<< RETURN

Reusing Shading for Interactive Global Illumination

GDC 2004

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Cornell University

Introduction

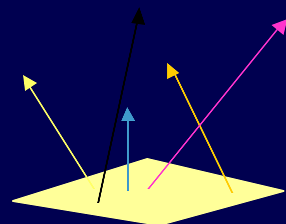
- What is this course about?
- Schedule
  - What is Global Illumination?
  - Computing Global Illumination
  - Reusing Shading
    - Image-space
    - Mesh-based
    - Fast GI

What is Global Illumination?

Session I

Assumptions: Geometric Optics

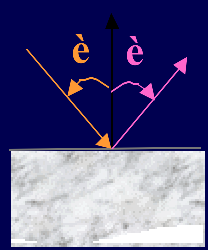
- Light travels in straight lines
- Rays do not interact with each other
- Rays have color(wavelength), intensity



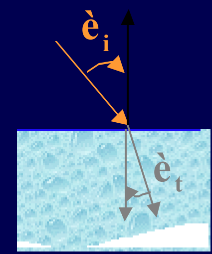
Reflections/Refractions

- Interface between 2 materials

reflection



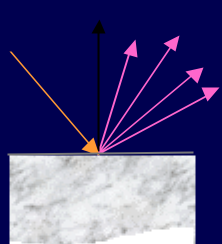
refraction



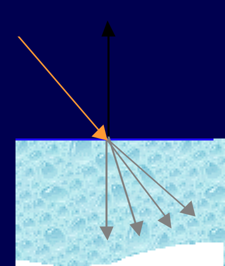
- Specular reflections and refractions
  - One direction

Realistic Reflections/Refractions

reflection

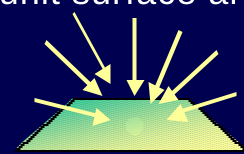


refraction



Radiometric Terms

- Power: energy per unit time
- Irradiance: Incident power per unit surface area
  - From all directions
  - Watt/m^2



- Radiosity: Exitant power per unit surface area
  - Same units

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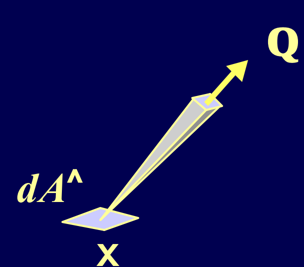
Radiance

- Radiance is radiant energy at x in direction θ: 5D function
  - $L(x \rightarrow \Theta)$: Power
    - per unit projected surface area
    - per unit solid angle

$$L(x \rightarrow \Theta) = \frac{d^2 P}{dA^{\perp} dw_{\Theta}}$$



  - units: Watt / m^2.sr

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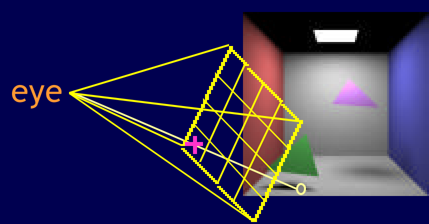
Why is radiance important?

- Response of a sensor (camera, human eye) is proportional to radiance



- Pixel values in image proportional to radiance received from that direction

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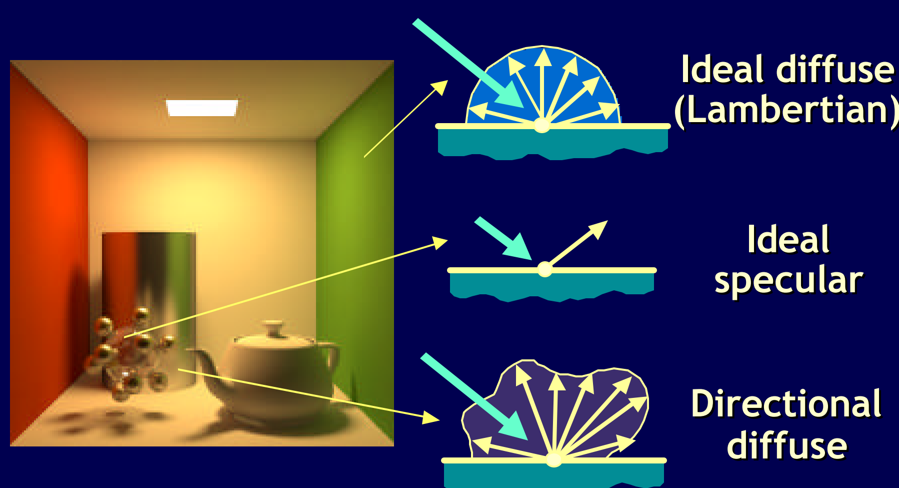
Materials - Three Forms



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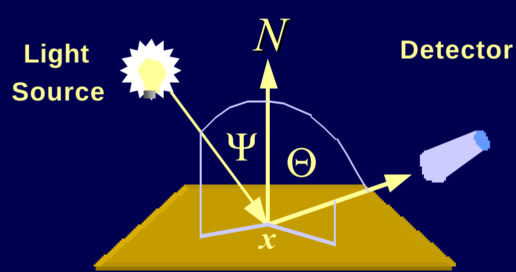
BRDF

- Bidirectional Reflectance Distribution Function



$$f_r(x, \Psi \rightarrow \Theta) = \frac{dL(x \rightarrow \Theta)}{dE(x \leftarrow \Psi)} = \frac{dL(x \rightarrow \Theta)}{L(x \leftarrow \Psi)\cos(N_x, \Psi) dw_\Psi}$$

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BRDF special case: ideal diffuse

Pure Lambertian

$$f_r(x, \Psi \rightarrow \Theta) = \frac{r_d}{p}$$

$$r_d = \frac{Energy_{out}}{Energy_{in}} \qquad 0 \leq r_d \leq 1$$

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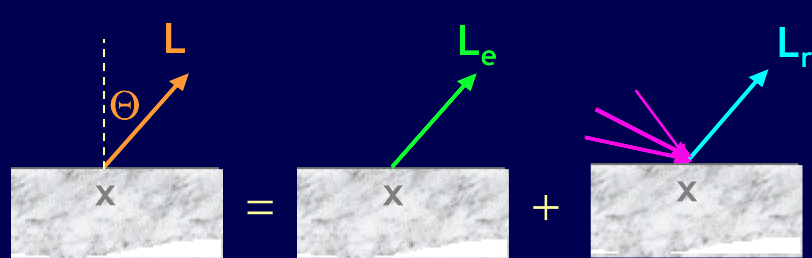
Rendering Equation (RE)

