DCGI

KATEDRA POČÍTAČOVÉ GRAFIKY A INTERAKCE

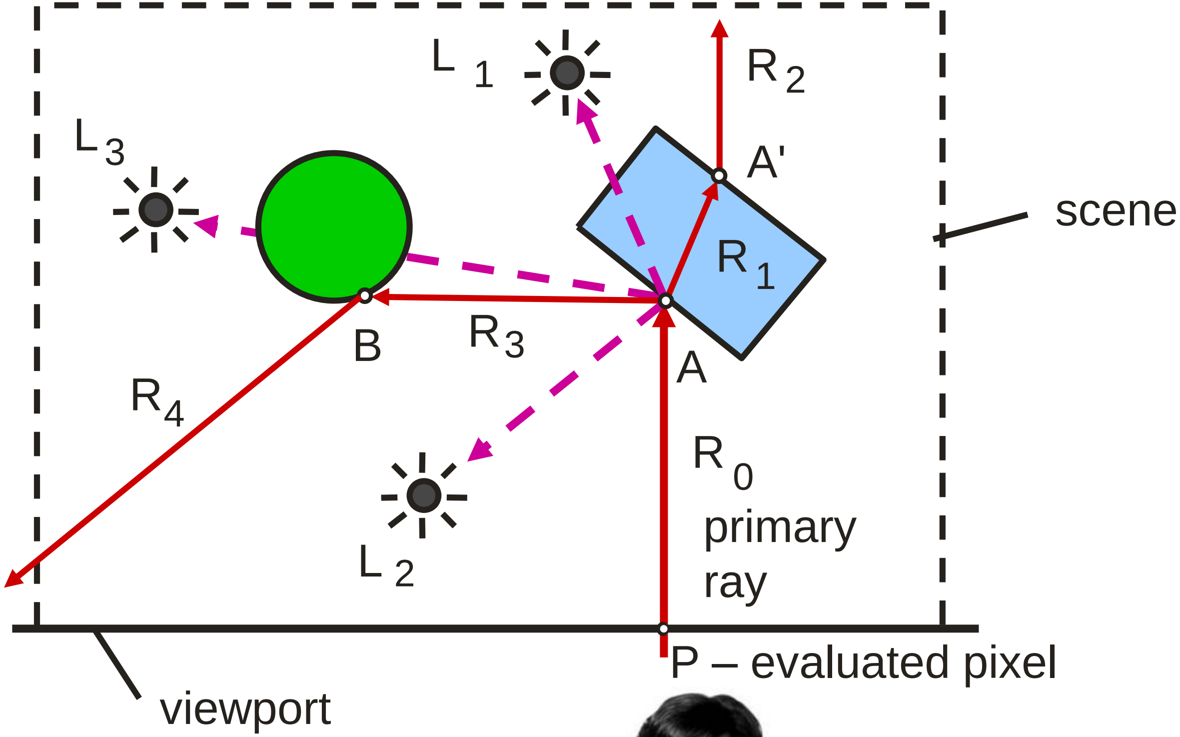
Ray Tracing

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)

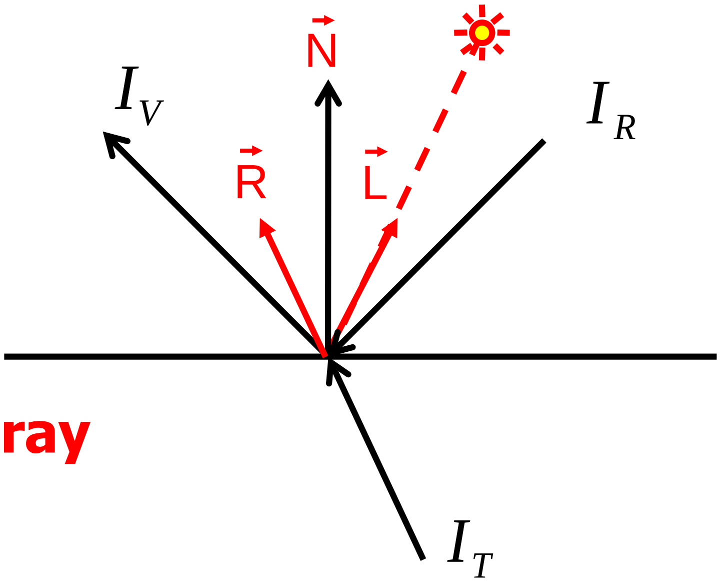
6. Assign to R the resulting color using sum of illumination from light sources and RR and RT

Extending Illumination Model

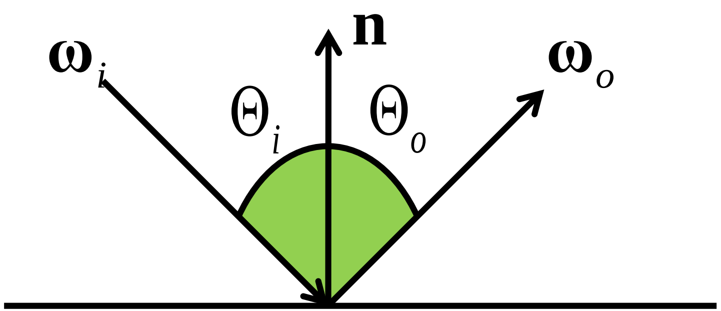
- $I_V = I_a + I_r + I_t + \sum I_d + I_s$
- I_a ambient component
- I_d diffuse component
- I_s specular component
- $I_r = k_s I_R$
- $I_t = k_t I_T$
- k_s ... specular coef.
- k_t ... transmittance coef.

