Lecture 12: Interactive Ray Tracing and Acceleration Structures

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HW 1

- Add whatever you need to ….
  - Get color in the materials
  - Diffuse, etc.
- Only direct lighting
- Only hard shadows
- So why spheres? So that radiosity/radiance conversions etc. work out.

Interactive Software Rendering

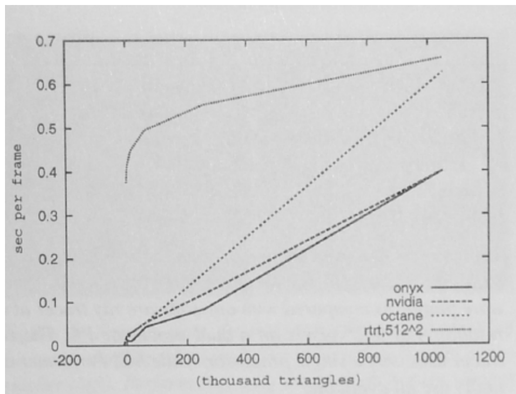
- Interactive
  - User-driven, not pre-scripted animation
  - At least a few frames per second (fps)
- Software
  - Major shading done in software
    - Can use hardware to help
- Rendering
  - Online, not pre-computed or captured
    - Eg, lightfields are pre-computed

Why Software Rendering?

- Global Illumination: Non-local information
- Extremely high complexity
- Arbitrary shading models
- Portability
  - No tweaking: just works
  - No scene dependent optimizations

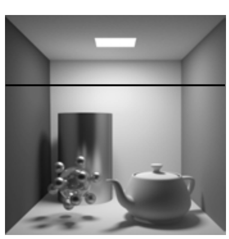
Performance Results II

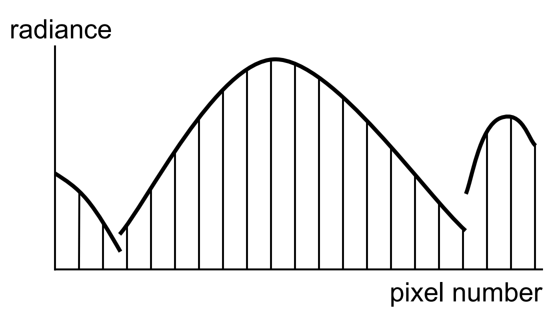
- Comparison to Rasterization-Hardware
  - Ray tracing scales well for large environments



Rendering as Sampling

- Ray tracers compute radiance at each pixel

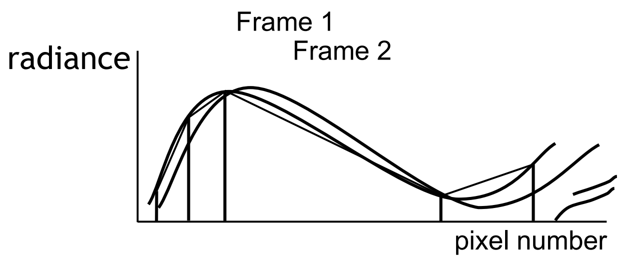




- Rendering = Sampling radiance

Coherence

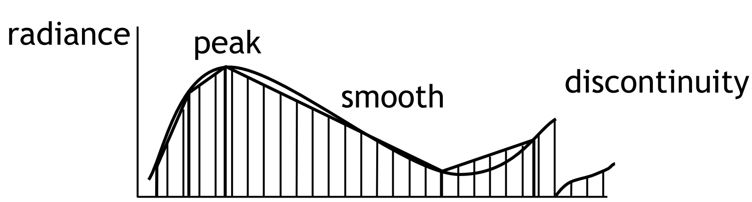
- Within one frame: spatial coherence



- Across many frames: temporal coherence

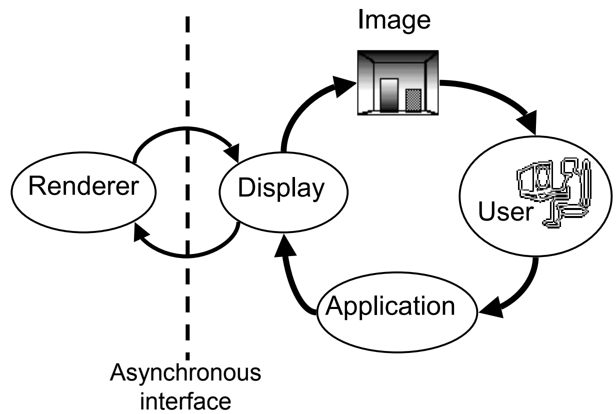
Strategy

- Insight: radiance is mostly smooth -- use sparse sampling and reconstruction



- Radiance samples are very expensive
- Goal: reconstruct most pixels by interpolation
- Issues: discontinuities, non-linear variations

