Computer Graphics

- Distribution Ray Tracing -

Philipp Slusallek

Overview

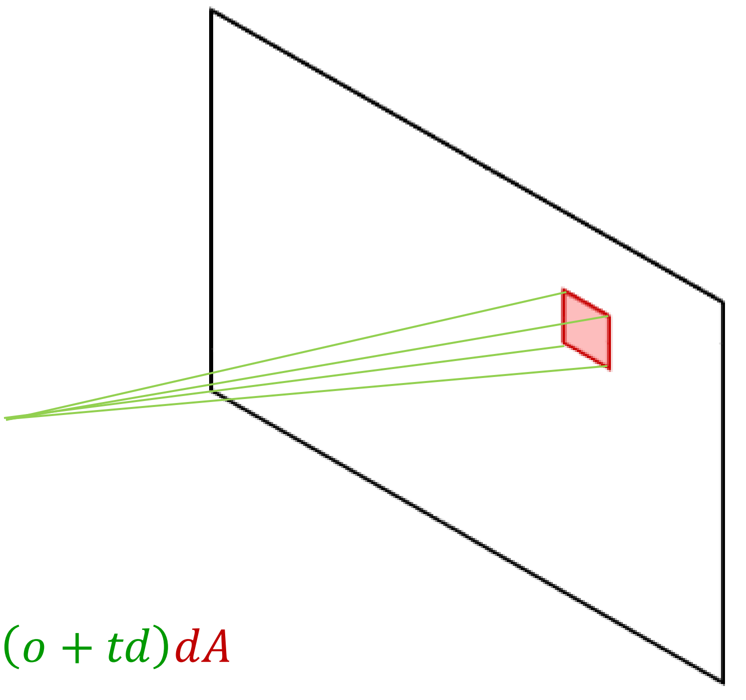
- **Other Optical Effects**
  - Not yet included in Whitted-style ray tracing
- **Stochastic Sampling**
- **Distribution Ray-Tracing**

Problems

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

Anti-aliasing

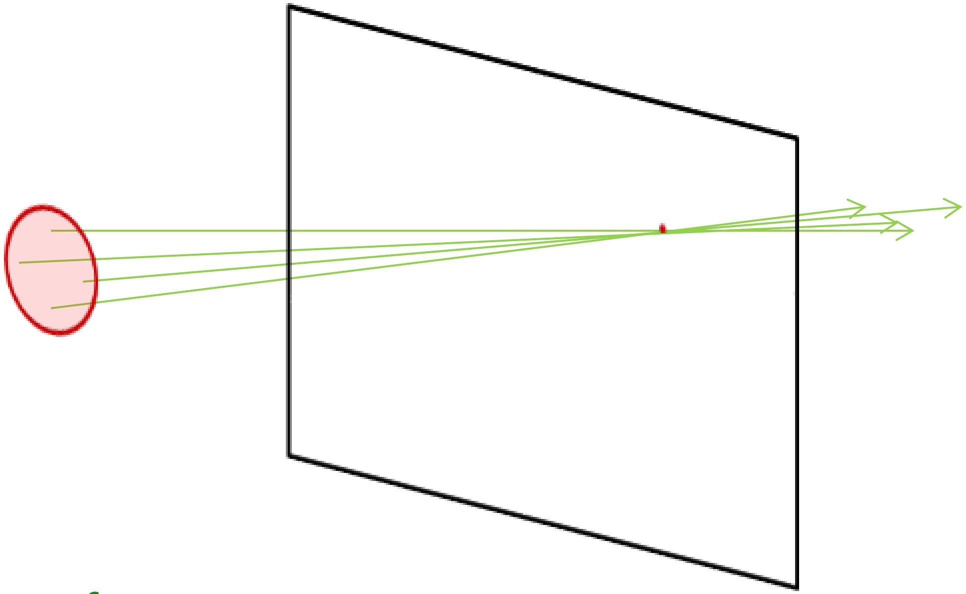
- **Anti-aliasing**
- **Depth of field**
- **Motion blur**
- **BRDF**
- **Area Lights**



$$I \approx \int_A L(o + td)\,dA$$

Depth of field

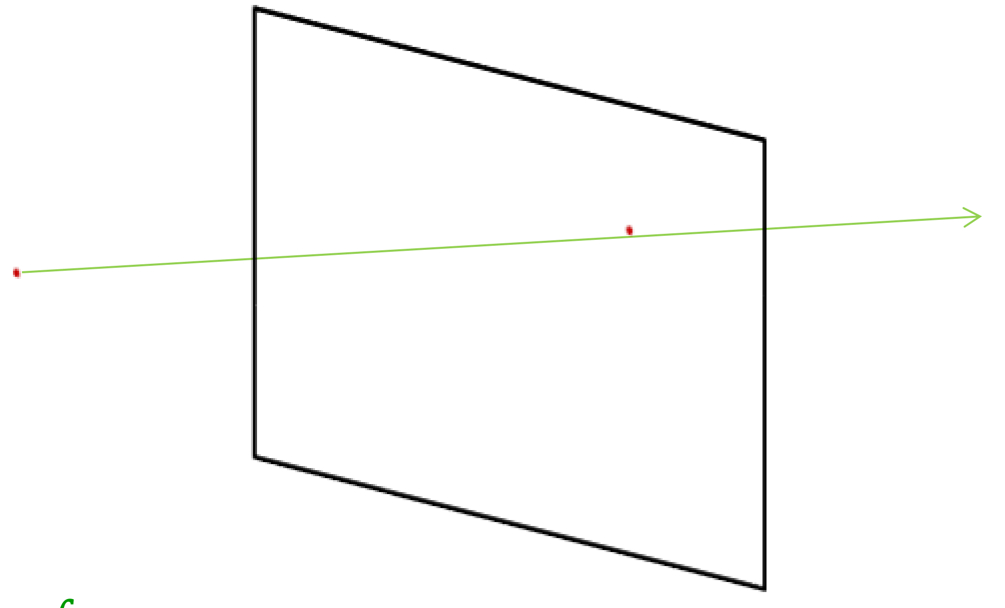
- **Anti-aliasing**
- **Depth of field**
- **Motion blur**
- **BRDF**
- **Area Lights**



$$I \approx \int_A L(o + td)\,dA$$

Motion blur

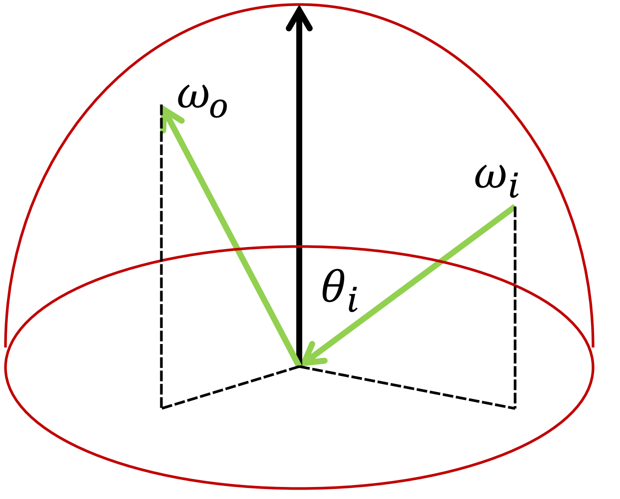
- **Anti-aliasing**
- **Depth of field**
- **Motion blur**
- **BRDF**
- **Area Lights**



$$L \approx \int_{[t_o,t_1]} L_T(o + td)\,dT$$

BRDF

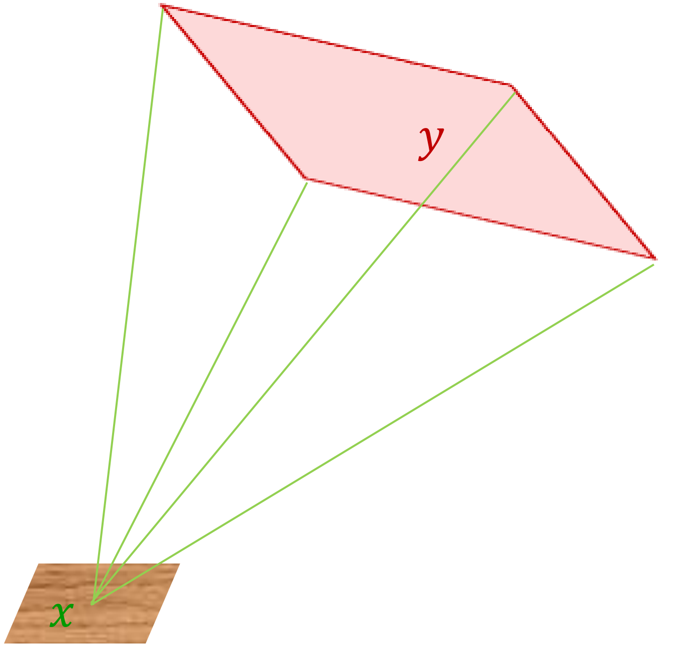
- **Anti-aliasing**
- **Depth of field**
- **Motion blur**
- **BRDF**
- **Area Lights**



$$L_o = L_e + \int_{\Omega_+} f_r L_i \cos\theta_i \, d\omega_i$$

Area Lights

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

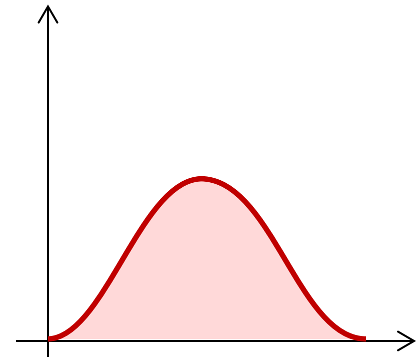


$$E_i = \int_A V(x,y)\,\frac{\cos\theta_A}{\|x-y\|^2}\,dA$$

Integration by MC-Sampling

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

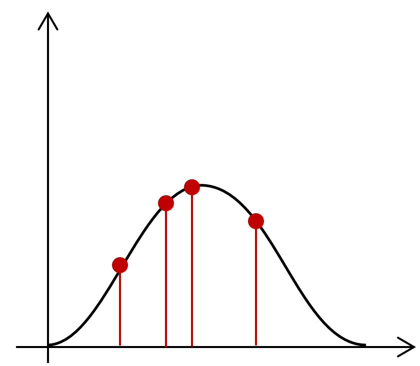
$$I = \int_D f(x)dx$$



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

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

$$x_i \text{ sampled} \propto p(x)$$



STOCHASTIC SAMPLING

(VERY SHORT INTRO)

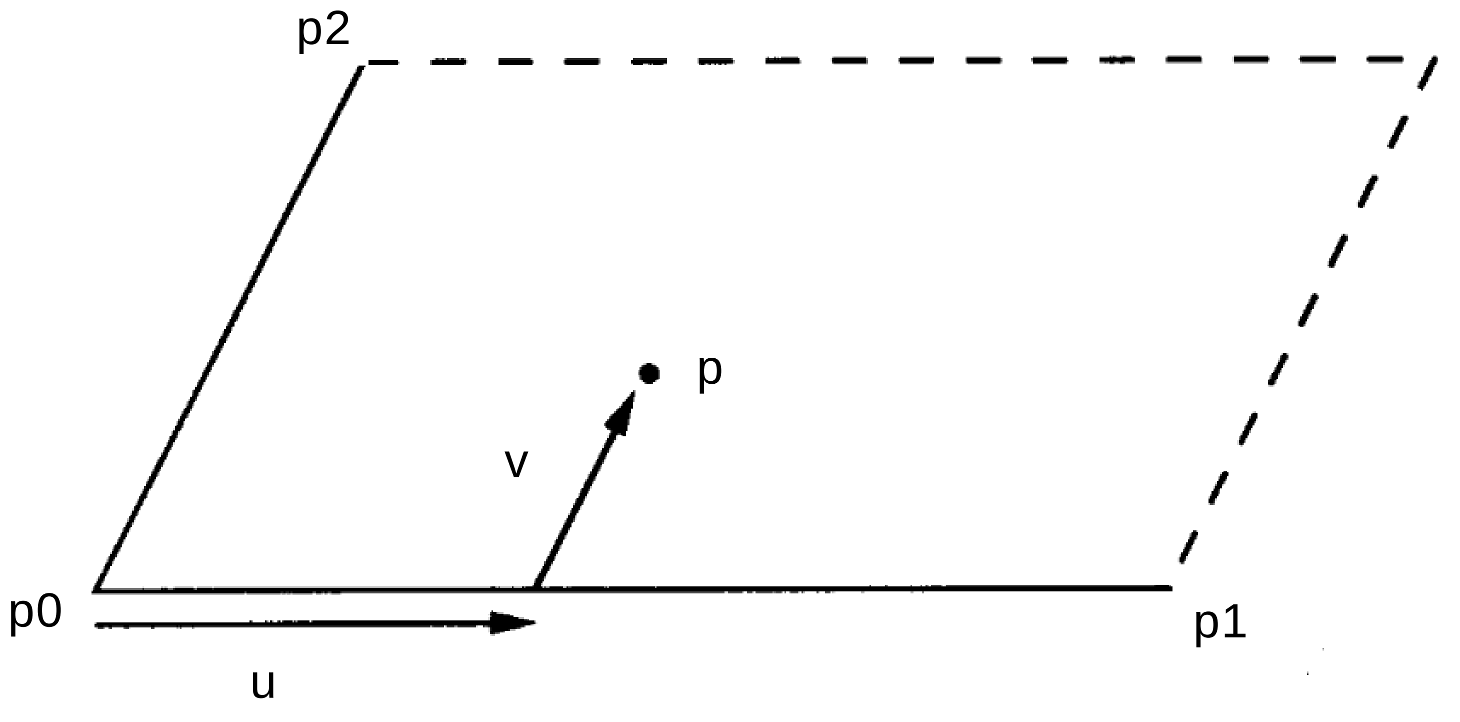
Random Number

- **Random Number**
  - Uniformly distributed
  - ξ in [0, 1)

