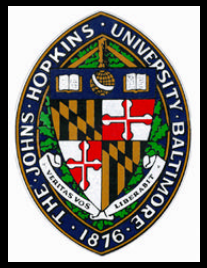
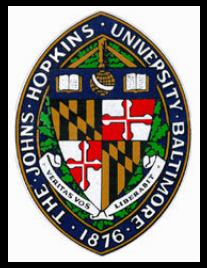


Ray Tracing



Recursive Ray Tracing

Gather light from various directions by tracing rays

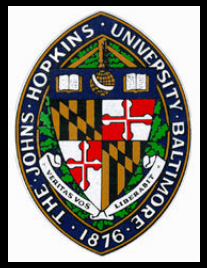
Each pixel shows light at a surface

- **trace ray from eye to surface**

Each surface illuminated by lights and other surfaces

- **trace rays from surface to other surfaces**

And so on...



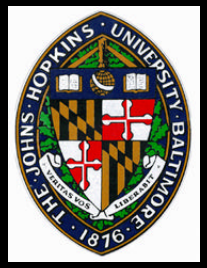
Types of Rays

Eye/pixel rays

Illumination/shadow rays

Reflection rays

Transmission/transparency rays



Eye Rays

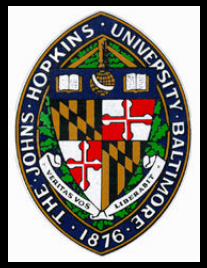
Same as in ray casting

Effectively determine visible surfaces

For perspective view, trace from eye through pixel

For orthogonal view, trace parallel rays through pixels in direction of projection

Stop at nearest intersection with surface

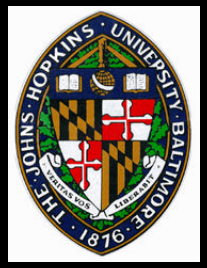


Illumination Rays

From surface point towards light source

Intervening surfaces may block or attenuate direct illumination

Light reaching surface applied using local illumination model



Reflection Rays

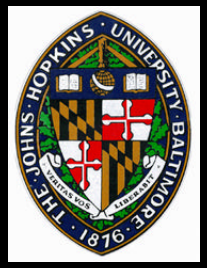
Gather non-local illumination reflecting (specularly) towards eye (incident ray)

From current point towards reflection direction

Contribute illumination from closest surface intersection

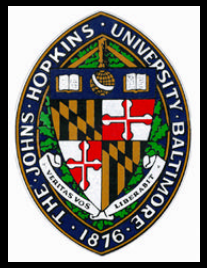
Assume perfect (sharp) specular reflection

Attenuated by specular coefficient



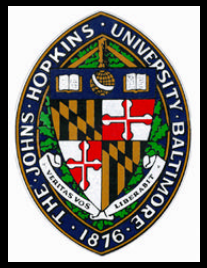
Transmission Rays

- Gather light transmitted through current surface
- Incident ray refracted according to index of refraction and Snell's law
- May use a single index of refraction (rather than per wavelength)
- Attenuated by transmission coefficient



Trace Algorithm

```
Trace(ray)
    Foreach object in scene
        Intersect(ray, object)
    If no intersections
        return BackgroundColor
    For each light
        Foreach object in scene
            Intersect(ShadowRay, object)
        Accumulate local illumination
    Trace(ReflectionRay)
    Trace(TransmissionRay)
    Accumulate global illumination
    Return illumination
```



