DCGI

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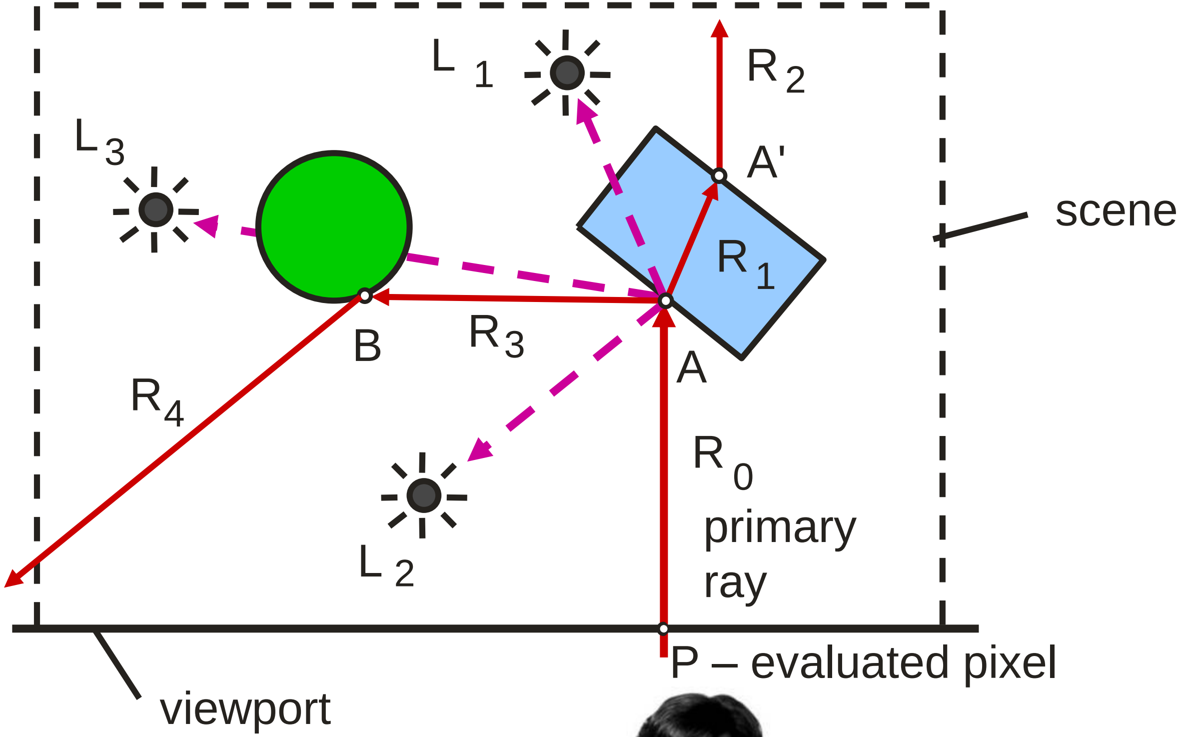
Ray Tracing

Jiří Bittner

Outline

- Whitted Ray Tracing MPG 15.9
- Path Tracing
- Ray Tracing Acceleration MPG 15.9.3

Ray Tracing Principle



[Whitted 1980]

(Backward) Ray Tracing - Algorithm

TraceRay (Ray *R*, recursion depth *H*)

1. Find intersection P of R with the nearest object

2. If no intersection // ray leaves the scene

   assign R background color and terminate

3. For all light sources:

   cast a **shadow ray** from *P.*

   if the shadow ray reaches the light source mark it visible

4. Evaluate light contribution at P from all **visible light sources**

5. If H < max depth :

   (a) **TraceRay** (Reflected ray *RR*, *H* + 1)

   (b) **TraceRay** (Refracted ray RT, *H* + 1)

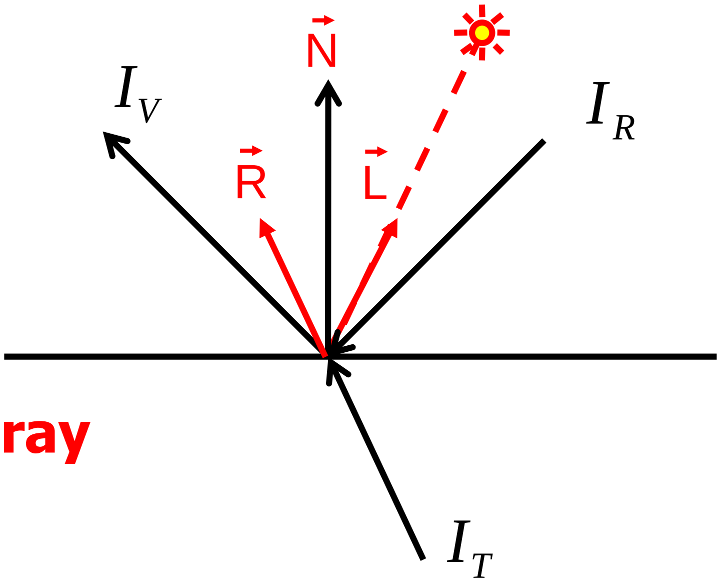
6. Assign to R the resulting color using sum of illumination from light sources and RR and RT

Extending Illumination Model

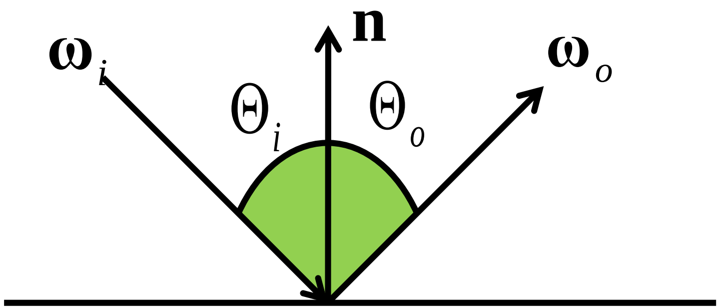
- $I_V = I_a + I_r + I_t + \sum I_d + I_s$
- I_a ambient component
- I_d diffuse component
- I_s specular component
- $I_r = k_s I_R$
- $I_t = k_t I_T$
- k_s ... specular coef.
- k_t ... transmittance coef.