- **Pseudo-Random Number**
  - Linear congruential
  - Mersenne-Twister
  - …
  - Speed / evenness trade-off

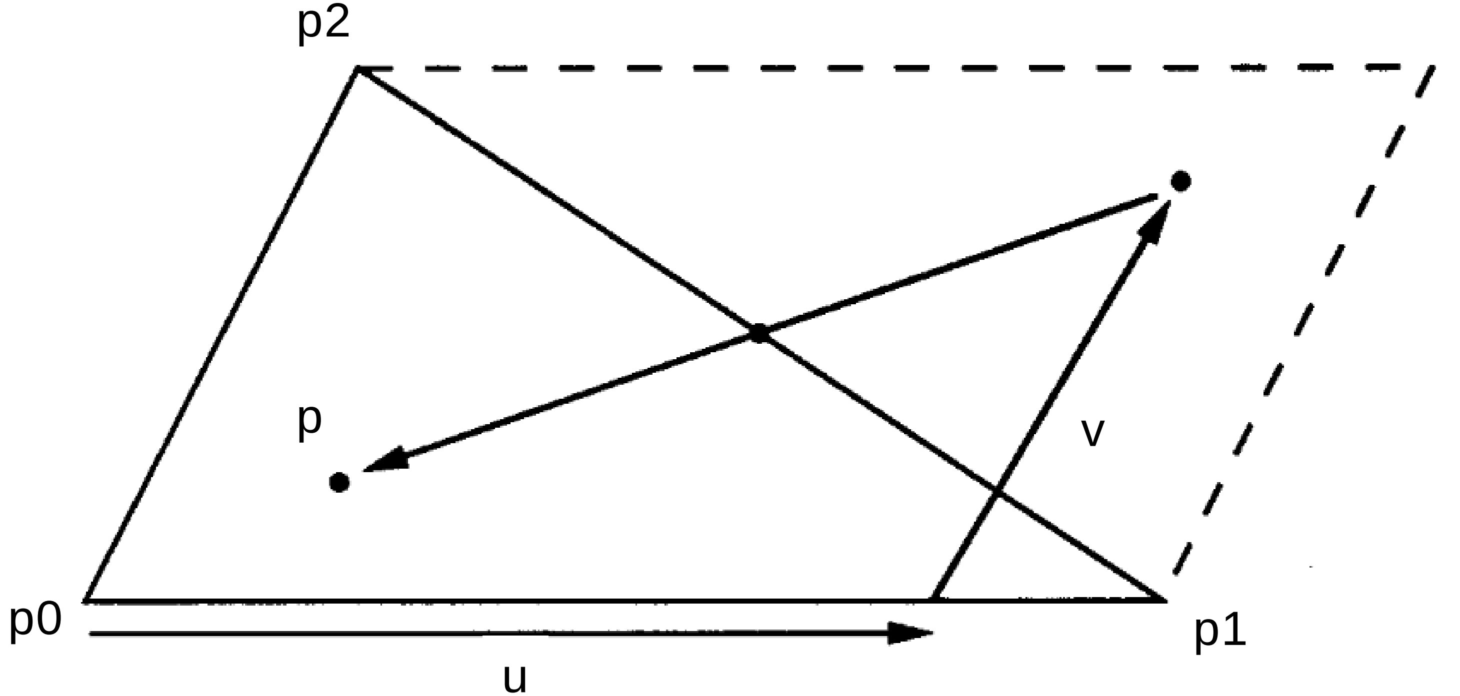
Parallelogram Sampling

- **Parametric Form**
  - $p(u,v) = p_0 + u(p_1 - p_0) + v(p_2 - p_0) = (1 - u - v)p_0 + up_1 + v\,p_2$
- **Random Sampling**
  - $p(\xi_1, \xi_2)$



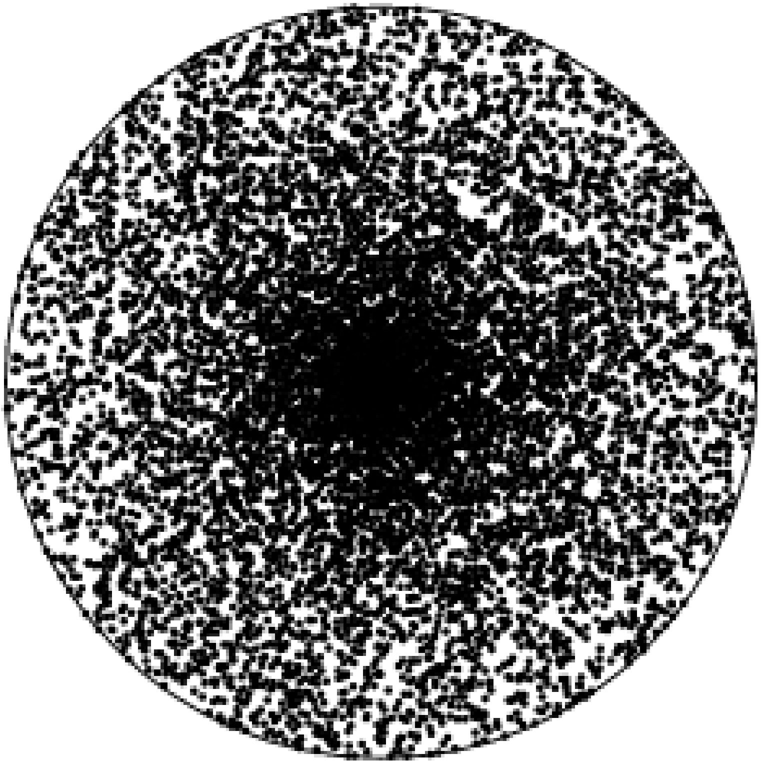
Triangle Sampling

- **Parametric Form**
  - $p(u, v) = (1 - u - v)p_0 + up_1 + v\,p_2$
- **Random Sampling**
  - if $\xi_1 + \xi_2 < 1$: $p(\xi_1, \xi_2)$
  - if $\xi_1 + \xi_2 > 1$: $p(1 - \xi_1, 1 - \xi_2)$



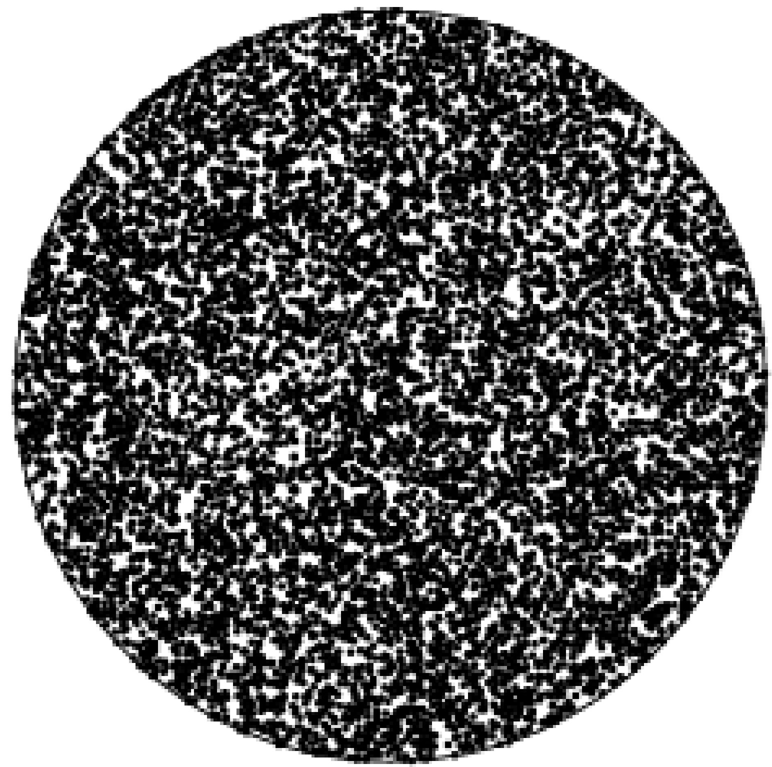
Disc Sampling

- **Parametric Form**
  - p(u, v) = Polar2Cartesian(R v, 2 π u) // disc radius R
- **Naïve Sampling (wrong!)**
  - $p(\xi_1, \xi_2)$



Disc Sampling

- **Parametric Form**
  - p(u, v) = Polar2Cartesian(R v, 2 π u) // disc radius R
- **Correct Sampling**
  - $p\left(\xi_1, \sqrt{\xi_2}\right)$
  - Results in uniform sampling over area

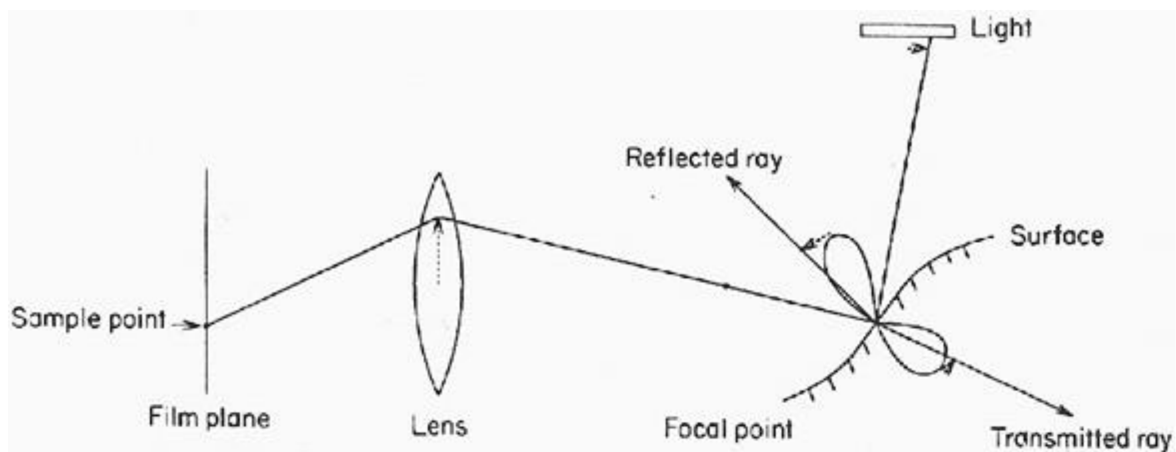


- **For other cases, see Phil Dutre's Global Illumination Compendium at** http://people.cs.kuleuven.be/~philip.dutre/GI/TotalCompendium.pdf