- RE describes energy transport in scene
- Input
  - Light sources
  - Surface geometry
  - Reflectance characteristics of surfaces
- Output: value of radiance at all surface points in all directions

Rendering Equation



$$L(x \rightarrow \Theta) = L_e(x \rightarrow \Theta) + L_r(x \rightarrow \Theta)$$

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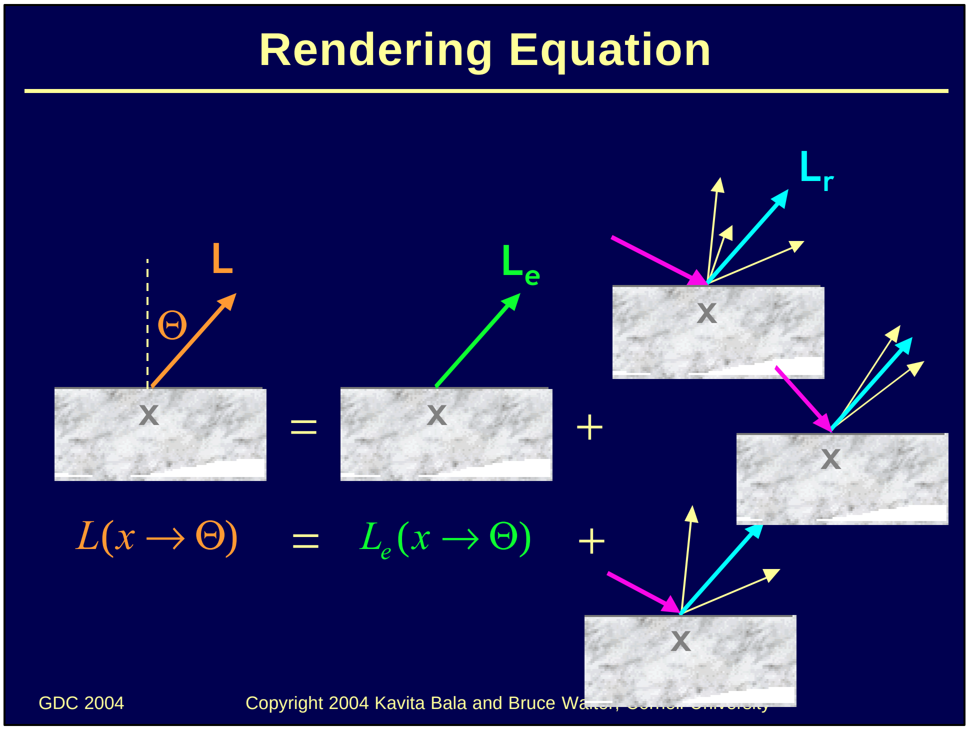
Rendering Equation
L
Θ
x
=
Le
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+
Lr
x
x
x
L(x → Θ) = Le(x → Θ) +
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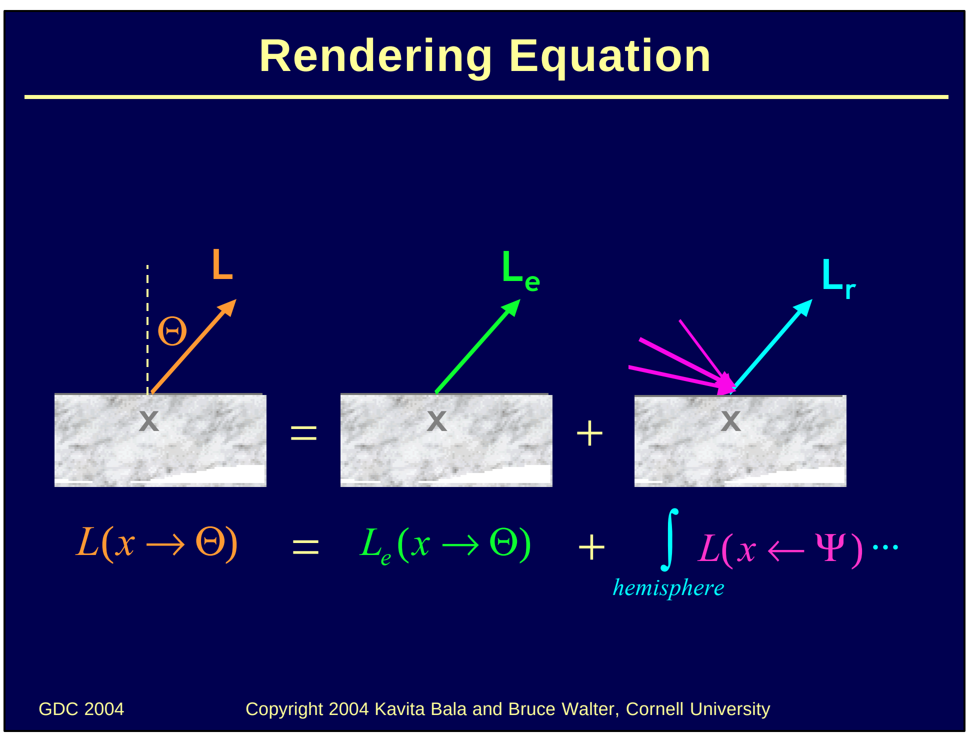
Rendering Equation
L
Θ
x
=
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+
Lr
x
L(x → Θ) = Le(x → Θ) + ∫ L(x ← Ψ) ···
hemisphere
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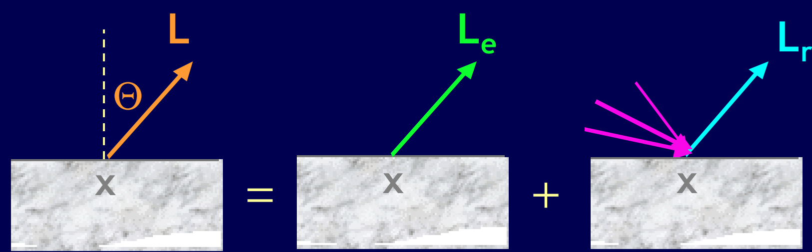
Rendering Equation



$$L(x \rightarrow \Theta) = L_e(x \rightarrow \Theta) + \int_{hemisphere} L(x \leftarrow \Psi)\ f_r(x, \Psi \leftrightarrow \Theta) \cos(\mathbf{N}_x, \Psi) dw_\Psi$$