Recursion

Shadow ray



Direction of Reflected Ray



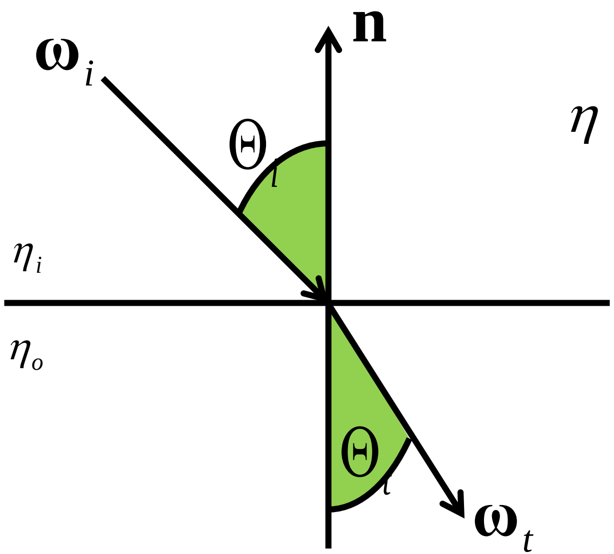
$$\Theta_o = \Theta_i$$

$$\boldsymbol{\omega}_o = \boldsymbol{\omega}_i + 2\cos\Theta_i \mathbf{n}$$
$$\boldsymbol{\omega}_o = \boldsymbol{\omega}_i - 2(\boldsymbol{\omega}_i \circ \mathbf{n})\mathbf{n}$$

Refracted Ray

$$\eta_i \sin\theta_i = \eta_o \sin\theta_t$$ Snell's law

$$\boldsymbol{\omega}_t = \eta_{io}\boldsymbol{\omega}_i - [\sqrt{1-\eta_{io}^2(1-\cos^2\theta_i)} + \eta_{io} cos\theta_i]\,\mathbf{n} \qquad \eta_{io} = \frac{\eta_i}{\eta_o}$$

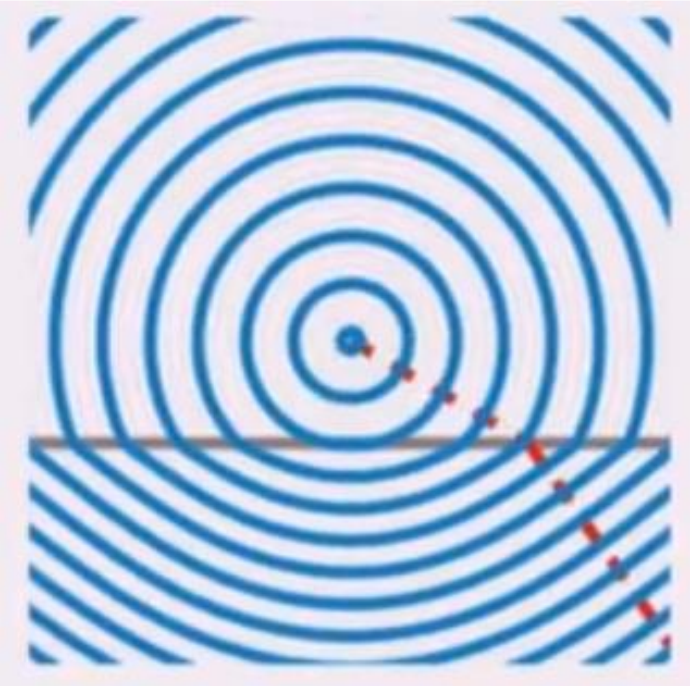


η index of refraction (air 1.000293, water 1.33, glass 1.6, diamond 2.4)

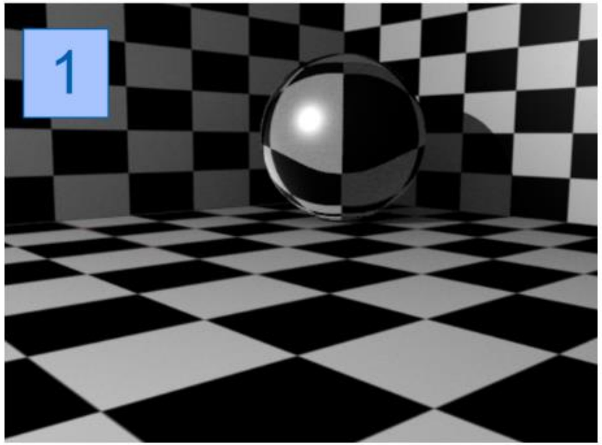
$$\sin^2\theta_t = \eta_{io}^2(1-\cos^2\theta_i) > 1$$

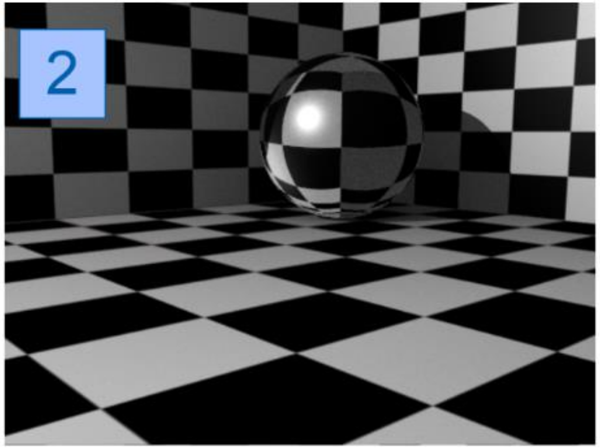
Total internal reflection – no refraction