Recursion

Shadow ray



Direction of Reflected Ray



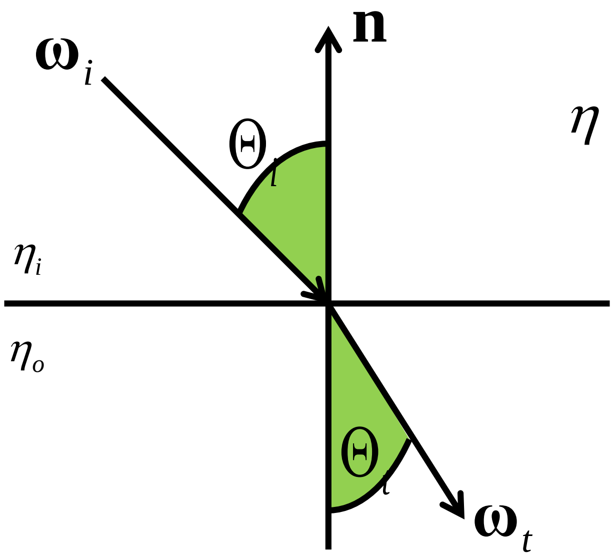
$$\Theta_o = \Theta_i$$

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

Refracted Ray

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

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

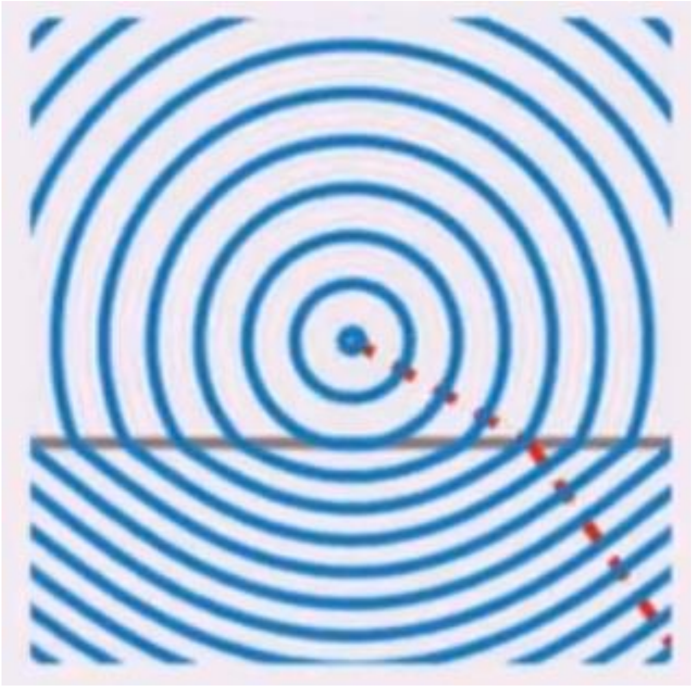


η index of refraction (air 1.000293, water 1.33, glass 1.6, diamond 2.4)

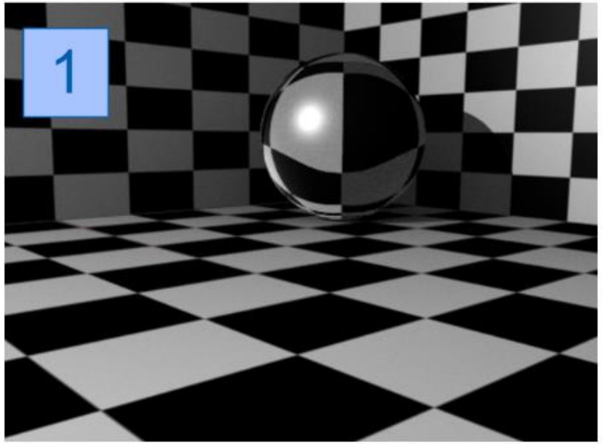
$$\sin^2\theta_t = \eta_{io}^2(1-\cos^2\theta_i) > 1$$

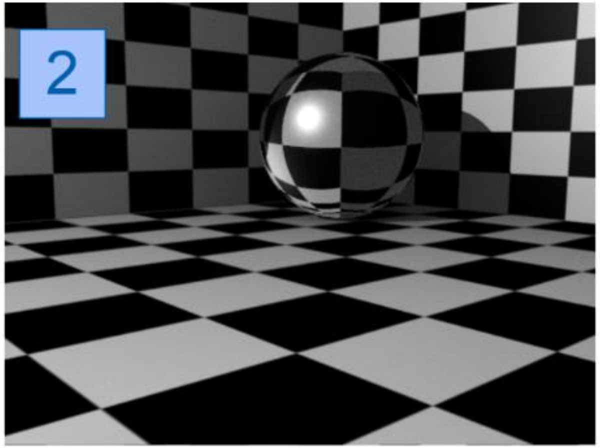
Total internal reflection – no refraction