Modified Visual Feedback Loop

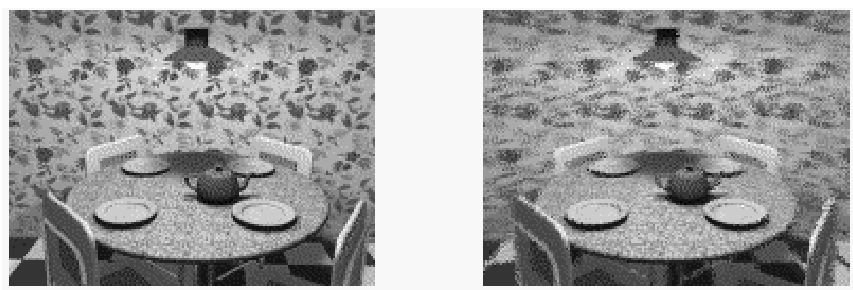


Display Process

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

Aside: Frameless Rendering

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



Frameless Rendering

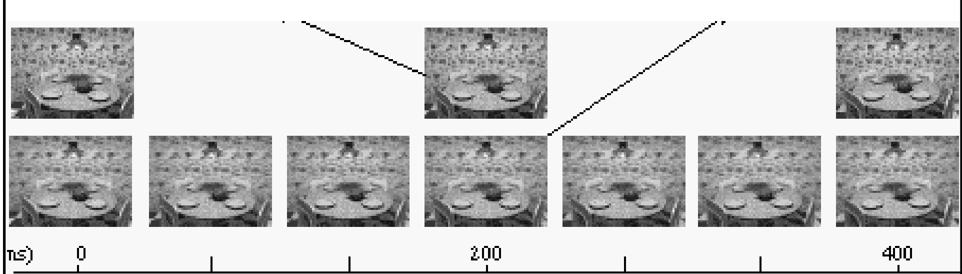


Figure 1. The bottom row shows 7 frames of a 15 Hz frameless rendering sequence with 33% of the pixels updated in each frame. The middle row shows 3 frames of a double-buffering sequence updated at 5 Hz.

Sparse Sampling Approaches

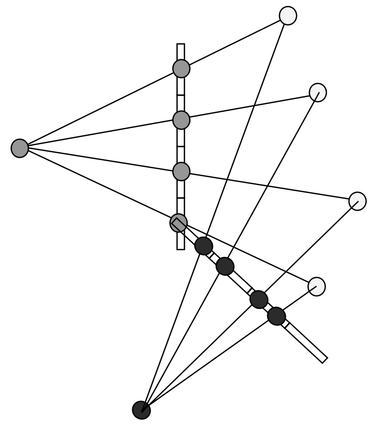
- 4D:
  - Radiance Interpolants
  - Holodeck
- 2D: Image based
  - Post-rendering Warp
  - Render Cache
  - Edge and Point Rendering
  - Corrective Texturing

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

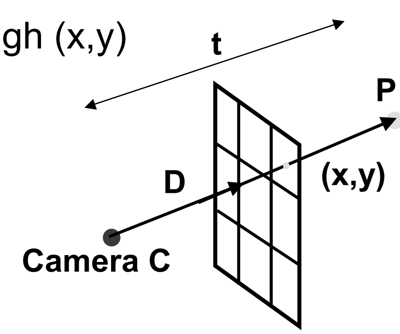
Aside: Pixel Reprojection

- Goal: Want image at new viewpoint
- Reproject points from input images



Aside: Pixel Reprojection

- Assume have depth/disparity per pixel
- If pixel (x,y) sees point P,
- $P = C + t\,D$
- C is camera position,
- D is direction from C through (x,y)
- t is distance along D

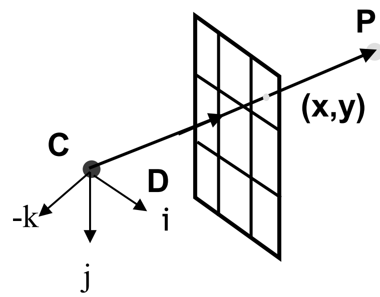


Aside: Pixel Reprojection

- Direction D

  $D = C + x\,i + y\,j + d\,k$

  (x, y) = pixel



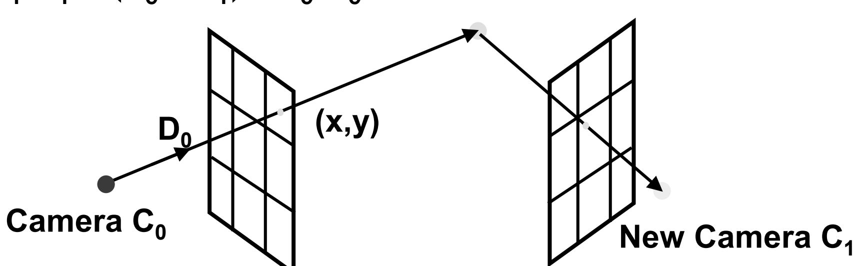
- C = camera center
- d = distance of image plane from C
- C, d are known