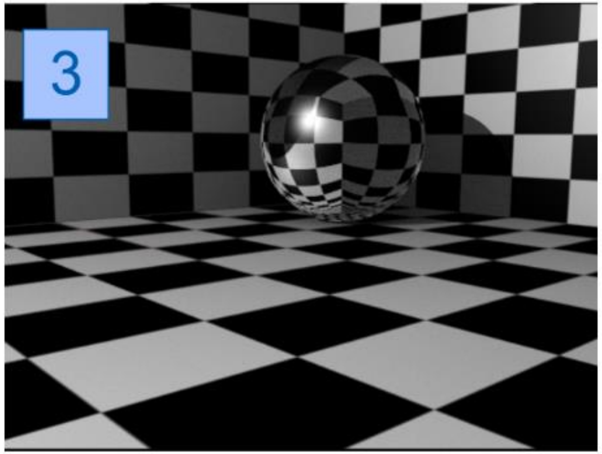
Refraction - Example



Index of Refraction - examples







1. IOR = 1.333 (water)
2. IOR = 1.517 (glass)
3. IOR = 2.417 (diamond)

Examples courtesy of L. Cmolik

Fresnel Equations

- Reflectivity (odrazivost) / transmissivity (propustnost) varies with incident angle! (also polarization matters)

reflected
$$F(\theta_i) = \left| \frac{\eta_{io} cos\theta_i - \sqrt{1 - (\eta_{io} sin\theta_i)^2}}{\eta_{io} cos\theta_i + \sqrt{1 - (\eta_{io} sin\theta_i)^2}} \right|^2$$

transmitted
$$T(\theta_i) = 1 - F(\theta_i)$$

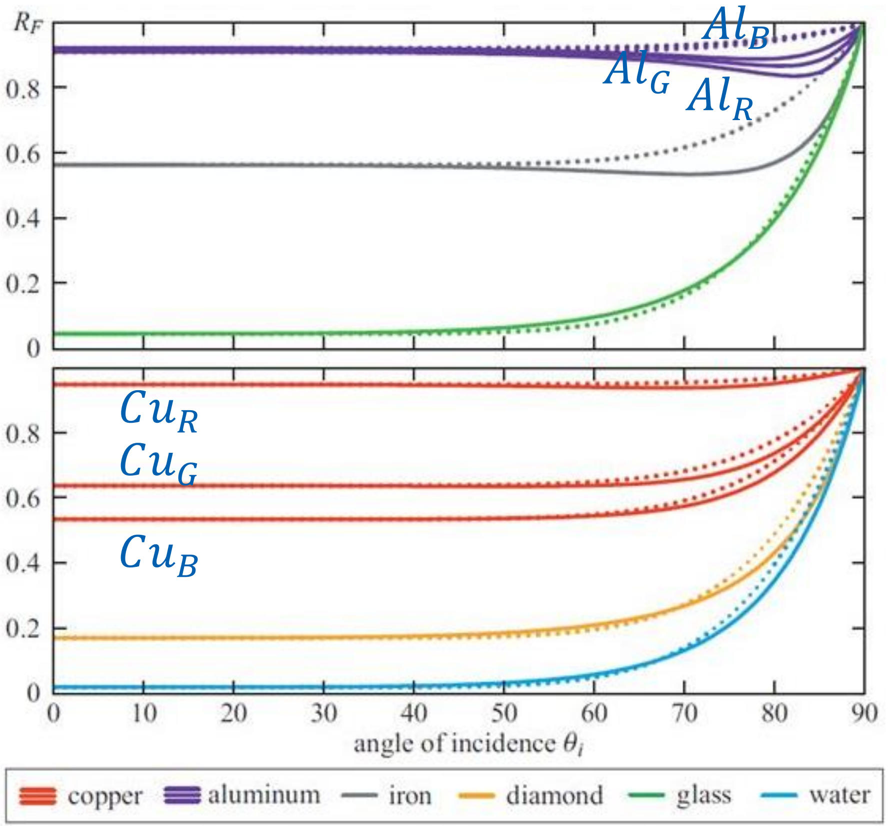
- Schlick approximation [1994]

$$F(\theta_i) = F_0 + (1 - F_0)(1 - cos\theta_i)^5 \qquad F_0 = \left(\frac{\eta_{io} - 1}{\eta_{io} + 1} \right)^2$$

Examples

solid = Fresnel
dotted = Schlick

$R(\theta_i)$



Source: Möller et al. RTR 3ed.

Outline

- Whitted Ray Tracing MPG 15.9
- Path Tracing
- Ray Tracing Acceleration MPG 15.9.3

Path Tracing

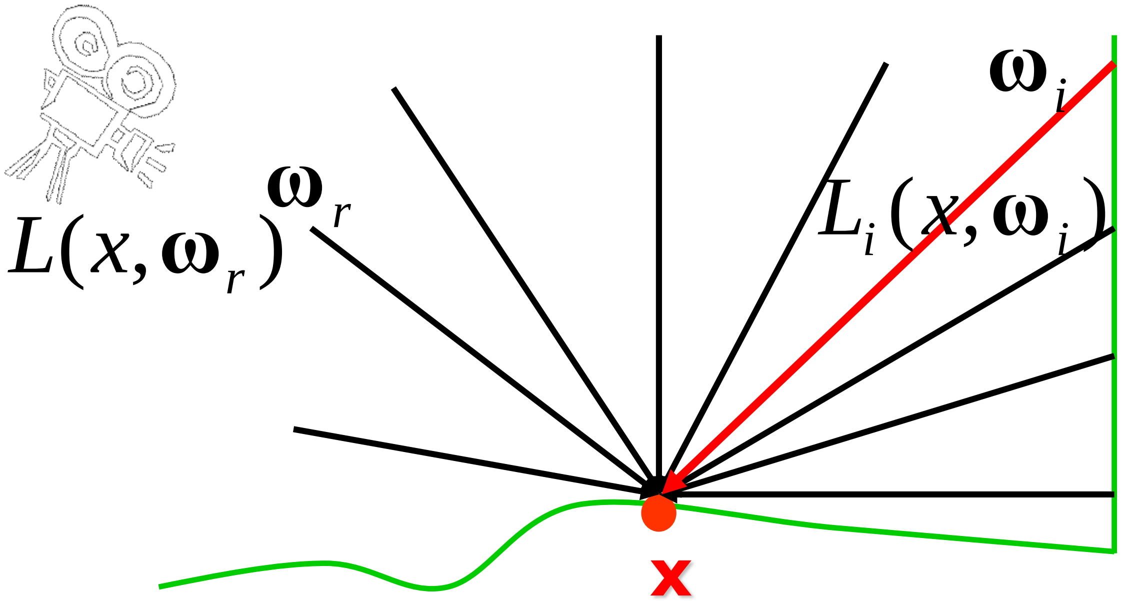
- Correct evaluation of indirect illumination
- Monte-Carlo integration → Unbiased image estimate