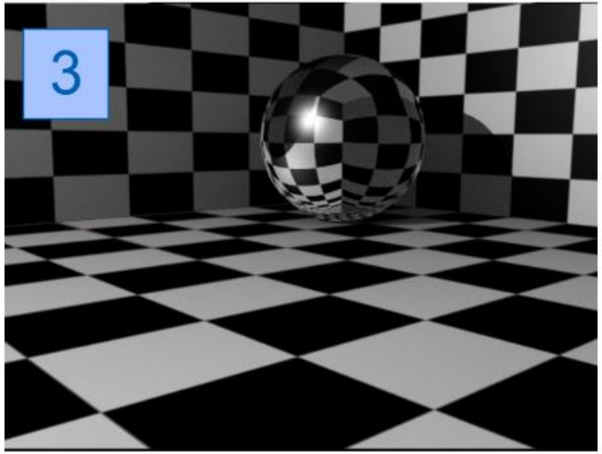
Refraction - Example



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

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

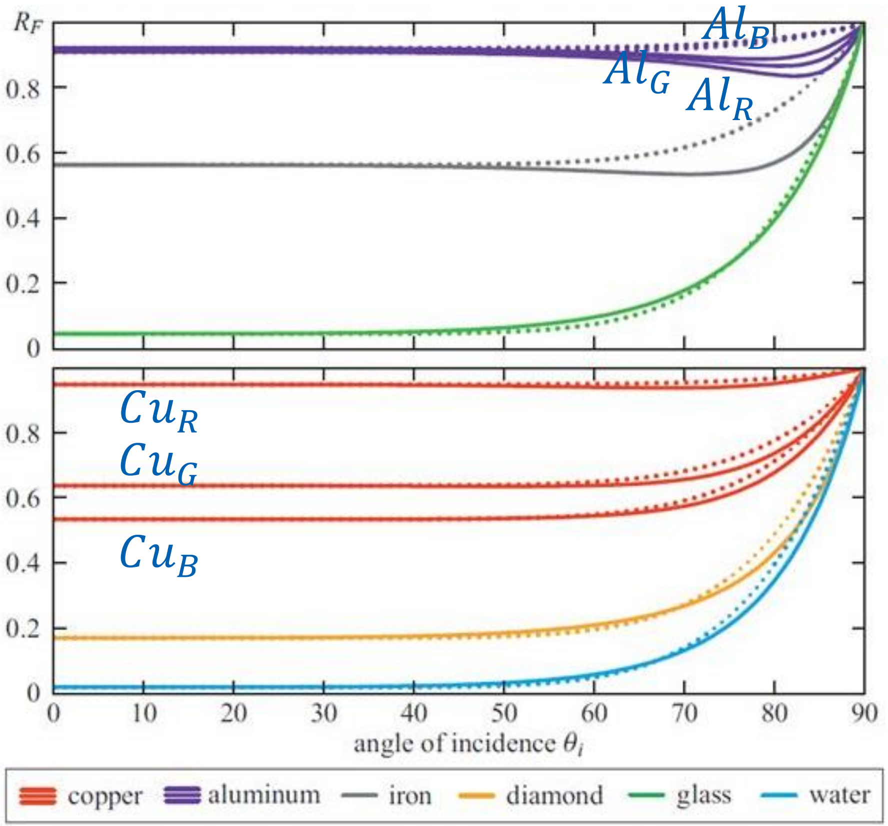
- Schlick approximation [1994]

$$R(\theta_i) = R_0 + (1-R_0)(1-\cos\theta_i)^5 \qquad R_0 = \left(\frac{\eta_{io}-1}{\eta_{io}+1} \right)^2$$

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

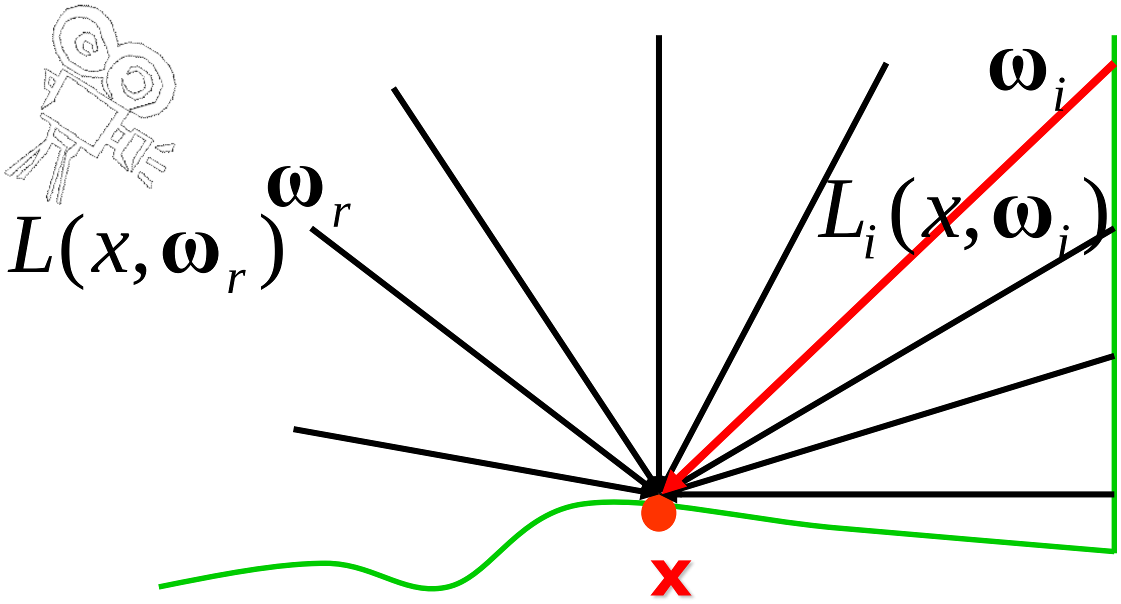
- Correct evaluation of indirect illumination
- Monte-Carlo integration → Unbiased image estimate

