CS530 - Visualization Spring 2013

Topics for Final Exam (Wednesday, May 1, LAMB 108)

Data Representation and Basic Processing

Grid structure
- geometry vs. topology
- structured vs. unstructured, impact on storage and query complexity
- curvilinear grids
- computational space vs. physical space
- common cell types and relation to different grid structures

Interpolation
- interpolation vs. approximation: basic idea, fundamental role in (scientific) visualization
- linear interpolation in triangles / tetrahedra, barycentric coordinates, inclusion test
- bilinear interpolation in rectangles: basic idea (compounded linear interpolations)
- bilinear interpolation in general quadrilaterals (computational space)
- trilinear interpolation in cuboids: basic idea
- nature of the interpolation along edges (2D and 3D), along faces (3D)
- global continuity and piecewise smoothness of the resulting interpolation over an entire grid.

Visual perception

Human Vision
- roles of vision - properties of vision (overview): strengths and weaknesses
- overview of light properties, large range of luminance values in everyday life, colors as spectral curves
- basic anatomy of the eye: cornea, lens, iris, retina, fovea, optic nerve
- photoreceptors: rods and cones and respective properties
- respective sensitivities of S, M, L cones - spatial distribution of cones vs. rods on the retina - role of ganglia as filters, notion of opponent color response
- notion of center-surround receptive fields associated with ganglia, role as low level edge detector
- pipeline of visual system: retina to optic nerve to LGN to visual cortex (basic knowledge)
- “what” vs. “where” pathways, respective strengths and shortcomings, evolution perspective
- notion of constancy, distal vs. proximal stimulus
- implications of these notions in optical illusions
- role of on center vs off center receptive fields in Hermann grid illusion
- basic principles that explain illusions
- depth cues: motor, monocular, binocular
- basic properties of motion perception

Color Perception
- connections to general human vision (photoreceptors, ganglia, parvocellular division)
- trichromatic color theory:
    - link to 3 types of photoreceptors
    - 3D color space, colors can be described as a combination of red, green, and blue components
    - shortcomings, color blindness

- opponent color theory: link to opponent color response
- perceptual distortions
- color spaces: perceptually based, device derived, intuitive (high level description), examples
  - CIE color space, notion of gamut of human color and chromaticity diagram
  - RGB color space: why is it so popular and why is it a problem?
  - HSV color space: hue, saturation, value

Scalar Field Visualization

Color Visualization

- different uses of colors
- various kinds of univariate colors scales
  - idea behind color model component scale, examples
  - redundant color scales: simultaneous variation of several perceptual dimensions, examples
  - double-ended scale
  - color scales as 1D curve in color space
- multivariate color scales
- Trumbo's principles to evaluate the effectiveness of a color scale

Isosurfacing

- notion of isocontour (level set) and associated properties
- gradient field: definition and relationship with isosurfaces
- interpretation as boundaries in scalar data sets
- cell-wise extraction in 2D quadrilaterals (piecewise linear approximation), algorithm description ("*marching squares*")
- ambiguities in 2D: linear model vs. bilinear interpolation, role of saddle point in deciding correct topology.
- marching cubes algorithm in 3D, different cases, lookup table, 15 basic configurations
- ambiguities in marching cubes: on faces, in the interior, causes, link to the complexity of the trilinear interpolation, solution based on saddle point (definition of saddle point and method)
- complexity of marching cubes: computation, storage
- span space: basic principle and usefulness in practice

Volume Rendering

- motivation, basic idea, physical metaphor used to turn a scalar volume into a visible object
- main differences compared to isosurfacing, respective pros and cons
- volume rendering integral
  - emission, absorption (different models), formulae
  - discrete approximation of VR integral, role of alpha blending, color, opacity
- notion of transfer function, role in volume rendering
- role of gradient in rendering and connection to isosurfacing
- typical applications of VR in visualization
- alpha blending (simple computation with a few objects)
- compositing: first, average, accumulate, MIP
- image order methods:
  - ray casting: basic idea
  - back-to-front vs. front-to-back rendering: basic idea, computation with alpha blending
  - pros and cons of ray casting method (speed, accuracy, memory requirement, ...)
- object order methods:

- projected tetrahedra (PT): basic idea, optical model + encoding with 3D texture lookup, pros and cons
- slice-based rendering: basic idea, image quality aspect, connection with volume rendering integral (alpha blending), mapping to GPU, pros and cons

Transfer Functions for Direct Volume Rendering

- spatial domain vs. value space: basic notion, mapping in between
- transfer functions:
    - why are they fundamental?
    - why are they difficult to design?
    - why are we typically trying to capture boundaries with the transfer function?
- existing approaches (we saw two main ideas):
    - salient isovalues (basic idea)
    - semi-automatic transfer function design (high-level knowledge of the procedure):
        - mapping from spatial domain to 3D histogram of value space to scalar measure of (signed) distance to boundary
        - boundary emphasis function controls the rendering
        - what makes this approach effective / intuitive for the user?
- multidimensional transfer functions: basic idea, motivation (shortcomings of 1D and 2D transfer functions), application to interactive rendering system (example of user interface supporting multidimensional transfer functions)