- Generating random reflection/refraction directions
- Appropriate sample distribution (importance sampling)

- One secondary ray per hit → single light path
- Many paths per pixel (samples per pixel)

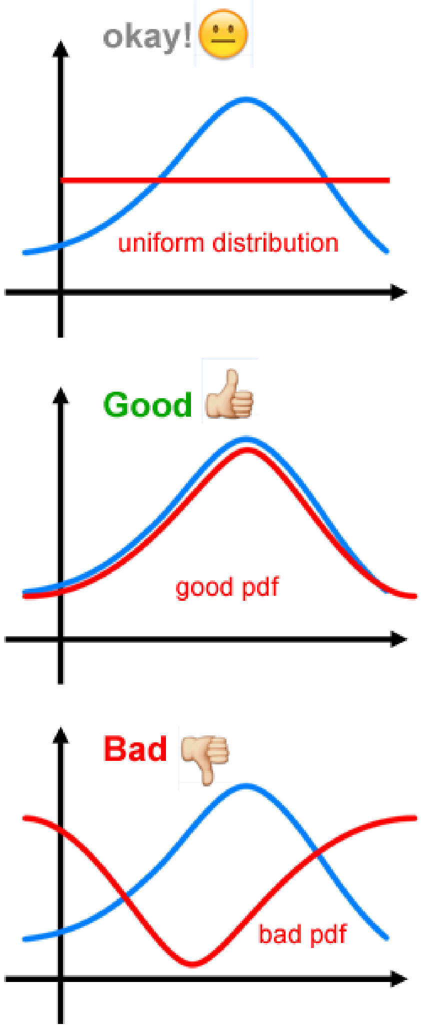
Path Tracing – Rendering Equation

$$L_r(x,\omega_r) = L_e(x,\omega_r) + \int_{\Omega} f_r(x,\omega_i,\omega_r)\, L_i(x,\omega_i) \cos\theta_i \, d\omega_i$$



Monte Carlo Integration

$$\int h(x)dx \approx \frac{1}{N}\sum_{k=1}^{N}\frac{h(x_i)}{pdf(x_i)}$$



Monte Carlo Integration

$$L_r(x,\omega_r) = L_e(x,\omega_r) + \int_\Omega f_r(x,\omega_i,\omega_r)\, L_i(x,\omega_i) \cos\theta_i \, d\omega_i \approx$$

$$L_e(x,\omega_r) + \frac{1}{N}\sum_{k=1}^{N} \frac{f_r(x,\omega_{i_k},\omega_r)\, L_i(x,\omega_{i_k}) \cos\theta_i}{pdf\left(\omega_{i_k}\right)}$$

MC Integration – Diffuse Surface, Uniform Distribution

$$L_r(\boldsymbol{x}, \boldsymbol{\omega}_r) \approx \frac{1}{N} \sum_{k=1}^{N} \frac{f_r(\boldsymbol{x}, \boldsymbol{\omega}_{i_k}, \boldsymbol{\omega}_r)\, L_i(\boldsymbol{x}, \boldsymbol{\omega}_{i_k}) \cos\theta_i}{pdf(\boldsymbol{\omega}_{i_k})}$$

$$L_r(\boldsymbol{x}, \boldsymbol{\omega}_r) \approx \frac{1}{N} \sum_{k=1}^{N} \frac{\frac{k_d}{\pi}\, L_i(x, \omega_{i_k}) \cos\theta_i}{\frac{1}{2\pi}}$$

MC Integration – Difuse Surface, Cosine Distribution

$$L_r(\boldsymbol{x}, \boldsymbol{\omega}_r) \approx \frac{1}{N} \sum_{k=1}^{N} \frac{f_r(\boldsymbol{x}, \boldsymbol{\omega}_{i_k}, \boldsymbol{\omega}_r) L_i(\boldsymbol{x}, \boldsymbol{\omega}_{i_k}) \cos\theta_i}{pdf(\boldsymbol{\omega}_{i_k})}$$

$$L_r(\boldsymbol{x}, \boldsymbol{\omega}_r) \approx \frac{1}{N} \sum_{k=1}^{N} \frac{\frac{k_d}{\pi} L_i(x, \omega_{i_k}) \cos\theta_i}{\frac{\cos\theta_i}{\pi}}$$

$$L_r(\boldsymbol{x}, \boldsymbol{\omega}_r) \approx \frac{k_d}{N} \sum_{k=1}^{N} L_i(x, \omega_{i_k})$$

Path Tracing

- Monte Carlo integration
- Many primary samples
- 1 secondary sample per hit point
- Stochastic decisions
  - Reflect / Refract
  - Diffuse / Specular
  - Importance sampling (pdf according to BSDF component)

Path Tracing

- Terminated by ray leaving the scene
  - HDR map lookup of $L_i(x, \omega_{i_k})$
- Russian roulette
  - Terminate the path with probability p_t
  - If survives multiply the incoming radiance by $\frac{1}{\mathrm{p_t}}$
- Next event estimation
  - Explicit sampling of lights with shadow rays (one to few lights per hit point)
  - Add to path contribution

smallpt: path tracing in 99 lines of C++ code
https://www.kevinbeason.com/smallpt/

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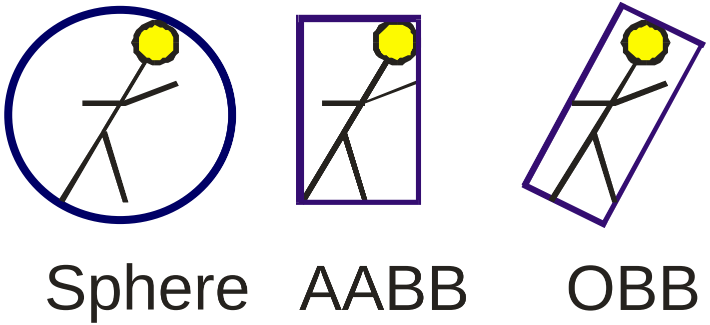
Acceleration Methods

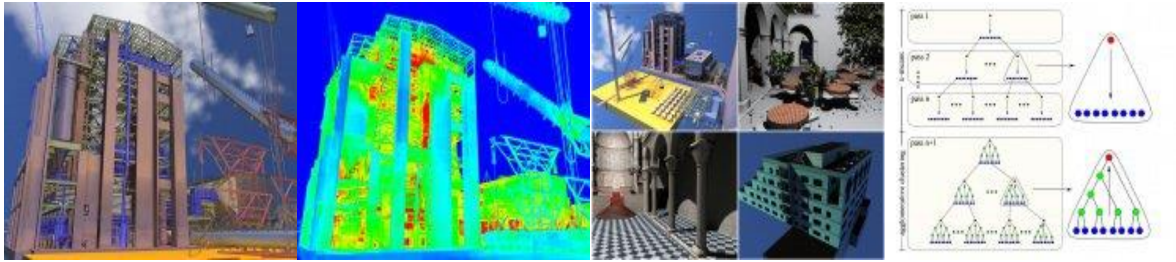
Ray tracing is costly – must accelerate!