- 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)

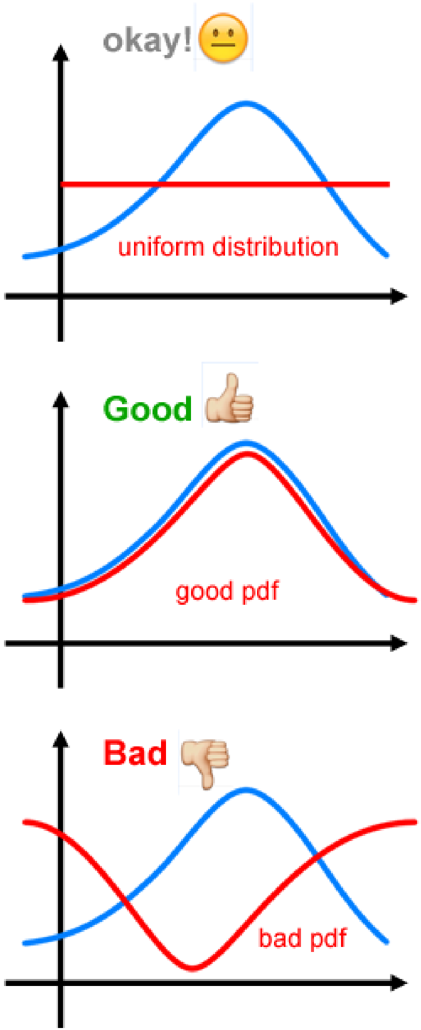
Path Tracing – Rendering Equation

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



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

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

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

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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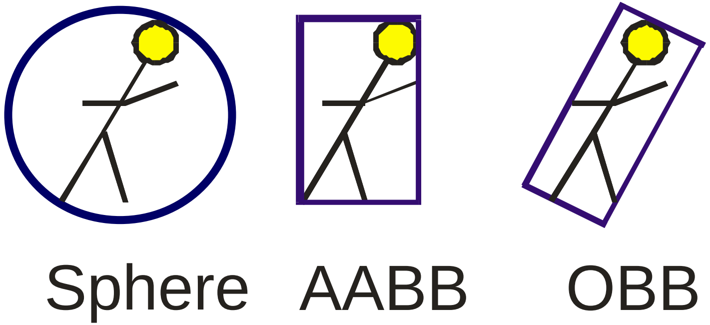
Acceleration Methods

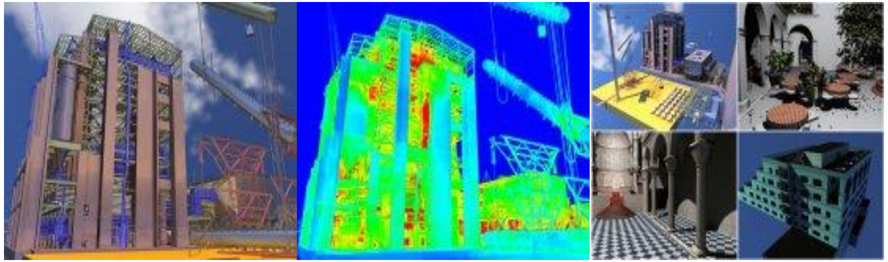
Ray tracing is costly – must accelerate!

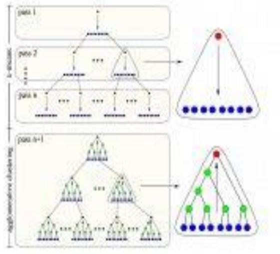
1. **Accelerating intersection computation**
    a) Faster ray / object intersection (low level optimizations)
    b) Less ray / object intersections (spatial data structures)
    c) Tracing more rays together
2. **Cast less rays**
    - Importance sampling
    - Adaptive antialiasing, adaptive depth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

