15-462 Computer Graphics I
Lecture 23

Review

End of graphics pipeline
Ray tracing and radiosity
Image processing
Non-photorealistic rendering
Assignment 7 movie

May 2, 2002
Frank Pfenning
Carnegie Mellon University

http://www.cs.cmu.edu/~fp/courses/graphics/

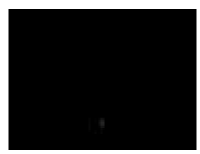
Outline

12 Physically-Based Modelling

- Dynamics
  – Generating motion by applying physical laws
  – Typical: Newton's laws, Hook's law
  – Particles, soft objects, rigid bodies
- Simulates physical phenomena
  – Gravity, momentum, collisions, friction, fluid flow
  – Solidity, flexibility, elasticity, fracture

Particle Systems

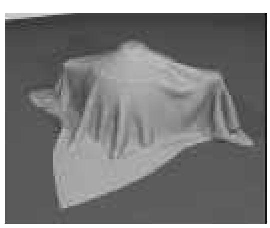
- Clouds, smoke, fire, waterfalls
- Each particle rendered as object



Matthew Lewis

Spring Forces

- Cloth in 2D, jello in 3D
- Collisions expensive to compute (hierarchical bounding boxes)
- Also: hair
  Wooten [Pixar]
- Also: paintbrushes
  [Lecture 22]



Solving Particle Systems

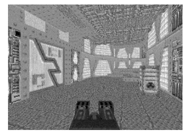
- Use solver for ordinary differential equations
- Discrete approximation (adjust stepsize)
- Euler's method
- Runge-Kutta method
- Specialized method for spring-mass systems
- Constraints
  – Hard: collisions, contact forces, joints
  – Soft: preservation of energy

13: Texture Mapping

- Adding realism in real time
- Standard applications and bag of tricks
- Texture is 2D image (typically)
- Texture coordinates map image onto surface
- Basic problem: aliasing, perspective
  - Mipmapping: texture depends on resolution
  - Bilinear or trilinear interpolation
- 3D textures (e.g. hair)
- Some tricks:
  - Environment mapping, light maps

Light Mapping

- Can paint light map or use radiosity
- Blend several textures



Radiance Texture Map Only

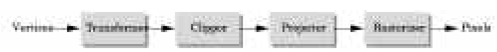
Radiance Texture + Light Map

From Quake

Light Map

14: Clipping and Scan Conversion

- Graphics Pipeline, revisited



- Transformation sequence
  1. Camera: From object coordinates to eye coords
  2. Perspective normalization: to clip coordinates
  3. Clipping
  4. Perspective division: to normalized device coords.
  5. Orthographic projection (setting $z_p = 0$)
  6. Viewport transformation: to screen coordinates

Clipping

- Eliminate objects outside viewing frustum
  - Clipping: in object space
  - Scissoring; in image space
- Cohen-Sutherland clipping: using outcode
- Liang-Barsky clipping: intersection point order
- Polygon clipping
  - Sutherland-Hodgeman clipping pipeline
- Improve efficiency via bounding boxes

15: Rasterization

- Final step in pipeline (scan conversion)
- Multiple tasks:
  - Filling polygon (inside/outside)
  - Pixel shading (color interpolation)
  - Blending (accumulation, not just writing)
  - Depth values (z-buffer hidden-surface removal)
  - Texture coordinate interpolation (texture mapping)
- Hardware efficiency is critical

Lines and Polygon

- Incremental algorithm (Bresenham’s) for lines
- Fill polygons line by line (“scan conversion”)
- Concave polygons
  - Use winding number or even-odd rule
  - Or tessellate into triangles

Aliasing

- Artefacts created during scan conversion
- Jagged edges, Moire patterns
- Antialiasing techniques
  - Area averaging [filter]
  - Adaptive supersampling [ray tracing]
  - Jittering
- Temporal aliasing
  - Motion blur through stochastic sampling in time

05/02/2002 15-462 Graphics I 13

Motion Blur Example

T. Porter, Pixar, 1984
16 samples/pixel

05/02/2002 15-462 Graphics I 14

Blending

- Use α channel (RGBA color)
- α determines opacity
- Use for effects such as shadows, blur
- Antialiasing via blending for triangle overlaps