1. **Accelerating intersection computation**
   a) Faster ray / object intersection (low level optimizations)
   b) Less ray / object intersections (spatial data structures)
   c) Tracing more rays together
2. **Cast less rays**
   - Importance sampling
   - Adaptive antialiasing, adaptive depth of recursion, …

Less Ray / Object Intersections

- Kd-tree, octree
- Bounding Volume Hierarchy
- Hot research topic at DCGI!

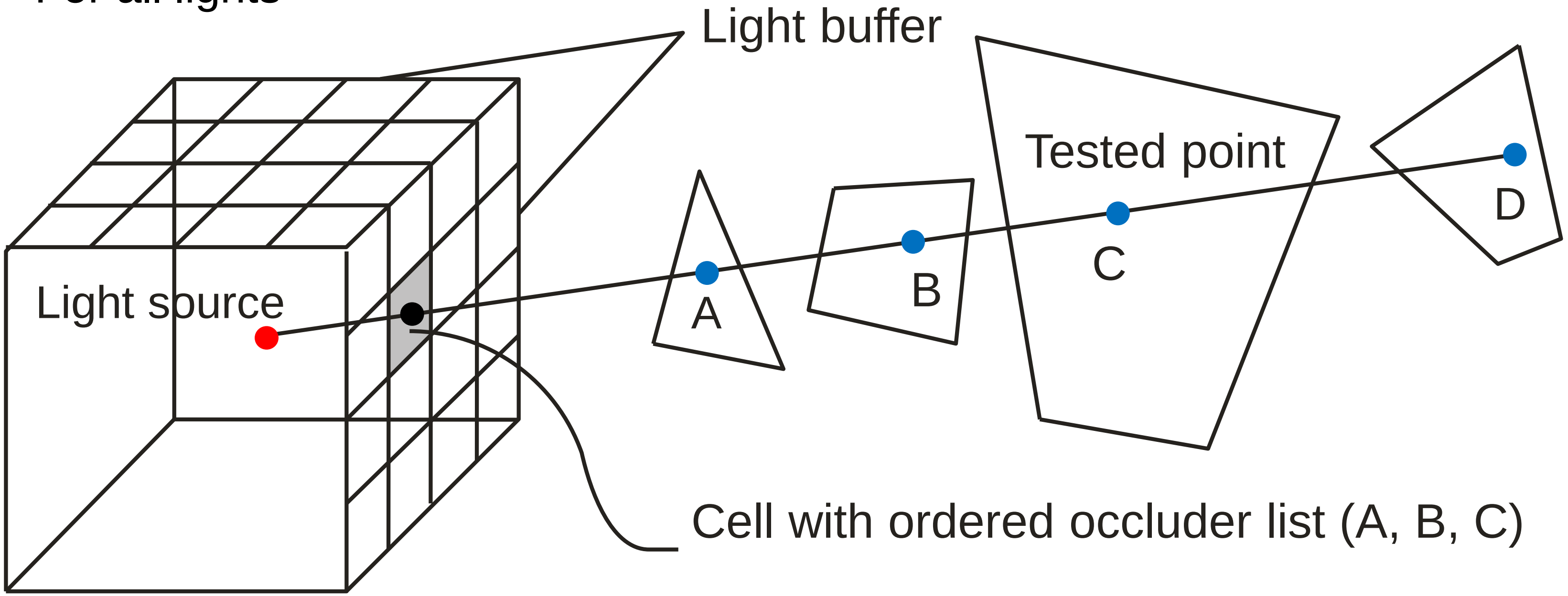




https://github.com/meistdan/ploc
https://github.com/meistdan/prbvh

