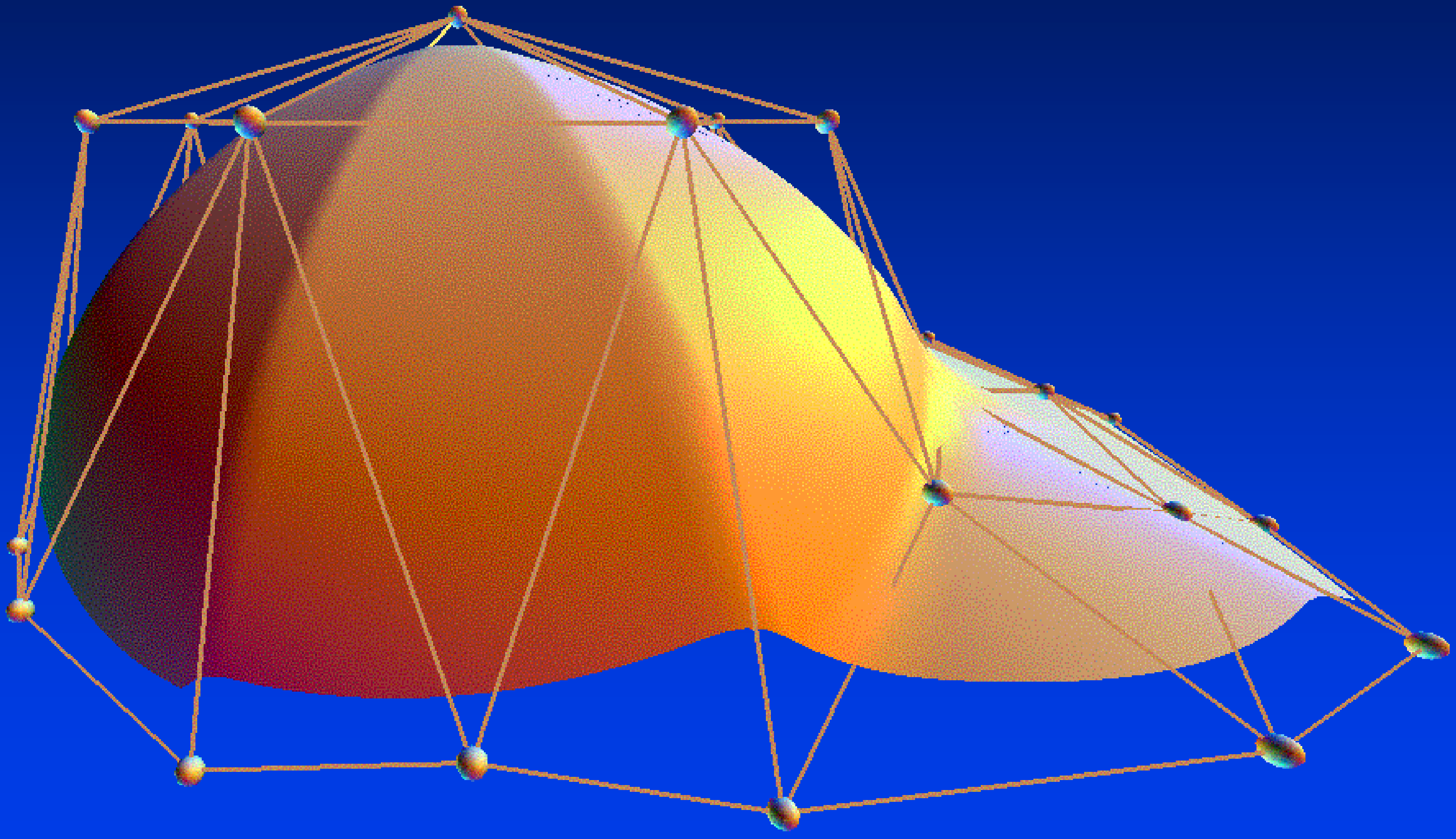


Hierarchical Editing

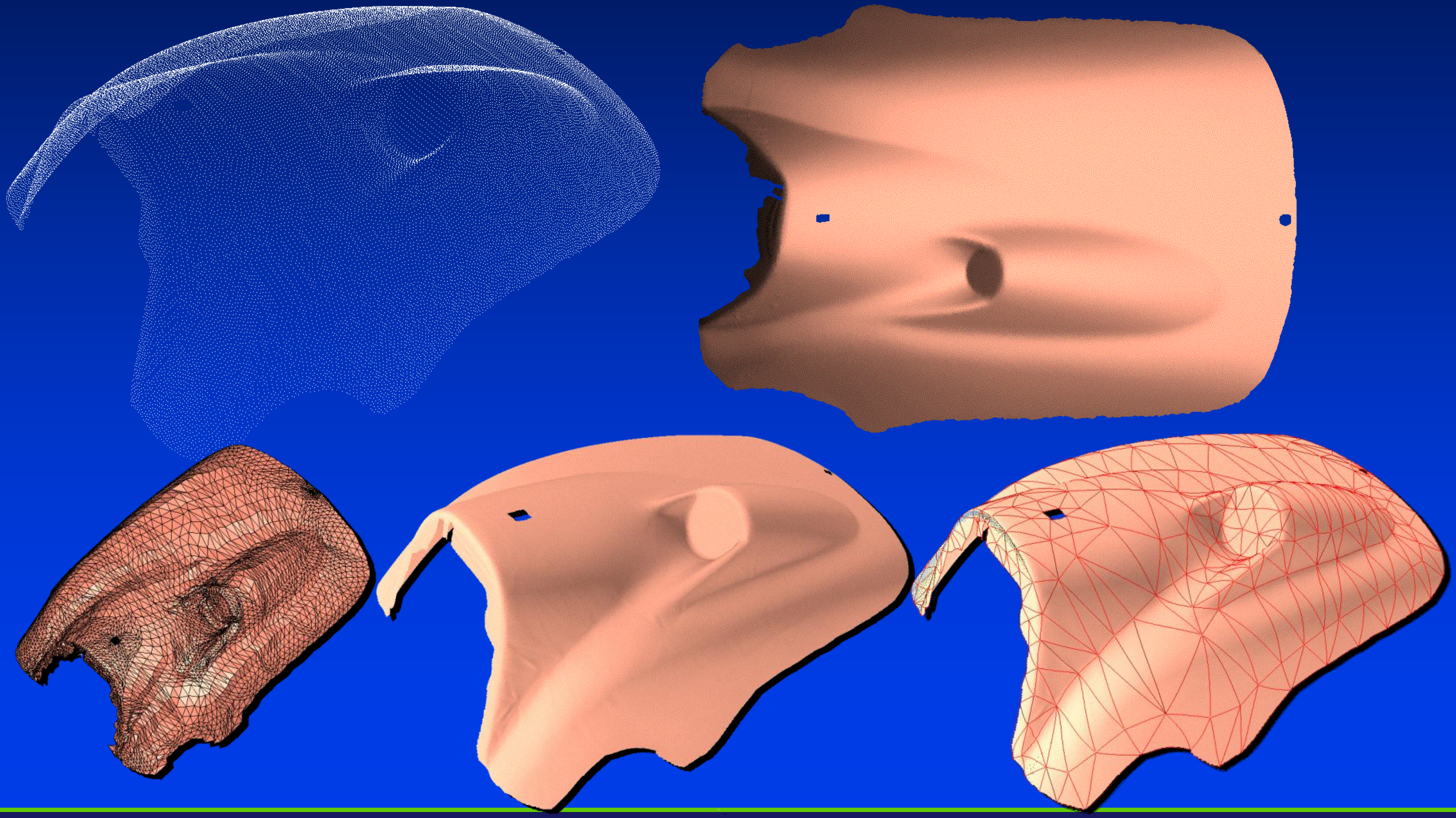
- Hierarchical subdivision surface manipulation with virtual (pseudo) skeleton