Less Ray / Object Intersections

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



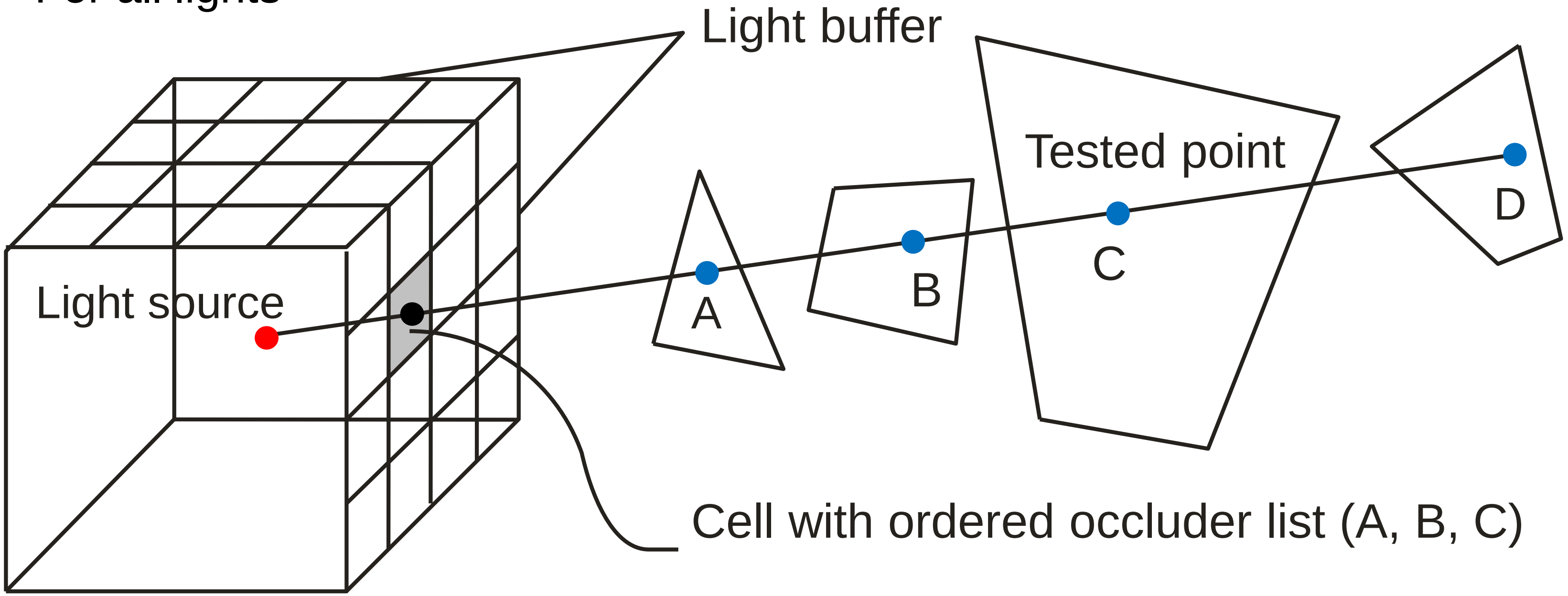




https://github.com/meistdan/ploc
https://github.com/meistdan/prbvh

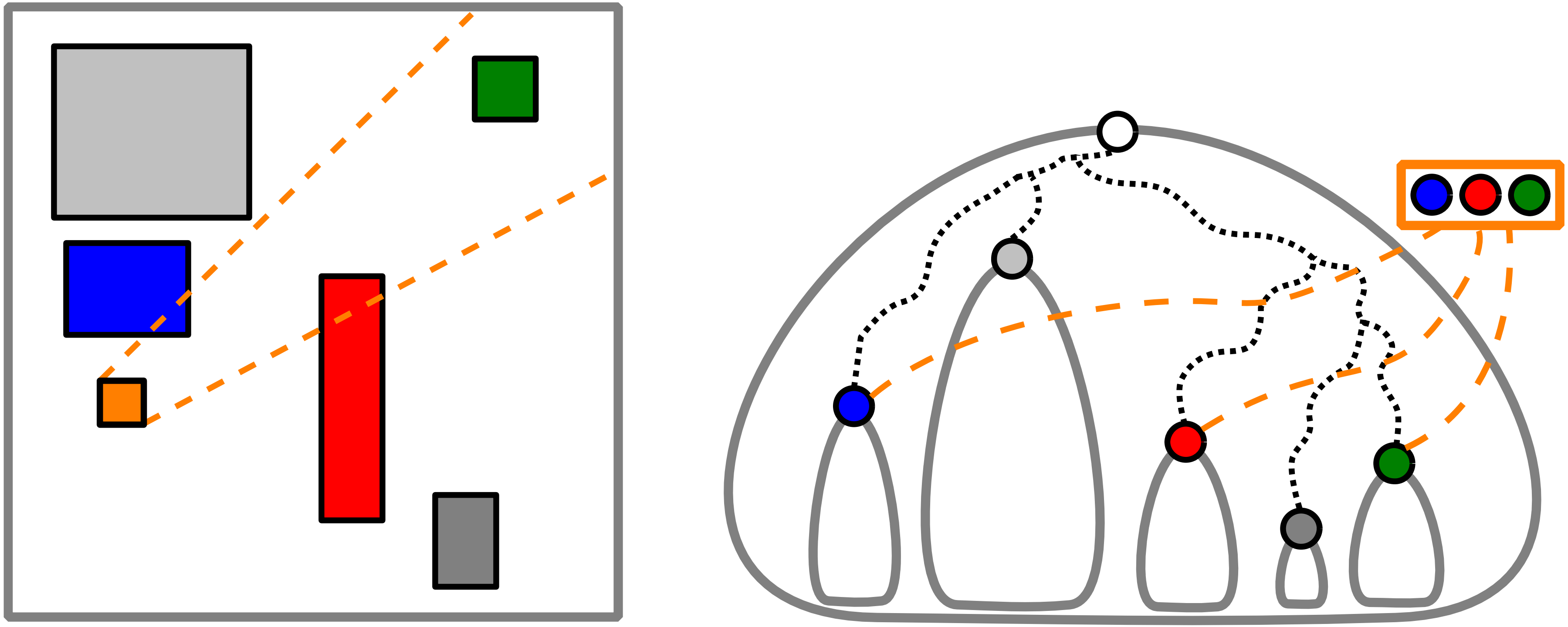
Less Ray / Object Intersections

