# Ray Tracing: Special Topics

**CSCI 4239/5239**
**Advanced Computer Graphics**
**Spring 2017**

# Theoretical foundations

Ray Tracing from the Ground Up Chapters 13-15

- Bidirectional Reflectance Distribution Function
  - BRDF
  - Describes how light is reflected on each bounce
  - Chains to transfer colors

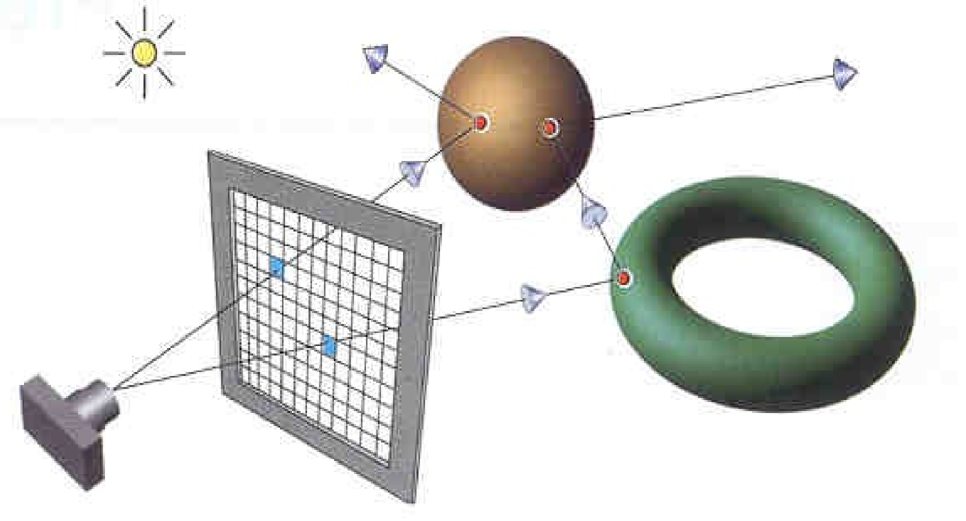


Figure 1. The ray-tracing process.

# Radiometric Quantities

- Radiant Energy $Q$ (J)
- Radiant Flux $\phi = dQ/dt$ (W)
- Radiant Flux Density $d\phi/dA$ (W/m$^2$)
- Irradiance E [Arriving flux density]
- Radiant exitance M [Leaving flux density]
- Radiant Intensity I $d\phi/d\omega$ (W/m$^2$/sr)
- Radiance L $d^2\phi/dA d\omega$ (W/m$^2$/sr)

# Ray Properties

- Radiance is constant along rays
- Radiance can be defined at the eye
- Radiance can be defined at a point