05/02/2002 15-462 Graphics I 15

16: Ray Tracing

- Local vs global rendering models
- Object space vs image space
- Three models
  - Graphics pipeline (Phong)
  - Ray tracing
  - Radiosity

05/02/2002 15-462 Graphics I 16

Backward Ray Tracing

- From viewer to light
- Basic algorithm
  - Calculate ray/object intersection
  - Cast shadow ray
  - Calculate reflected and transmitted rays
  - Call ray tracer recursively
- Ray-surface intersection for basic shapes
- Support constructive solid geometry (CSG)

05/02/2002 15-462 Graphics I 17

Raytracing Example II

www.povray.org

05/02/2002 15-462 Graphics I 18

17: Spatial Data Structures

- Employed for optimization in various contexts
  - Ray tracing (check fewer ray/object intersections)
  - Radiosity
  - Hidden-surface removal
  - Clipping
  - Collision detection
- Basic bounding volumes
  - Boxes, axis-aligned
  - Boxes, oriented
  - Spheres
  - Finite intersections or unions of above

Hierarchical Bounding Volumes

- Use tree data structure
- Larger bounding volumes contain smaller ones
- Reduce O(n) to O(log(n)) for certain operations
- May be easy or difficult to compute

Spatial Subdivision

- For each segment of space, keep list of intersecting surfaces or objects
- Example data structures
  - Regular grids
  - Octrees (axes-aligned, non-uniform)
  - BSP trees (recursive subdivision by planes)
- Effiency depends on world characteristics
- Example: painter's algorithm using BSP trees

Constructive Solid Geometry

- Generate complex shapes from simple building blocks
- Particularly applicable for man-made objects
- Efficient with ray tracing
- Use operations
  - Intersection
  - Union (joining objects)
  - Subtraction (e.g., drilling holes, cutting)

18: Radiosity

- Local illumination: Phong model (OpenGL)
  - Light to surface to viewer
  - No shadows, interreflections
  - Fast enough for interactive graphics
- Global illumination: Ray tracing
  - Multiple specular reflections and transmissions
  - Only one step of diffuse reflection
- Global illumination: Radiosity
  - All diffuse interreflections; shadows
  - Advanced: combine with specular reflection

Classical Radiosity Method

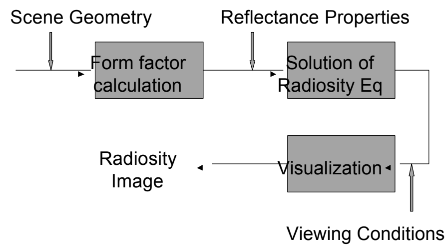
- Divide surfaces into patches (elements)
- Model light transfer between patches as system of linear equations
- Important assumptions:
  - Reflection and emission are diffuse
  - No participating media (no fog)
  - No transmission (only opaque surfaces)
  - Radiosity is constant across each element
  - Solve for R, G, B separately

Radiosity Equation

- Assume n surface patches
- Variables
  - A_i Area of element i (computable)
  - B_i Radiosity of element i (unknown)
  - E_i Radiant emitted flux density of element i (given)
  - ρ_i Reflectance of element i (given)
  - $F_{j\,i}$ Form factor from j to i (computable)

$$A_i B_i = A_i E_i + \rho_i \sum_{j=1}^{n} F_{ji} A_j B_j$$

Radiosity “Pipeline”



Computing Form Factors

- Visibility
  - Hemicube: exploit z-buffer hardware
  - Ray casting
- For inter-visible elements
  - Solve analytically for simple elements
  - Numeric approximation otherwise

Classical Radiosity Algorithms

- Matrix Radiosity
  - Diagonally dominant matrix
  - Use Gauss-Seidel iterative solution
  - Time and space complexity is $O(n^2)$ for n elements
  - Memory cost excessive
- Progressive Refinement Radiosity
  - Solve equations incrementally with form factors
  - Time complexity is $O(n \cdot s)$ for s iterations
  - Used more commonly (space complexity $O(n)$)

19: Global Illumination

- Improvements on Radiosity
- Substructuring
  - Subdivide patches into elements, adaptively
  - Analyze transport from patch onto elements
  - Do not considere element-to-element factors
- Progressive Refinement
  - Shoot light instead of gathering light