- Applicable for each wavelength

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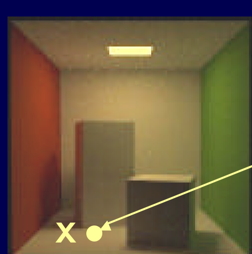
Rendering Equation



$$L(x \rightarrow \Theta) = L_e(x \rightarrow \Theta) + \int_{hemisphere} L(x \leftarrow \Psi) f_r(x, \Psi \leftrightarrow \Theta) \cos(\mathbf{N}_x, \Psi) dw_\Psi$$

incoming radiance

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Computing Global Illumination

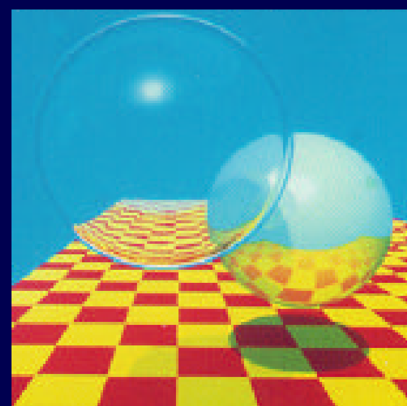
Session II

Classic Ray Tracing

- Introduced in 1980 by Turner Whitted
- Existing rendering:
  - Phong shading
  - Local illumination (specular, diffuse)

Insights

- Trace rays from eye into scene
  - Backward ray tracing
- Find visible objects
- Shade visible points
  - Shadows
  - Reflections
  - Refractions



Whitted 1980: First ray traced image

- First global illumination algorithm!

Whitted RT Assumptions

- Light Source: point light source
  - Hard shadows
  - Single shadow ray direction
- Material: Blinn-Phong model
  - Diffuse with specular peak
- Light Propagation
  - Occluding objects
  - Specular interreflections only
    - trace rays in mirror reflection direction only

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History

- Problems with classic ray tracing:
  - Not realistic: only perfect specular and perfect refractive/reflection between surfaces
  - View-dependent
- Radiosity (1984)
  - Global Illumination in diffuse scenes
  - Discretize scene
- Monte Carlo Ray Tracing (1986)
  - Global Illumination for any environment

Radiosity Advantages

- Physically based approach for diffuse environments
- Can model diffuse interactions, color bleeding, indirect lighting and penumbra (area light sources)
- Boundary element (finite element) problem
- Accounts for very high percentage of total energy transfer

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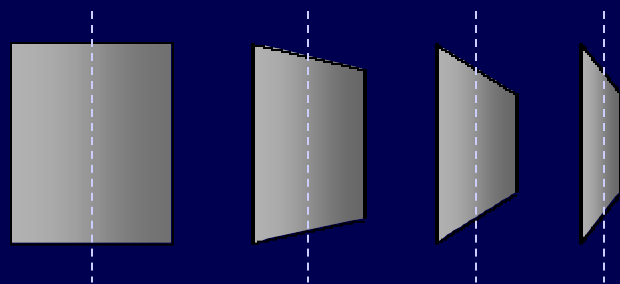
Key Idea #1: diffuse only



- Radiance independent of direction
- Surface looks the same from any viewpoint
- No specular reflections

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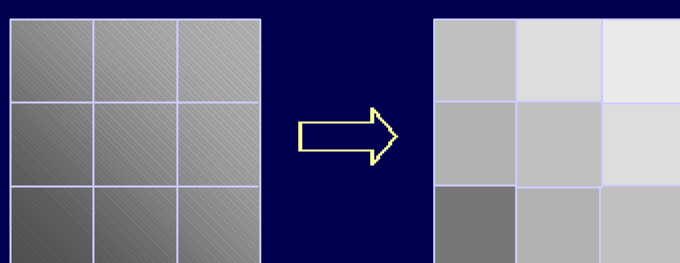
Key Idea #2: “constant”polygons

- Radiosity solution is an approximation, due to discretization of scene into patches



- Subdivide scene into small polygons

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Radiosity Equation

- Radiosity equation for each polygon i

$$Radiosity_1 = Radiosity_{self,1} + \sum_{j=1}^{N} a_{j\to 1} Radiosity_j$$

$$Radiosity_2 = Radiosity_{self,2} + \sum_{j=1}^{N} a_{j\to 2} Radiosity_j$$

$$\ldots$$

$$Radiosity_N = Radiosity_{self,N} + \sum_{j=1}^{N} a_{j\to N} Radiosity_j$$

- N equations; N unknown variables

Solutions

(RenderPark)

Radiosity: Typical Image

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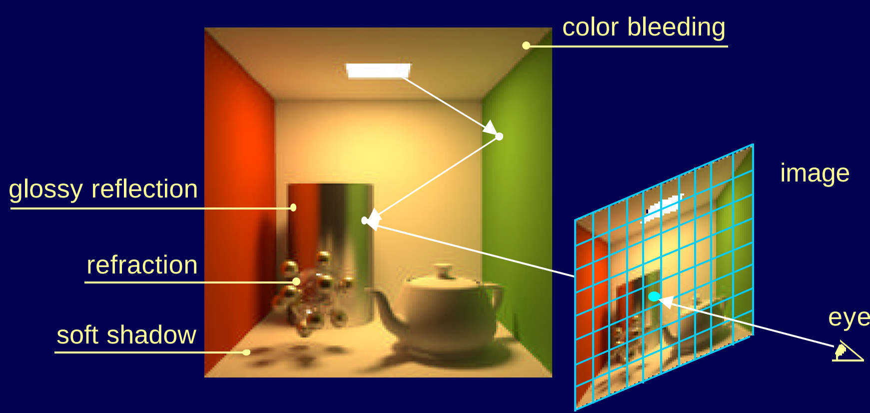
Rendering



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Path Tracing

- Monte Carlo Method
  - Randomly choose potential light paths
  - Average contribution over many such paths
- Problems
  - Noise
  - Slow to converge

