Review

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

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

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

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

Motion Blur Example

T. Porter, Pixar, 1984
16 samples/pixel

Blending

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

16: Ray Tracing

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

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)

Raytracing Example II

www.povray.org
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)
- Efficiency 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)
  - $\rho_i$: Reflectance of element i (given)
  - $F_{ij}$: Form factor from j to i (computable)

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

Radiosity “Pipeline”

- Scene Geometry
- Reflectance Properties
- Solution of Radiosity Eq
- Visualization
- Viewing Conditions

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 $O(n^s)$ for s iterations
  - Used more commonly (space complexity $O(n)$)

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 $F_{ij}$
  - For each $j \neq i$, approximate $B_j' = \rho_j B_i F_{ij} (A_j / A_i)$
  - Pick next source i and iterate until convergence
  - Each iteration is $O(n)$
  - May or may not keep $F_{ij}$ after each iteration
  - Avoid double-counting ("unshot energy")

19: Global Illumination

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

22: Non-Photorealistic Rendering
- Cartoons
- Artistic expression in paint, pen-and-ink
- Technical illustrations
- Scientific visualization [lecture 21]

Pen-and-Ink Illustrations
- 3D Model
- Lighting
- Camera
- Visible Polygons
  - Procedural Stroke Texture
  - Stroke Clipping
  - Outline Drawing
- How much 3D information do we preserve?

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

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

Michael Maxim

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 2nd 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!