DISTRIBUTION RAY-TRACING

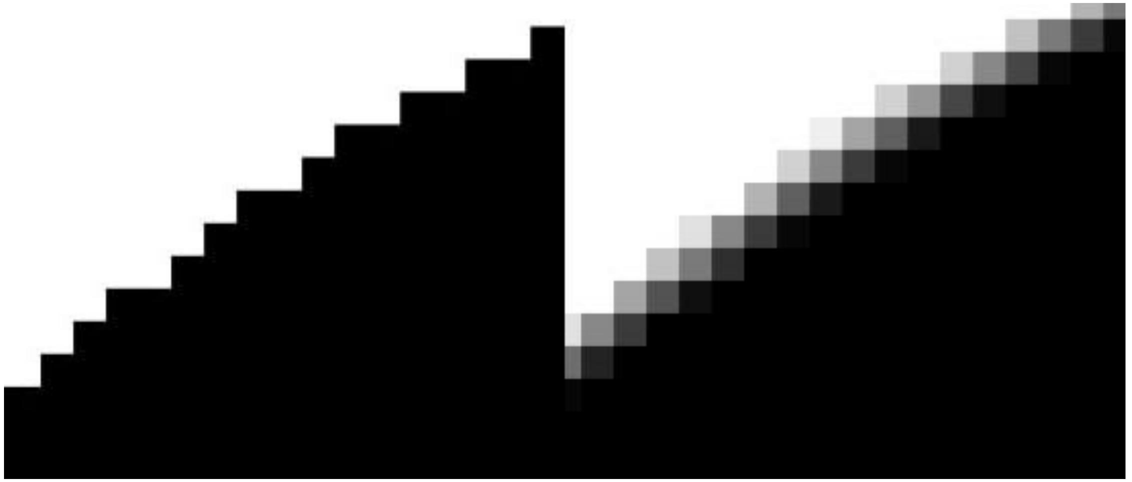
Distribution Ray Tracing

- **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

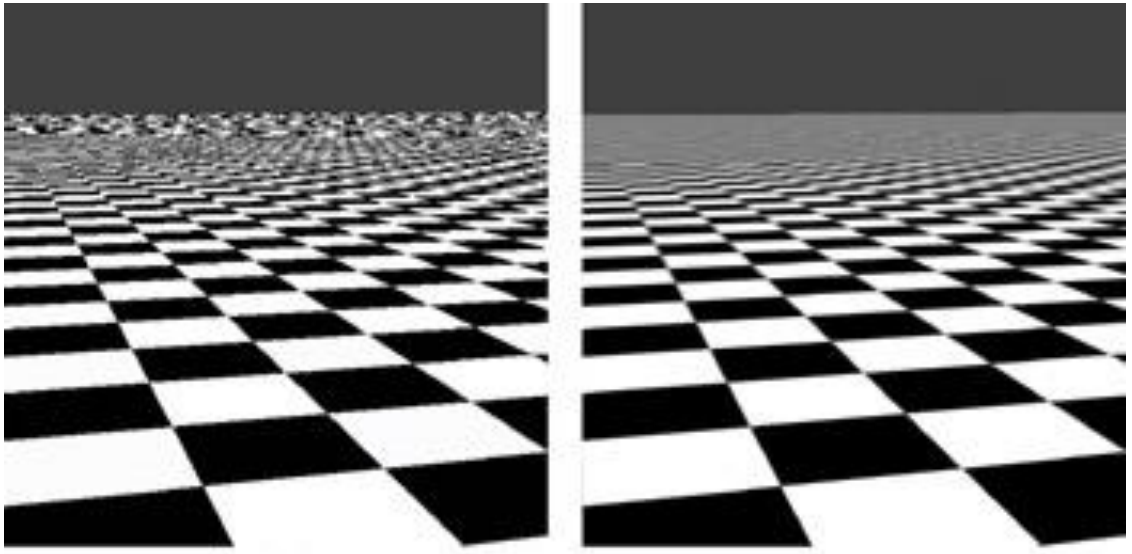


Anti-Aliasing

- **Artifacts**
  - Jagged edges



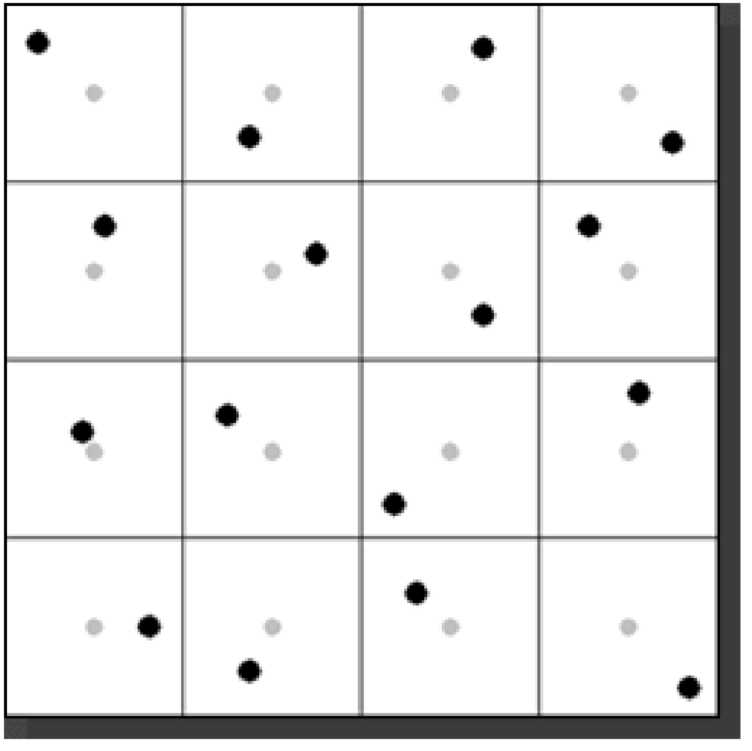
  - Aliased patterns



(a) (b)

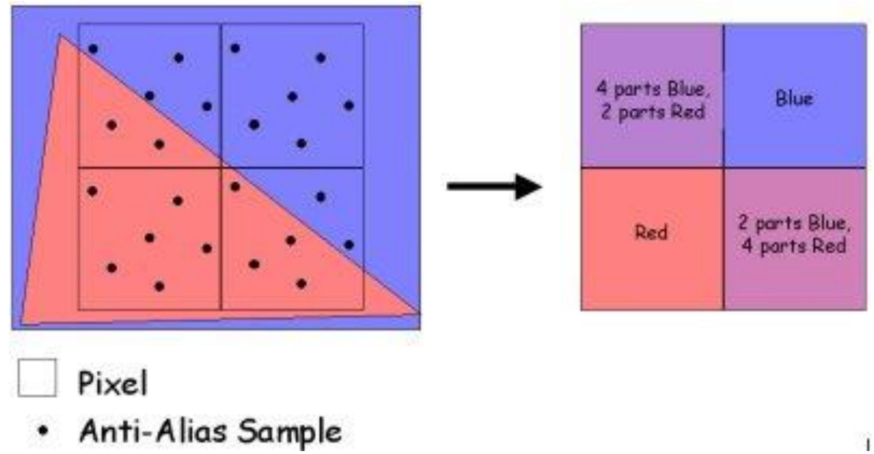
Anti-Aliasing

- **Approach**
  - Average samples over pixel area
  - Akin to sensor cells of measuring device collecting photons
- **Random offset of pixel raster coords from center**
  - `prc[coord] = pid[coord] + 0.5 + (`$\xi - 0.5$`)`

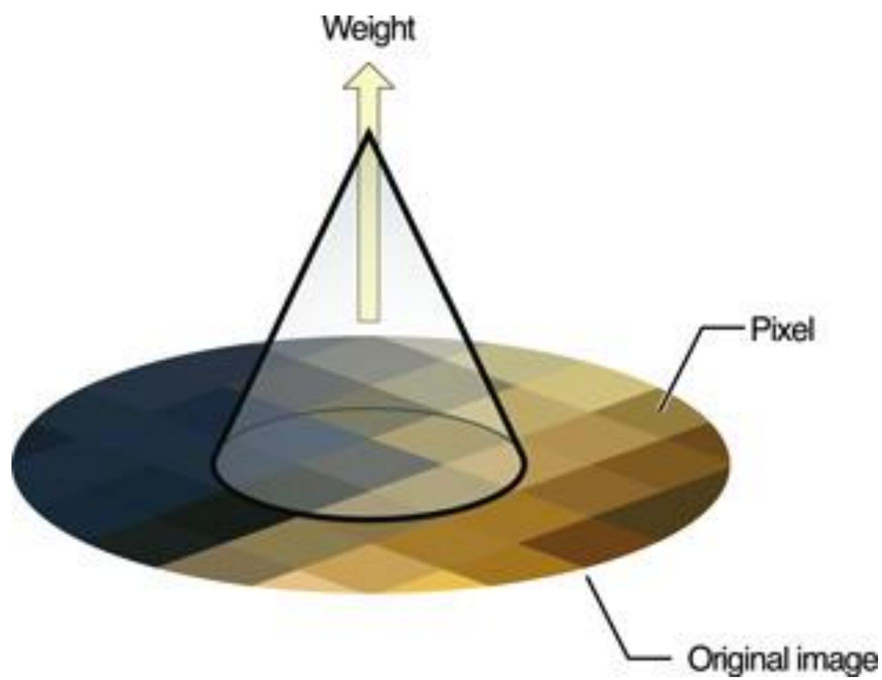


Anti-Aliasing

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

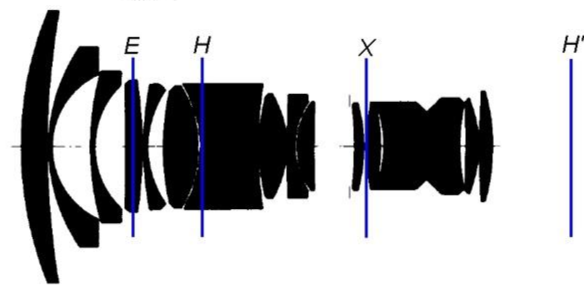


- **Filtering**
  - Weighted average
  - Filter f(x, y)
  - $L = \frac{\sum_{i=1}^{n} f(\xi_{i1},\xi_{i2}) L(\xi_{i1},\xi_{i2})}{\sum_{i=1}^{n} f(\xi_{i1},\xi_{i2})}$



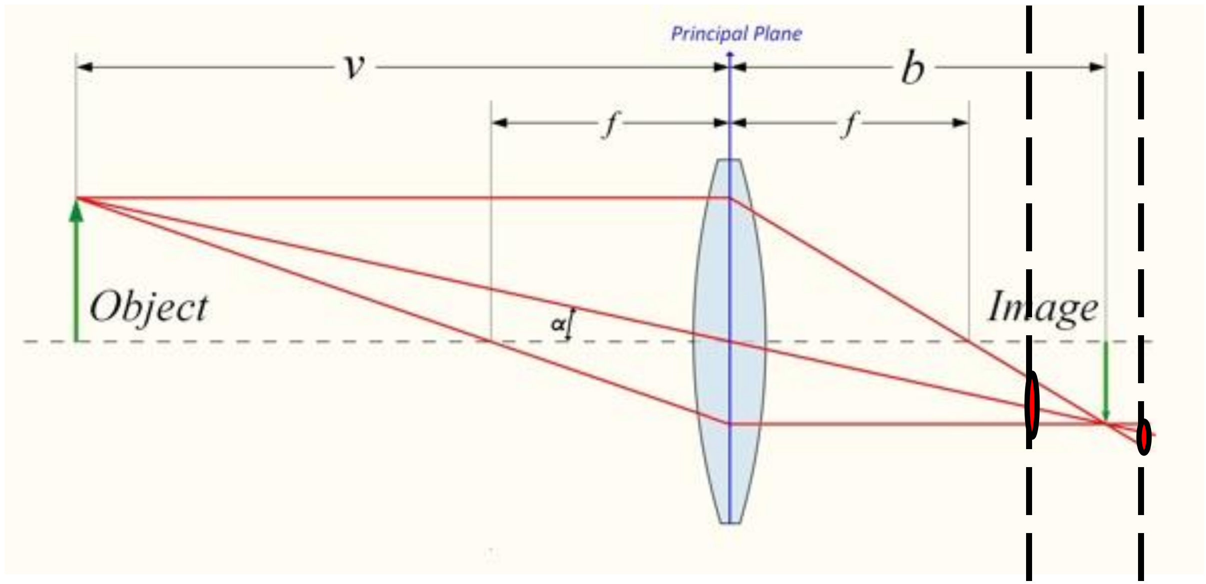
Depth of Field

- **Real Camera**
  - Complex lenses that focus one distance onto the image
    - Finite aperture size
  - Blurred features except for focal plane