Triangular B-splines

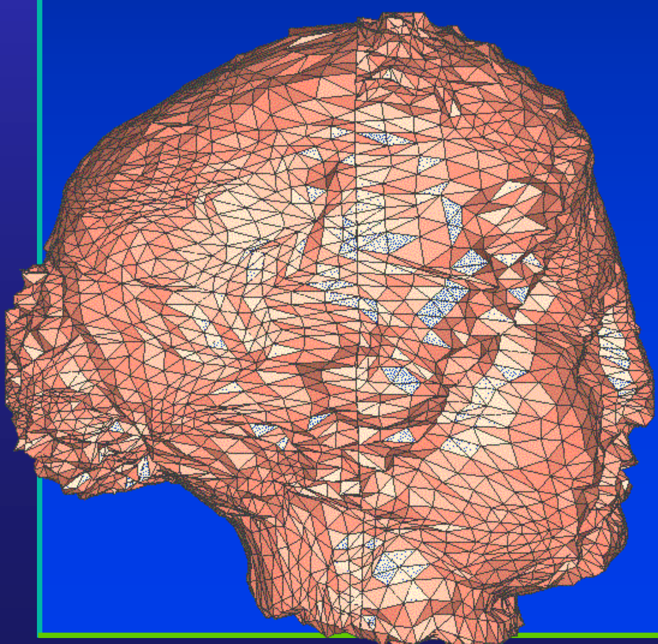


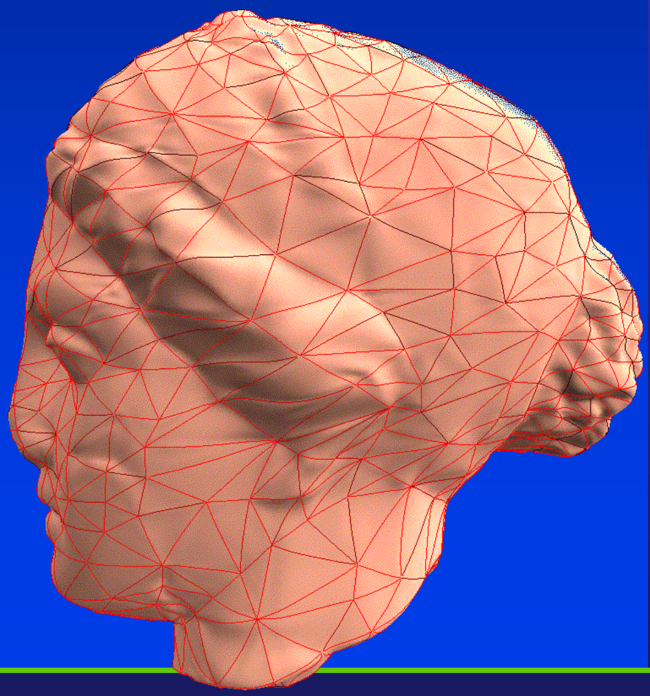
Reverse Engineering (from Points to Splines)