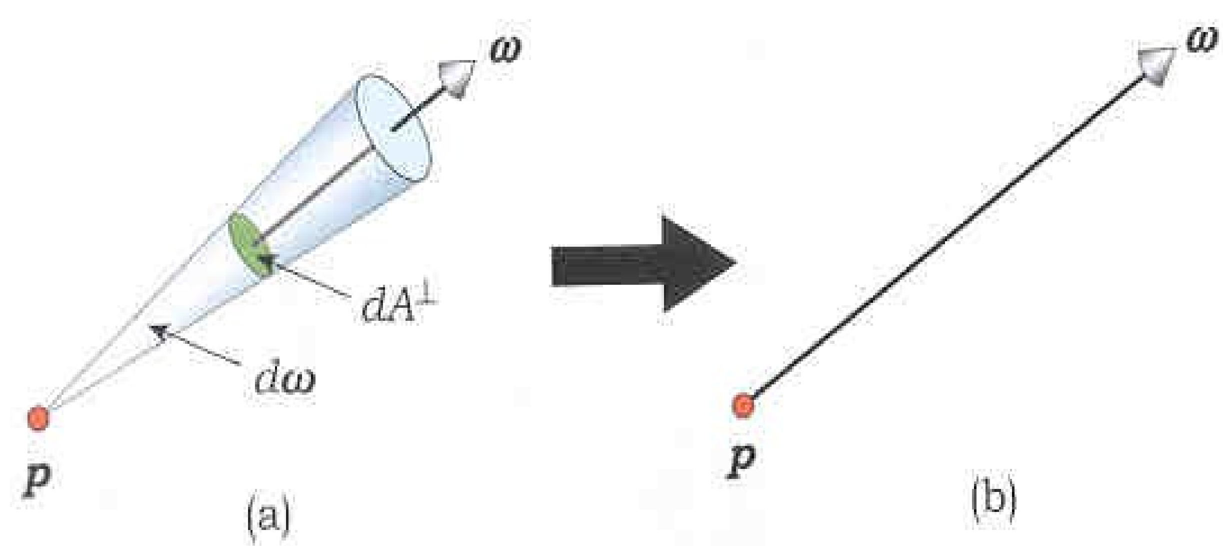



**Figure 13.1.** (a) Radiant flux in a cone of incident angles $d\omega$ passing through a surface element $dA^{\perp}$. (b) In the limit $d\omega \rightarrow 0$ and $dA \rightarrow 0$, the radiance is defined as coming from a single direction $\omega$. The point $p$ can be an arbitrary point in space.

# Angular Dependence on Irradiance

- Lambert's Law
  - $L = d^2\phi / dA \cdot d\omega \cdot \cos\theta$

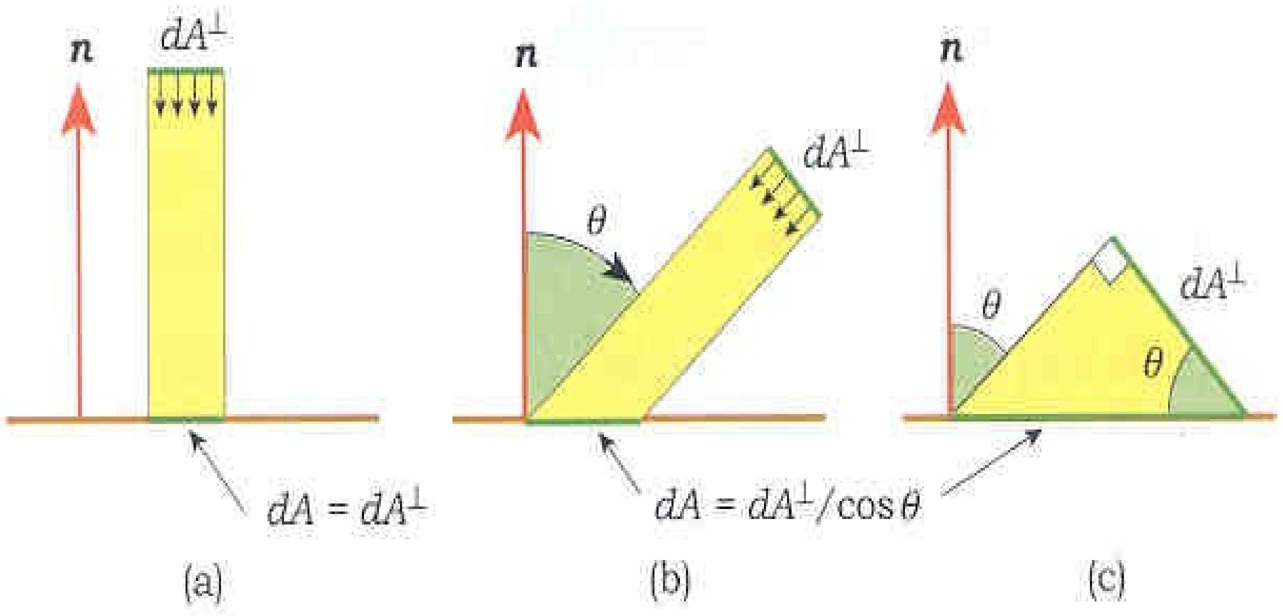



**Figure 13.2.** (a) and (b) Irradiance spreads out over a larger area as the incidence angle θ increases. (c) An enlarged view of the incident beam.