Aside: Pixel Reprojection

$P = C_0 + t_0\, D_0(x,y)$

$C_0 + t_0\, D_0 = C_1 + t_1\, D_1$

$t_1\, D_1 = (C_0 - C_1) + t_0\, D_0$

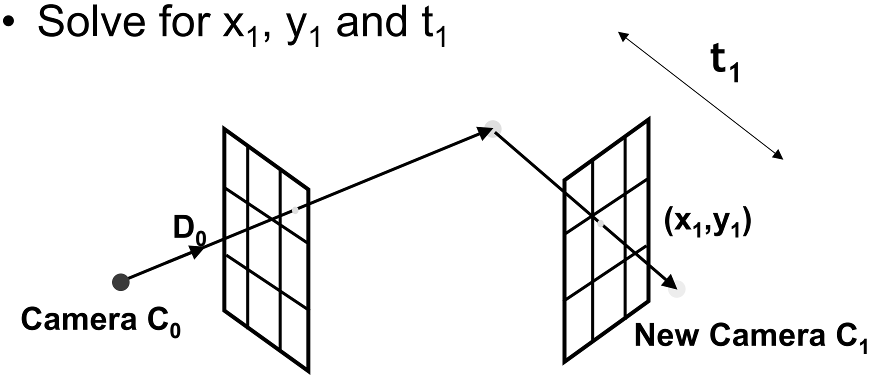


C_0, C_1, D_0, t_0 are known

$t_1\, D_1$ defines the reprojected pixel

Aside: Pixel Reprojection

- $D_1 = C_1 + x_1 i + y_1 j + d_1 k$
- Solve for x_1, y_1 and t_1



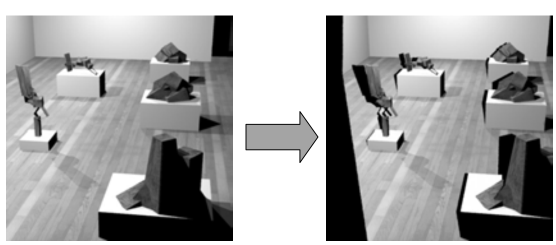
Post-Rendering 3D Warp

- Problem:

  Pixels do not project to pixel centers

  Multiple pixels project to same pixel in new view

  Holes and missing data



Reference frame Warped frame

The camera is moving to the left in this example.

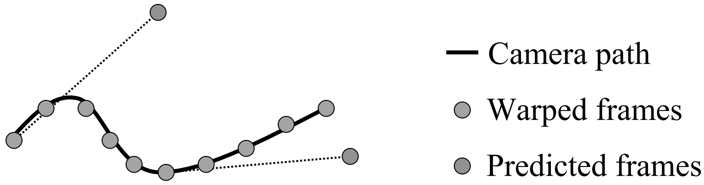
How to fill holes?

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

Prior reference Warped frame Next reference

Problem: Post-Rendering Warp

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



Sparse Sampling Approaches

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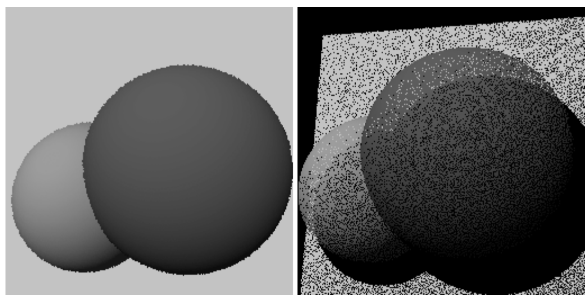
  - Holodeck
- 2D: Image based
  - Post-rendering Warp
  - Render Cache
  - Edge and Point Rendering
  - Corrective Texturing

Render Cache (Walter et al.)

- Interactivity is important
  - Maintain relatively constant framerate
    - e.g., > 5 fps
  - Degrade gracefully as rendering becomes more expensive
- Cache shaded pixels as 3D colored points
- Render new image
  - Project points onto current image plane
  - Filter to reduce artifacts
- Prioritize future rendering
  - Identify problem pixels
  - Sparse sampling for limited render budget

Approach

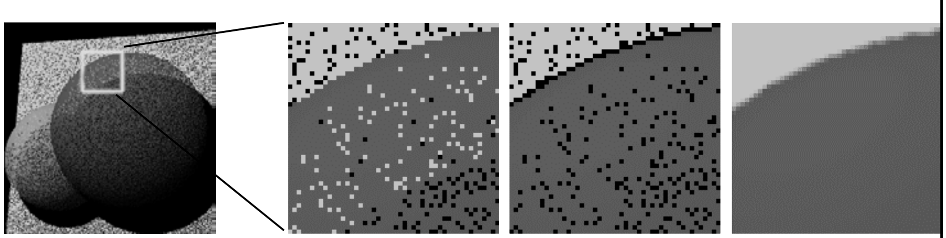
- Data: Cloud of unordered points with:
  - 3D position,color, age, object id
- Approach: reproject points into image plane
  - Occlusion errors, holes in data



Initial view After reprojection

Image Estimation

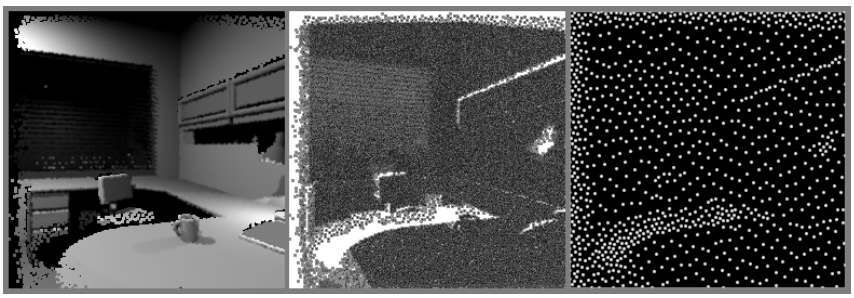
- Depth cull heuristic
  - Problem: occluded points may be visible
    - Z-buffering only works within a pixel
  - Clean up using nearby depth information
- Interpolate 3x3



Raw projection depth cull interpolation

Sampling

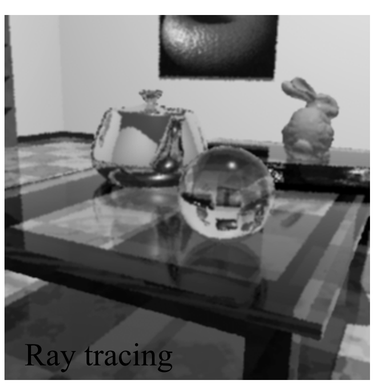
- Choose pixels for rendering: sparse sampling
- Requested pixels sent to renderer(s)
  – Results returned at some later frame