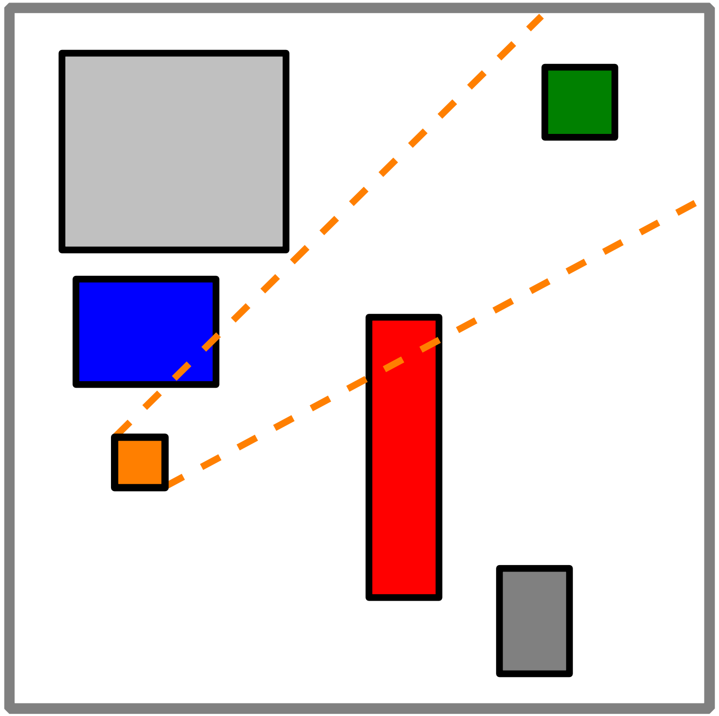
Less Ray / Object Intersections

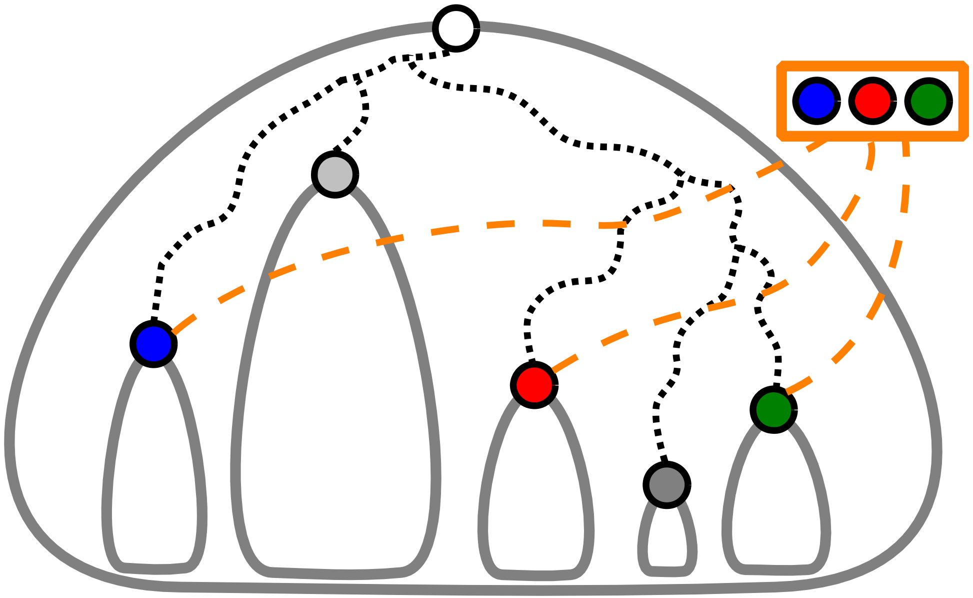
- Light buffer [Haines & Greenberg 1986]
  - Faster shadow rays
  - For all lights



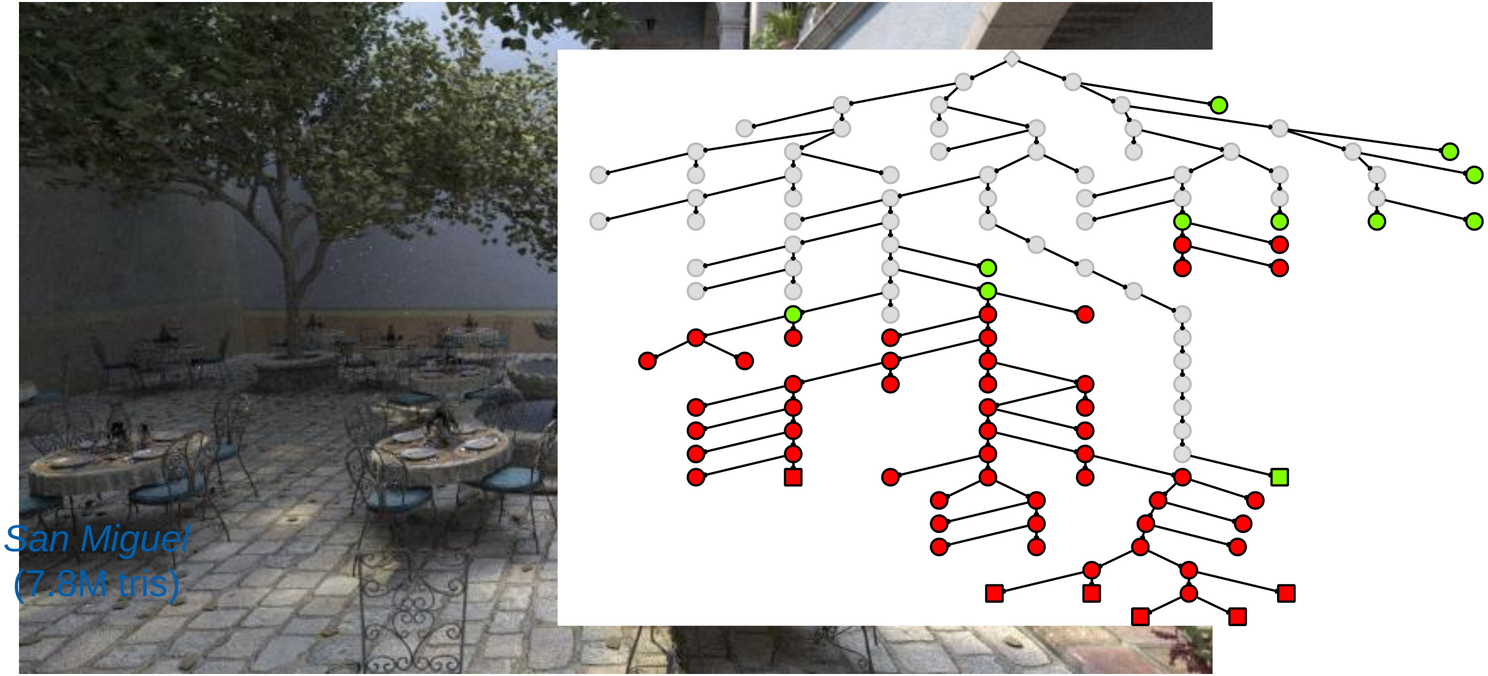
Less Ray / Object Intersections

- Ray Classification for BVH [Hendrich et al. 2019]





Ray Classification for BVH



https://github.com/jakubhendrich/pbrt-v3/tree/frustum_shafts

Ray Sorting

- Meister et at. On Ray Reordering Techniques for Faster GPU Ray Tracing (I3D 2020)