Approaches

- Bidirectional
- Metropolis
- Photon Mapping
- Instant Radiosity

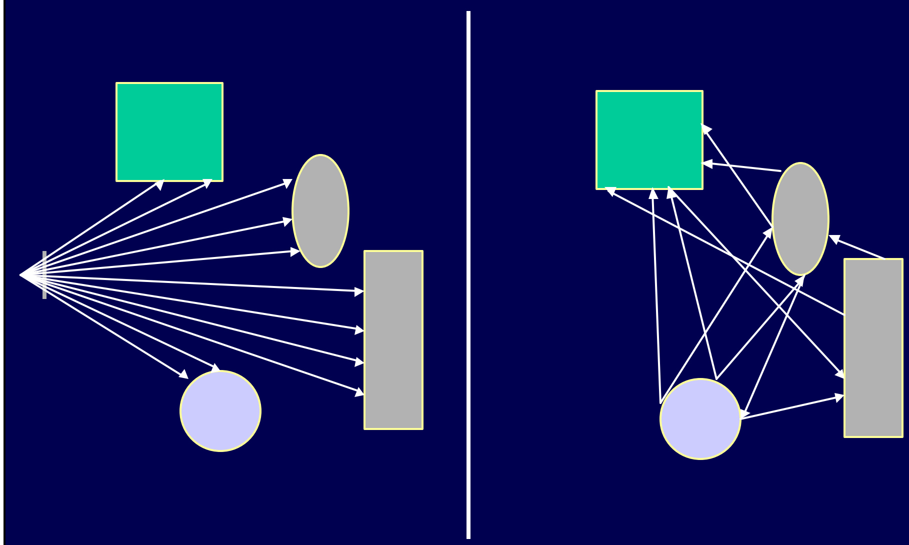
Fast Global Illumination

Session III

Hardware's Strengths

- What is the hardware good at?
  - Fast visibility determination (z-buffer)
  - Fast texture map lookup
  - Fast shading
    - Can even be per-pixel with latest boards

Hardware’s Strengths



Hardware’s Strengths

- Fast visibility determination (z-buffer)
  - Fast in an amortized sense
    - One rendering determines the visible surface seen at all pixels simultaneously
  - Great for some visibility queries types
    - Primary (eye) rays
    - Shadow rays (point sources)
  - Not so good for other types
    - Reflection & refraction from curved surfaces
    - Indirect illumination
    - Adaptive sampling

Hardware's Strengths

- Fast texture map lookup
  - Cheap anti-aliasing & anisotropic filtering
  - Most flexible part of graphics hardware
    - Surface texturing
    - Bump mapping
    - Reflection mapping
    - Shadow mapping
    - Even arbitrary BRDF approximations
  - Very powerful
    - But not as compute intensive

Hardware's Strengths

- Fast shading
  - Latest boards can do per-pixel shading
  - Programmable, but limited operations
  - Local shading only
    - All inputs must be provided ahead of time
    - Non-local shading can only be approximated
      - Shadows, reflections, indirect, etc

Hardware's Strengths

- Conclusion
  - Hardware still has the edge due to its dedicated pipeline
  - Advantage may actually be decreasing
  - Software attractive for its flexiblility
    - If it can be made "fast enough" for interactive use
    - And handle scene and/or effects the hardware cannot handle

Interactive Software Rendering

- Interactive
  - User-driven, not pre-scripted animation
  - At least a few frames per second (fps)
- Software
  - Major shading done in software
    - Can use hardware to help
- Rendering
  - Online, not pre-computed or captured
    - Eg, lightfields are pre-computed

Ray Tracing (or Ray Casting)

- Very common visibility tool for software
  - Flexible
  - Efficient for large models
    - Using an acceleration structure (grids, bsp, etc)
  - Usually the largest computational bottleneck
  - Easily parallelizable
    - Each pixel can be computed in parallel

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Interactive RT [Parker et al.]

- SGI Origin 2000
  - 64 processors
  - Shared memory
- Whitted-style ray tracing
  - Shadow, reflection, and refraction rays
- Non-polygonal primitives
  - Spheres and splines

15 fps

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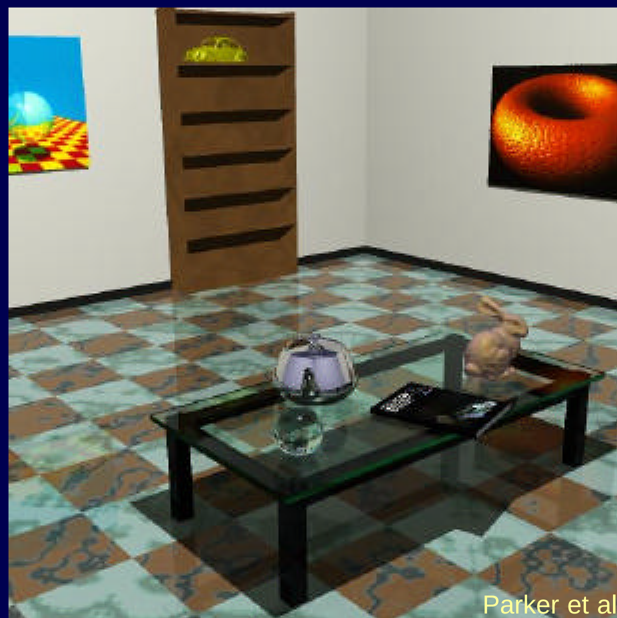


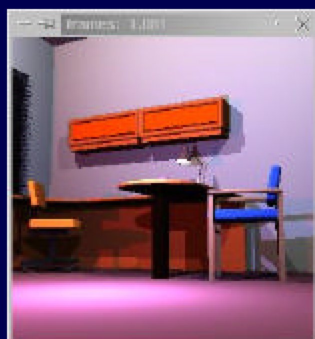
4 fps

Coherent RT [Wald et. al.]

- Created a highly optimized ray tracing engine for Intel-based PCs
  - Carefully profiled their ray tracer
    - Discovered it was often memory bound
  - Hand-crafted and tuned their code
    - Created both C and assembly versions
    - Used compact, cache-friendly data structures
    - Optimized for SIMD (SSE)
    - Reordered computations for better coherence

