Computer Graphics

- Distribution Ray Tracing -

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Overview

• **Other Optical Effects**
  – Not yet included in Whitted-style ray tracing

• **Stochastic Sampling**

• **Distribution Ray-Tracing**
Problems

- Anti-aliasing
- Depth of field
- Motion blur
- BRDF
- Area Lights
Anti-aliasing

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- Depth of field
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\[ I \approx \int_A L(o + td) dA \]
Depth of field

- Anti-aliasing
- Depth of field
- Motion blur
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\[ I \approx \int_A L(o + td) dA \]
Motion blur

- Anti-aliasing
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\[ L \approx \int_{[t_o,t_1]} L_T(o + td) dT \]
BRDF

• Anti-aliasing
• Depth of field
• Motion blur
• BRDF
• Area Lights

\[ L_o = L_e + \int_{\Omega_+} f_r L_i \cos \theta_i \, d\omega_i \]
Area Lights

- Anti-aliasing
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\[ E_i = \int_A V(x, y) \frac{\cos \theta_A}{\|x - y\|^2} dA \]
Integration by MC-Sampling

- **Features**
  - Anti-aliasing
  - Depth of field
  - Motion blur
  - BRDF
  - Area Lights

- **Monte-Carlo (MC) Integration**
  - Stochastic sampling of domain
  - Averaging of results, weighted by probability
  - Careful choice of samples essential for good results

\[
I = \int_D f(x) \, dx
\]

\[
I \approx \frac{D}{n} \sum_{i=1}^{n} \frac{f(x_i)}{p(x_i)}
\]

\[x_i \text{ sampled } \propto p(x)\]
STOCHASTIC SAMPLING
(VERY SHORT INTRO)
Random Number

• **Random Number**
  – Uniformly distributed
  – $\xi$ in $[0, 1)$

• **Pseudo-Random Number**
  – Linear congruential
  – Mersenne-Twister
  – ...
  – Speed / evenness trade-off
Parallelogram Sampling

- **Parametric Form**
  \[ p(u, v) = p_0 + u(p_1 - p_0) + v(p_2 - p_0) = (1 - u - v)p_0 + up_1 + vp_2 \]

- **Random Sampling**
  \[ p(\xi_1, \xi_2) \]
Triangle Sampling

- **Parametric Form**
  - \( p(u, v) = (1 - u - v)p_0 + up_1 + vp_2 \)

- **Random Sampling**
  - if \( \xi_1 + \xi_2 < 1 \) : \( p(\xi_1, \xi_2) \)
  - if \( \xi_1 + \xi_2 > 1 \) : \( p(1 - \xi_1, 1 - \xi_2) \)
Disc Sampling

- **Parametric Form**
  - $p(u, v) = \text{Polar2Cartesian}(R v, 2 \pi u) \ // \text{disc radius } R$

- **Naïve Sampling (wrong!)**
  - $p(\xi_1, \xi_2)$
Disc Sampling

- **Parametric Form**
  - \( p(u, v) = \text{Polar2Cartesian}(R v, 2 \pi u) \) \( \text{// disc radius } R \)

- **Correct Sampling**
  - \( p(\xi_1, \sqrt{\xi_2}) \)
  - Results in uniform sampling over area

DISTRIBUTION RAY-TRACING
Distribution Ray Tracing

- Apply random sampling for many aspects in RT
  - Pixel
    - Anti-aliasing
  - Lens
    - Depth of field
  - Time
    - Motion blur
  - BRDF
    - Glossy reflections & refractions
  - Area Lights
    - Soft shadows

- Base on paper:
  R. Cook et al., *Distributed Ray Tracing*, Siggraph’84
Anti-Aliasing

- **Artifacts**
  - Jagged edges
  - Aliased patterns
Anti-Aliasing

- **Approach**
  - Average samples over pixel area
  - Akin to sensor cells of measuring device collecting photons

- **Random offset of pixel raster coords from center**
  - \( prc[\text{coord}] = pid[\text{coord}] + 0.5 + (\xi - 0.5) \)
Anti-Aliasing

• **Basic Method**
  – Plain average
  – Box filter \( f(x, y) = 1 \)
  – \( L = \frac{\sum_{i=1}^{n} L(\xi_{i1}, \xi_{i2})}{n} \)

• **Filtering**
  – Weighted average
  – Filter \( f(x, y) \)
  – \( L = \frac{\sum_{i=1}^{n} f(\xi_{i1}, \xi_{i2}) L(\xi_{i1}, \xi_{i2})}{\sum_{i=1}^{n} f(\xi_{i1}, \xi_{i2})} \)
Depth of Field

• **Real Camera**
  – Complex lenses that focus one distance onto the image
  • Finite aperture size
  – Blurred features except for focal plane
Depth of Field

**Thin Lens**
- Focus light rays from point on object onto image plane
  - Sharp features at focal plane
  - Blurred features before/beyond focal plane
- Depth of field: depth range with acceptably small *circle of confusion*
  - Smaller than one pixel
Depth of Field