Another Example

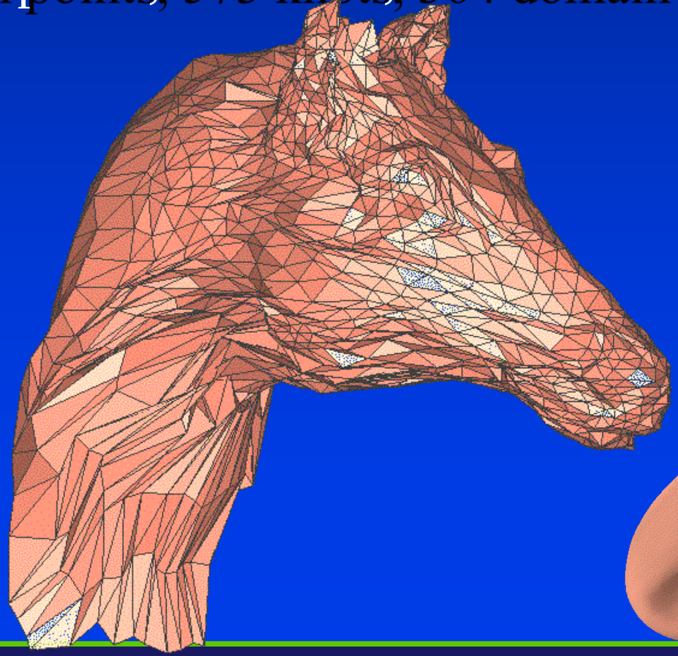
- Venus model: 50,002 points (parameterization data courtesy of Hugues Hoppe)
- C^2 surface:
  - max error 0.64%, mean-square-root error 0.097%
  - 4,381 control points, 1,668 knots, 1,055 domain triangles





Horse Example

- Horse head model: 24,236 points after up-sampling (parameterization data courtesy of Hugues Hoppe)
- C^2 surface:
  - max error 1.04%, mean-square-root error 0.19%
  - 1,663 control points, 573 knots, 364 domain triangles



My Goals for this Course

- My bottomline is that everybody in this class will learn something by the end of this semester, so that people are NOT wasting their time here
- My strategy: breadth (I will make the slides available to everybody) + depth (I will pay attention to several important topics)
- In order to realize these goals, I would like to get everybody involved, and I very much encourage INTERACTION!
- Students must finish their assignments (paper reading, project proposal, various check points) and projects and they should give presentations to the entire class
- Success in graduate education: a good idea (research project) + technical writing (putting together technical reports) that will lead papers in conferences and journals + communication skills (oral presentations at conferences)

Outline

- Mathematical tools and fundamental algorithms
- Geometric modeling concepts and simulation techniques
- Parametric and implicit theory
- Subdivision and multi-resolution
- Differential geometry concepts
- Graphics, visualization, and other visual computing applications
- Advanced topics

References

- Curves and Surfaces for Computer Aided Geometric Design: A Practical Guide, Fourth Edition, Gerald Farin, September 1996
- Geometric Modeling, Second Edition, Michael E. Mortenson, John Wiley & Sons, January 1997
- The NURBS Book, Second Edition, Les A. Piegl and W. Tiller, Springer Verlay, January 1997

Other Books

- Computer Graphics, Hearn and Baker, 3rd Edition, Prentice Hall, 2003.
- Computer Graphics: Principles and Practice, James D. Foley, Andries van Dam, Steven K. Feiner, and John F. Hughes, 2nd edition, Addison Wesley, 1990.
- 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.

Other Books

- Differential Geometry of Curves and Surfaces, M.P. do Carmo, Prentice-Hall, Englewood Cliffs, NJ, 1976.
- Introduction to Applied Mathematics, G. Strang, Wellesley Cambridge Press, 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.

Journals and Conferences

- Computer Graphics (proceedings of ACM SIGGRAPH)
- ACM Transactions on Graphics
- IEEE Transactions on Visualization and Computer Graphics
- IEEE Computer Graphics and Applications
- Computer-Aided Design
- Computer Aided Geometric Design
- Others!!!

Graphics and Visualization Overview

- What is computer graphics
- What is visualization (scientific visualization, information visualization)

What is Computer Graphics

- The creation of, manipulation of, analysis of, and interaction with **pictorial representations** of objects and data **using computers**

  - Dictionary of Computing

- Computer Graphics is also called Image Synthesis
- **A picture is worth a thousand words**

  - Chinese Proverb

Computer Graphics

- (Realistic) pictorial synthesis of real and/or imaginary objects from their computer-based models (datasets)
- It typically includes modeling, rendering (graphics pipeline, and human-computer interaction
- So, we are focusing on computer graphics hardware, software, and mathematical foundations
- Computer Graphics is computation
  - A new method of visual computing
- Why is Computer Graphics useful and important?

Basic Elements of Computer Graphics

- Graphics modeling: representation choices
- Graphics rendering: geometric transformation, visibility, discretization, simulation of light, etc.
- Graphics interaction: input/output devices, tools
- Animation: lifelike characters, their interactions, surrounding environments

Mathematical Background

- Computer Graphics has a strong 2D/3D geometry component
- Basic linear algebra is also helpful – matrices, vectors, dot products, cross products, etc.
- More continuous math (vs. discrete math) than in other typical computer science courses
- Function plots, curves, and surfaces

Primary Topics

- Overview, applications
- Basic components, history development
- Hardware, system architecture, raster-scan graphics
- Line drawing, scan conversion
- 2D transformation and viewing
- 3D transformation and viewing
- Hierarchical modeling
- Interface
- Geometric models
- Color representations
- Hidden object removal
- Illumination models
- Advanced topics

A Very Good Textbook for General Issues in Computer Graphics

- Computer Graphics with OpenGL, 3rd Edition, Donald Hearn and M. Pauline Baker, Prentice Hall, 2004.