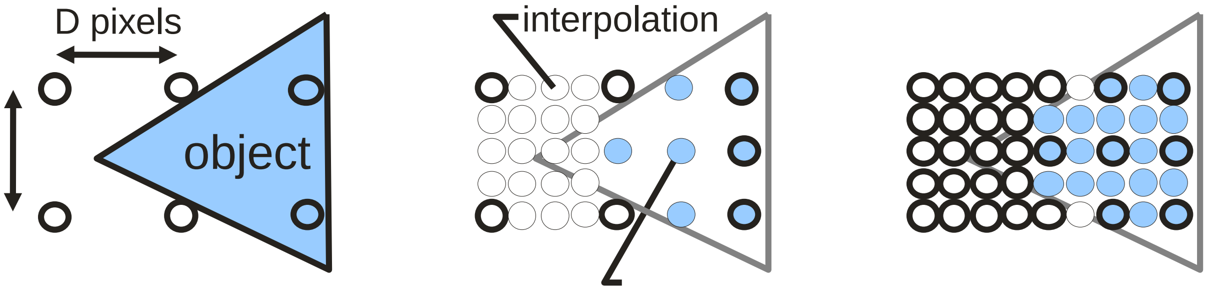
2355 MRays/s | 3593 MRays/s | 3914 MRays/s

New October 2022: Ray Reordering through the new NVIDIA Shader Execution Reordering extension
https://developer.nvidia.com/blog/improve-shader-performance-and-in-game-frame-rates-with-shader-execution-reordering/

Cast Less Rays

- Importance sampling
  - Material BSDF
  - Potential light contribution (scenes with many lights)
- Controlling recursion depth
  - Static using a constant (e.g. 5)
    - too deep for non reflecting surfaces
    - Systematic error (bias)
  - Adaptive using importance of contribution
    - Initial contribution 100%, reflection/refraction multiply with rs (<1)
    - Russian roulette – unbiased (but increases noise)!
- Adaptive sampling of primary rays

Adaptive Sampling



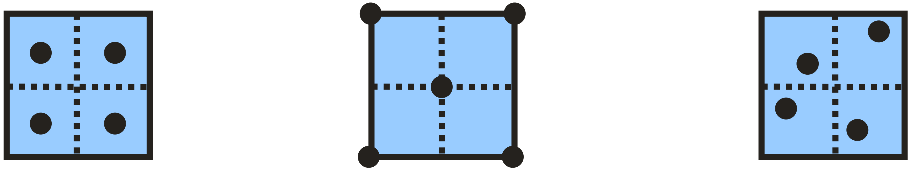
coarse sampling

fine sampling

result

Supersampling

1 pixel:



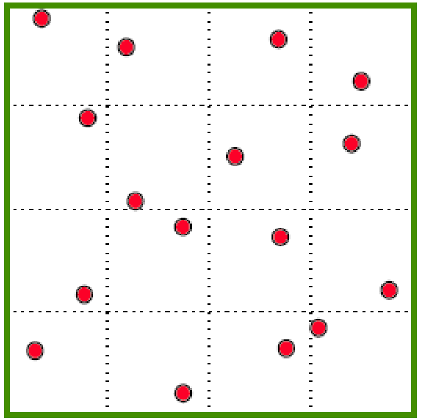
subpixel centers

center and corners

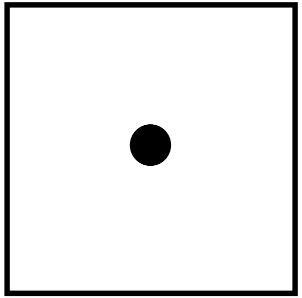
jittering

Jittering

- Jittering = organized sampling in a grid
  - Stratified sampling
  - Avoids creating larger sample clusters
  - Better distribution than random sampling
  - *Disadvantage* – up to four samples can get clustered
- Sample relaxation



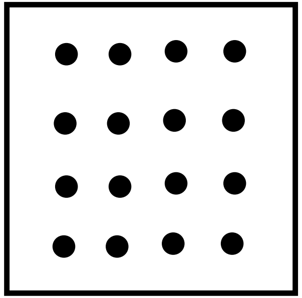
Antialiasing using Supersampling



pixel

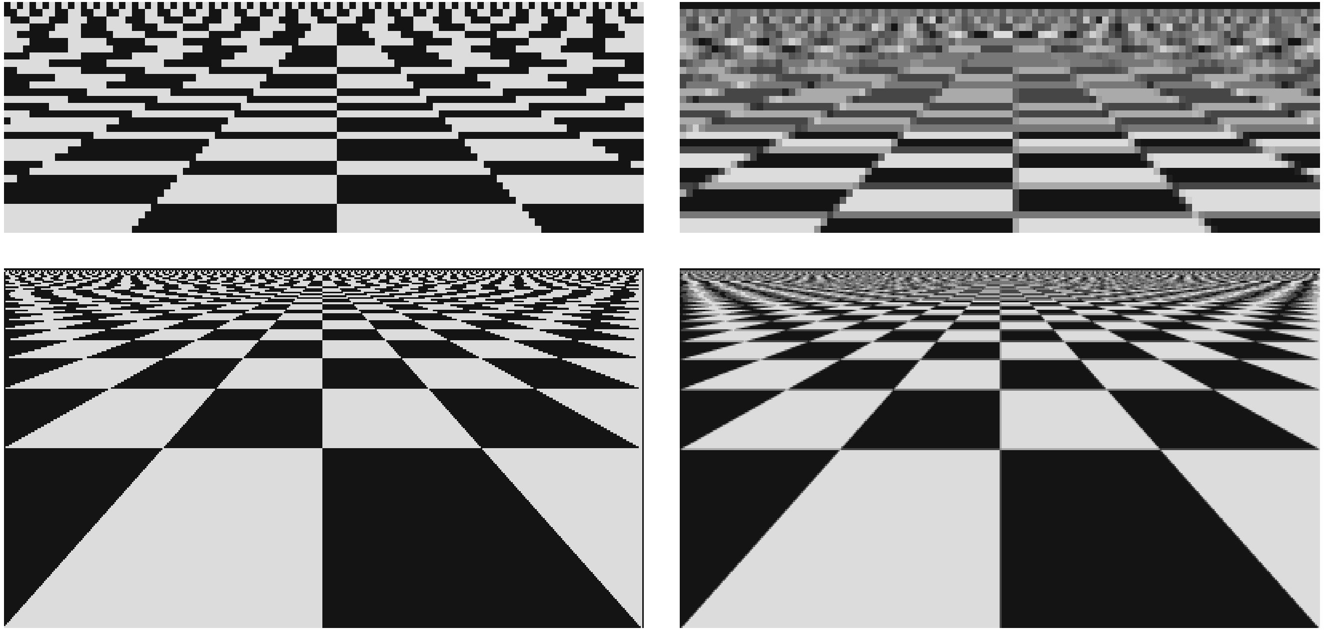
$$pixel = \sum_{s} w_s \, . \, sample_s$$