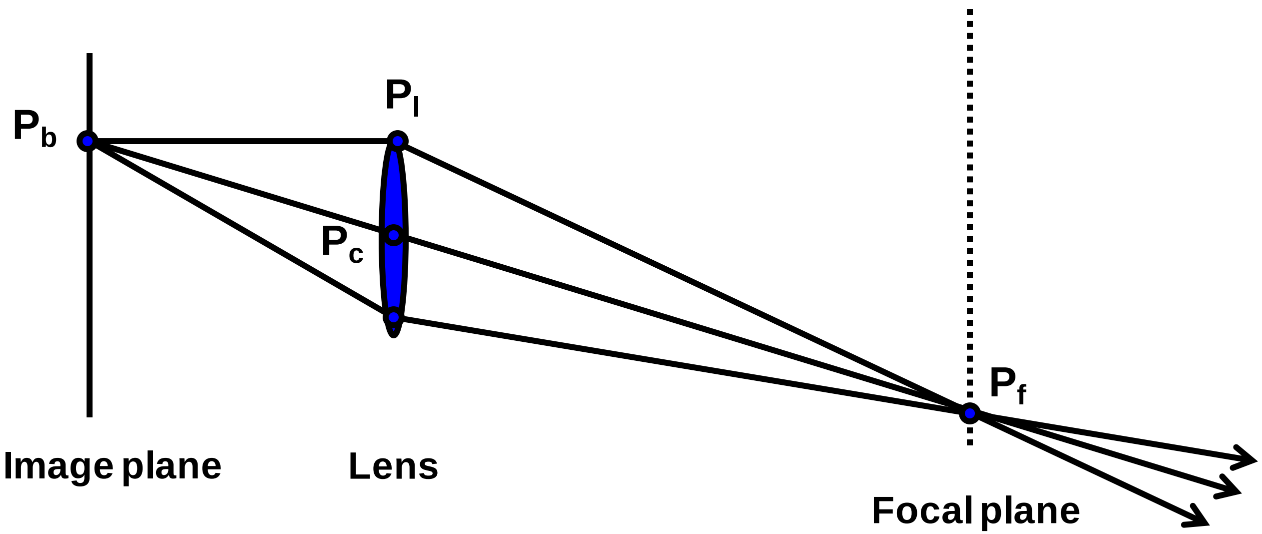
Depth of Field

- **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

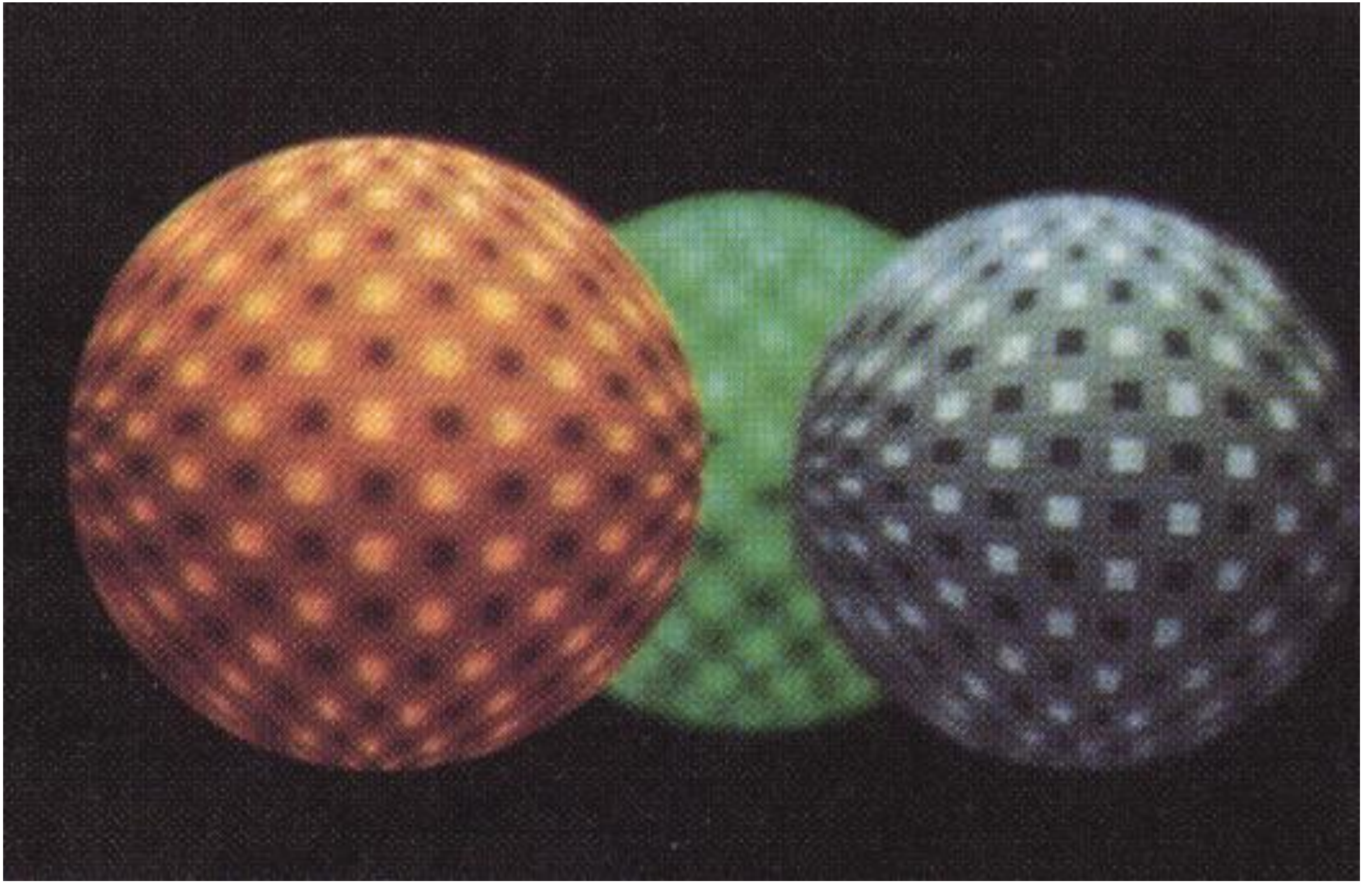


Depth of Field

- **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_l: ray.origin += P_c + x * camera.right + y * camera.up
  - Might include modeling the shape of the aperture
- **Compute new ray direction**
  - Compute ray.direction = P_f - P_l → vector from P_l to P_f
  - Normalize