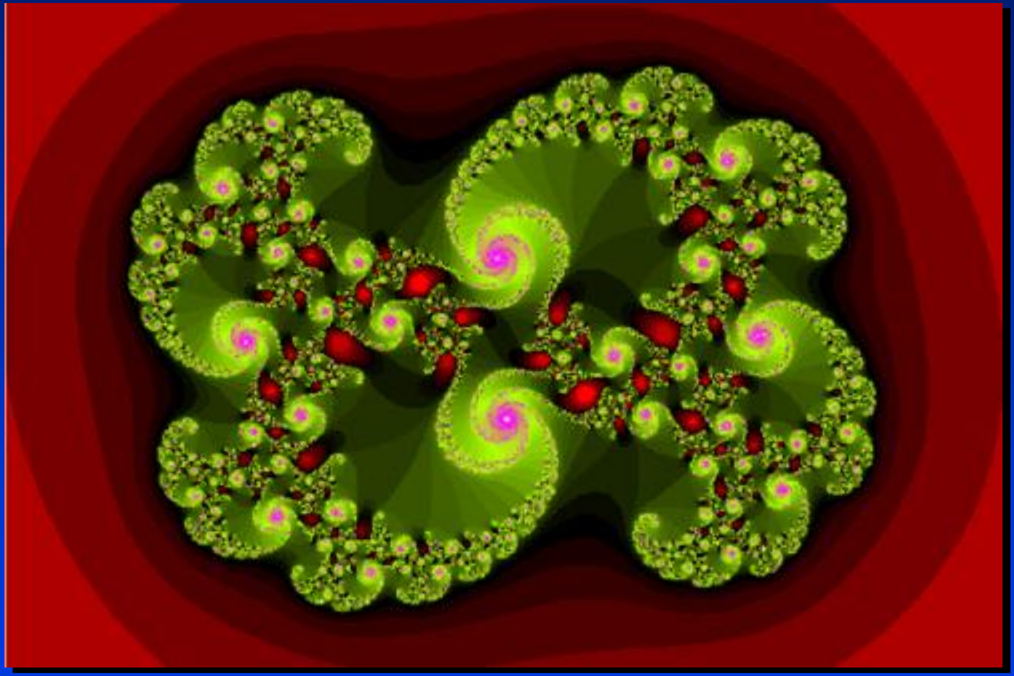
OpenGL Reference Books

1. OpenGL Programming Guide, 4th Edition: The Official Guide to Learning OpenGL, Version 1.4, Addison-Wesley, 2004.
2. OpenGL Reference Manual, 4th Edition: The Official Reference Document to OpenGL, Version 1.4, Addison-Wesley, 2004.

Why Graphics and Visualization

- A Chinese proverb: “ a picture is worth a thousand words.”
- **“A picture is worth more than a thousand words.” – ancient proverb**