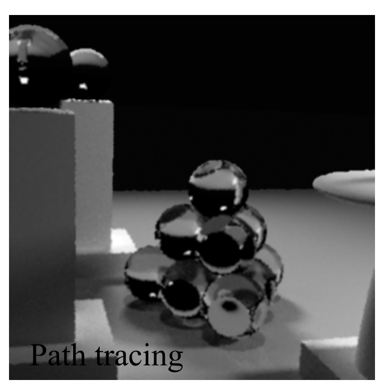
Displayed image Priority image Requested pixels

Render Cache Adv and Limitations

- Improved interactivity
- Independent display process
- Drawback: pixel artifacts



Ray tracing



Path tracing

Sparse Sampling Approaches

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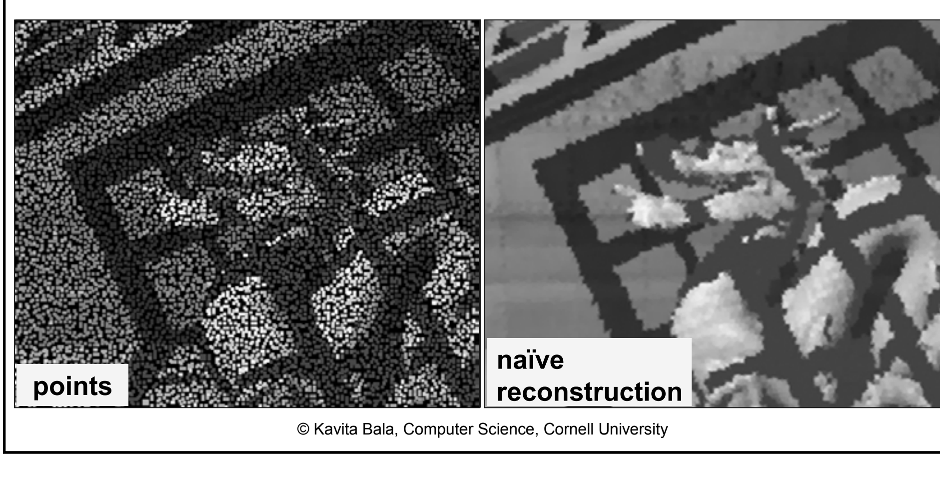
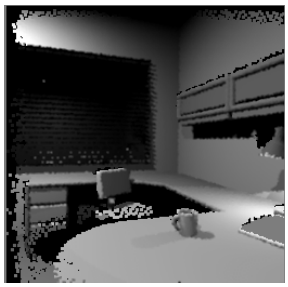
Edge-and-Point [Bala'03]

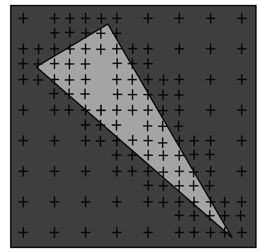
- Goal: Interactive high-quality rendering
  - Expensive shading: e.g., global illumination
  - But, mostly smooth (coherent)