Progressive Refinement

- Basic algorithm
  - Initialize emitting element with $B_i = E_i$
  - Initialize others with with $B_i = 0$
  - Pick source i (start with brightest)
  - Using hemicube around source, calculate $F_{i\,j}$
  - For each $j \neq i$, approximate $B'_j = \rho_j B_i F_{i\,j} (A_i / A_j)$
  - Pick next source i and iterate until convergence
- Each iteration is $O(n)$
- May or may not keep $F_{i\,j}$ after each iteration
- Avoid double-counting (“unshot energy”)

Light Transport and Global Illumination

- Diffuse to diffuse
- Diffuse to specular
- Specular to diffuse
- Specular to specular
- Ray tracing (viewer dependent)
  - Light to diffuse
  - Specular to specular
- Radiosity (viewer independent)
  - Diffuse to diffuse

Two-Pass Approach

- View-dependent specular is tractable
- View-independent diffuse is tractable
- First pass view independent
  - Enhanced radiosity
- Second pass is view dependent
  - Enhanced ray tracing

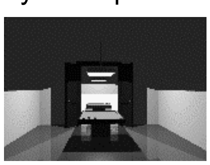
Pass 1: Enhanced Radiosity

- Diffuse transmission (translucent surfaces)
  - Backwards diffuse form factor
- Specular transmission
  - Extended form factor computation
  - Consider occluding translucent surfaces
  - Window form factor
- Specular reflection
  - Create "virtual" (mirror-image) environment
  - Use specular transmission technique
  - Mirror form factor

Pass 2: Enhanced Ray Tracing

- Classical ray tracing
  - Specular to specular light transport
- For diffuse-to-specular transport:
  - Should integrate incoming light over hemisphere
  - Approximate by using small frustum in direction of ideal reflection
  - Use radiosity of pixels calculated in Pass 1
  - Apply recursively if visible surface is specular

Two-Pass Radiosity Example


20: Image Processing

- Display color models
  - 1 bit: black and white display (cf. Smithsonian)
  - 8 bit: 256 colors at any given time via colormap
  - 16 bit: 5, 6, 5 bits (R,G,B), 2^{16} = 65,536 colors
  - 24 bit: 8, 8, 8 bits (R,G,B), 2^{24} = 16,777,216 colors
- Image processing
  - Point processing
  - Filtering
  - Compositing
  - Image compression
  - Others [Sullivan guest lecture]

Linear and Shift-Invariant Filters

- Linear with respect to input signal
- Shift-invariant with respect to parameter
- Convolution in 1D
  - a(t) is input signal
  - b(s) is output signal
  - h(u) is filter

$$b(s) = \sum_{t=-\infty}^{+\infty} a(t)h(s-t)$$

- Convolution in 2D

$$b(x,y) = \sum_{u=-\infty}^{+\infty} \sum_{v=-\infty}^{+\infty} a(u,v)h(x-u,y-v)$$

Filter Examples

- Blurring filter
- Noise reduction filter
- Edge filter
- Sharpening filter

Dithering

- Compensates for lack of color resolution
- Eye does spatial averaging
- Black/white dithering for gray scale
- Color dithering (calculate RGB separately)
- Floyd-Steinberg error diffusion
  - Scan image in raster order
  - Draw least error value (approximate true color)
  - Divide error into 4 fractions on unwritten pixels

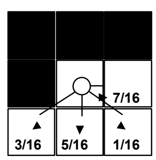


Image Compression

- Exploit redundancy
  - Coding: some pixel values more common
  - Interpixel: adjacent pixels often similar
  - Psychovisual: some color differences imperceptible
- Distinguish lossy and lossless methods
- Coding redundancy
  - Dictionary to map short codes to long sequences
  - Huffmann or Lempel-Ziv-Welch (LZW; gzip)
- Interpixel redundancy
  - Run-length coding, quadtrees, region encoding

Lossy Compression

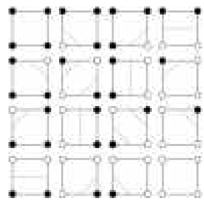
- Exploit psychovisual redundancy
- Discrete cosine transform
- JPEG (Joint Photographic Expert Group)
  - Subdivide image into n $\times$ n blocks (n = 8)
  - Apply discrete cosine transform for each block
  - Quantize, zig-zag order, run-length code coefficients
  - Use variable length coding (e.g. Huffman)
- Many natural images can be compressed to 4 bits/pixels with little visible error