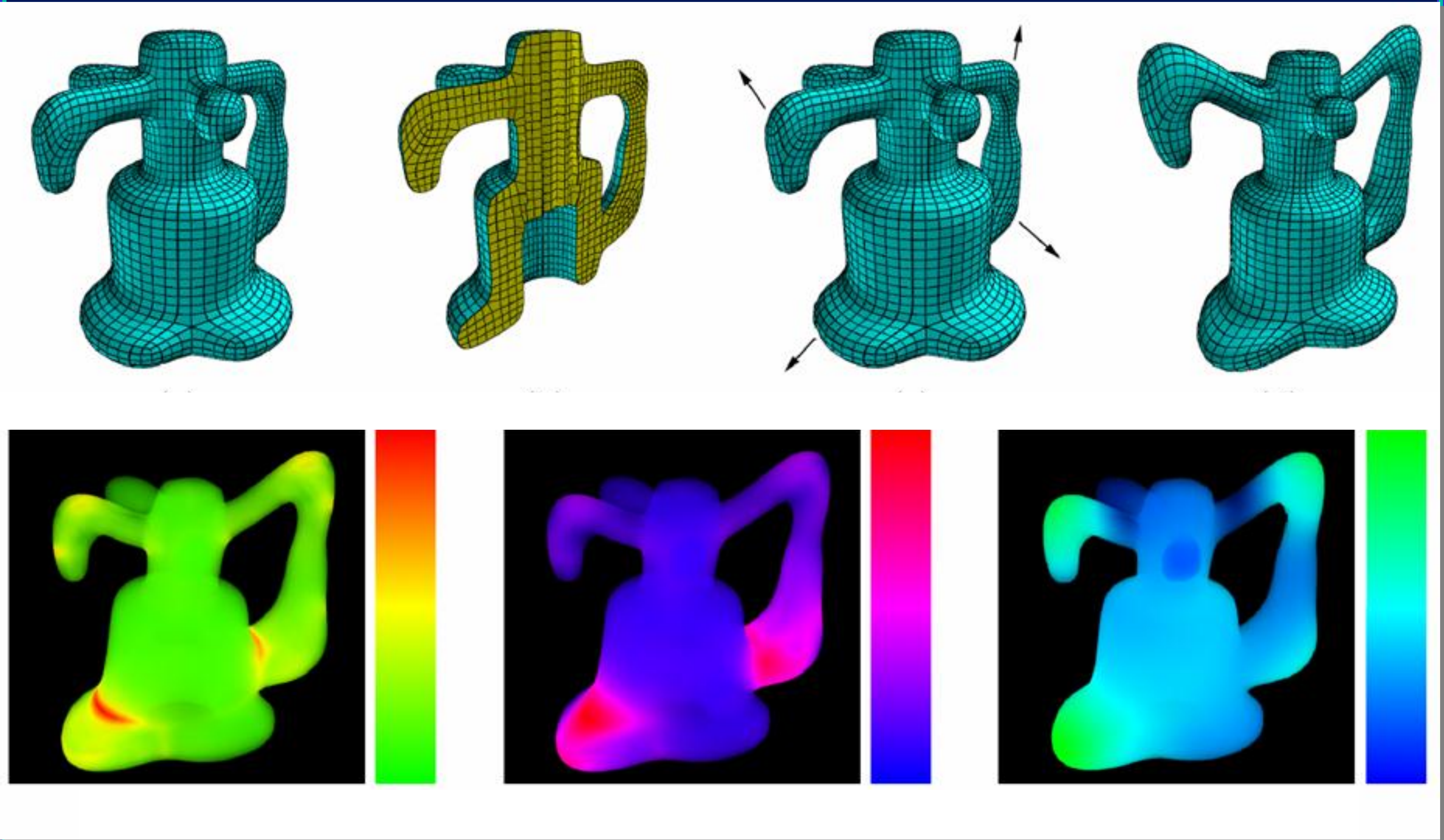
One Picture



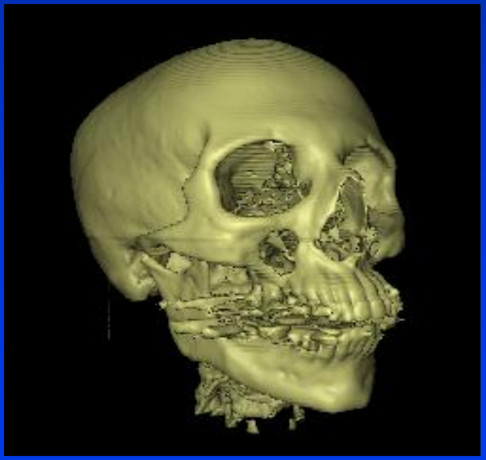
Many Words…

1000 words (or just 94 words), many letters though…

It looks like a swirl. There are smaller swirls at the edges. It has different shades of red at the outside, and is mostly green at the inside. The smaller swirls have purple highlights. The green has also different shades. Each small swirl is composed of even smaller ones. The swirls go clockwise. Inside the object, there are also red highlights. Those have different shades of red also. The green shades vary in a fan, while the purple ones are more uni-color. The green shades get darker towards the outside of the fan……………………………………………..

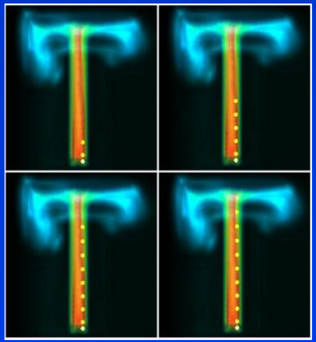


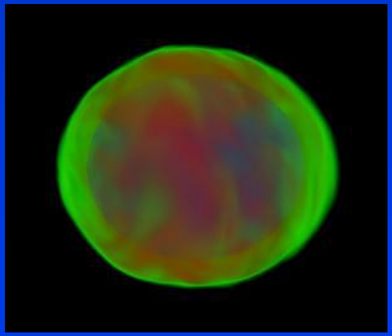
Graphics Examples



What is Visualization

Visualization is a method of extracting meaningful information from complex or voluminous datasets through the use of interactive graphics and imaging





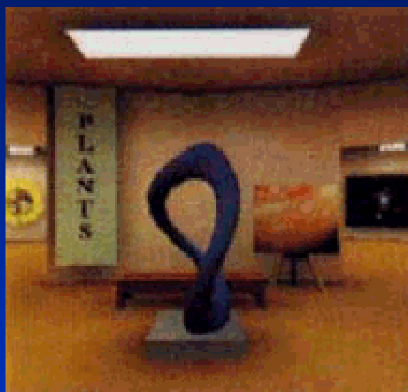
Why Visualization

- Enable scientists (also engineers, physicians, general users) to observe their simulation and computation
- Enable them to describe, explore, and summarize their datasets (models) and gain insights
- Offer a method of SEEING the UNSEEN
- Reason about quantitative information
- Enrich the discovery process and facilitate new inventions

Why Visualization

- Analyze and communicate information
- Revolutionize the way scientists/engineers/physicians conduct research and advance technologies
- About 50% of the brain neurons are associated with vision
- The gigabit bandwidth of human eye/visual system permits much faster perception of visual information and identify their spatial relationships than any other modes
  - Computerized human face recognition