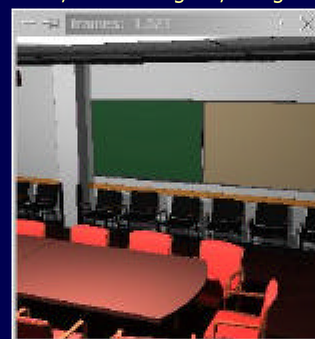
Test Scenes I

- Test scenes: 800 triangles to >8 million



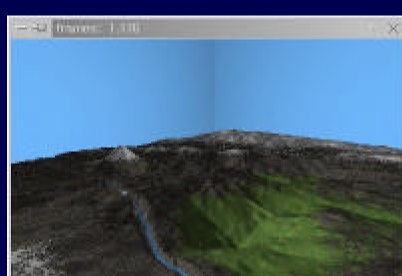
Office:
34,000 triangles, 3 lights

Conference Room:
280,000 triangles, 2 lights



Test Scenes II

- Test scenes: 800 triangles to >8 million

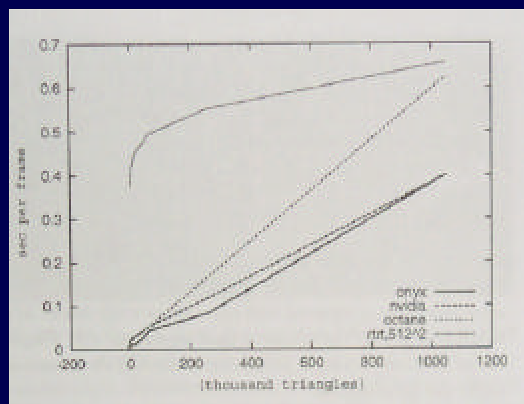


Terrain:
1 million triangles (textured)

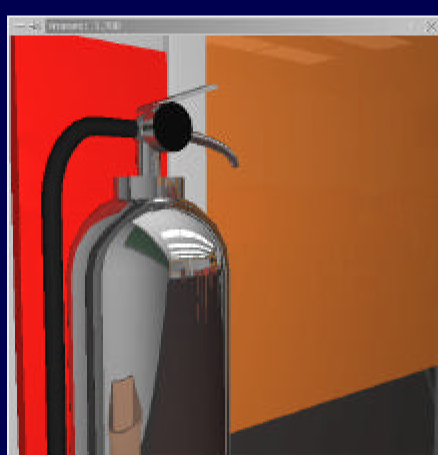
Berkeley Soda Hall:
1.5 to 8 million triangles

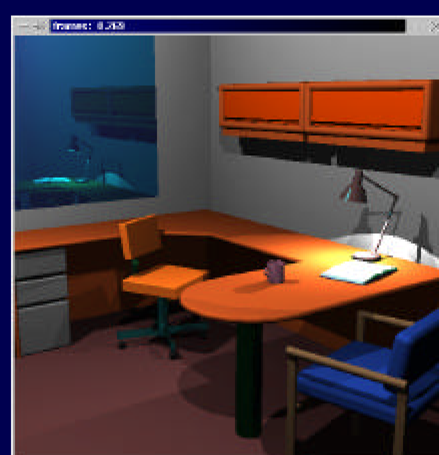
Performance Results III

- Comparison to Rasterization-Hardware
  - Ray tracing scales well for large environments



Sample Images





Fast RT [Benthin et. al.]

- SIMD and careful hand coding of inner loops
- 0.4 – 2 Million rays per second
  - Athlon MP 1800+
- *Instant Radiosity* used for global illumination
- Up to 48 processors for interactive performance

Reusing Shading for Global Illumination

Session IV

Reusing Shading

- Full simulation can take hours
- Interactive rendering by exploiting coherence

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Display Process

- Automatically exploit spatial and temporal coherence
- Layered on top of an existing (slow) global illumination renderer
- Provide interactive performance

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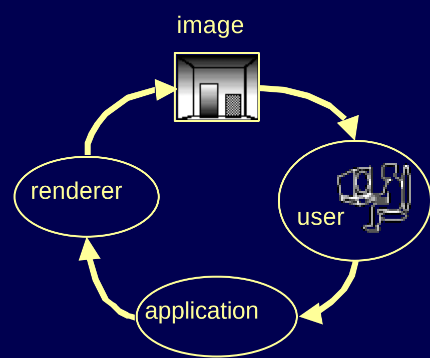
Interactive Global Illumination

- Standard visual feedback loop
  - Entirely synchronous
  - Framerate is limited by the renderer



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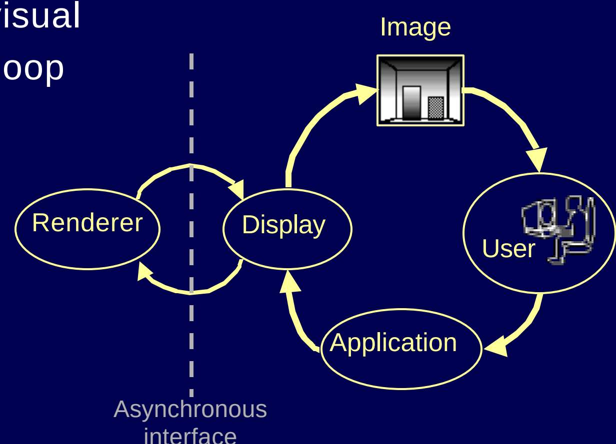
Interactive Global Illumination

- Modified visual feedback loop



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Interactive Global Illumination

- Interactive requirements
  - Image quality
  - Responsiveness
    - Don't make the user wait
    - Provide rapid user feedback
  - Consistency
    - Don't surprise or distract the user
    - Avoid sudden changes if possible
      - Eg, in quality, frame rate, popping, etc.

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Issues

- How to cache results for reuse?
  - Interpolate images from sparse data
  - Handle camera motion between frames
    - Handle occlusion changes
- Which samples should be rendered?
  - Prioritize for maximum benefit
- What if scene or shading changes?
  - Detect and discard data that is no longer valid

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Approaches

- Image based
  - Post-rendering Warp *(Mark97)*
  - Corrective texturing *(Stamminger00)*
- Point based
  - Render Cache *(Walter99,02)*
  - Edge-and-Point Rendering (Bala03)
- Mesh based
  - Tapestry *(Simmons00)*
  - Shading Cache *(Tole02)*
- 4D approaches
  - Holodeck *(Ward98,99)*
  - Radiance Interpolants (Bala99)

Frameless Rendering

- Update pixels as they are computed
  - Don't wait for full frame to finish

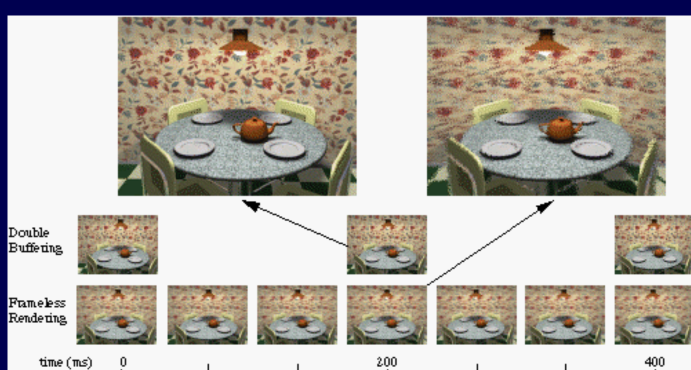


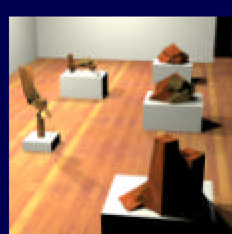
Figure 1. The bottom row shows 7 frames of a 15 Hz frameless rendering sequence with 33% of the pixels updated in each frame. The middle row shows 3 frames of a double-buffering sequence updated at 5 Hz.