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

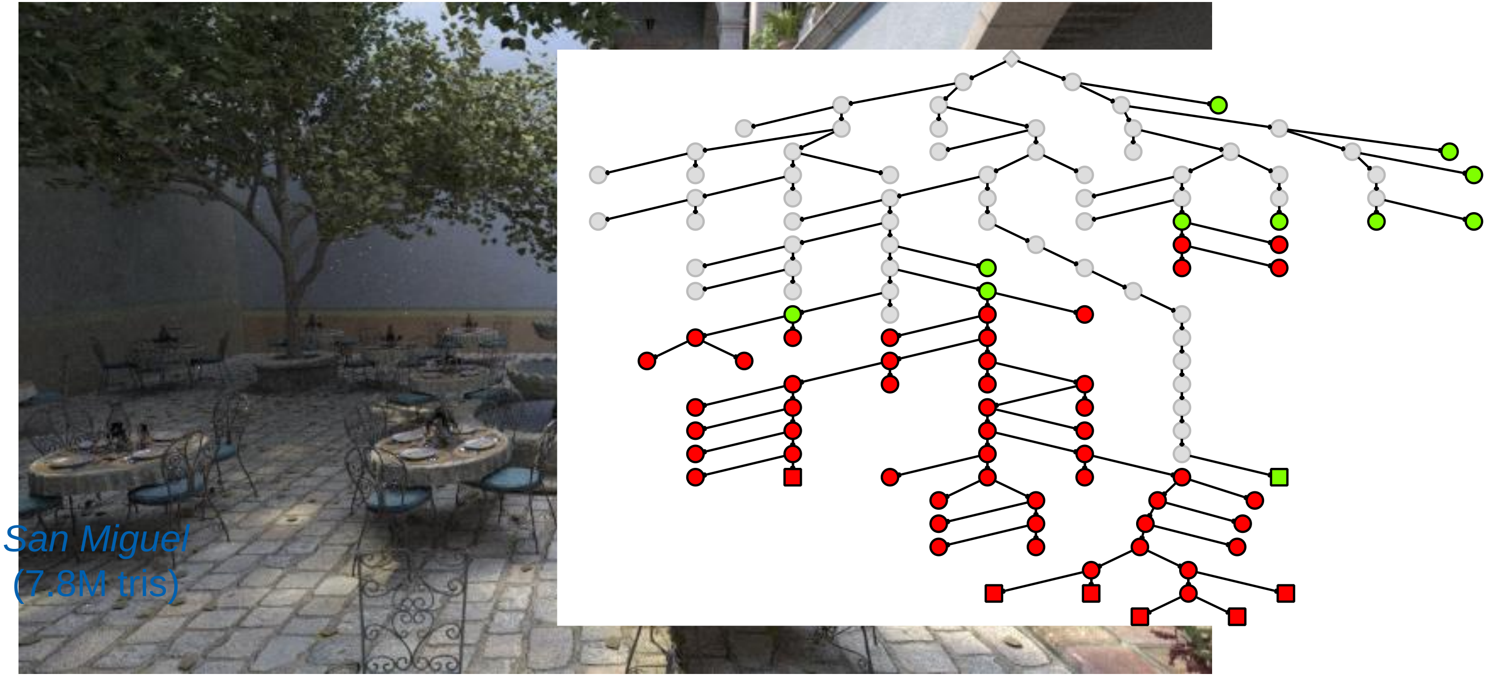


Less Ray / Object Intersections

- 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

Acceleration Methods

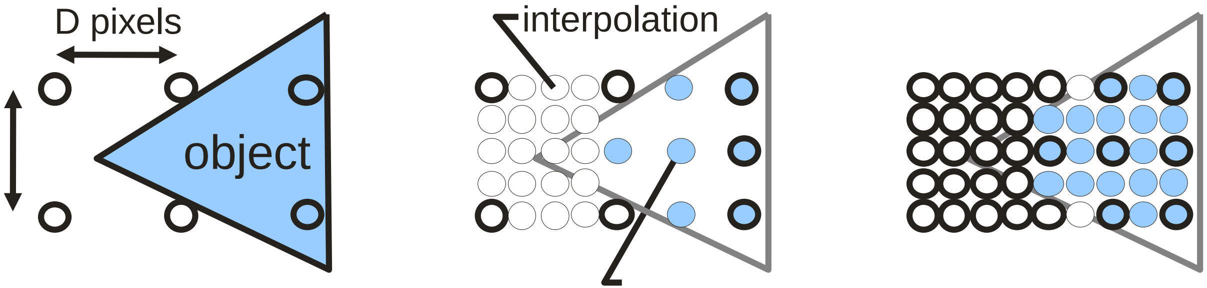
Ray tracing is costly – must accelerate!