More Examples

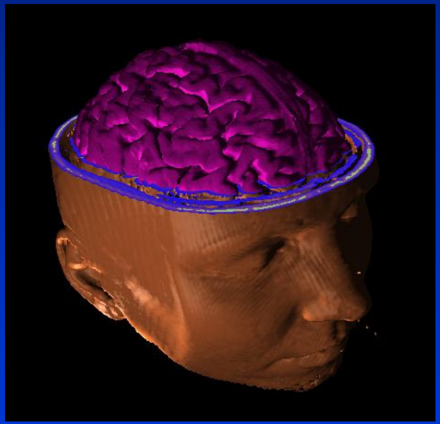


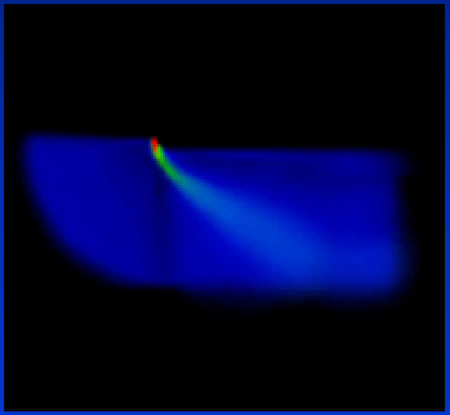
Images

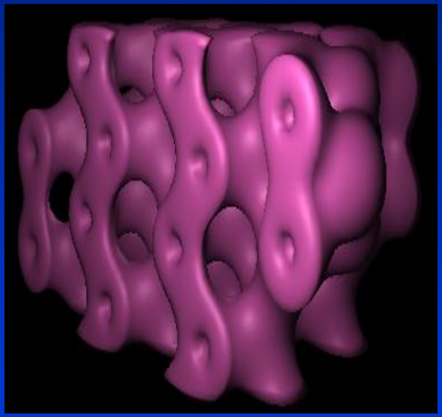
Points

Volumes

More Examples



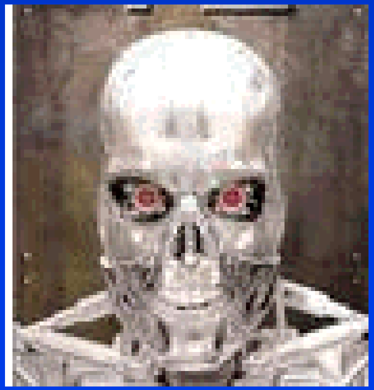




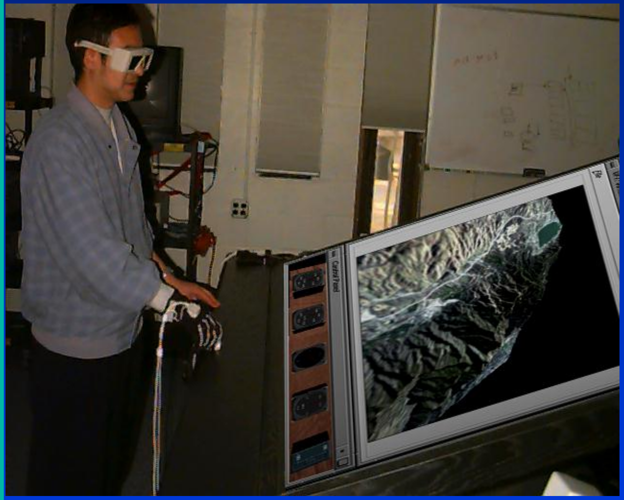
Terrain Modeling and Rendering

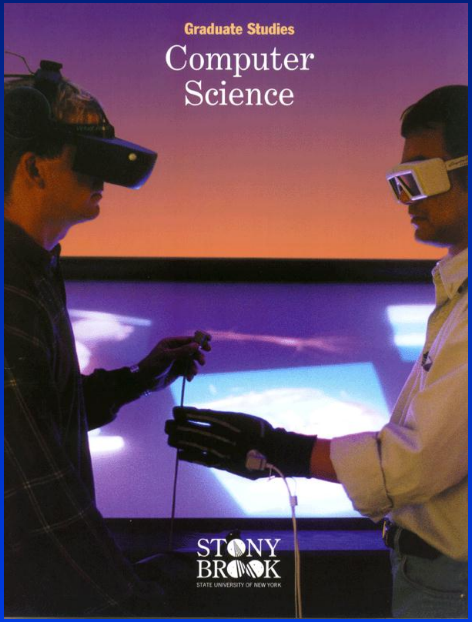
Medicine and Health-care

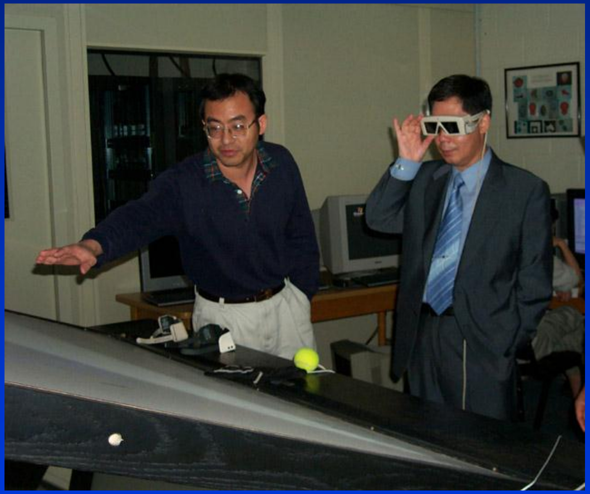
Entertainment



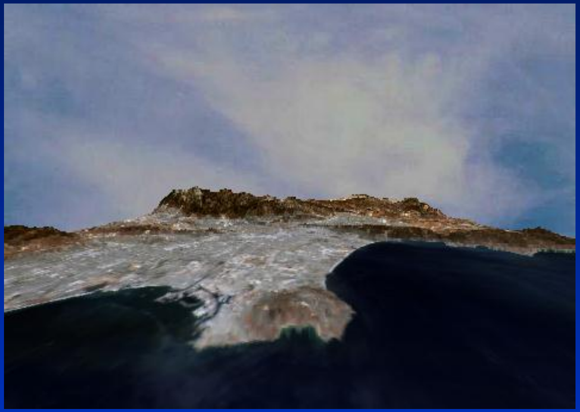
Virtual Environment

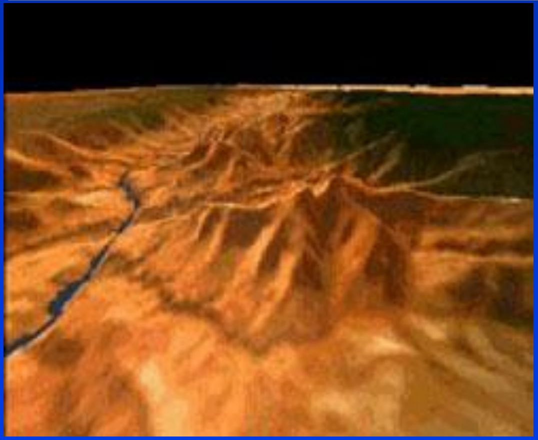






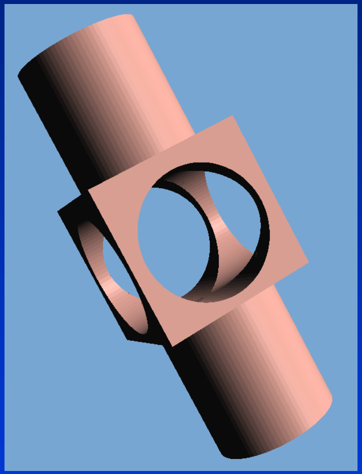
National Security





Tourism

Design and Manufacturing



In the Future

- **Network and Internet Graphics**

3D Advertisement

Server

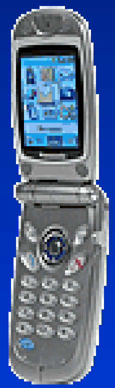
Virtual Museum

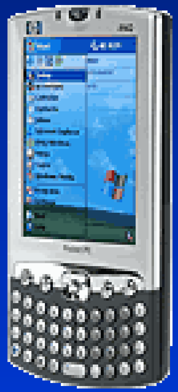
Client

Live Sports Broadcast

In the Future

- **Wireless Graphics**





What Are Our Ultimate Goals?

- A large variety of datasets (acquired via scanning devices, super-computer simulation, mathematical descriptions, etc.)