- **Compute ray through lens center**
  - Compute focus point $P_f$ on focal plane, determined by $P_b$ and $P_c$

- **Compute new ray origin**
  - Sample coordinates $(x, y)$ of aperture diameter ($= f / N$)
  - Compute $P_i$: $\text{ray.origin} += P_c + x \times \text{camera.right} + y \times \text{camera.up}$
  - Might include modeling the shape of the aperture

- **Compute new ray direction**
  - Compute $\text{ray.direction} = P_f - P_i \rightarrow$ vector from $P_i$ to $P_f$
  - Normalize
Depth of Field

Cook et al. Siggraph'84
Depth of Field

- Zero Aperture
Depth of Field

- Small Aperture
Depth of Field

- Large Aperture
Depth of Field

- Very Large Aperture
Motion Blur

- **Real Camera**
  - Finite exposure time
  - Shutter opening at $t_0$
  - Shutter closing at $t_1$

$$t_0 + (t_1 - t_0) \xi$$
Motion Blur

- **Real Camera**
  - Finite exposure time
  - Shutter opening at $t_0$
  - Shutter closing at $t_1$

- **Approach**
  - Sample time $t$ in $[t_0, t_1)$: $t = t_0 + \xi (t_1 - t_0)$
  - Assign time $t$ to new camera ray/path
  - Models with moving camera and/or moving objects in the scene
    - Time-dependent transformations
    - Transform objects or inverse-transform ray to proper positions at $t$
  - Assume instantaneous opening and closing
    - Can be generalized by modeling shape of aperture over time

- **Gotchas**
  - Acceleration structures built over dynamic objects
Motion Blur
Reflections/Refractions

- **Dielectric Materials**
  - $\eta_i$ – refractive index $\frac{c}{v}$
  - Light: fastest path
  - Snell’s law:
    \[
    \frac{\sin \theta_1}{\sin \theta_2} = \frac{\eta_2}{\eta_1}
    \]
  - if
    \[
    \sin \theta_2 = \frac{\eta_1}{\eta_2} \sin \theta_1 > 1
    \]
    ... then total inner reflection
Reflections/Refractions

• Which ray to trace?
  – Both: may be exponential
Reflections/Refractions

• Which ray to trace?
  – Pick one at random:
    • $\xi < 0.5$ – reflection
    • $\xi \geq 0.5$ – refraction
  – Compensate for the energy-loss
    • $L_o = 2 \cdot L_i \cdot f_r$
Fuzzy Reflections/Refractions

- **Real Materials**
  - Never perfectly smooth surfaces

- **Empirical Approach**
  - Compute orthonormal frame around reflected/refracted direction
  - Sample coordinates \((x, y)\) on disc: \(\text{ray.direction} += x \times a + y \times b\)

- **Or better use \(\cos^n\) sampling** (→ GI Compendium)
Fuzzy Reflections/Refractions

• **Gotchas**
  – Perturbed ray may go inside
  – Check sign of dot product with N
  – Ignore rays on wrong side

• **Inter-Reflections/Refractions**
  – Recursively repeat process
    • At surfaces with corresponding materials
Fuzzy Reflections/Refractions
Soft Shadows

- **Real Light Sources**
  - Finite area
Soft Shadows

- **Approach**
  - Random sample point on surface of light source
  - Scale intensity by area and cosine
Soft Shadows

- Small vs. Large Area Light
Combined Effects

• **High-Dimensional Sampling Space**
  – number of anti-aliasing samples
  – \(x\) number of lens samples
  – \(x\) number of time samples
  – \(x\) number of material samples
  – \(x\) number of light samples

  ➔ Exponential growth:
  • Increasing number of higher-order rays with decreasing effect on final pixels ➔ bad

• **Solution: Path-Based Approach**
  – Avoid exponential growth in ray tree
  – Pick a single sample at each step: ➔ Create a sample *path*
  – Average results over several paths per pixel ➔ *path tracing* (RIS)
    • Theoretical underpinning: Monte-Carlo Integration
Comparison to Path Tracing

Distribution Ray Tracing

Path Tracing

(figure by Kajiya)
Recent Advances in Lighting Sim.

• **Importance Caching for Complex Illumination**
  – By Iliyan Georgiev et al., Eurographics 2012
Recent Advances in Lighting Sim.

- **Light Transport Simulation with Vertex Connection and Merging (VCM)**
  - By Iliyan Georgiev et al., Siggraph 2012
Recent Advances in Lighting Sim.

- Light Transport Simulation with Vertex Connection and Merging (VCM)
  - By Iliyan Georgiev et al., Siggraph 2012
Recent Advances in Lighting Sim.

- **Optimal Multiple Importance Sampling**
  - By Pascal Grittmann, Jarozlav Krivanek, et al., Siggraph 2019

![Diagram showing recent advances in lighting simulation](image.png)
Recent Advances in Lighting Sim.

- **Variance-Aware Path Guiding**
  - By Alexander Rath, Pascal Grittmann, et al., Siggraph 2020