1. **Accelerating intersection computation**
   a) Faster ray X object intersection
   b) Less ray X object intersections
   c) Tracing more rays together / exploit ray coherence
2. **Cast less rays**
   - Importance sampling
   - Adaptive antialiasing, adaptive depth of recursion, …

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

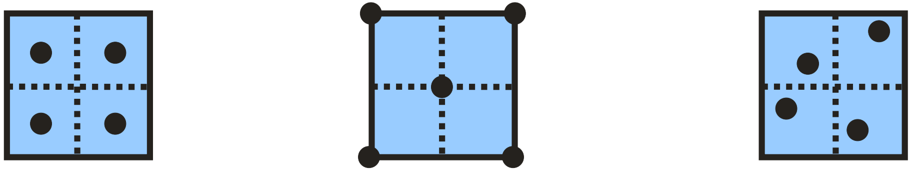
Adaptive Sampling



coarse sampling   fine sampling   result

Supersampling

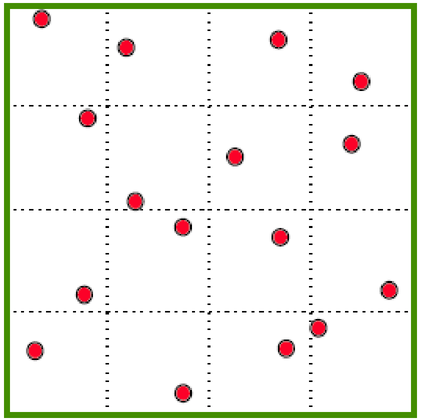
1 pixel:



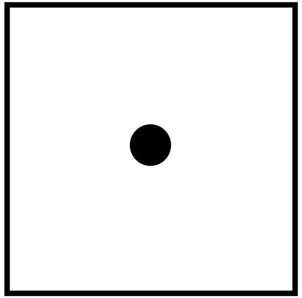
subpixel centers   center and corners   jittering