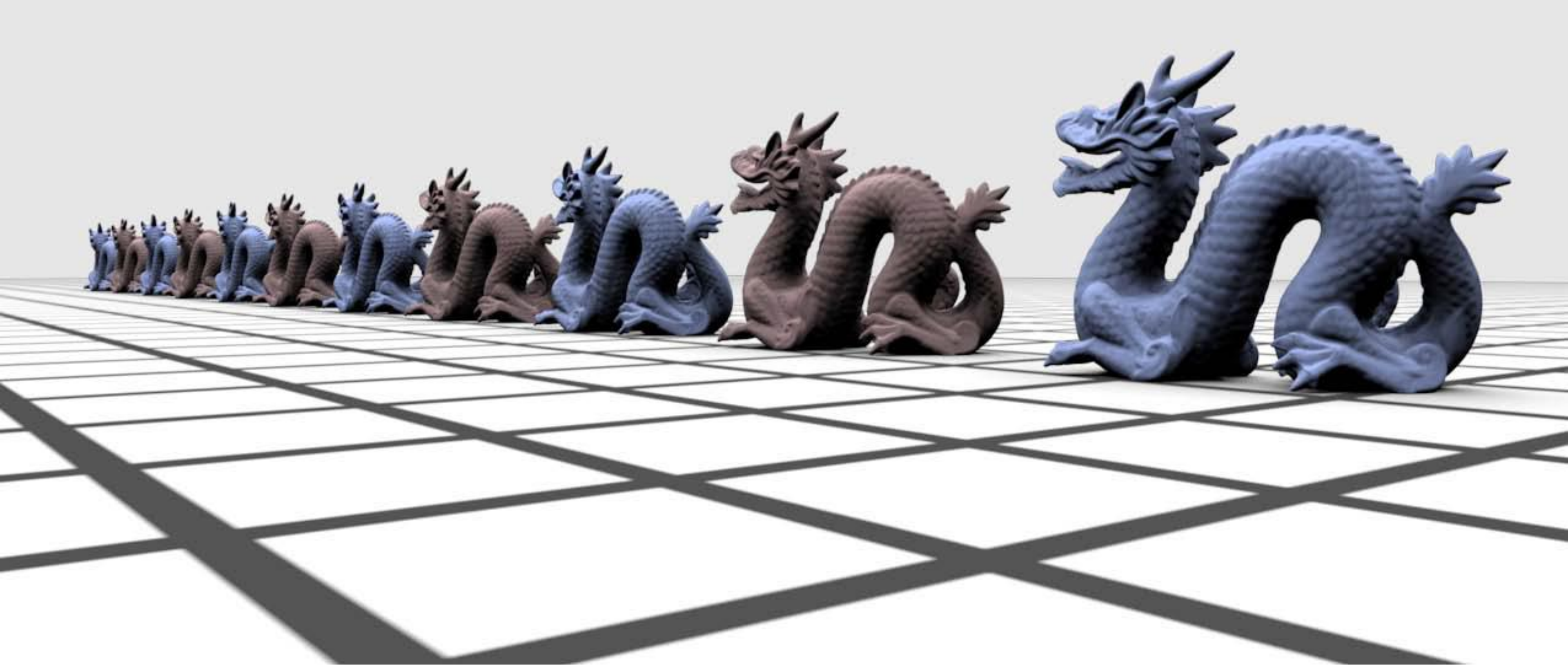
Depth of Field



Cook et al. Siggraph'84

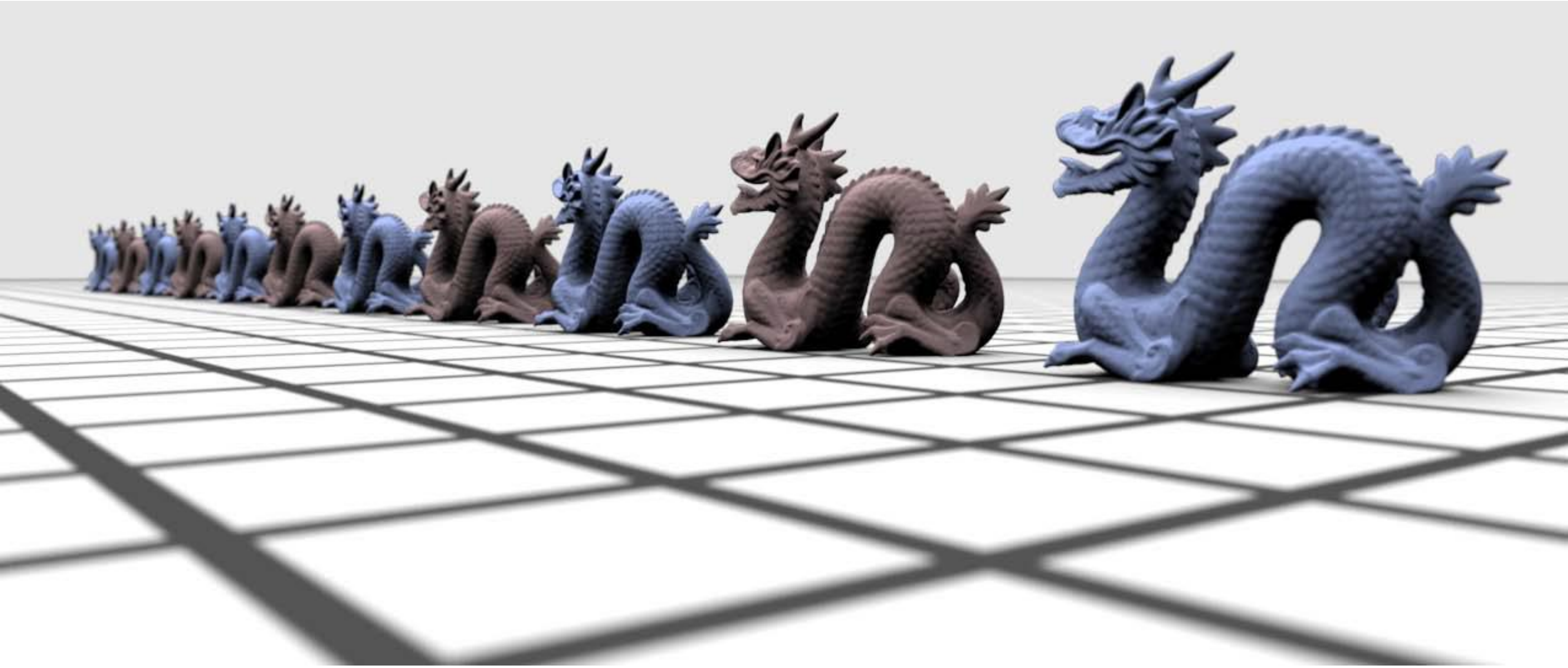
Depth of Field

- **Zero Aperture**



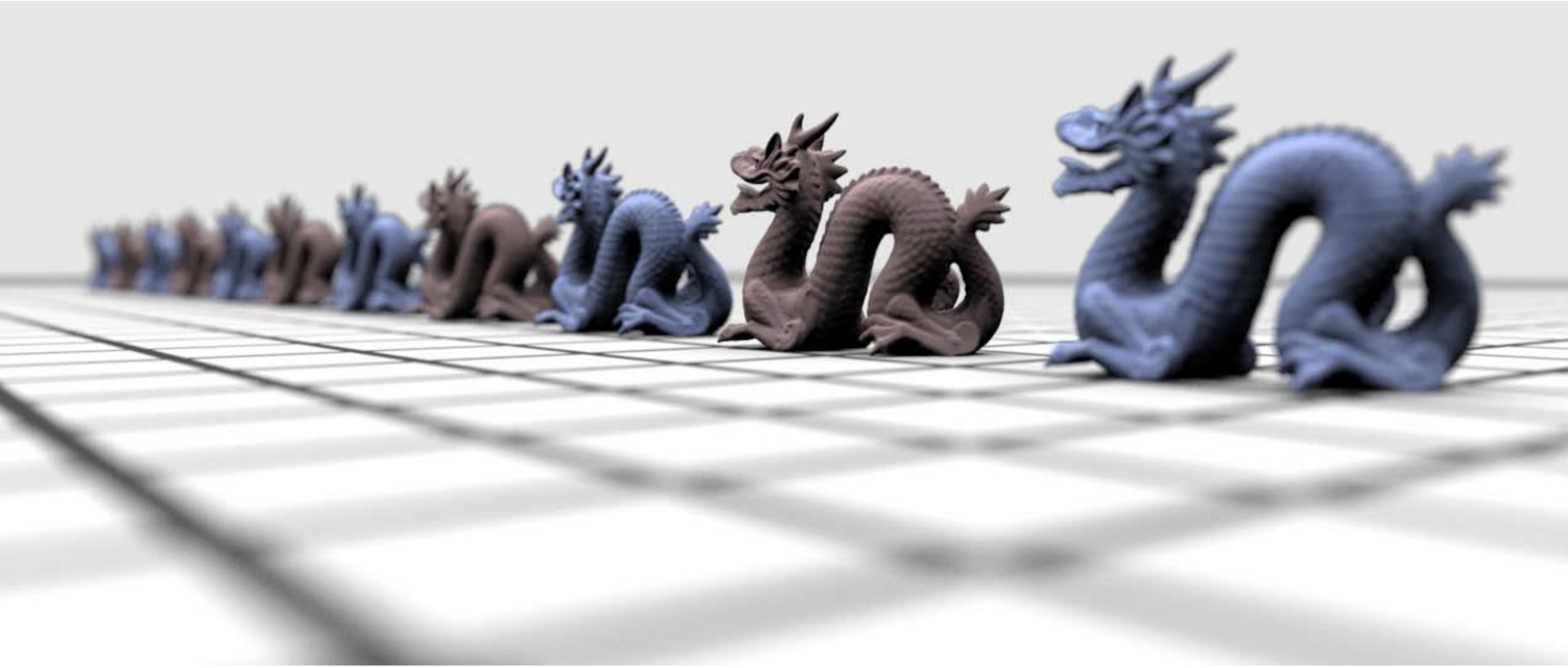
Depth of Field

- **Small Aperture**



Depth of Field

- **Large Aperture**

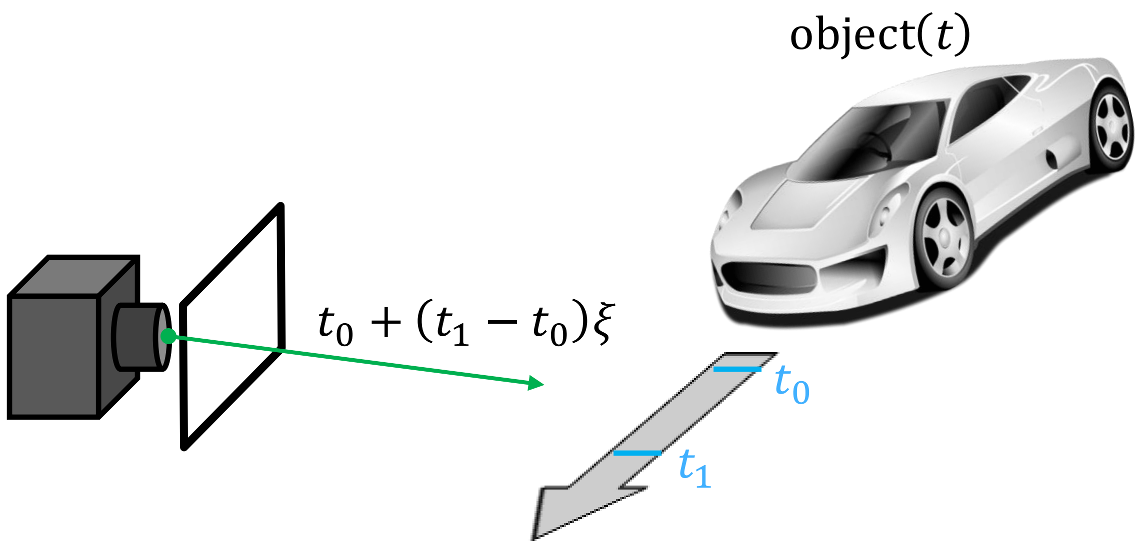


Depth of Field

- **Very Large Aperture**

Motion Blur

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



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

Cook et al. Siggraph'84

Reflections/Refractions

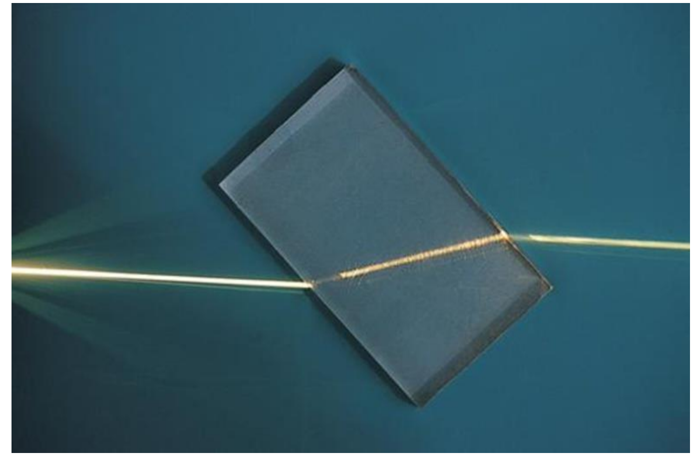
- **Dielectric Materials**
  - η_i – refractive index $\frac{c}{v}$
  - Light: fastest path
  - Snell's law:

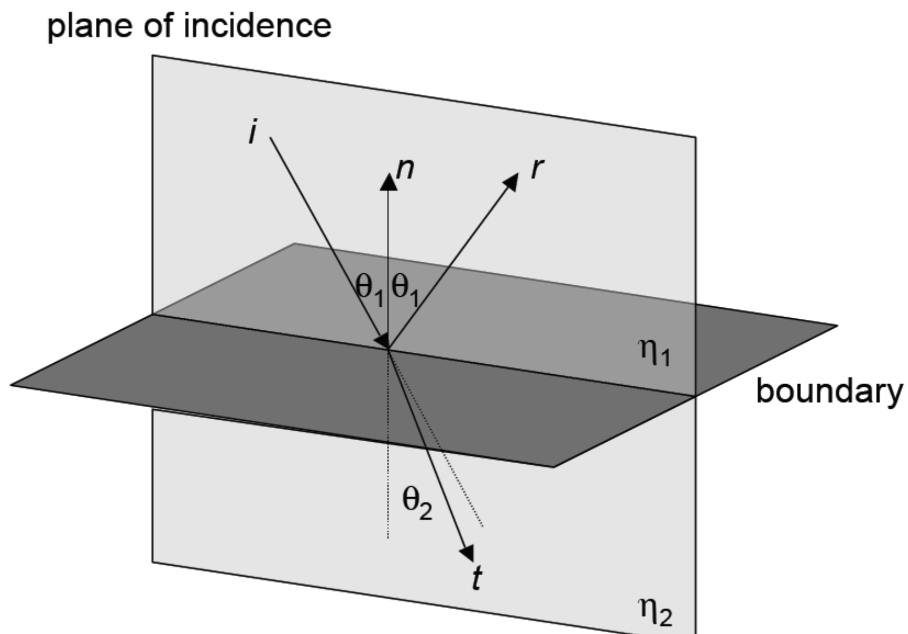
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\eta_2}{\eta_1}$$