21: Visualization

- Generally, no 3D model to start with
- Very large data sets
- Visualize both real-world and simulation data
- Types of data
  - Scalar fields (e.g. x-ray densities)
  - Vector fields (e.g. velocities in wind tunnel)
  - Tensor fields (e.g. stresses in mechanical part)
- Each static or varying through time

Marching Squares and Cubes

- Implicit curve g(x,y) = c or surface f(x,y,z) = c
- Test g or f on grid points
- Approximate curve or surface based on continuity and smoothness assumptions
- Contour lines (2D)
- Isosurfaces (3D)



Volume Rendering

- Use voxels (3D “pixels”) and transparency
- Transfer function: data sets to RGBA
  – Psychologically motivated, change interactively
- Volume rendering
  – Volume ray casting (integrate along ray)
  – Splatting (draw shape for each voxel)
  – 3D texture mapping (texture for each layer)

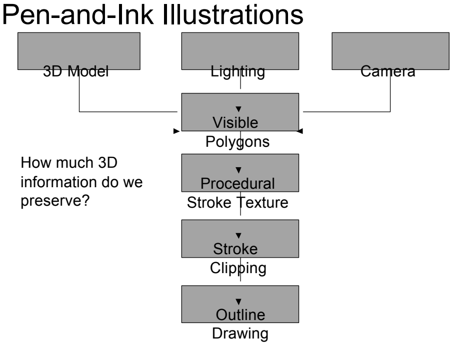
Visualizing Vector Fields

- Hedgehogs (3D directed line segments)
- Flow lines (color for vector length)
- Animation (partical systems)

22: Non-Photorealistic Rendering

- Cartoons
- Artistic expression in paint, pen-and-inki
- Technical illustrations
- Scientific visualization [lecture 21]

Pen-and-Ink Illustrations

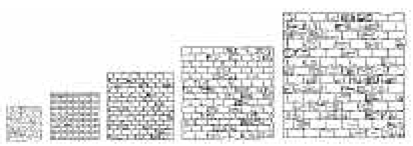


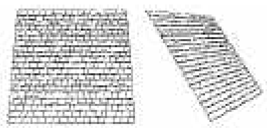
Prioritized Stroke Textures

- Technique for limiting human intervention
- Collection of strokes with associated priority
- When rendering
  – First draw highest priority only
  – If too light, draw next highest priority, etc.
  – Stop if proper tone is achieved
- Procedural stroke textures
- Support scaling
- Also applies to non-procedural stroke textures

Stroke Texture Operations

Scaling





Changing Viewing Direction (Anisotropic)

Stroke Textures and Indication

Bold strokes indicate detail segments

With indication

Without indication

Painterly Rendering

- Physically simulation
  - Watercolor
  - Oil paint brush strokes
- Painting "over" image
  - Brush stroke parameters determine style
  - Superficially adequate, lack of artistic sensitivity

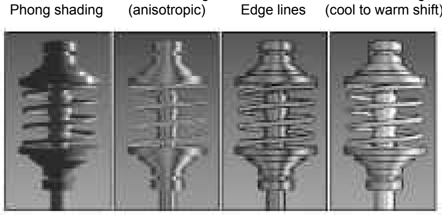
Layered Painting

Blurring

Adding detail with smaller strokes

Technical Illustration Example

Phong shading | Metal shading (anisotropic) | Edge lines | Tone shading (cool to warm shift)



Summary

- 12: Physically-Based Modelling
- 13: Texture Mapping
- 14: Clipping and Scan Conversion
- 15: Rasterization
- 16: Ray Tracing
- 17: Spatial Data Structures
- 18: Radiosity
- 19: Global Illumination
- 20: Image Processing
- 21: Scientific Visualization
- 22: Non-Photorealistic Rendering

Assignment 7 Movie

Announcements

- Assignment 8
  - Was due before lecture
  - Model solutions available tomorrow (Friday) morning
- Final
  - Monday, May 6, 1:00-4:00, WeH 7500
  - Emphasis on 2^{nd} half of course (this lecture)
  - Problems similar to midterm and assignments
  - Open book, open notes, no laptop
  - Worth 250 points
- Please fill out TA evaluation forms

Finally...

- It's been fun --- thanks!