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



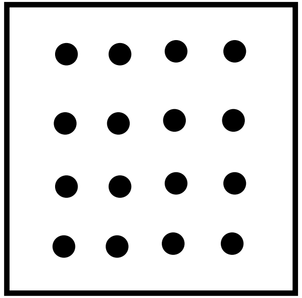
Antialiasing using Supersampling



pixel

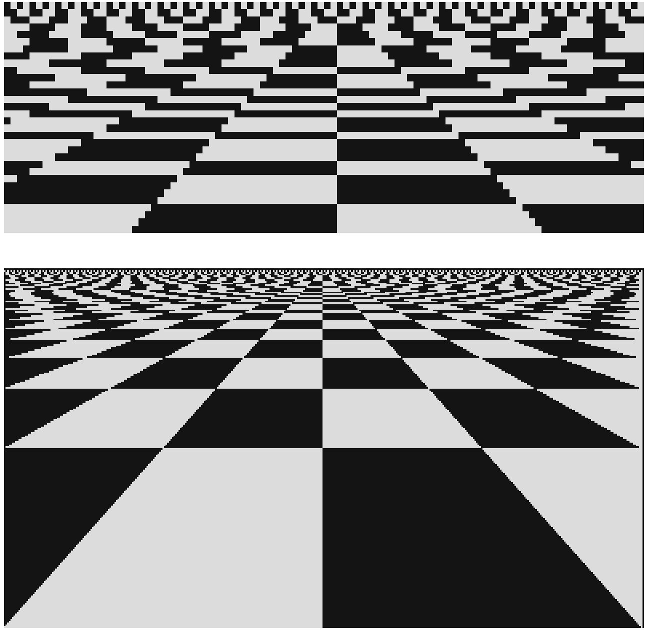
$$pixel = \sum_{s} w_s \cdot sample_s$$

filter applied on sample position

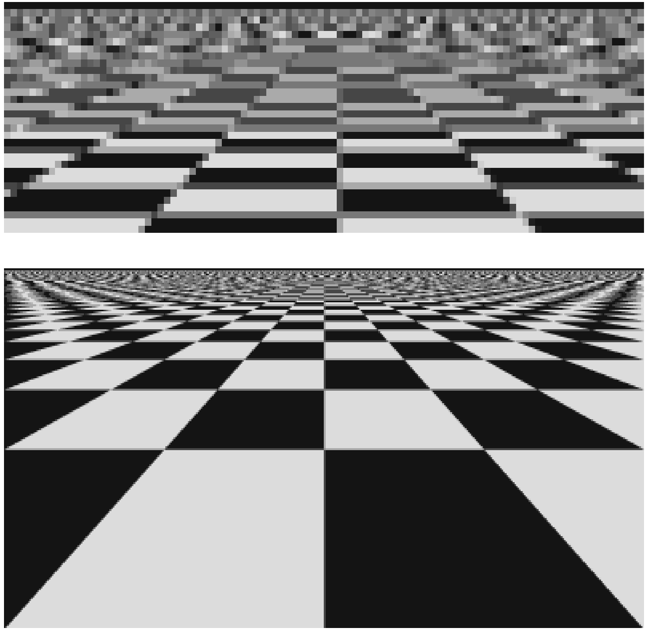


samples

Point Sampling vs. Supersampling



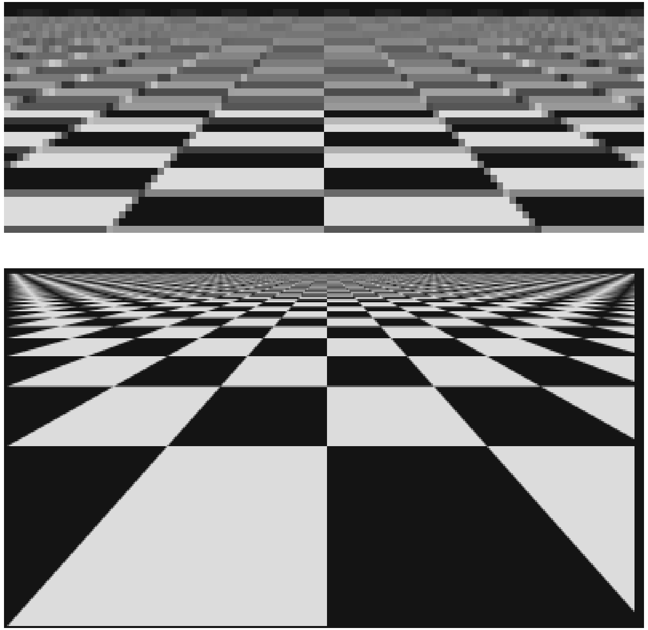
Point



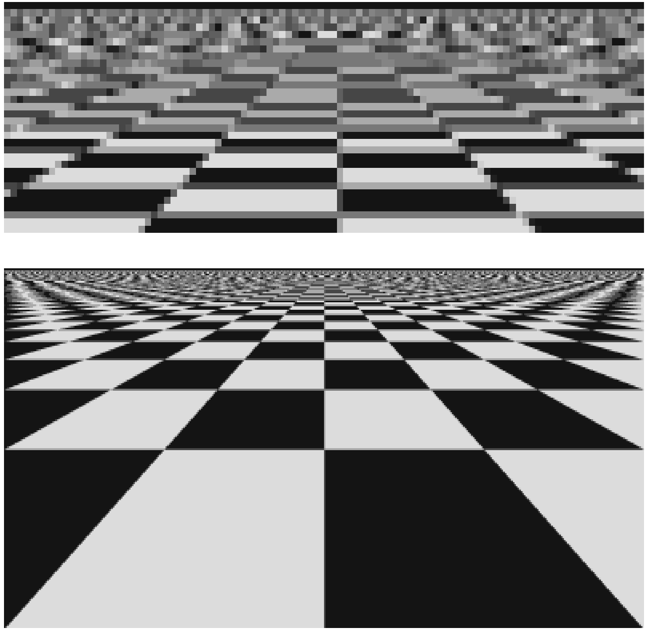
Supersampling 4x4

Checkerboard sequence by Tom Duff

Exact Solution vs. Supersampling

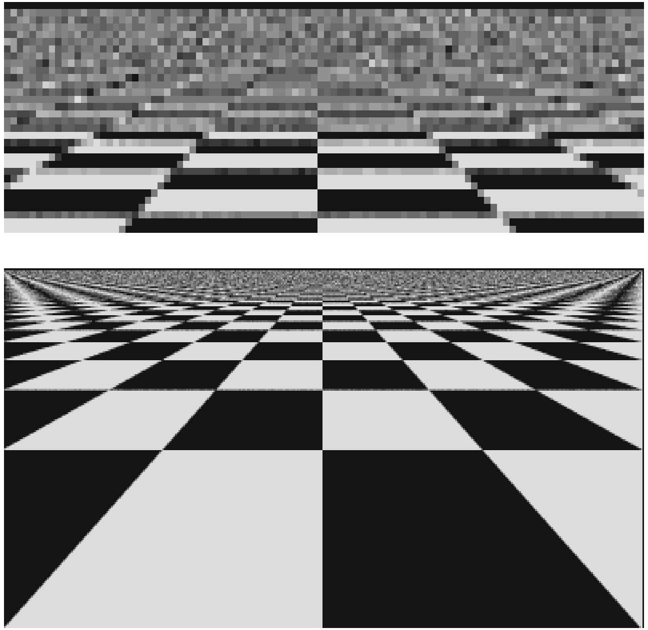


Exact visible area calculation

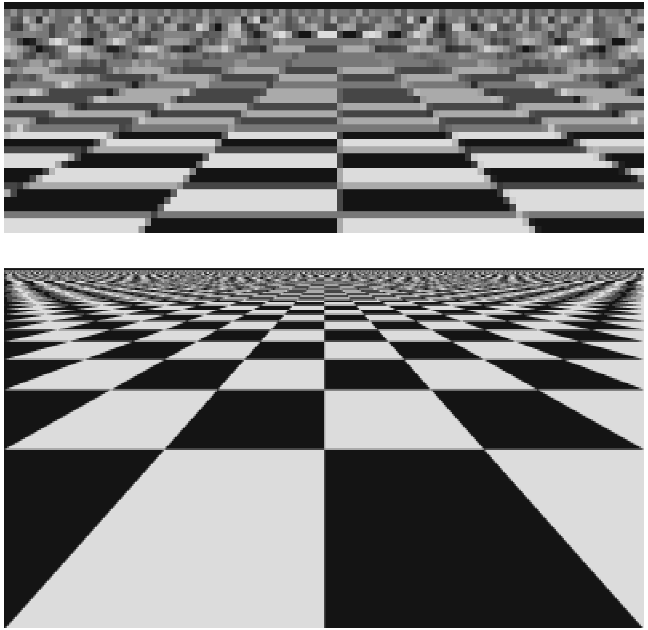


Supersampling 4x4

Jittering vs. Regular Supersampling



Jittering 4x4



Supersampling 4x4

Interactive Path Tracing - Example

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Questions?