Post-Rendering 3D Warp

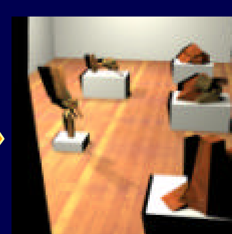
- Render subset of frames
  - E.g, every 6th frame is rendered
- Use standard image warping techniques to compute the other frames

Post-Rendering 3D Warp

- Problem: holes and missing data



Reference frame

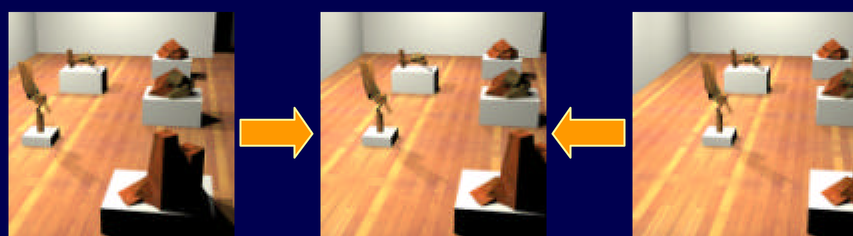


Warped frame

The camera is moving to the left in this example.

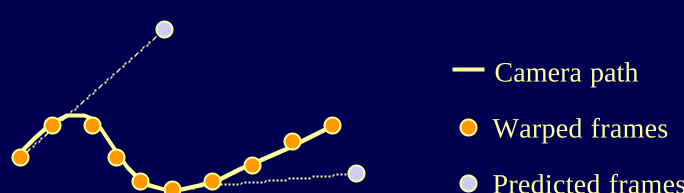
Post-Rendering 3D Warp

- Warp from both past and future reference frames
  - Heuristics for combining pixel results



Post-Rendering 3D Warp

- Must predict the locations of future frames
  - Longer predictions become rapidly less accurate



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Corrective Texturing

- Start with a standard hardware rendering of scene
  - Graphics hardware very good at interactive display
  - Start with a radiosity solution
- Compare to underlying renderer
  - Apply corrections where they differ
  - Corrections applied as projective textures

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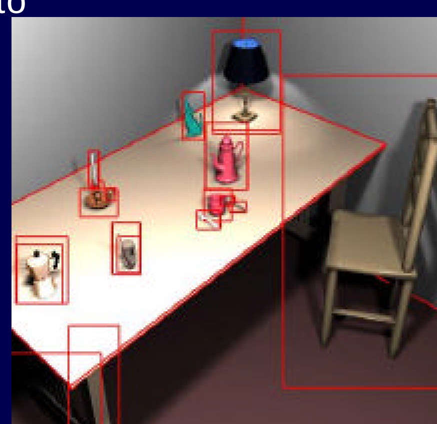
Corrective Texturing

- Corrective textures are dynamically assigned to objects



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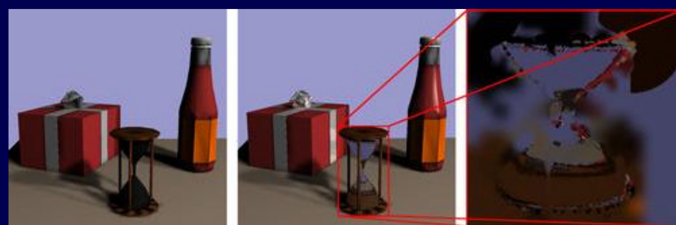
Corrective Texturing



Radiosity solution | Corrected image | Corrective texture

Corrective Texturing

- Sparse rendered samples compared to hardware displayed results
  - Differences splatted into textures
  - More samples generated near points which had large differences
  - Samples which are likely to have changed are deprecated so that can be overwritten by future results

Approaches

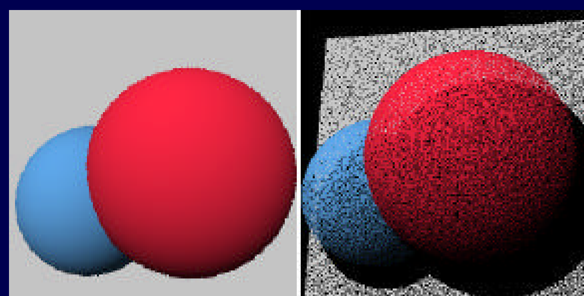
- Image based
  - Post-rendering Warp *(Mark97)*
  - Corrective texturing *(Stamminger00)*
- Point based
  - Render Cache *(Walter99,02)*
  - Edge-and-Point Rendering (Bala03)
- Mesh based
  - Tapestry *(Simmons00)*
  - Shading Cache *(Tole02)*
- 4D approaches
  - Holodeck *(Ward98,99)*
  - Radiance Interpolants (Bala99)

Render Cache

- Results stored as cloud of unordered points with:
  - 3D position (located on surfaces)
  - Color
  - Age
  - Object identifier

Render Cache

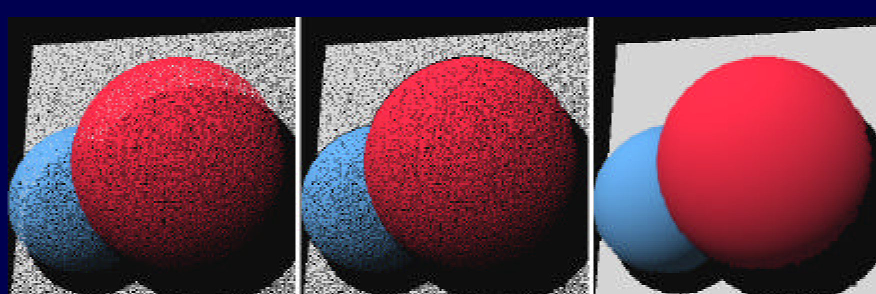
- Reproject points into current frame
  - Occlusion errors
  - Holes in data