- A pipeline of data processing that consists of data modeling (reconstruction), representation, manipulation (rigid transformation or deformation), classification (segmentation), feature extraction, simulation, analysis, visual display, conversion, storage, etc.
- Visual information processing

What Are Our Ultimate Goals?

- Datasets that are huge, multi-dimensional, time-evolving, unstructured, multi-attributes (geometric info. + material distributions), scattered (both temporal and spatial)…
- We are investigating mathematical tools and computational techniques for data modeling, reconstruction, manipulation, simulation, analysis, and display

Challenges

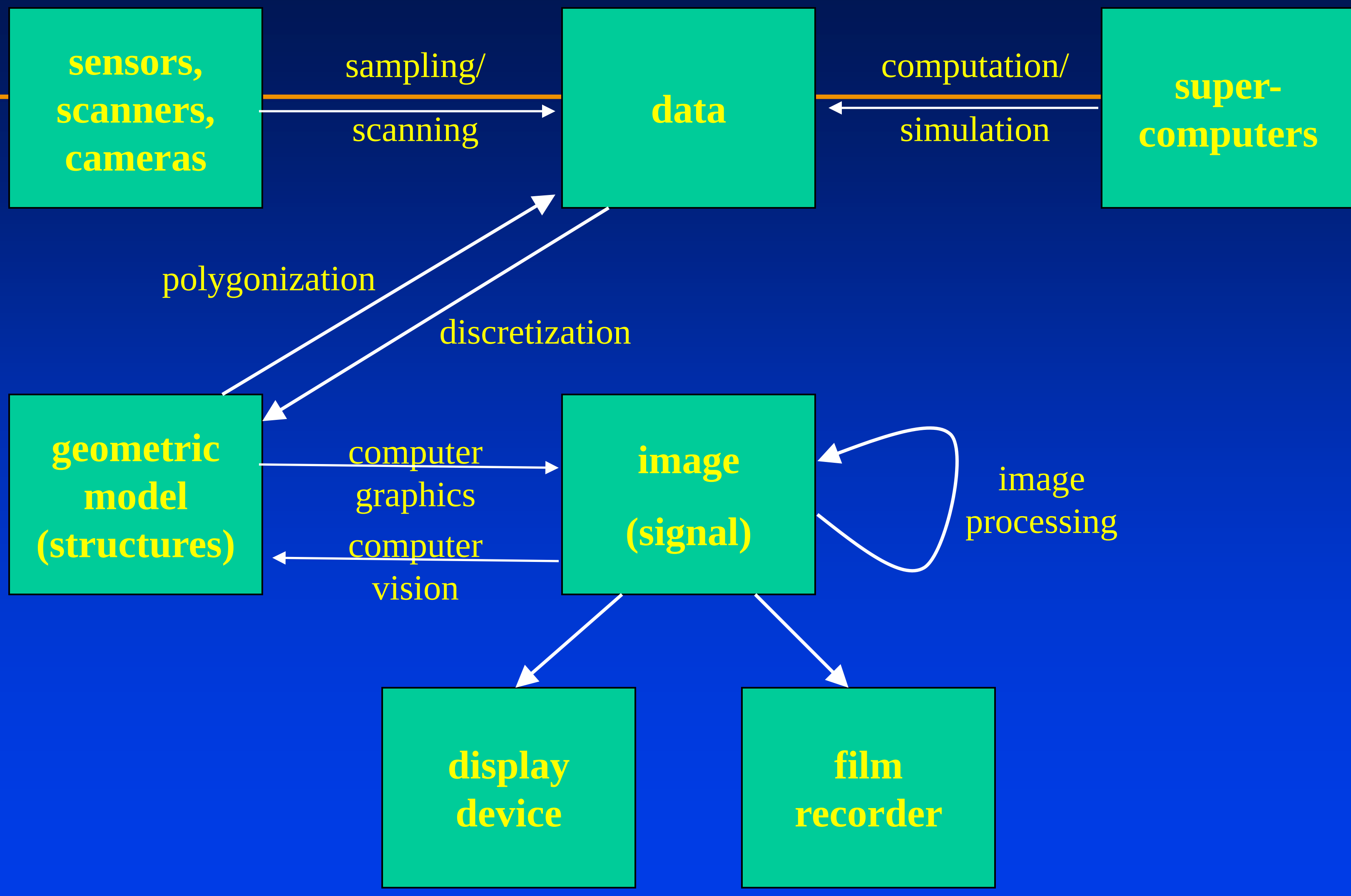
- TOO MUCH data
- The number of data sources keeps increasing
- Sensor quality and resolution are increasing
- Existing instruments are still available
- The speed of supercomputer is faster than ever
- We must do something (besides collecting and storing the datasets)
- We must deal with the huge datasets effectively
- Visual communication, improve our visual interaction with data