Edge-and-Point Motivation: Performance

- Discontinuities are perceptually important
  - Artifacts are disturbing



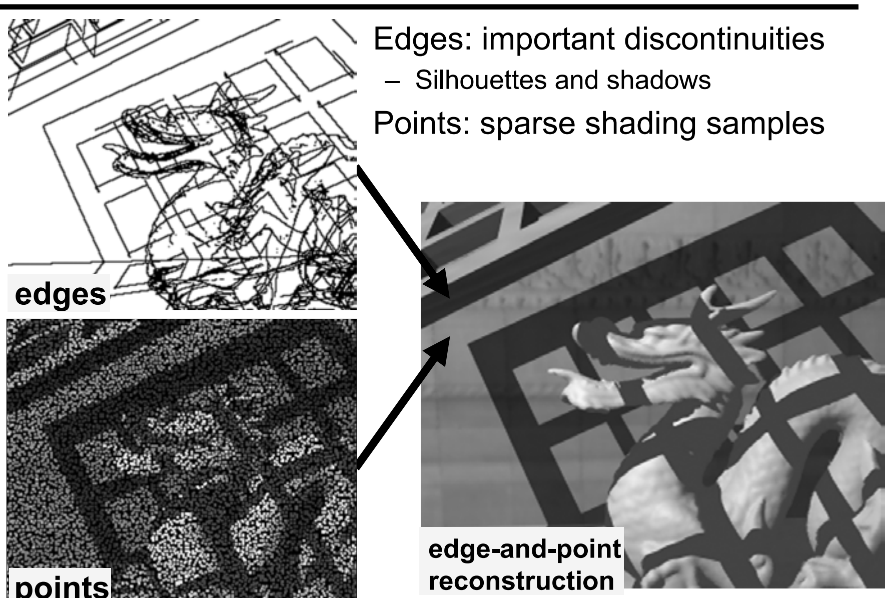


- Finding discontinuities by sampling is expensive

Edge-and-Point Rendering

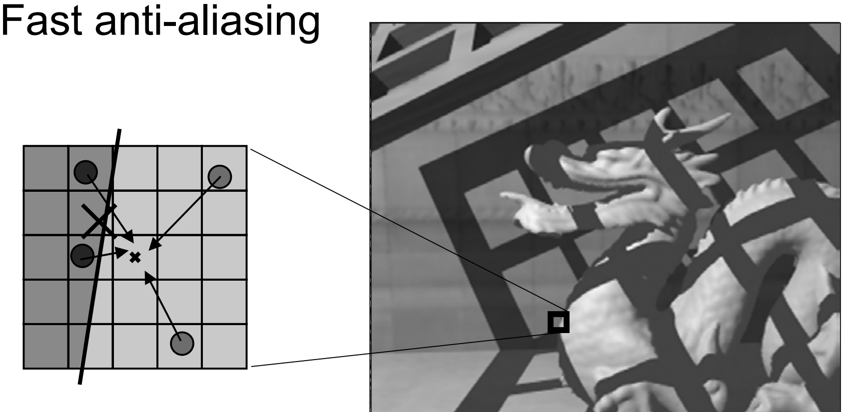
Edges: important discontinuities
- Silhouettes and shadows

Points: sparse shading samples

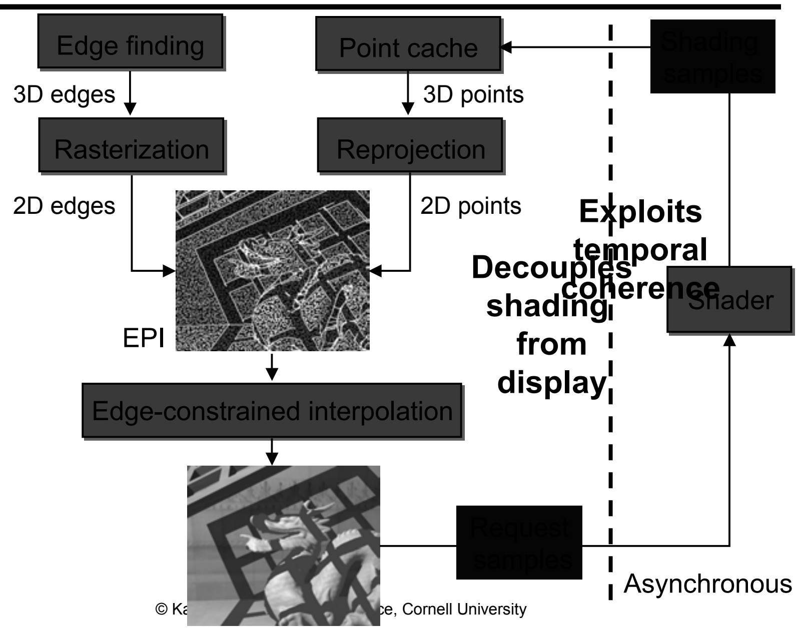


Edge-and-Point Image

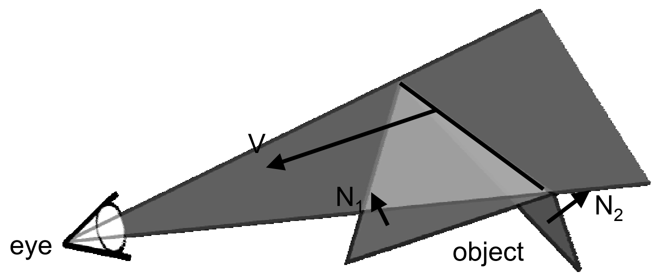
- Alternative display representation
- Edge-constrained interpolation preserves sharp features
- Fast anti-aliasing



System

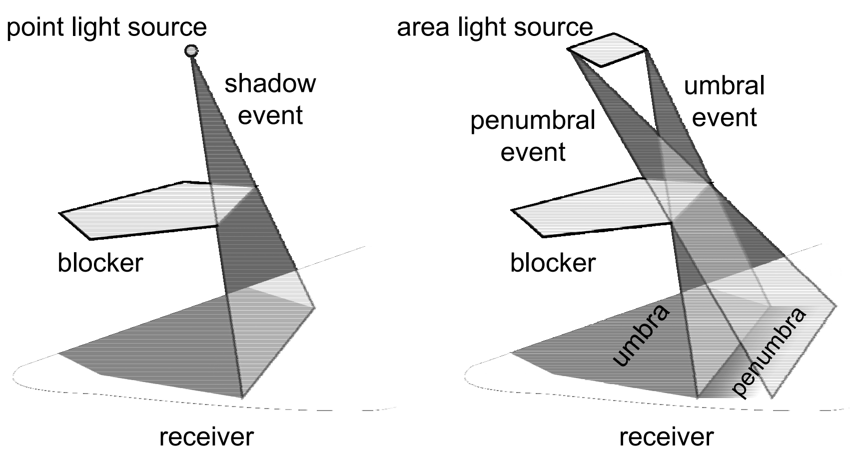


Silhouettes



$N_1 \cdot V > 0$ (forward facing)
$N_2 \cdot V < 0$ (backward facing)