Spheres and Checkerboard

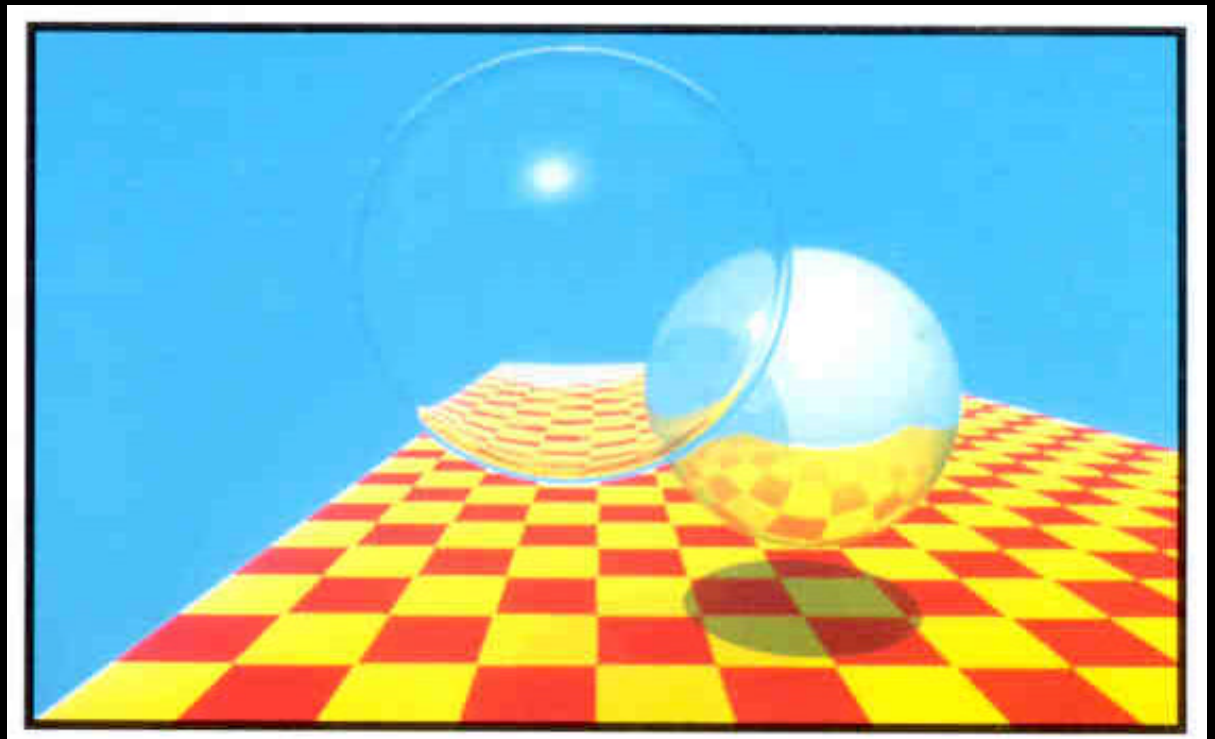
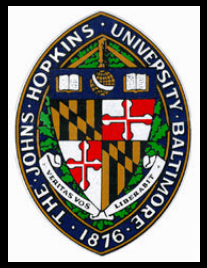
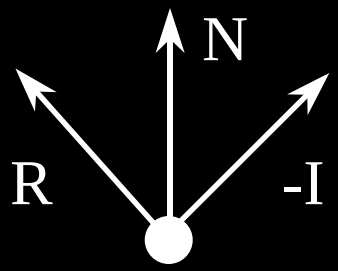


Plate III.10 Spheres and checkerboard. An early image produced with recursive ray tracing (Section 16.12). (Courtesy of Turner Whitted, Bell Laboratories.)

Turned Whitted, 1980 (Foley/vanDam III.10)