Initial view After reprojection

Render Cache

- Use occlusion culling heuristic
- Interpolation to fill holes
  - Fixed size kernels, 3x3 and 7x7



Reprojection Occlusion cull Interpolation

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Render Cache

- Priority image for sampling
  - High priority for sparse regions
  - High priority for old points
- Convert priority image to sparse set of locations to be rendered
  - Uses error-diffusion dither
- Also uses predictive sampling
  - Try to sample new regions just before they become visible

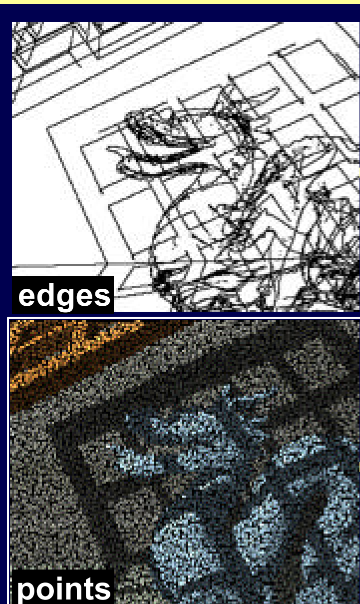
Render Cache

Displayed image   Priority image   Requested pixels

Render Cache

- Recomputes old samples to detect changes
  - Nearby points are aged to raise priority and cause point invalidation
- Object motion
  - Associated points can be transformed along with the object

Edge-and-Point Rendering



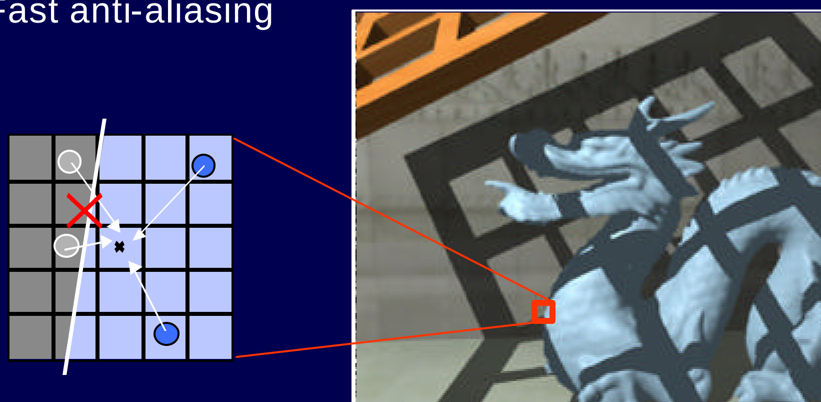
Edges: important discontinuities

– Silhouettes and shadows

Points: sparse shading samples

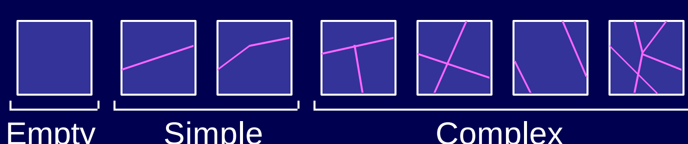
Edge-and-Point Image

- Alternative display representation
- Edge-constrained interpolation preserves sharp features
- Fast anti-aliasing



Pixel types

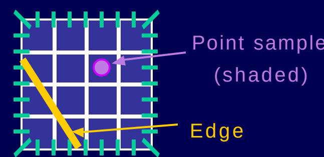
- Pixels can have arbitrary edge complexity
- Classify pixels into 3 groups
  - Empty: no edges
  - Simple: can be approximated by 1 edge
  - Complex: everything else



  - Typical pixel classification statistics
    - empty (85-95%), simple (4-10%), complex (1-4%)

Edge-and-Point Image (EPI)

- Goal: compact and fast
  - Store at most one edge and one point per pixel
  - Limited sub-pixel precision



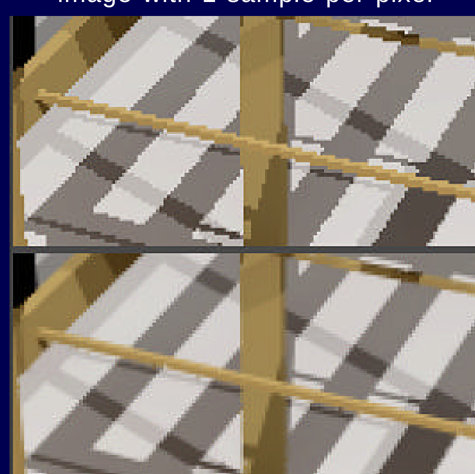
EPI pixel

- Combine edges and points in image space
  - View-driven, lazy evaluation

Fast Anti-aliasing

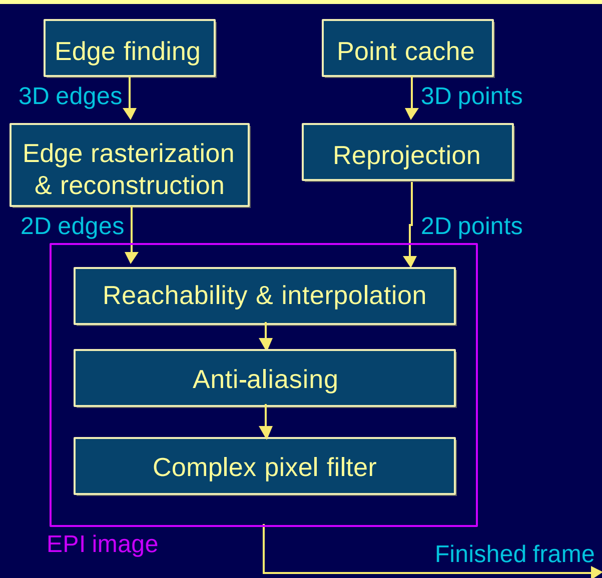
Our result using
<1 sample per pixel

Magnified view of a ray traced image with 1 sample per pixel



Magnified view of our results

Putting it Together



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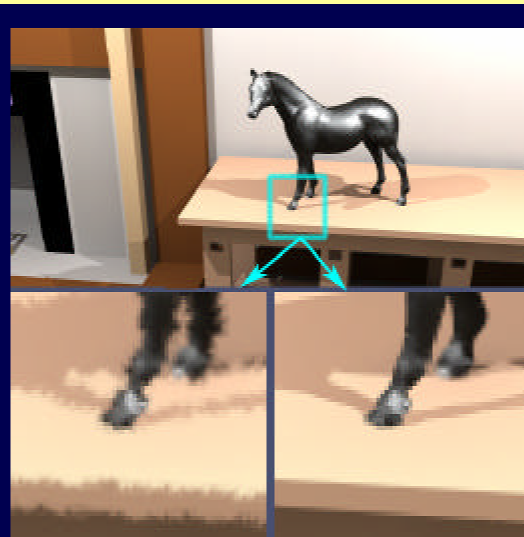
Results: Quality