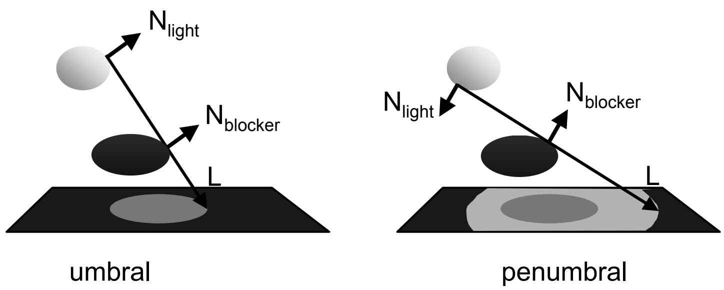
Shadows: Hard and Soft



Hard shadows

Soft shadows

Umbra and Penumbra Conditions



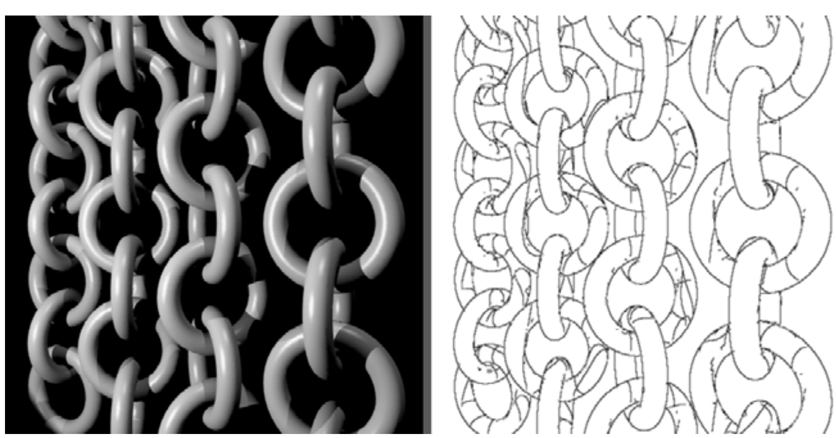
- Event plane tangential to light and blocker

  $L \cdot N_{blocker} = L \cdot N_{light} = 0$

  $N_{light} \cdot N_{blocker} = 1$ (umbral), -1 (penumbral)

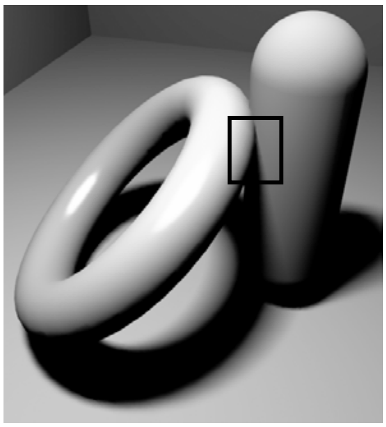
Edge Finding

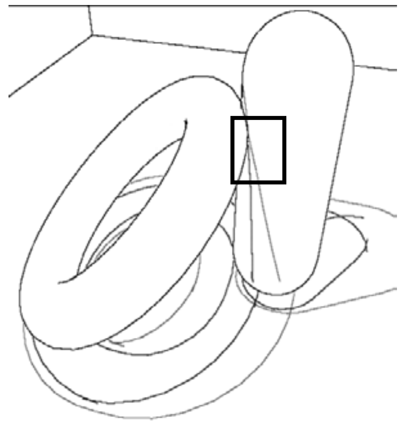
- Hierarchical trees: fast edge finding
  - Interval-based



Soft Shadow Edges

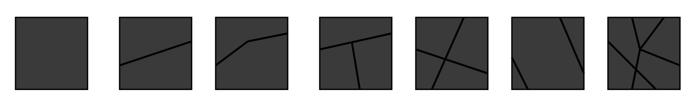
Black: silhouettes,
Red: umbral edges, Blue: penumbral edges





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

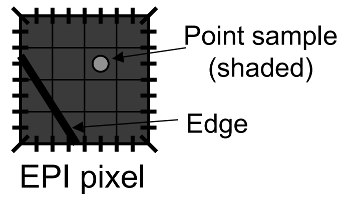


Empty Simple Complex

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

Edge-and-Point Image (EPI)

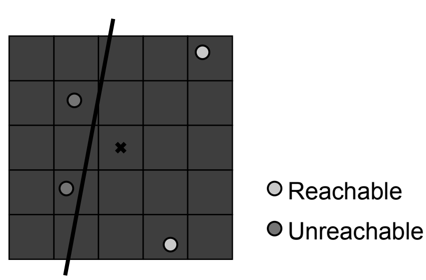
- Goal: compact and fast
  - Store at most one edge and one point per pixel
  - Limited sub-pixel precision

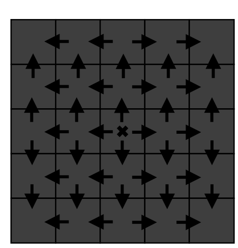


- Combine edges and points in image space
  - View-driven, lazy evaluation

Reachability

- Reachable samples
  - Pixel's 5x5 neighborhood
  - Connected without crossing any edges (or complex pixels)
- Propagated outward from each pixel

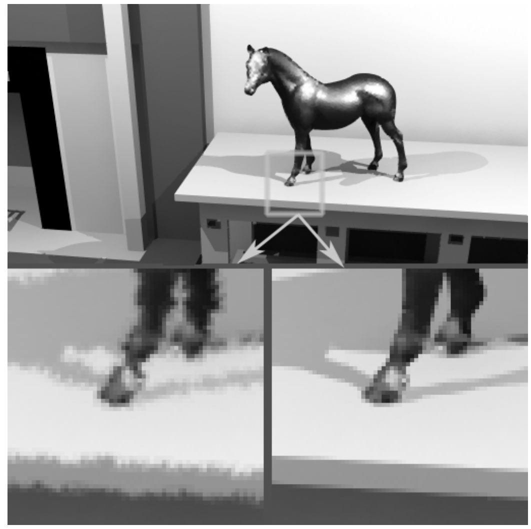




Propagation

Results: Quality

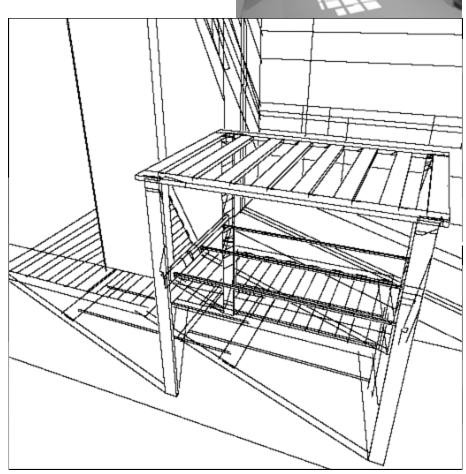
- Global illumination
- 3 lights
- 150k polygons