# Notation and Directions

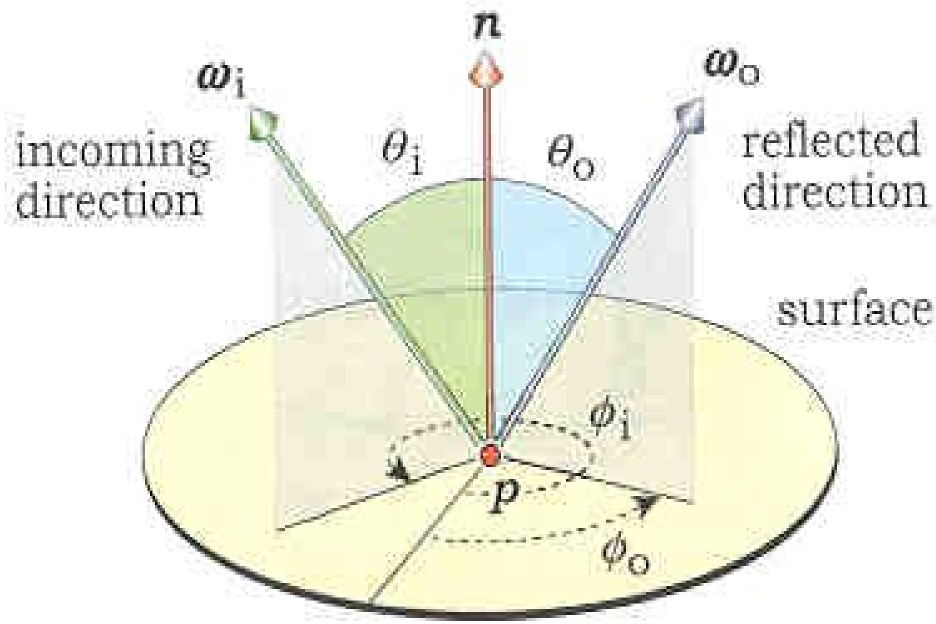



**Figure 13.3.** The incoming direction $\omega_i$ and reflected direction $\omega_o$ point away from the surface and are on the same side of the surface as the normal. Each direction is defined by its polar and azimuth angles $(\theta, \phi)$. These are arbitrary directions; for perfect mirror reflection, $\phi_o = \phi_i \pm \pi$, as illustrated in Figure 24.2(b).

# BRDF

- Definition
  - $f(p,\omega_i,\omega_o) = dL_o(p,\omega) / dL_i(p,\omega) \cos\theta_i \, d\omega_i$
- Properties
  - Reciprocity
    - $f(p,\omega_i,\omega_o) = f(p,\omega_o,\omega_i)$
  - Linearity
    - Sum all BDRFs at a point
  - Conservation of energy
    - Total re-radiated energy must be less than incident

# Common BDRFs

- Diffuse $f(p,\omega_i,\omega_o) = M_d(p)$

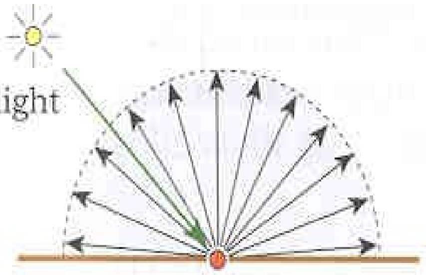



Figure 13.6. Light being scattered from a perfectly diffuse surface.

- Specular $f(p,\omega_i,\omega_o) = M_s(p)\ (R\bullet\omega_o)^S$
  - $R = 2(N\bullet L)N-L$

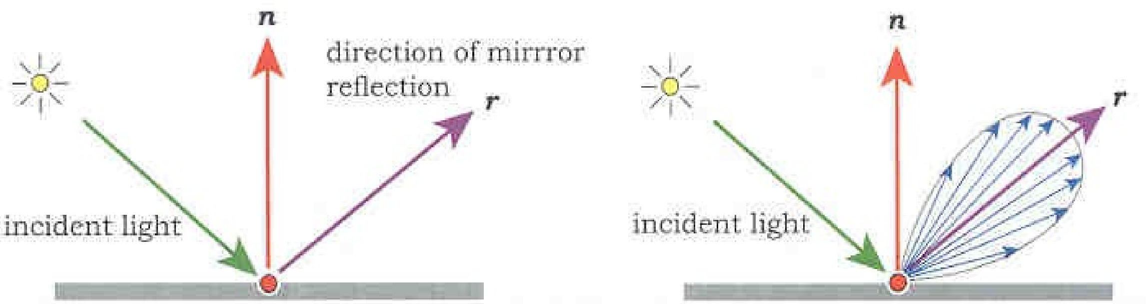



Figure 14.3. (a) Perfect specular reflection; (b) glossy specular reflection.