  - if

$$\sin\theta_2 = \frac{\eta_1}{\eta_2}\sin\theta_1 > 1$$

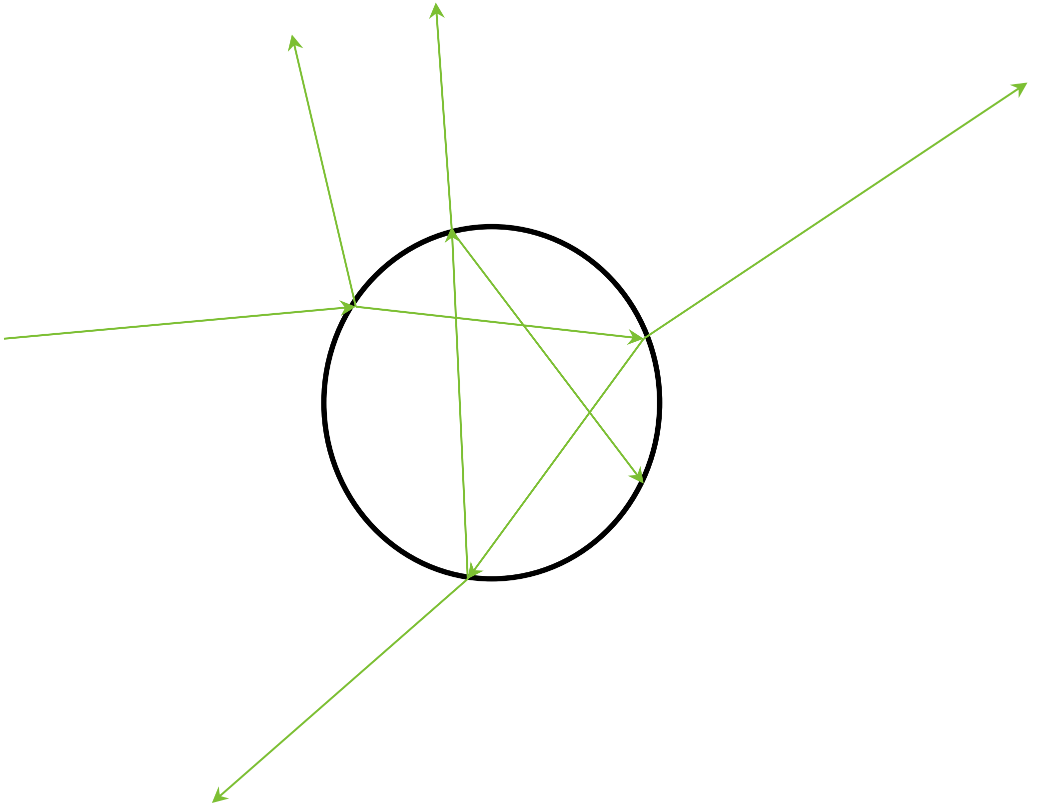
... then total inner reflection





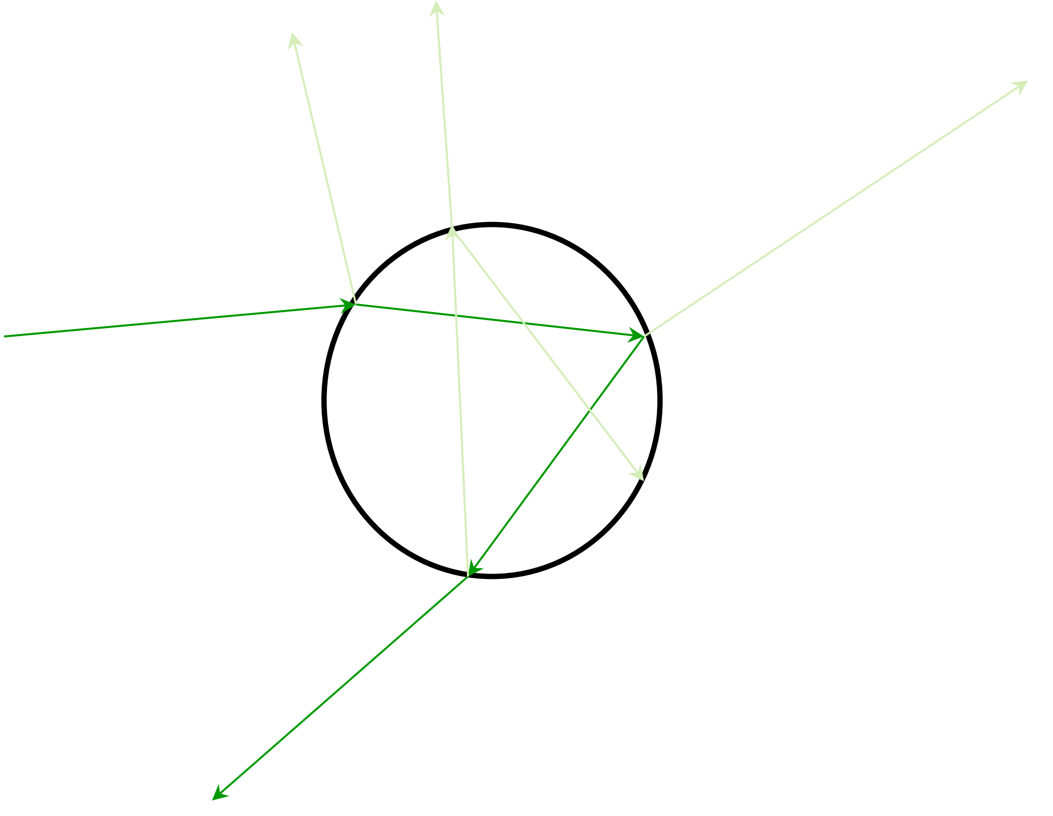
Reflections/Refractions

- **Which ray to trace?**
  - Both: may be exponential



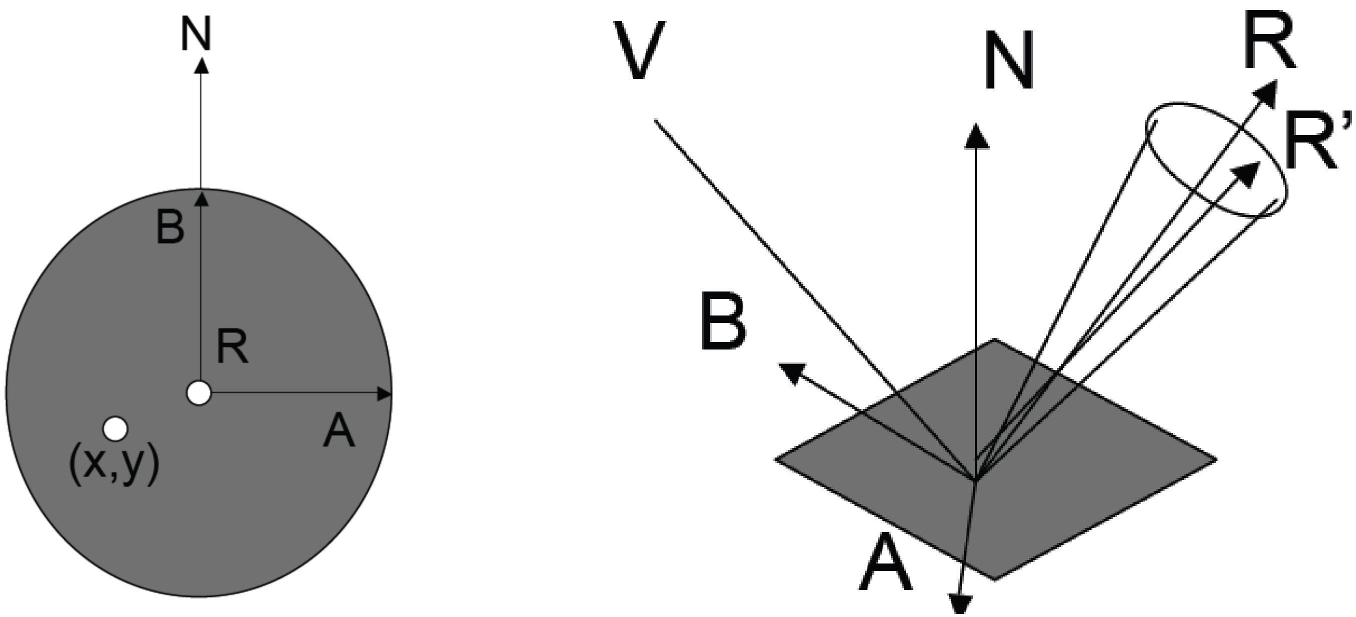
Reflections/Refractions

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



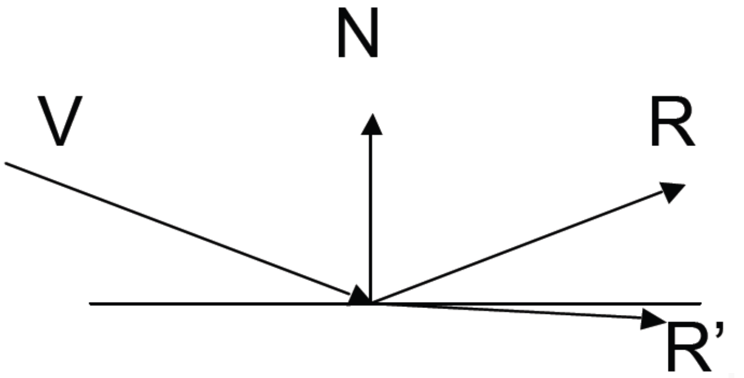
Fuzzy Reflections/Refractions

- **Real Materials**
  - Never perfectly smooth surfaces
- **Empirical Approach**
  - Compute orthonormal frame around reflected/refracted direction
  - Sample coordinates (x, y) on disc: ray.direction += x * a + y * b
- **Or better use $\cos^n$ sampling (→ GI Compendium)**

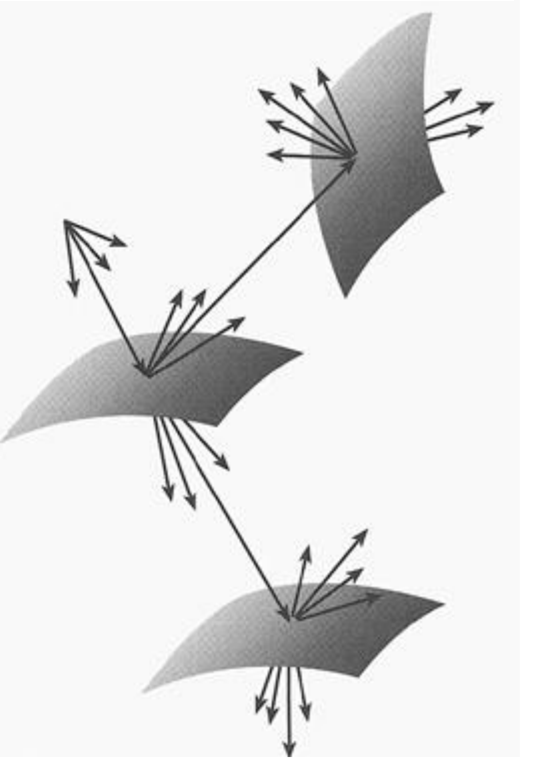


Fuzzy Reflections/Refractions

- **Gotchas**
  - Perturbed ray may 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



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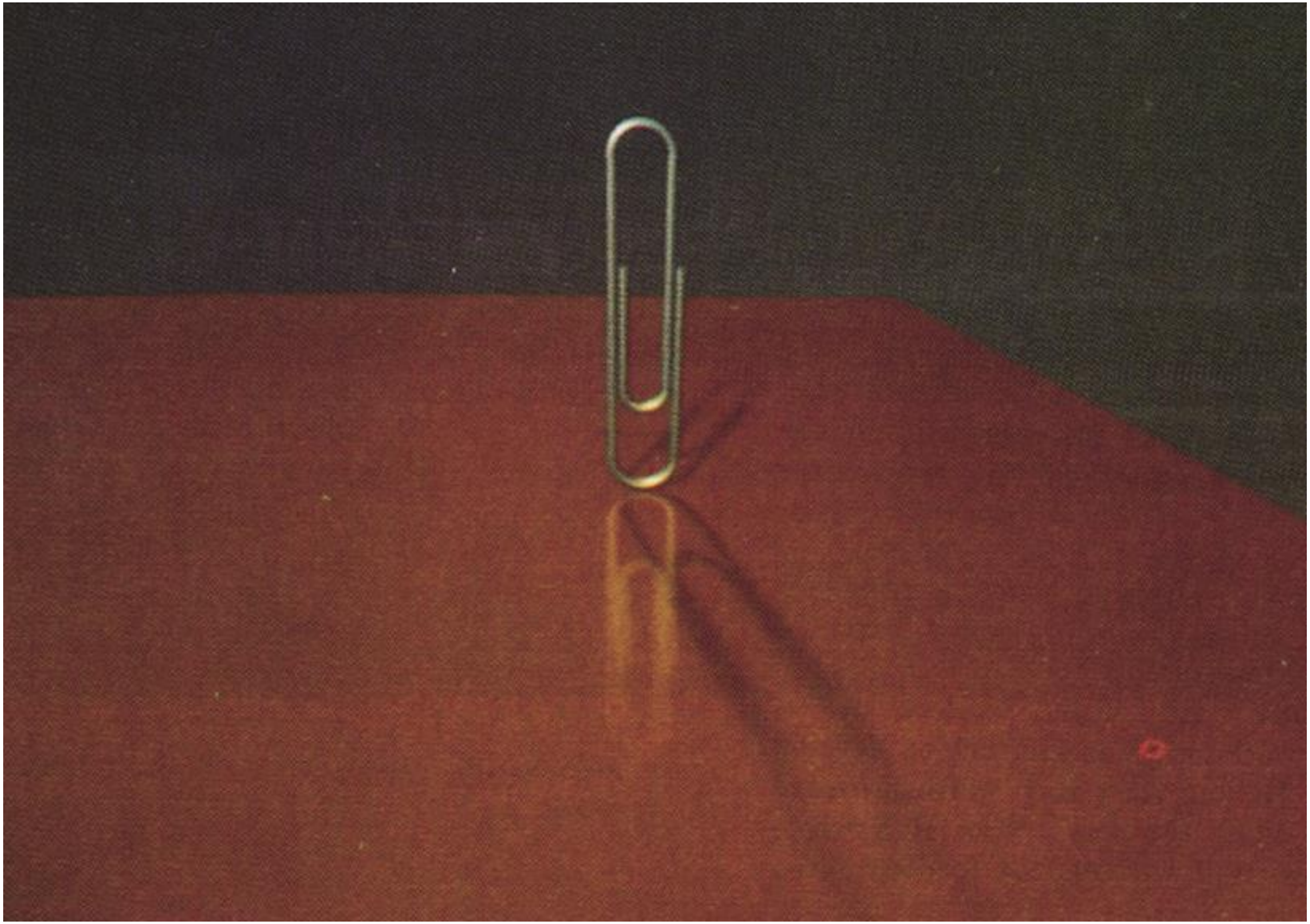
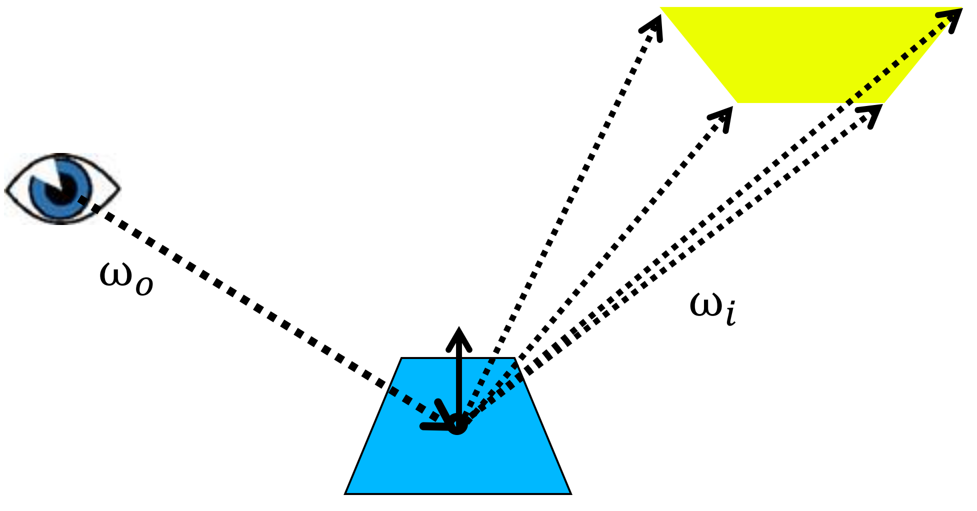
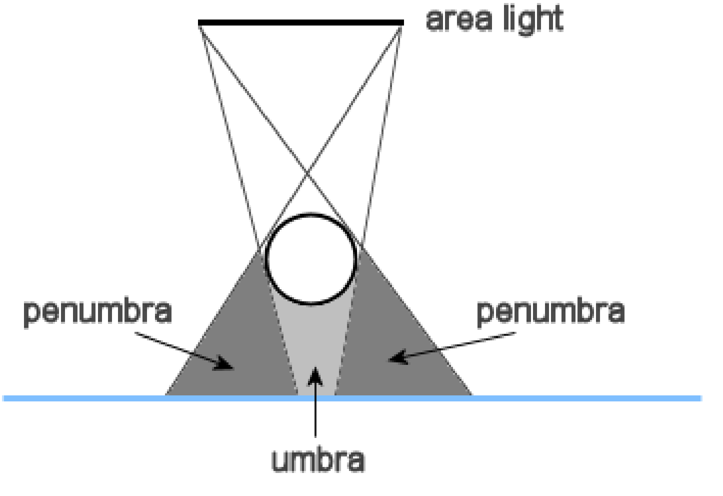