Without Edges **With Edges**

Tea Stand

- Global illumination



Sparse Sampling Approaches

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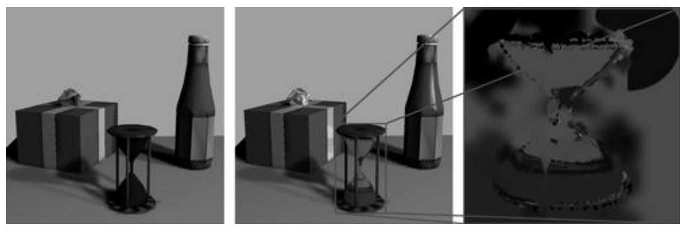
  - Holodeck
- 2D: Image based
  - Post-rendering Warp
  - Render Cache
  - Edge and Point Rendering
  - Corrective Texturing

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

Corrective Texturing



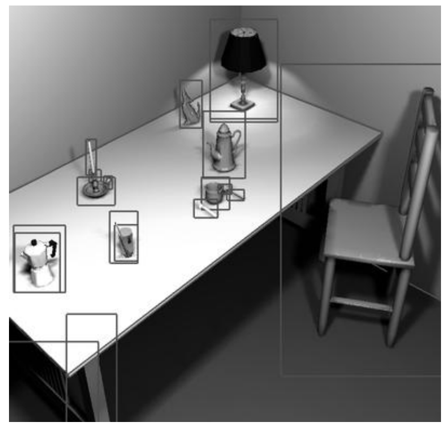
Radiosity solution | Corrected image | Corrective texture

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

Corrective Texturing

- Corrective textures are dynamically assigned to objects



Comparison

	Target renderer speed	Sparseness ratio	Typical frame rates
Warp	< 1s	4 - 10	20 - 60 fps
Corrective Tex.	20 - 200s	250 - 1000	5 - 10 fps
RC	.5 - 10s	8 – 100	10 - 20 fps
EPI	.5 - 10s	8 - 100	10 - 20 fps

Comparison

	Hardware accelerated	Independent of scene complexity	Moving objects	Quality
Warp	No	Yes	No	?
Corrective Tex.	Yes	No	No	Not really
RC	No	Yes	Yes	No
EPI	Yes	Yes	Yes	Yes

Prediction

- Hardware
  - Speed
  - Programmability
- Software
  - High-complexity data sets
  - Complex GI
- Hybrid techniques

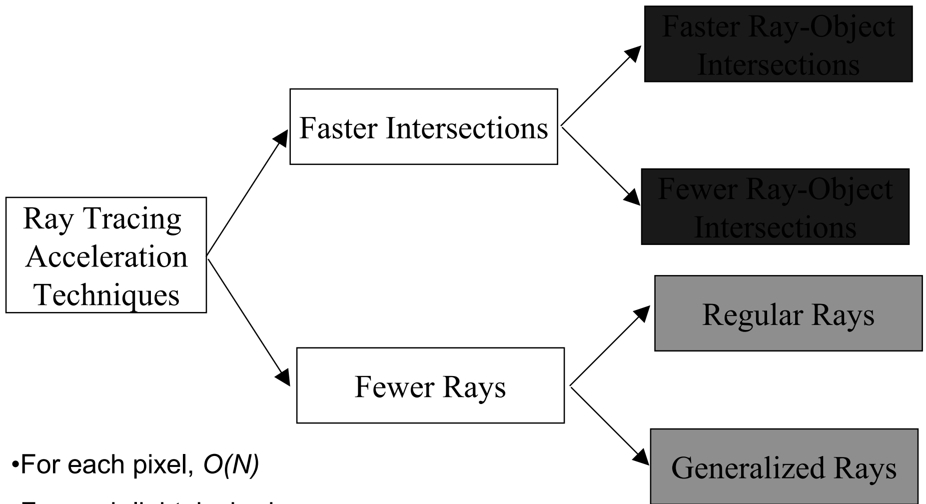
Dealing with High Complexity

- Many Lights
- Display systems
  - Point-based approaches
- Visibility pre-processing systems
- Image-Based Rendering

Acceleration Data Structures

CS 665

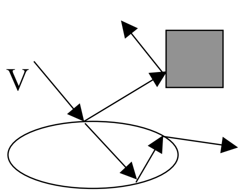
Making RT faster



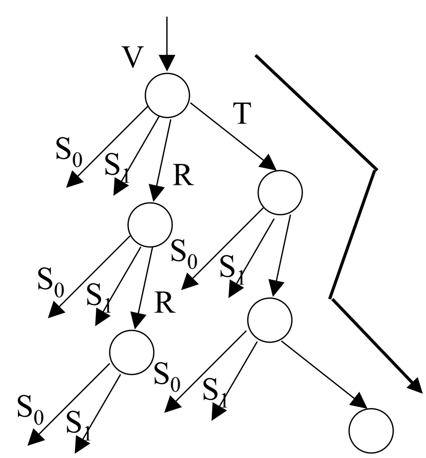
- For each pixel, *O(N)*
- For each light, k shadow rays
- For GI and antialiasing: many rays per pixel