- Global Illumination
  - 3 lights
  - 150k polygons
- Sparseness Ratio
  - 100: 1
- Performance
  - 8-14 fps



Without Edges **With Edges**

GDC 2004

Approaches

- Image based
  - Post-rendering Warp *(Mark97)*
  - Corrective texturing *(Stamminger00)*
- Point based
  - Render Cache *(Walter99,02)*
  - Edge-and-Point Rendering (Bala03)
- Mesh based
  - Tapestry *(Simmons00)*
  - Shading Cache *(Tole02)*
- 4D approaches
  - Holodeck *(Ward98,99)*
  - Radiance Interpolants (Bala99)

GDC 2004

Holodeck

- Uses Radiance as its renderer
- Rendered samples stored in a 4D data structure
  - Similar to Light Field or Lumigraph
  - Can be very large
    - Paged to disk if necessary
  - Lazily evaluated
    - Samples generated near current viewpoint
  - Position and other parameters are specified by the user

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Holodeck

- Uses Gouraud-shaded triangle mesh
  - Get samples near current viewpoint
  - Samples become vertices in a mesh
  - Delaunay triangulation of samples in direction space about a center of projection
  - Hardware provides fast display including interpolation between samples

Holodeck

- Mesh construction
  - Choose center point
  - Construct Delaunay triangulation
    - Based on sample point's projection onto a sphere about the center point
  - Display mesh using hardware
  - Update incrementally with new samples
- If user moves too far, then must choose new center and rebuild mesh

Holodeck

- Depth heuristic to reduce occlusion errors
- Special techniques for designated moving objects

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Tapestry

- Based on Holodeck system with several enhancements:
  - Prioritized sampling
  - Incremental “recentering” of spherical Delaunay mesh as viewpoint moves
  - Fixed cache size
    - Max vertices = pixels
  - Sample invalidation
    - Occlusion and color change heuristics

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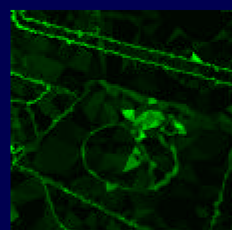
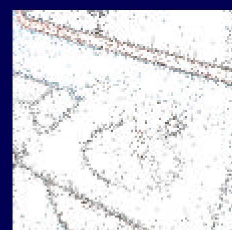
Tapestry

- Each triangle assigned a priority
  - Color & depth differences and age
  - Rasterize priority using hardware
  - Quasi-random sampling with rejection

Image



Priority



Samples

Shading Cache

- Display mesh is refinement of original scene mesh
  - No occlusion errors
  - Hardware handles textures
  - Display mesh >= original mesh
  - Easier to handle moving objects
- Decouples frame update from mesh update

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Shading Cache

- Adds flood-fill heuristic for sampling
  - Discontinuities require locally dense subdivision
- Mesh de-refinement
  - If not recently visible
  - If denser than pixel spacing
  - If color changes are detected

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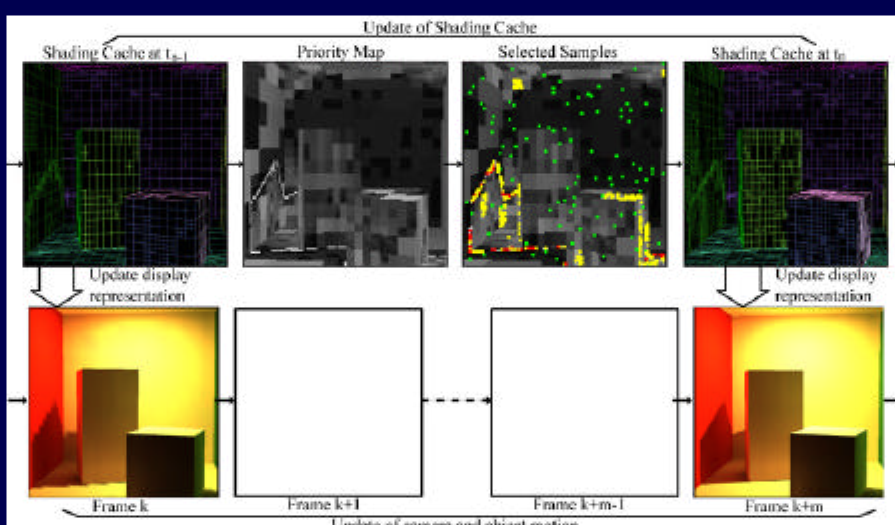
Shading Cache



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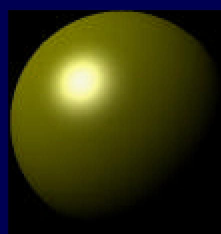
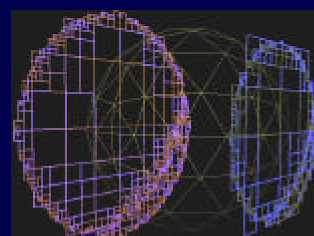
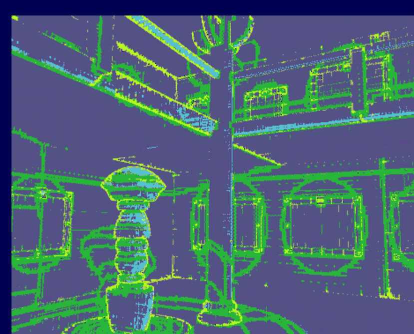
Radiance Interpolants Bala[96,97,99]

- Radiance interpolant:
  - Set of sparse samples (in 4D line space) of radiance function
  - Bounded-error, accurate reconstruction





Results: Museum Scene



gray: interpolation success
yellow: silhouettes; green: shadows

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Downloadable Versions

- Render Cache
  - http://www.graphics.cornell.edu/research/interactive/rendercache/
- Holodeck
  - http://radsite.lbl.gov/radiance

Conclusion

- Software Interactive Rendering is possible now with current machines
  - Good scaling with scene complexity
  - Much greater shading flexibility
- Many interesting challenges still remain
  - Higher resolutions
  - Fully dynamic environments
  - Anti-aliasing

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