Cook et al. Siggraph'84

Soft Shadows

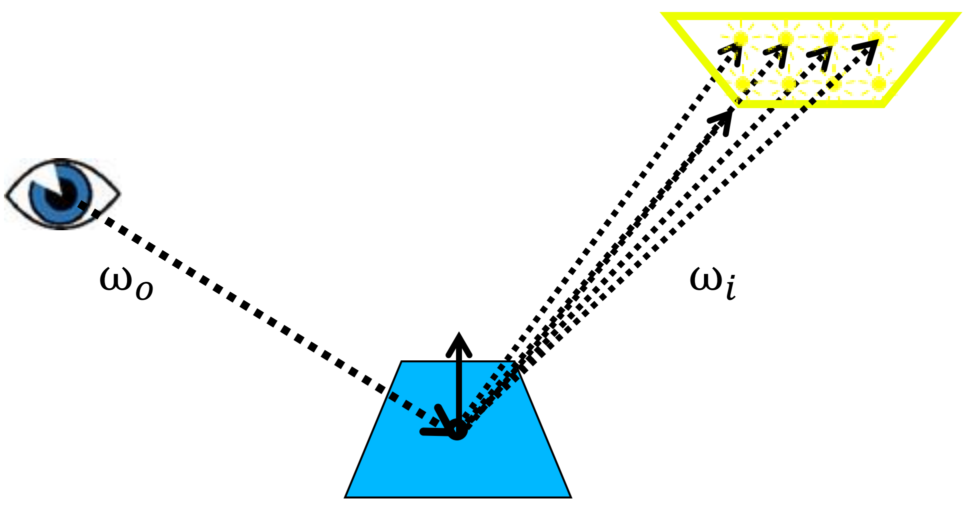
- **Real Light Sources**
  - Finite area

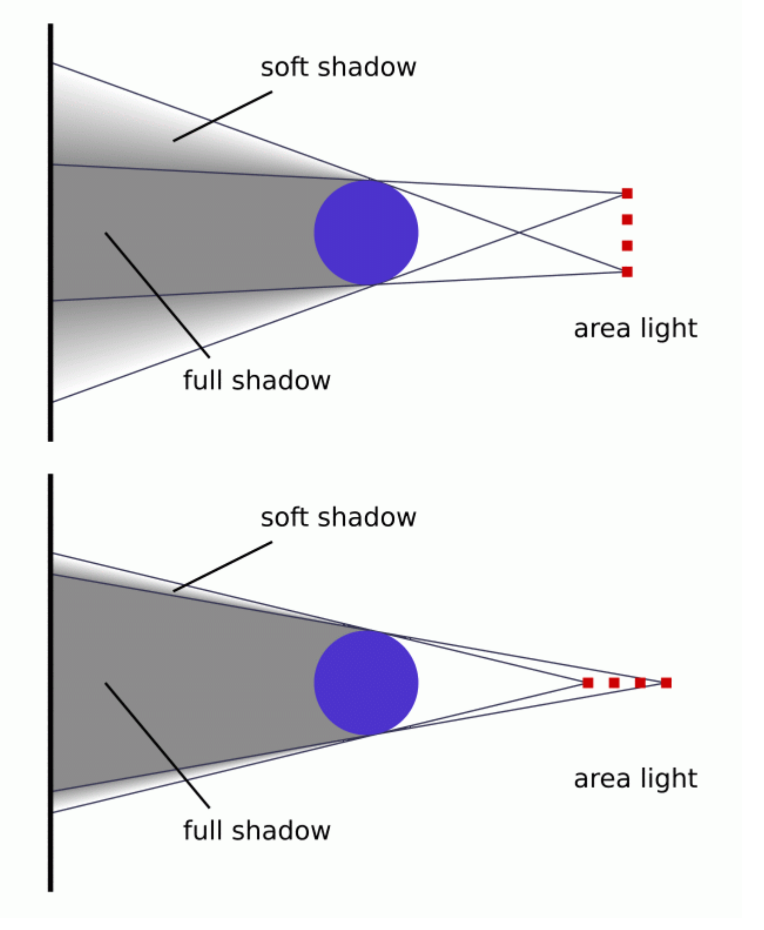




Soft Shadows

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





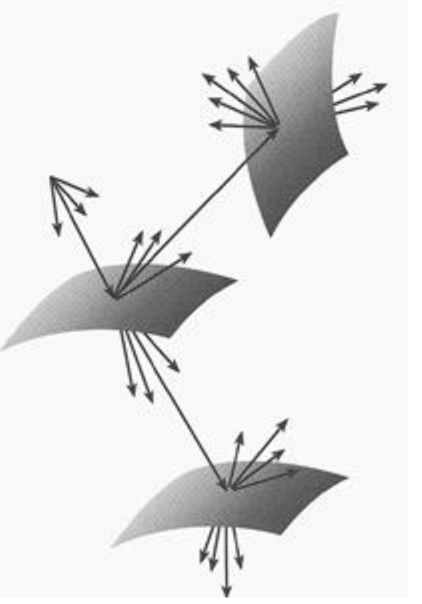
Soft Shadows

- **Small vs. Large Area Light**

Combined Effects

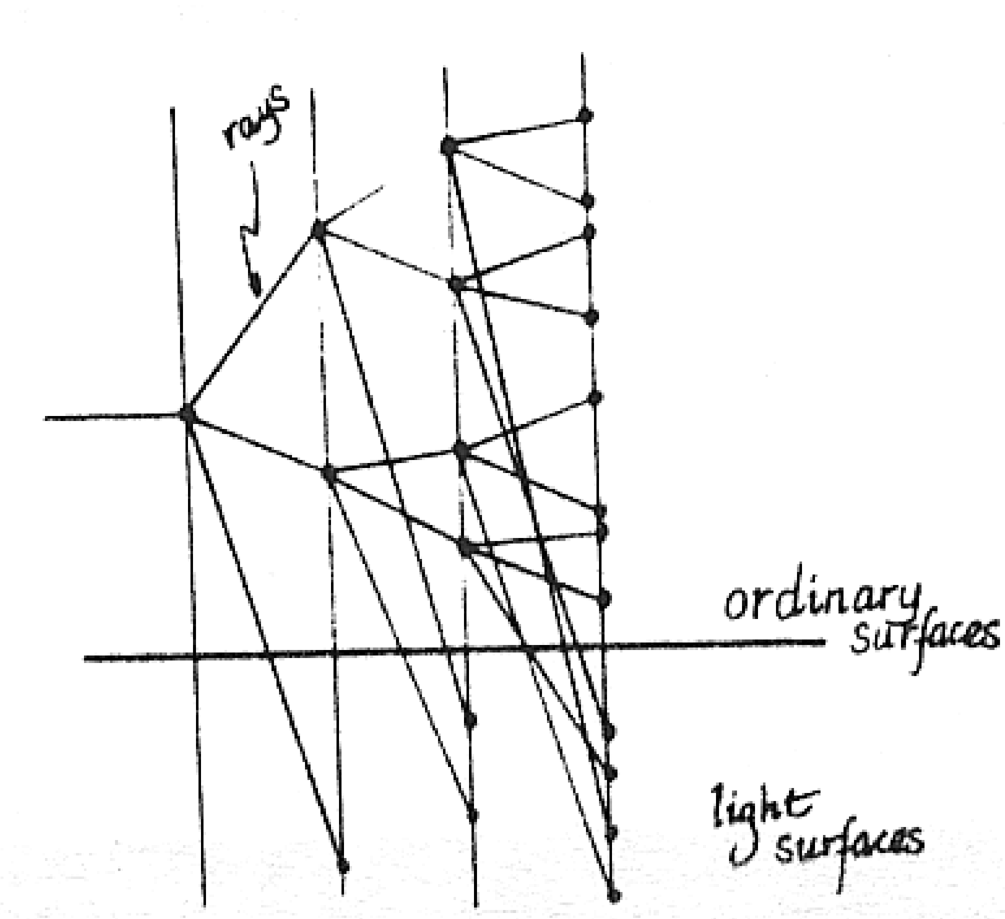
- **High-Dimensional Sampling Space**
  - number of anti-aliasing samples
  - x number of lens samples
  - x number of time samples
  - x number of material samples
  - x number of light samples

  → Exponential growth:
  - Increasing number of higher-order rays with decreasing effect on final pixels → bad²

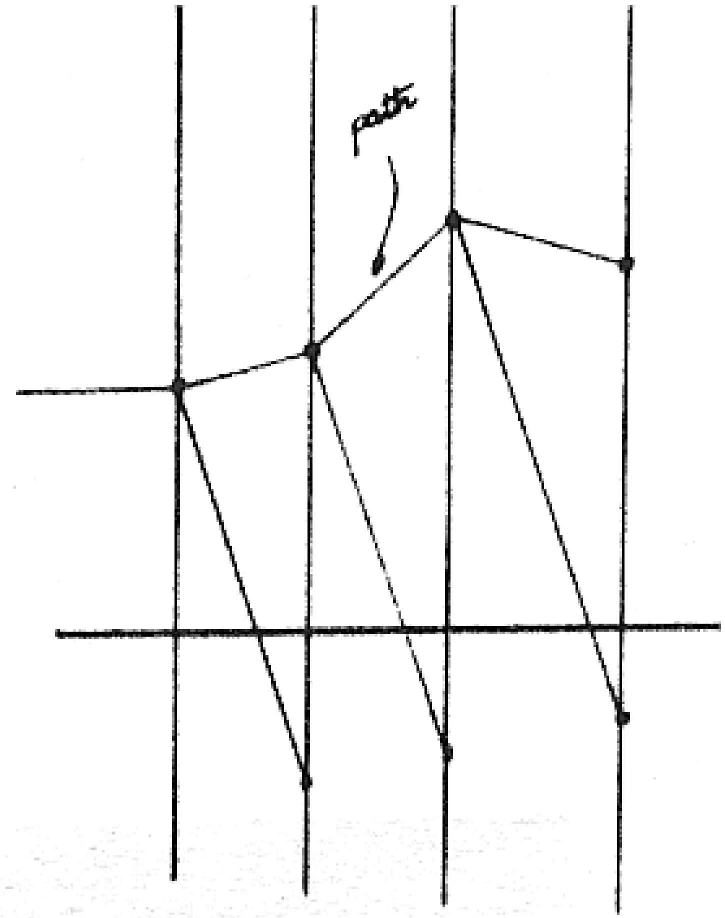


- **Solution: Path-Based Approach**
  - Avoid exponential growth in ray tree
  - Pick a single sample at each step: → Create a sample *path*
  - Average results over several paths per pixel → *path tracing* (RIS)
    - Theoretical underpinning: Monte-Carlo Integration