# Bouncing Rays from Surfaces

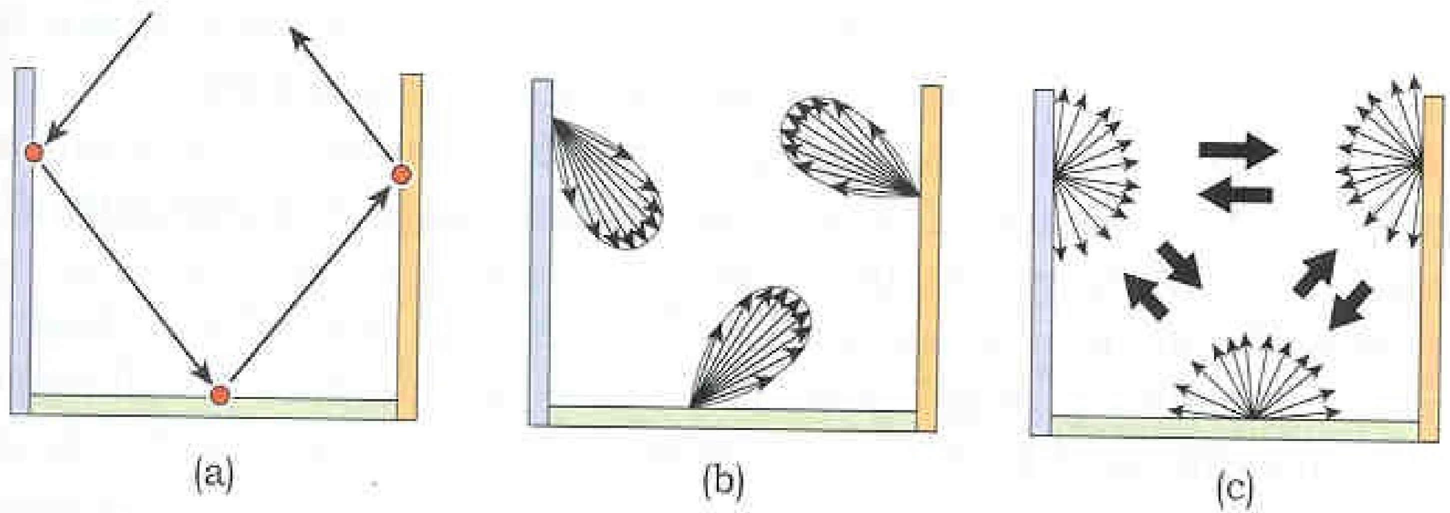



**Figure 14.4.** (a) Mirror reflection can be modeled by tracing a single reflected ray at each hit point; (b) modeling glossy specular light transport between surfaces requires many rays to be traced per pixel; (c) modeling perfect diffuse light transport between surfaces also requires many rays to be traced per pixel.

# Antialiasing


**Figure 4.4.** Shaded sphere: (a) one sample per pixel; (b) 16 samples per pixel; (c) enlarged view of top-right section of (b).