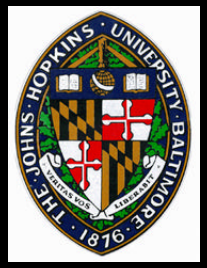


Computing Reflection Ray

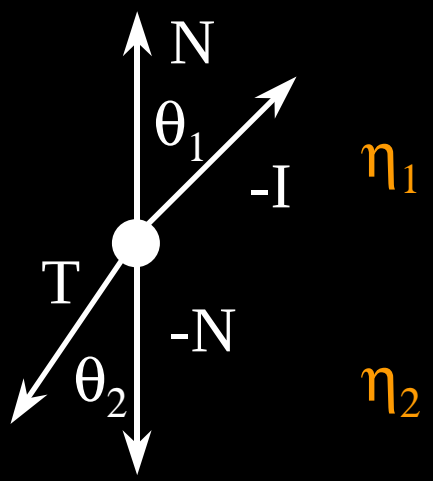


I = incident ray
N = normal vector
R = reflected ray

$$R = (-I.N)N + I + (-I.N)N = I - 2(I.N)N$$

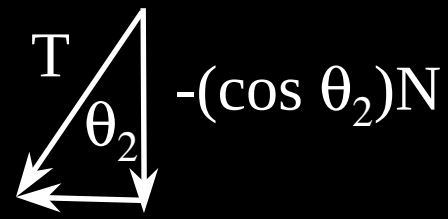


Computing Transmission Ray



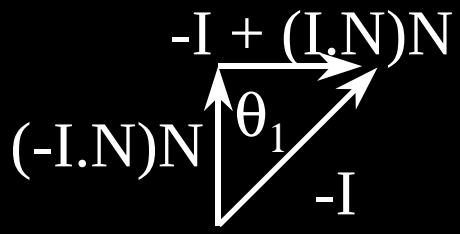
Snell's Law

$\eta_{12} = \eta_1 / \eta_2 = \sin\theta_2 / \sin\theta_1$



$(\sin\theta_2)M$

$T = (\sin\theta_2)M - (\cos\theta_2)N$



$\sin\theta_1 = \| -I + (I.N)N \|$

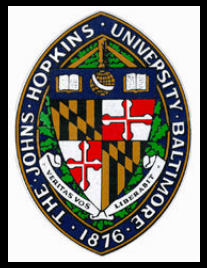
$M = [I - (I.N)N] / \sin\theta_1$

$T = (\sin\theta_2 / \sin\theta_1)[I - (I.N)N] - (\cos\theta_2)N$

$= \eta_{12} I - [\eta_{12}(I.N) - (\cos\theta_2)]N$

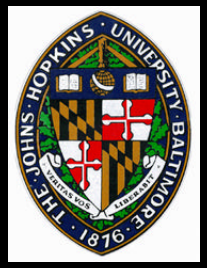
$= \eta_{12} I - [\eta_{12}(I.N) - \mathrm{sqrt}(1 - \sin^2\theta_2)]N$

$= \eta_{12} \mathbf{I} - [\eta_{12}(I.N) - \mathrm{sqrt}(1 - \eta_{12}^2\sin^2\theta_1)]\mathbf{N}$



Accumulating Light Contributions at a Point

- I = Σ local illumination (attenuated illum. rays)
  - + attenuated reflection ray
  - + attenuated transmission ray
- Illumination rays attenuated by transmission coefficients of light occluders
- Reflection ray attenuated by specular coefficient
- Transmission ray attenuated by trans. coefficient
- All rays may be attenuated by $1/r^2$

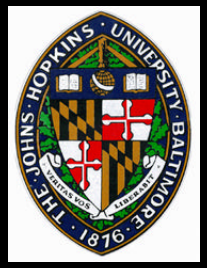


Sampling Issues

Currently using only a single sample for each

- **Pixel**
- **Reflection**
- **Transmission**
- **Frame time**
- **Eye point**

All of these can cause forms of *aliasing*



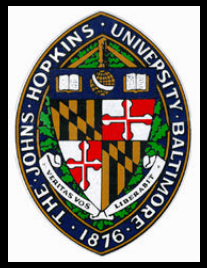
Sampling Theory

Aliasing: a high frequency signal masquerading as a lower frequency

Nyquist limit: maximum frequency signal that may be adequately sampled

(1/2 sampling frequency)

Aliasing may occur when we take regularly-spaced samples of frequencies above the Nyquist limit