Comparison to Path Tracing



Distribution Ray Tracing

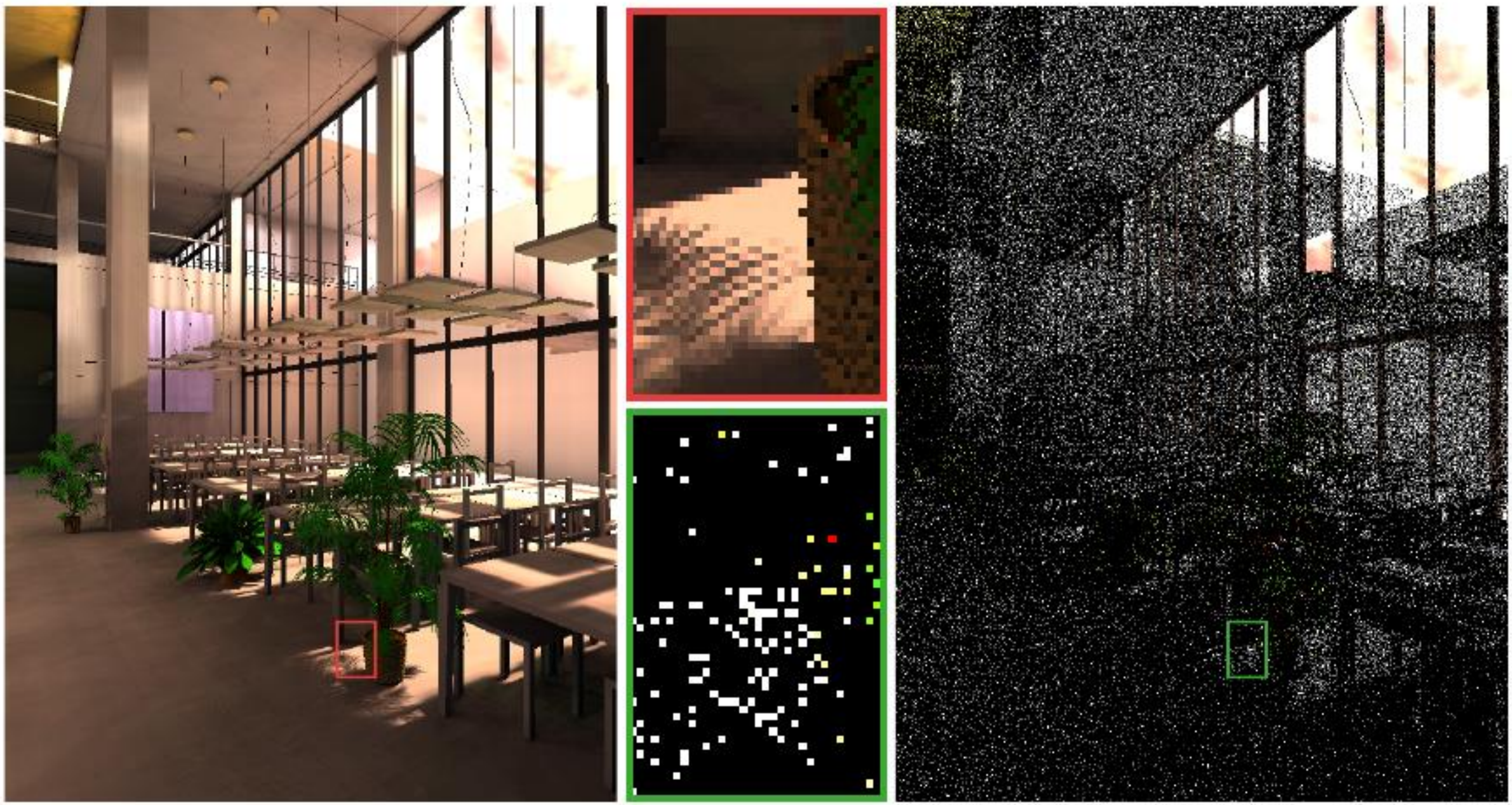


Path Tracing

(figure by Kajiya)

Recent Advances in Lighting Sim.

- **Importance Caching for Complex Illumination**
  - By Iliyan Georgiev et al., Eurographics 2012



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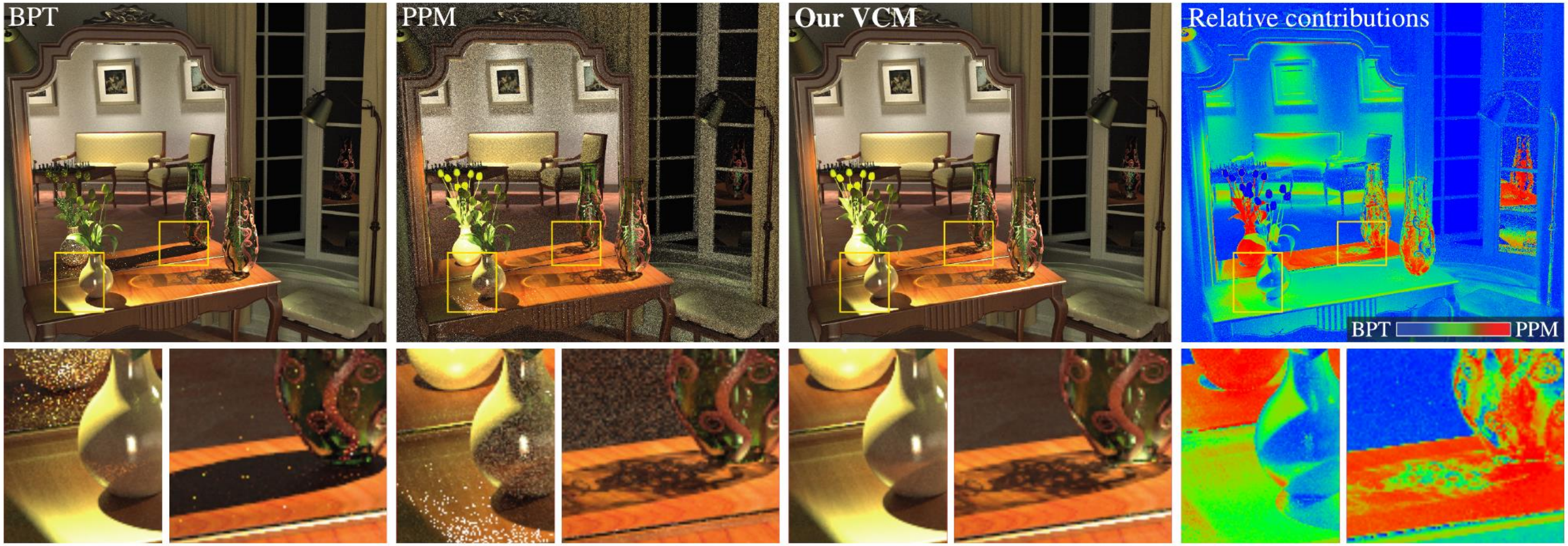
- **Light Transport Simulation with Vertex Connection and Merging (VCM)**
  - By Iliyan Georgiev et al., Siggraph 2012



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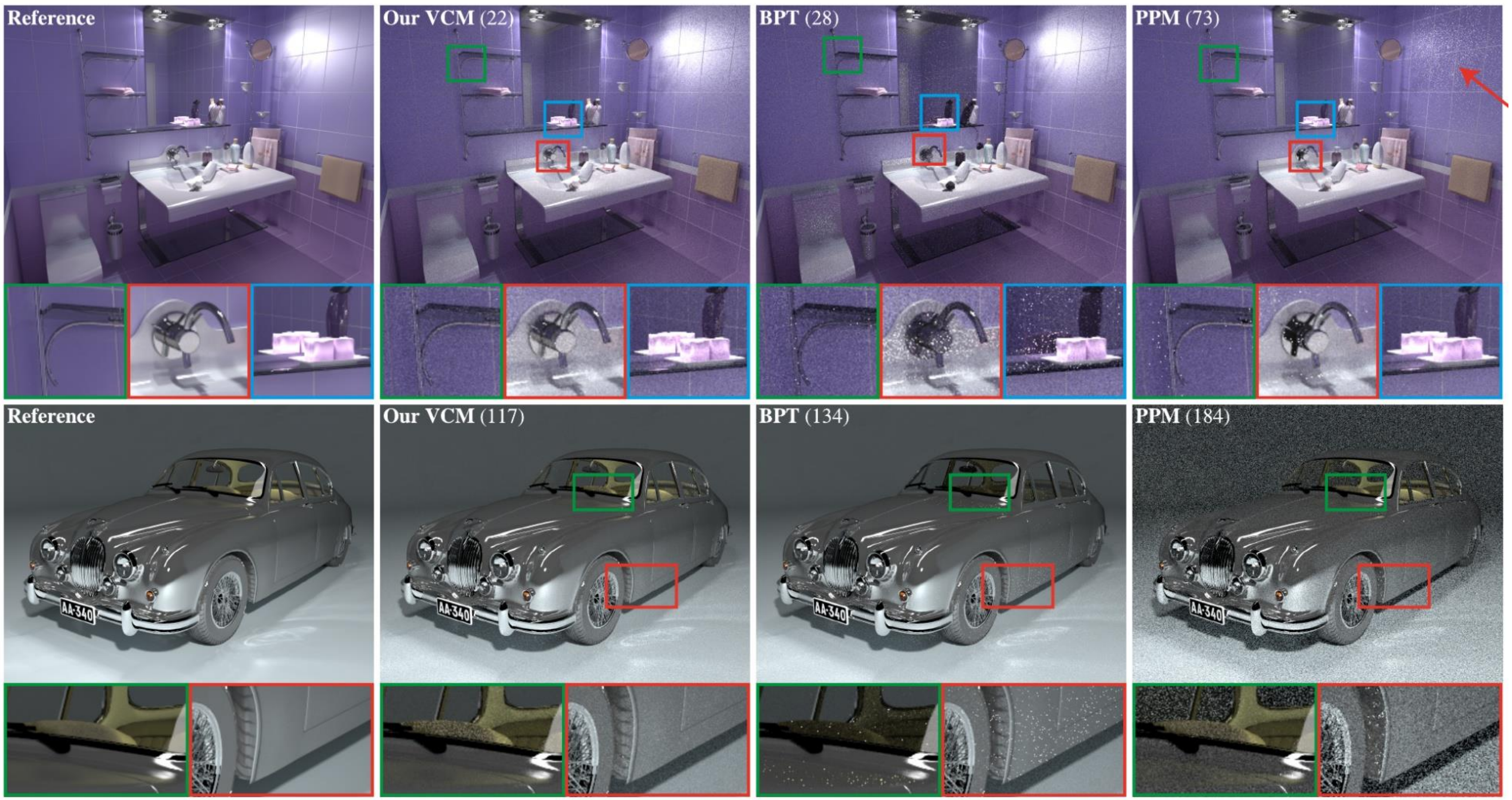
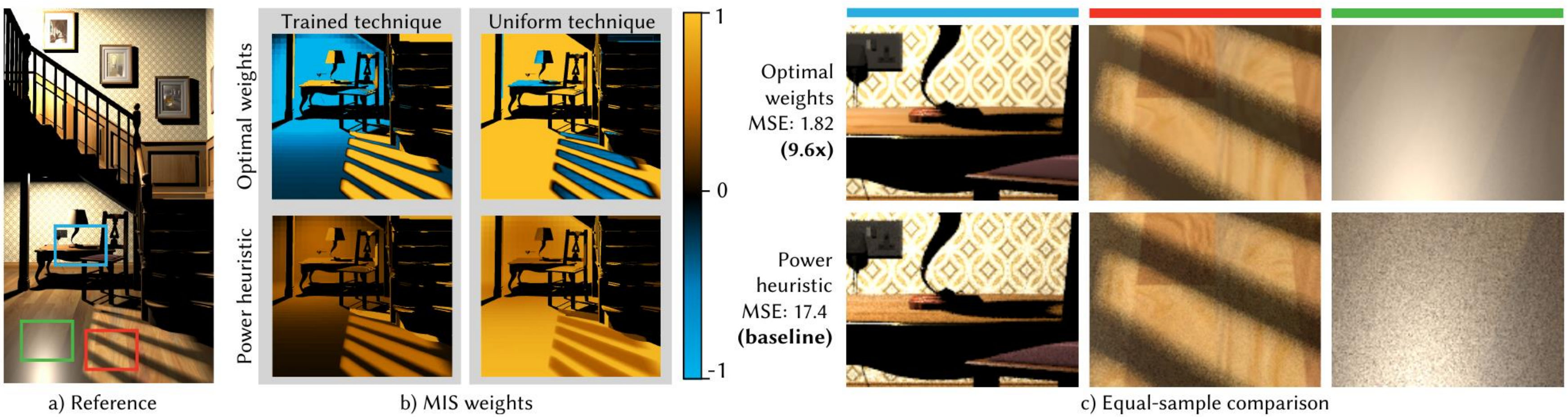


Recent Advances in Lighting Sim.

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



Recent Advances in Lighting Sim.

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