# Super-sampling Pixels

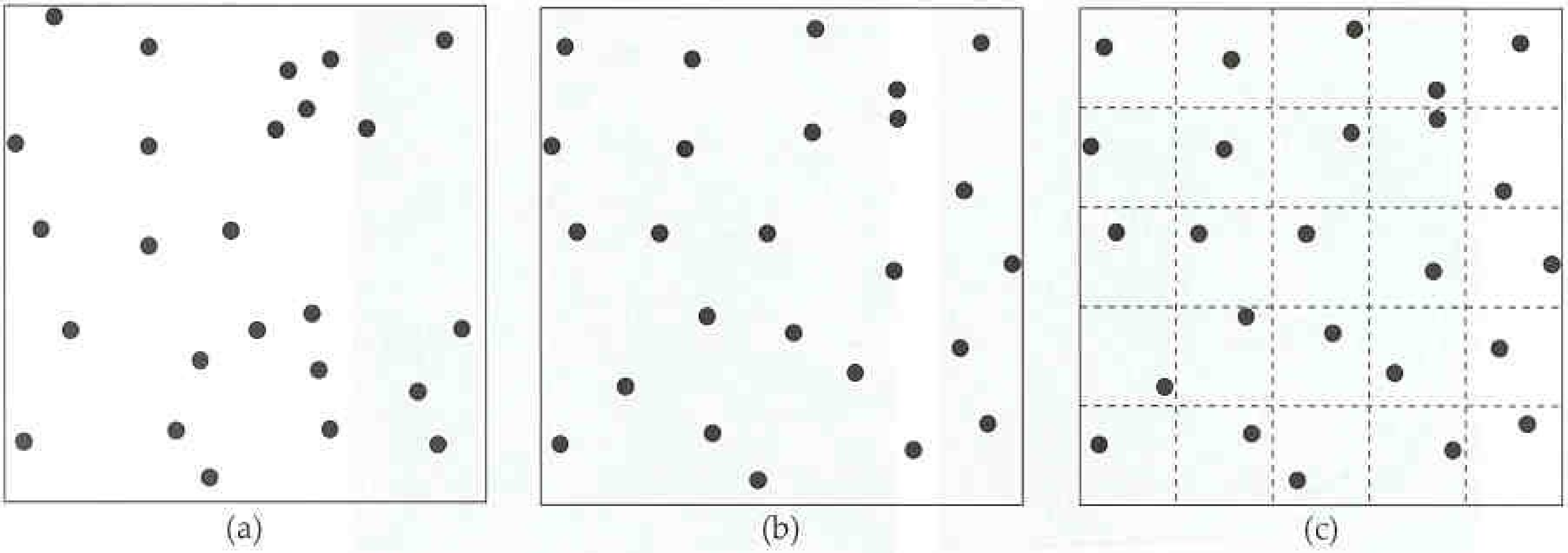



**Figure 4.7.** (a) 25 random samples in a pixel; (b) 25 jittered samples; (c) same as (b) but with sub-grid lines shown.