filter applied on
sample position



samples

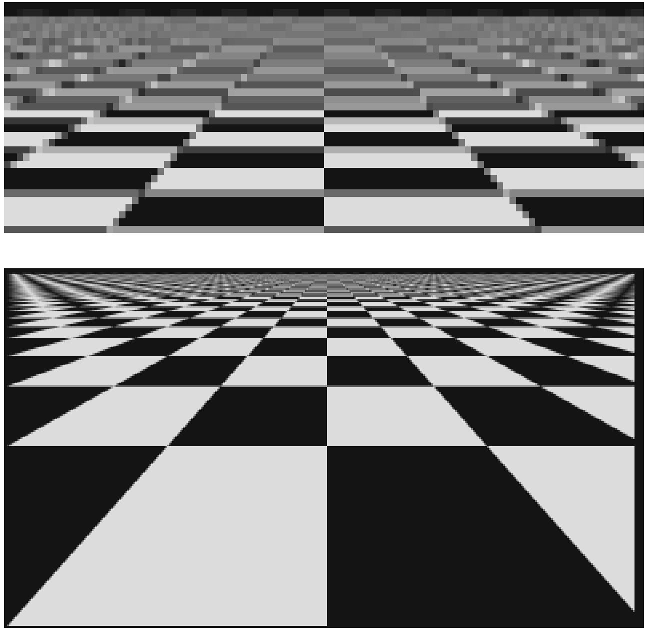
Point Sampling vs. Supersampling

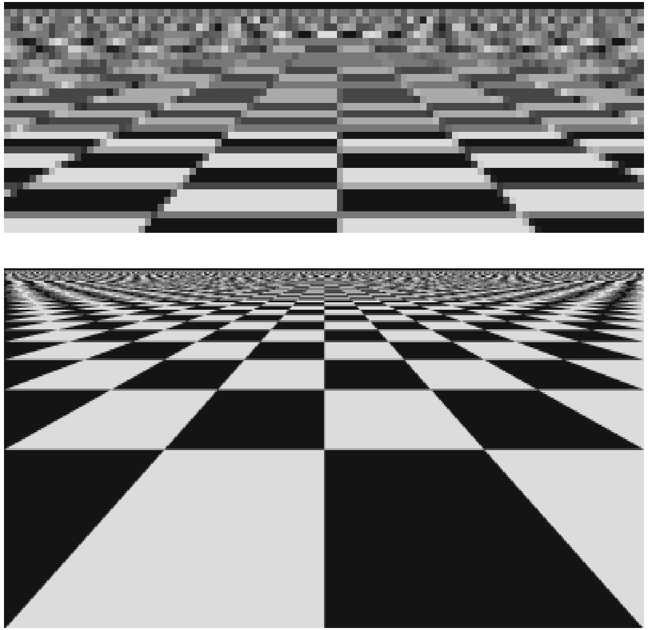


Point **Supersampling 4x4**

Checkerboard sequence by Tom Duff

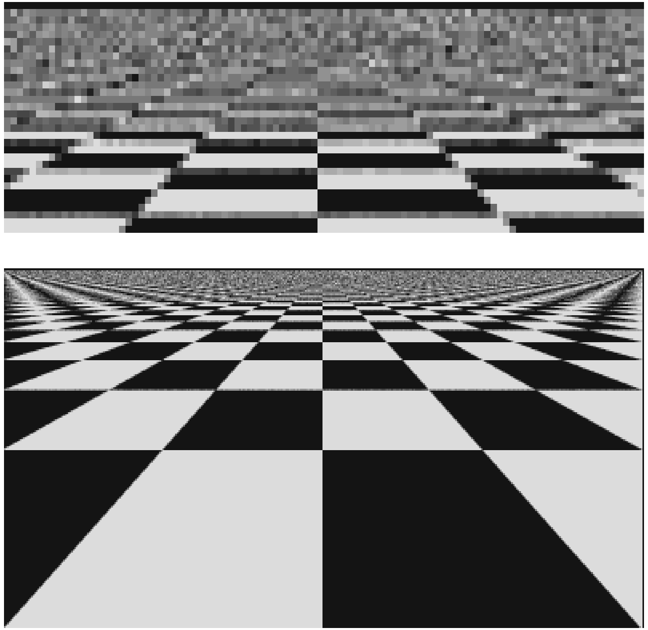
Exact Solution vs. Supersampling



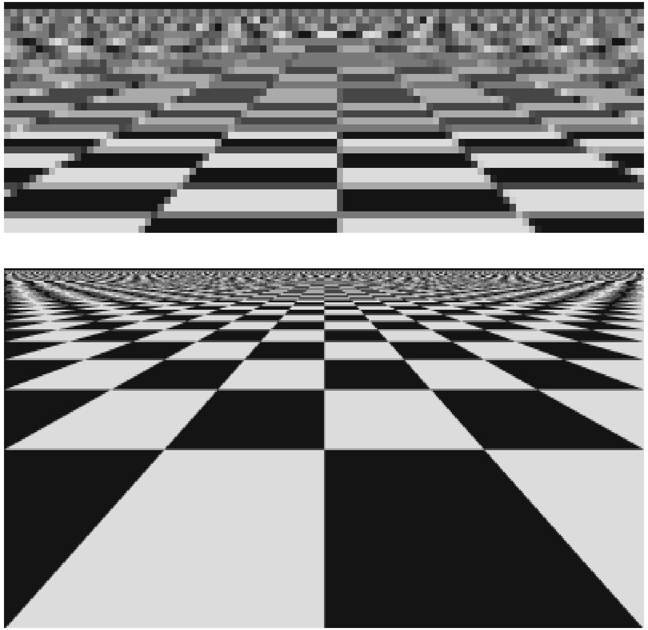


Exact visible area calculation **Supersampling 4x4**

Jittering vs. Regular Supersampling



Jittering 4x4



Supersampling 4x4

Interactive Path Tracing - Example

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Questions?