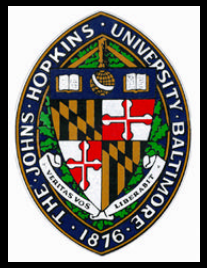


Examples of Aliasing

Reverse-rotating wagon wheels in films (temporal aliasing)

"Jaggies" on polygon edges or specular highlights (spatial aliasing)

Creeping effects (jaggies in motion)



Aliasing Illustration

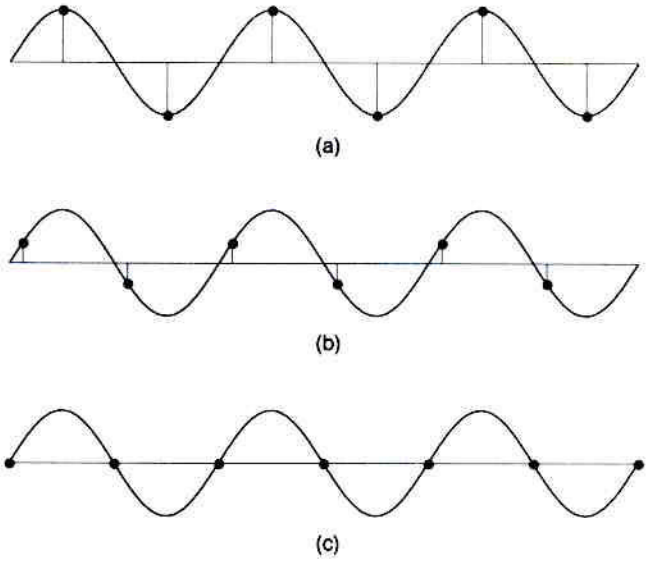


Fig. 14.16 Sampling at the Nyquist rate (a) at peaks, (b) between peaks, (c) at zero crossings. (Courtesy of George Wolberg, Columbia University.)

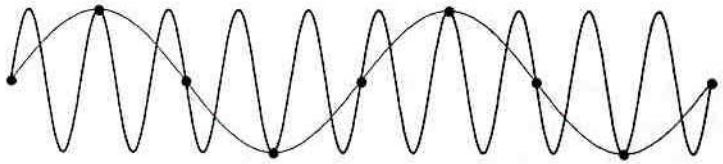
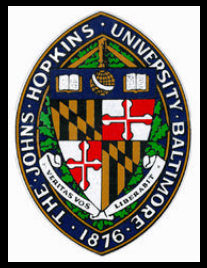
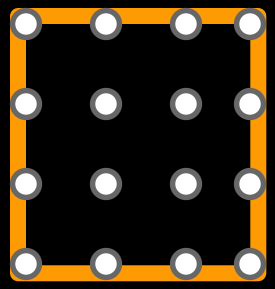


Fig. 14.17 Sampling below the Nyquist rate. (Courtesy of George Wolberg, Columbia University.)

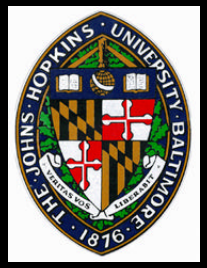
Figures by George Wolberg, from Foley, vanDam, et al., *Computer Graphics: Principle and Practice*, p. 627-628



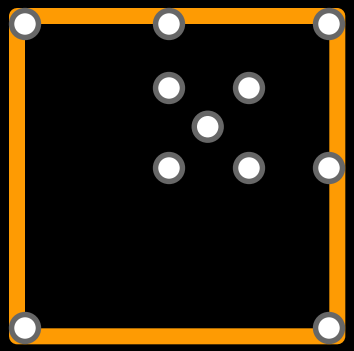
Anti-aliasing - Supersampling



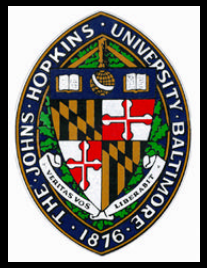
- Shoot multiple rays through each pixel
- Aim through centers of a regular grid (e.g. 3x3 or 4x4 grid of samples)
- Average resulting intensity values (box filter reconstruction)
- Reduces spatial aliasing effects