Fewer Rays: Regular Rays

- Regular rays
  - Adaptive tree-depth control
  - Adaptive antialiasing

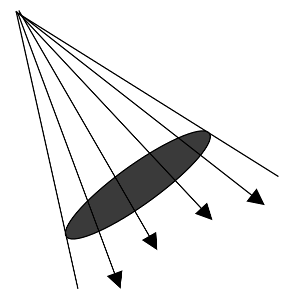


$K_t \,.\, K_s \,.\, K_t$. Shading

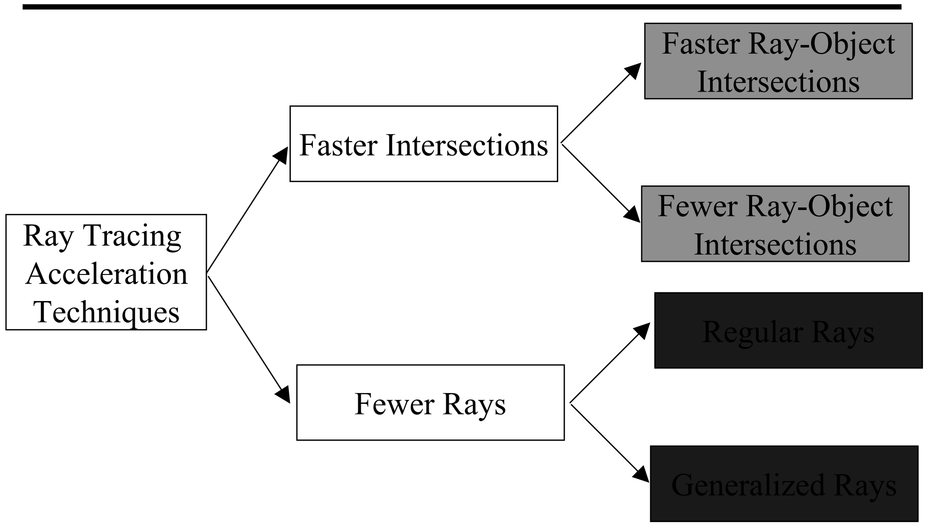


Generalized Rays

- Generalized rays represent a set of rays
  - Cone
  - Beam
- Pros
  - Good for anti-aliasing
  - Decreases number of rays
- Cons
  - More complex intersection tests
  - Reflections and refractions get hairy

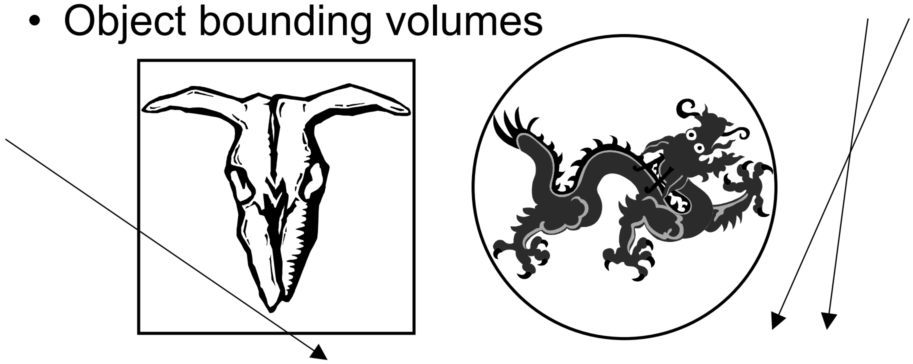


Making RT faster



Faster Ray-Object Intersections

- Object bounding volumes



- Avoid intersection tests for expensive objects: e.g., polygon sets, spline surfaces
  - Ray/sphere or ray/cuboid test is fast

Intersection: sphere

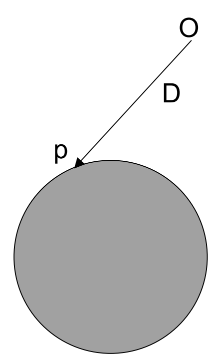
Assume sphere $x^2 + y^2 + z^2 = 1$

Point of intersection $p = O + t_{intersection} D$

p lies on sphere

Solve $A\, t_{intersection}^2 + B\, t_{intersection} + C = 0$

$A = 1$, $B = 2\,(O.D)$, $C = (O.O - 1)$



$t_{intersection} = (-B \pm S)/(2\,A)$,

$S = \mathrm{sqrt}\,(B*B - 4\,AC)$

Intersection: cube

tNear = -inf, tFar = +inf

For each pair of planes for the x,y,z axes {

  Solve for O[i] + D[i] t1 = Min[i]

  Solve for O[i] + D[i] t2 = Max[i]

  What if t1 > t2? swap

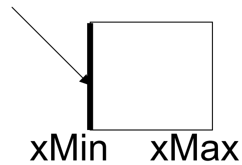
  t_{Near} = max (t1, t_{Near})

  t_{Far} = min (t2, t_{Far})

}

if (t_{Near} > t_{Far}) missed box

else hit box



Tight Fit to Bounding Volume