Challenges

- Data-driving, scientific computing to steer calculations
- Real-time interaction with computer and data experimentation
- Drive and gain insight into the scientific discovery process

Related Fields

- Computer graphics (image synthesis)
  - Generate images from complex multivariate datasets
- Image processing, signal processing
- Image understanding (pattern recognition)
  - Interpret image data
- Computational vision
- Human-computer interaction
  - Mechanisms to communicate, use, perceive visual information
- Computer-aided design
- Neurological/physiological studies on human brain and our visual system


sensors, scanners, cameras
sampling/
scanning
data
computation/
simulation
super-computers
polygonization
discretization
geometric model (structures)
computer graphics
computer vision
image (signal)
image processing
display device
film recorder

Computer Graphics Pipeline

- Data acquisition and representation
- Modeling data and their (time-varying) behaviors (e.g., physical experiments or computational simulations)
- Graphics system for data rendering
- Image-based techniques

Data Sources

- Scanned, computed, modeled data
- The first process is data-gathering
- Large variety of data sources
- Extremely large-scale datasets

Data Acquisition and Processing

- Pixels and voxels
- Regular & irregular grids
- Numerical simulations
- Surface or volumetric data
- Scalar, vector, tensor data with multiple attributes
- Higher-dimensional and/or time-varying data
- Popular techniques
  - Contouring, iso-surfaces, triangulation, marching cubes, slicing, segmentation, volume rendering, reconstruction
- Image-based processing techniques
  - Sampling, filtering, anti-aliasing, image analysis and manipulation

Information Domain

- Sciences (e.g., statistics, physics)
- Engineering (e.g., empirical observations for quality control)
- Social events (e.g., population census)
- Economic activities (e.g., stock trading)
- Medicine (e.g., computed tomograph (CT), magnetic resonance imaging (MRI), X-rays, ultrasound, various imaging modalities)
- Geology

Information Domain

- Biology (e.g., electronic microscopes, DNA sequences, molecular models, drug design)
- Computer-based simulations (e.g., computational fluid dynamics, differential equation solver, finite element analysis)
- Satellite data (e.g., earth resource, military intelligence, weather and atmospheric data)
- Spacecraft data (e.g., planetary data)
- Radio telescope, atmospheric radar, ocean sonar, etc.
- Instrumental devices recording geophysical and seismic activities (e.g., earthquake)

Graphics and Visualization

- Data acquisition, representation, and modeling
- Imaging processing
- Visualization (displaying) methods and algorithms
- More advanced research topics

Pathway to Success

- Highly-motivated
- Hard-working
- Start as soon as possible
- Communicate with the instructor on a regular basis
- Actively interact with your fellow students
- Visit libraries and internets frequently for papers and software system
- Read as many papers as possible
- Work on your course project

Computer Graphics

- "The purpose of scientific computing is insight, not numbers," by Richard Hamming many years ago
- These fields are all within computer science and engineering, yet computer graphics spans multi-disciplines
- Computer Graphics (another definition)
  - Application of computers to the disciplines of sciences/engineering

Computer Graphics

- Computer Graphics is application-driven, so what are its applications?

Applications

- Simulation and training: flight, driving
- Scientific visualization: weather, natural phenomena, physical process, chemical reaction, nuclear process
- Science: Mathematics, physics (differential equations) biology (molecular dynamics, structural biology)
- Environments sciences
- Engineering (computational fluid dynamics)
- Computer-aided design/manufacturing (CAD/CAM): architecture, mechanical part, electrical design (VLSI)

Applications

- Art and Entertainment, animation, commercial advertising, movies, games, and video
- Education, and graphical presentation
- Medicine: 3D medical imaging and analysis
- Financial world
- Law
- WWW: graphical design and e-commerce
- Communications, interface, interaction
- Military
- Others: geographic information system, graphical user interfaces, image and geometric databases, virtual reality, etc.

Key Components

- Modeling: representation choices of different models
- Rendering: simulating light and shadow, camera control, visibility, discretization of models
- HCI (human-computer interface): specialized I/O devices, graphical user interfaces
- Animation: lifelike characters, natural phenomena, surrounding environments

We Are Focusing on Geometry

- Geometric Foundations of Graphics and Visualization
- Not a course to teach basis knowledge on graphics and visualization (basic stuff shall be acquired elsewhere, we only require knowledge at the undergraduate level)
- This is a fun course!!!