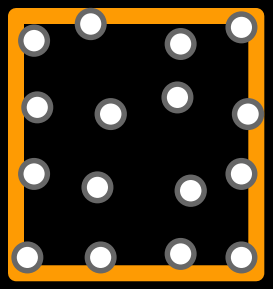
Adaptive Supersampling



- Sample at corners and center
- Add samples if gradient is more than some threshold
- Add samples only in necessary regions
- Reduces aliasing effects more efficiently
- Still may not sample adequately



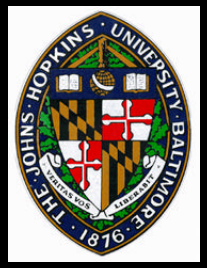
Jittering



Apply random perturbations to sample positions of uniform or adaptive grid

Does not increase sampling rate, but removes regularity

Converts aliasing to *noise*, which is perceptually more tolerable



Aliasing vs. Noise

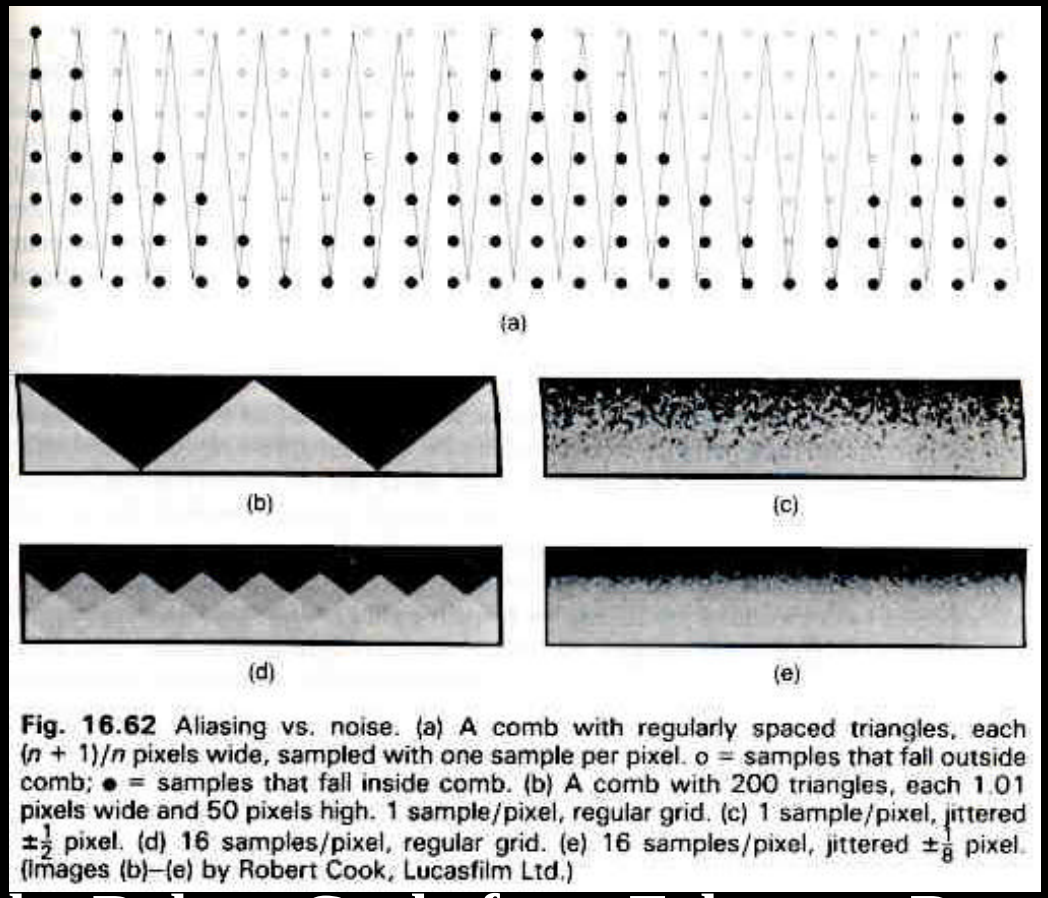
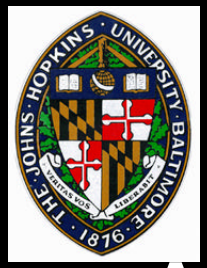