Vector Field Visualization

Vector Visualization Basics

- goals and challenges ("*vectors are more than a bunch of numbers*")
- connection to experimental techniques: inspiration and challenge

Vector Field Math

- vector field definition
- connection to (ordinary) differential equation, notion of flow, existence, uniqueness
- why can't streamlines intersect?
- numerical integration of ODE:
    - what does it mean to integrate an ODE?
    - why use numerical methods?
    - Euler: equation, geometric interpretation, accuracy issues
    - RK2: equation, geometric interpretation
    - RK4: basic idea (extension of RK2), accuracy
    - distinction between high-order approximation and accurate approximation
    - adaptive step size adaptivity (e.g., RK45): basic idea, role in practice

Streamline-based techniques

- streamlines vs. streaklines vs. timelines vs. pathlines: precise definition for each of them, interpretation in terms of tracers in a flow, what is the difference between a streakline, a streamline, and pathline in an unsteady flow? In a steady flow?
- role and limitations of streamlines in flow visualization
- stream ribbons: basic idea, why/when are they better than streamlines?
- streamline seeding:
    - what does seeding mean?
    - basic motivation (effective use of streamlines)

    - method of Turk and Banks: basic idea (target density function as gray-scale image, continuous flow domain vs. discrete analysis in image space, iterative modifications to improve the distribution, ...
    - farthest point seeding: basic idea, use of Delaunay triangulation to control density (what key property of the Delaunay triangulation is used?)

Stream surfaces
- definition, (s,t) parameterization (what are streamlines in this parameterization, what are timelines?), benefit over individual streamlines in 3D
- naive implementation: how? what are the issues with this method? (cf. Project 5)

Dense Techniques
- Line Integral Convolution (LIC)
    - basic idea: low-pass filtering / smoothing of white noise texture along individual streamlines
    - why do streamline patterns form in the resulting texture? Why do neighboring streamlines have different colors?
    - issue of low contrast: why?
    - Enhanced LIC: basic idea
- challenges associated with texture-based visualization of unsteady flow: lack of frame to frame coherency: why?
- Moving textures
    - shortcomings of forward advection: why?
    - blur in backward advection: why?
    - technique based on coarse mesh advection.
    - how do these various solutions compare?
- Image-based Flow Visualization (IBFV): basic idea, extension to curved surfaces

Tensor Field Visualization

Tensor math
- tensor as linear mapping between vector spaces (a tensor turns a vector into another vector)
- algebraic definition of symmetry / antisymmetry (cf. scalar product)
- eigenvalues: definition, geometric interpretation, how are they computed? Be ready to derive the expression in 2D.
- anisotropy vs. isotropy, link to eigenvalues
- eigenvectors: definition, no intrinsic norm or orientation, defined up to a non-zero constant
- fundamental special case of real symmetric tensors

Tensor glyphs
- definition of a glyph
- ellipsoid glyph: why is that a natural choice for 3D symmetric tensors? why is there a problem with negative eigenvalues?
- alternative glyph possibilities (cylinder, parallelepiped): issue of broken symmetries
- shortcomings of ellipsoids: visual ambiguities
- improvement through superquadrics: seamless interpolation between sharp edges and smooth curves

Hyperstreamlines
- notion of eigenvector field: how is it defined (sorted eigenvalues...)
- integral curves in eigenvector fields: how are they defined, difference with streamlines

- practical computation: ensuring orientation consistency at each step.
- hyperstreamline: combination of integral curve along one eigenvector field and ellipse in the orthogonal plane defined by the other two eigenvectors and eigenvalues (c.f. assignment #5)

Topological Methods

Vector fields

- flow induced by a vector field, phase portrait (studying streamlines instead of vector values)
- topology as the decomposition of the domain into regions sharing same origin (source) and same destination (sink)
- notion of limit set (sink, source, saddle, cycle)
- critical points: definition, major types in 2D, notion of asymptotic convergence.
- Jacobian: definition, expression in 2D and 3D. relationship between eigenvalues of Jacobian and nature of a critical point.
- link between sign of the (real part of the) eigenvalues and sink / source / saddle behavior of a critical point (1D explanation)
- link between complex conjugate eigenvalues and spiral pattern
- separatrices: role in the topology, definition (cf. saddle)
- practical computation of the topology in 2D: how to find critical points in a triangle? a quadrilateral? how to characterize their type based on the interpolation scheme? how to compute separatrices in the case of saddles? how to control the length of the integration for separatrices.

Scalar fields

- gradient field: definition, link between local extrema of the scalar field and critical points (zeros) of its gradient field
- relationship between isocontour tangents and gradient field. what does that mean for relationship between isocontour and streamlines of gradient field?
- why is gradient field rotation-free? What does that mean?
- Hessian: definition, why is it symmetric? What does that imply for the possible types of critical points in this case?