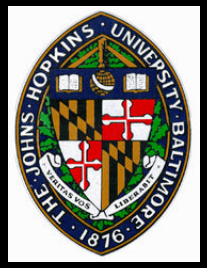
Fig. 16.62 Aliasing vs. noise. (a) A comb with regularly spaced triangles, each $(n + 1)/n$ pixels wide, sampled with one sample per pixel. o = samples that fall outside comb; • = samples that fall inside comb. (b) A comb with 200 triangles, each 1.01 pixels wide and 50 pixels high. 1 sample/pixel, regular grid. (c) 1 sample/pixel, jittered $\pm\frac{1}{2}$ pixel. (d) 16 samples/pixel, regular grid. (e) 16 samples/pixel, jittered $\pm\frac{1}{8}$ pixel. (Images (b)–(e) by Robert Cook, Lucasfilm Ltd.)

Figures by Robert Cook, from Foley, vanDam, et al., *Computer Graphics: Principles and Practice*, p. 791.



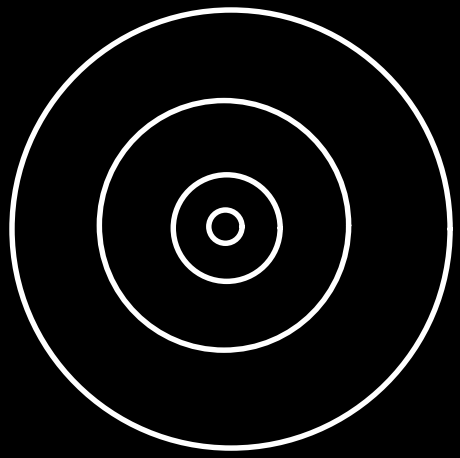
Distributed Ray Tracing

- Apply distribution-based sampling to many parts of the ray-tracing algorithm
- Fuzzy reflection/transmission
  - perturb directions reflection/transmission, with distribution based on angle from ideal ray
- Motion blur
  - perturb eye ray samples in time
- Depth of field
  - perturb eye position on lens
- Fuzzy shadows/penumbra
  - sample illumination rays across area light

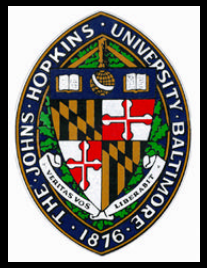


Importance Sampling

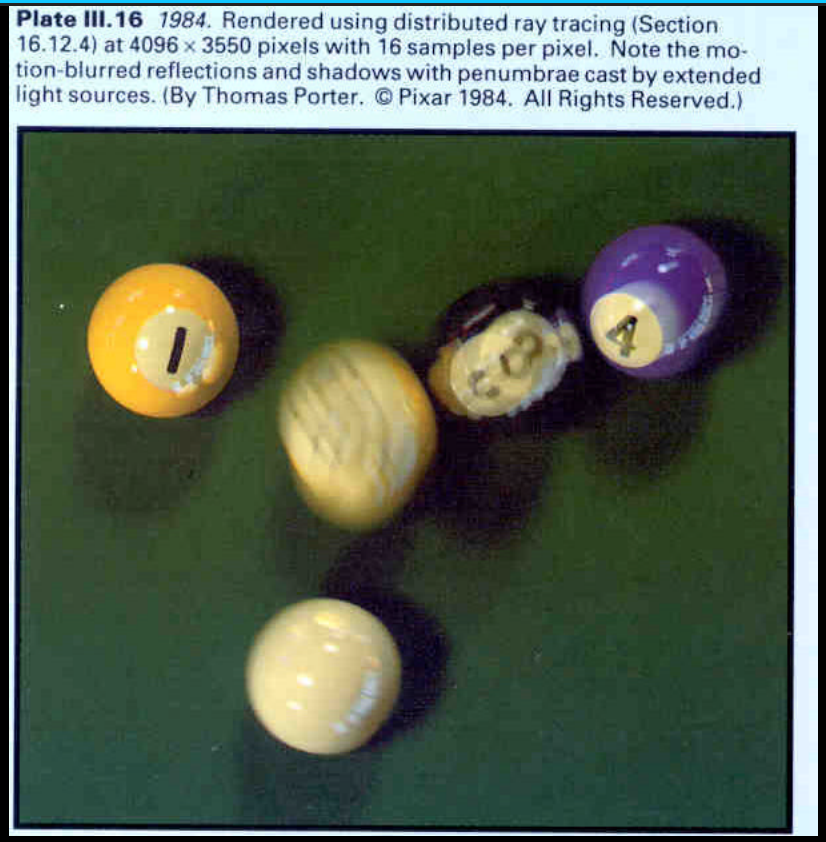
- **Divide sample space into blocks of equal area under weighting function**
- **Assign each pixel sample a different (random) block**
- **Perturb randomly within block (ideally, points in block have nearly equal weight…)**



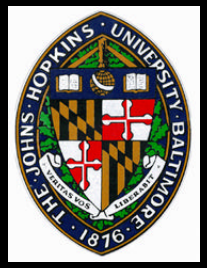
possible block arrangement for reflection ray direction



Motion Blur Illustration



"1984," by Thomas Porter, Pixar. Exerpted from Foley, vanDam, et al., *Computer Graphics: Principles and Practice,* plate III.16



Depth of Field Illustration

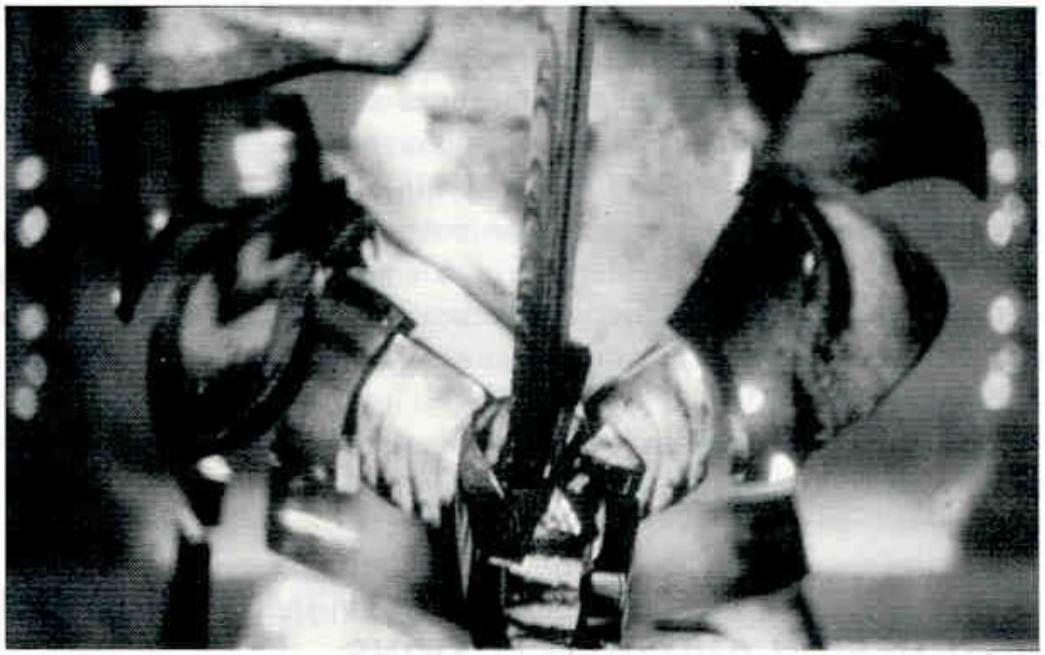
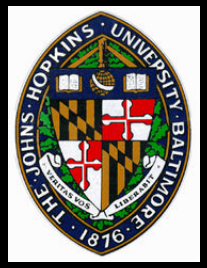


Fig. 17. Example of depth of field from *Young Sherlock Holmes*. Copyright 1985, Paramount Pictures Corp.

from *Young Sherlock Holmes*, Paramount Pictures Corp, 1985. Exerpted from *An Introduction to Ray Tracing*, Andrew Glassner, ed., p. 195



Penumbras and Blurry Reflection

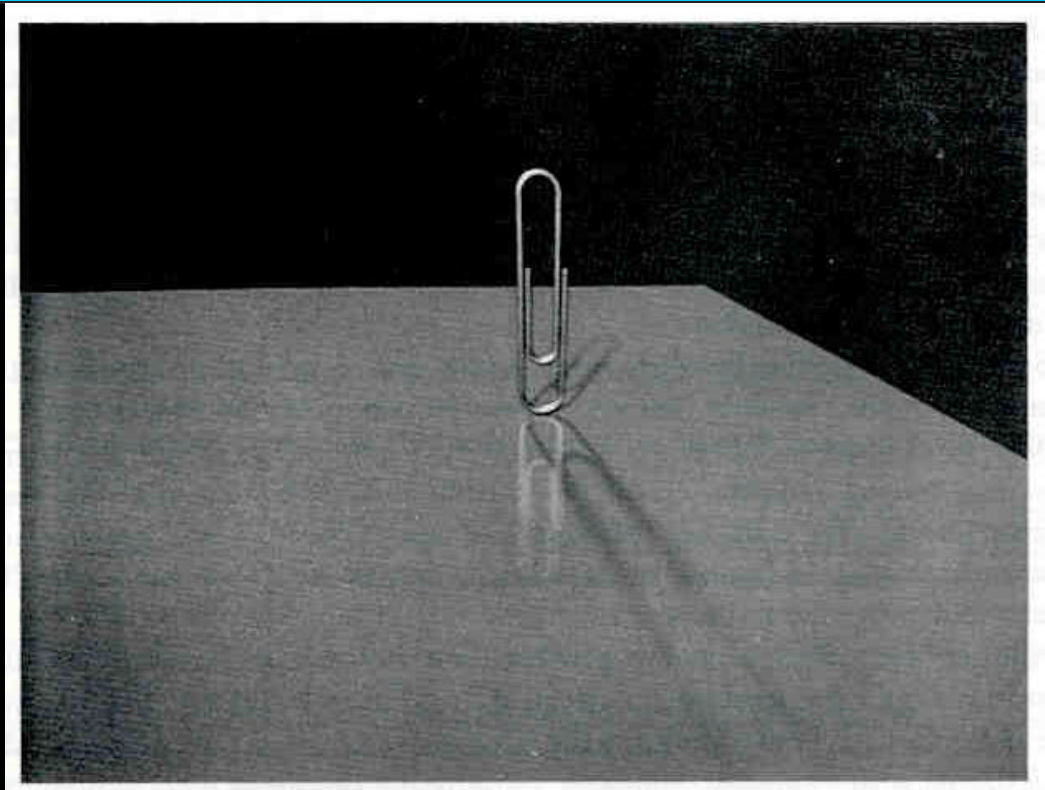


Fig. 18. Example of penumbras and blurry reflection.

Exerpted from "Stochastic Sampling and Distributed Ray Tracing," by Robert L. Cook, in *An Introduction to Ray Tracing*, Andrew Glassner, ed., p. 195