# Super-sampling Area Lights

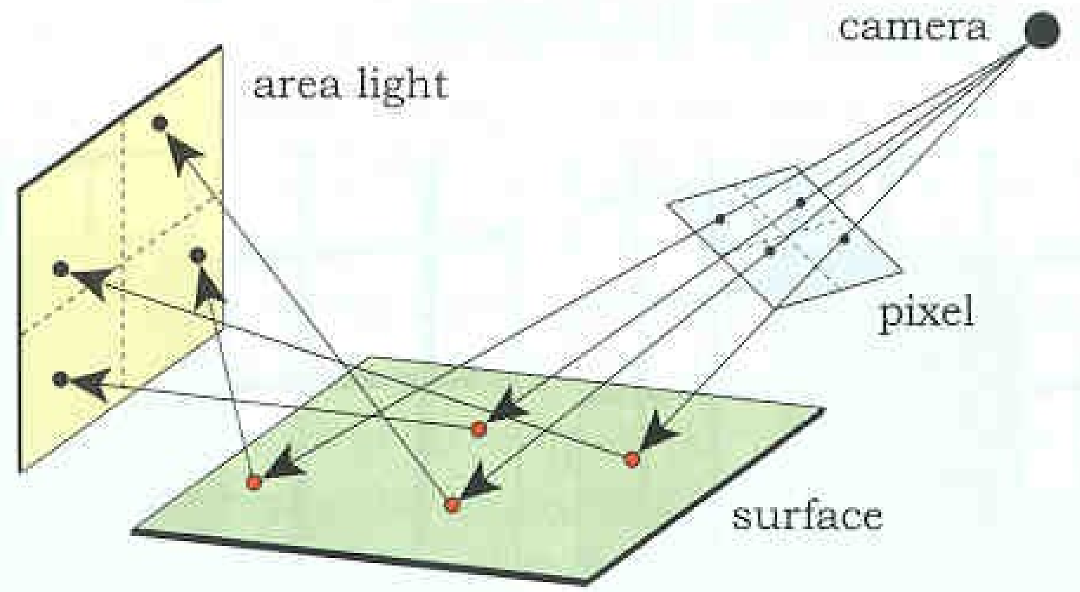



**Figure 5.2.** Shading a surface with an area light and four samples per pixel.

# Side-effects of Sampling Pattern

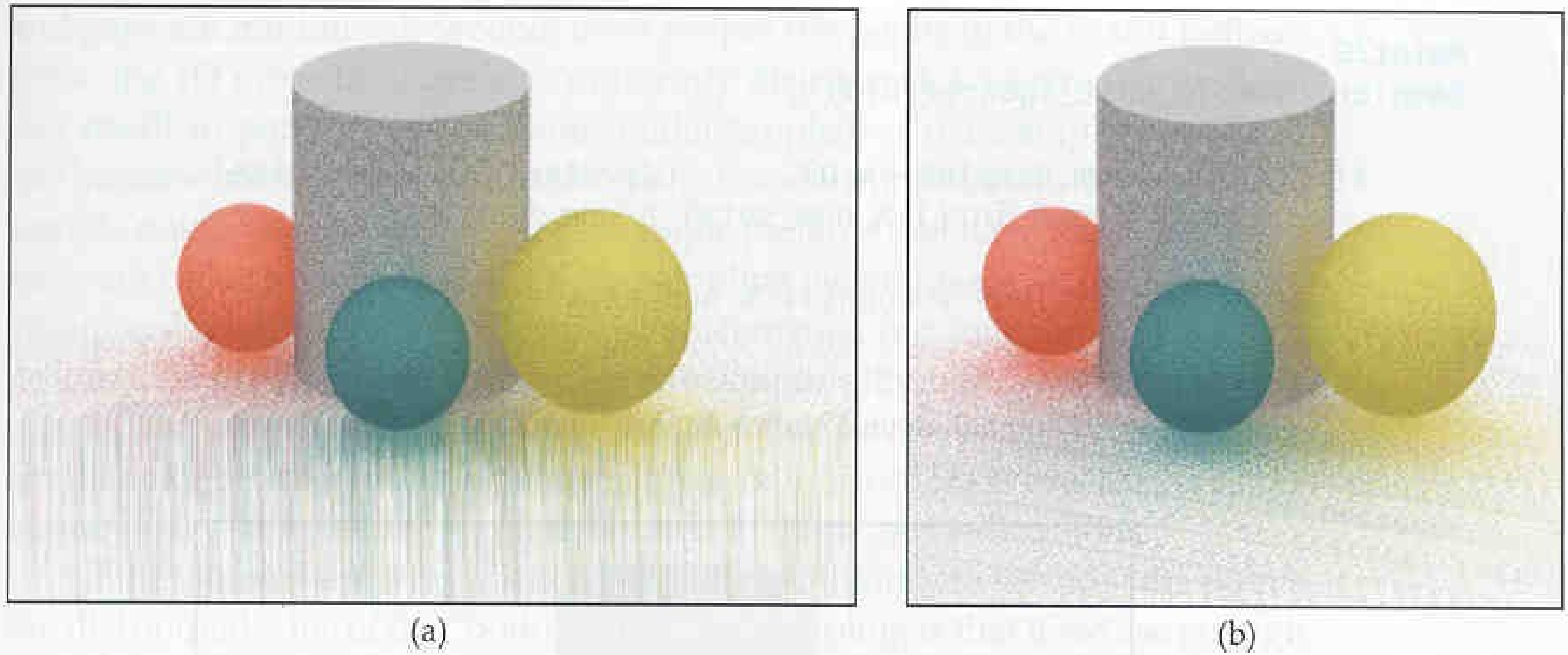



**Figure 5.6.** Global illumination images that exhibit bad aliasing caused by using the same samples in vertical columns (a) and in a regular horizontal displacement (b).

# Depth of Field

- Important for realism
  - Background is “fuzzy”
- Partly out of focus
  - Imperfect optics
  - Turbulence
- Graphic backgrounds are often too perfect

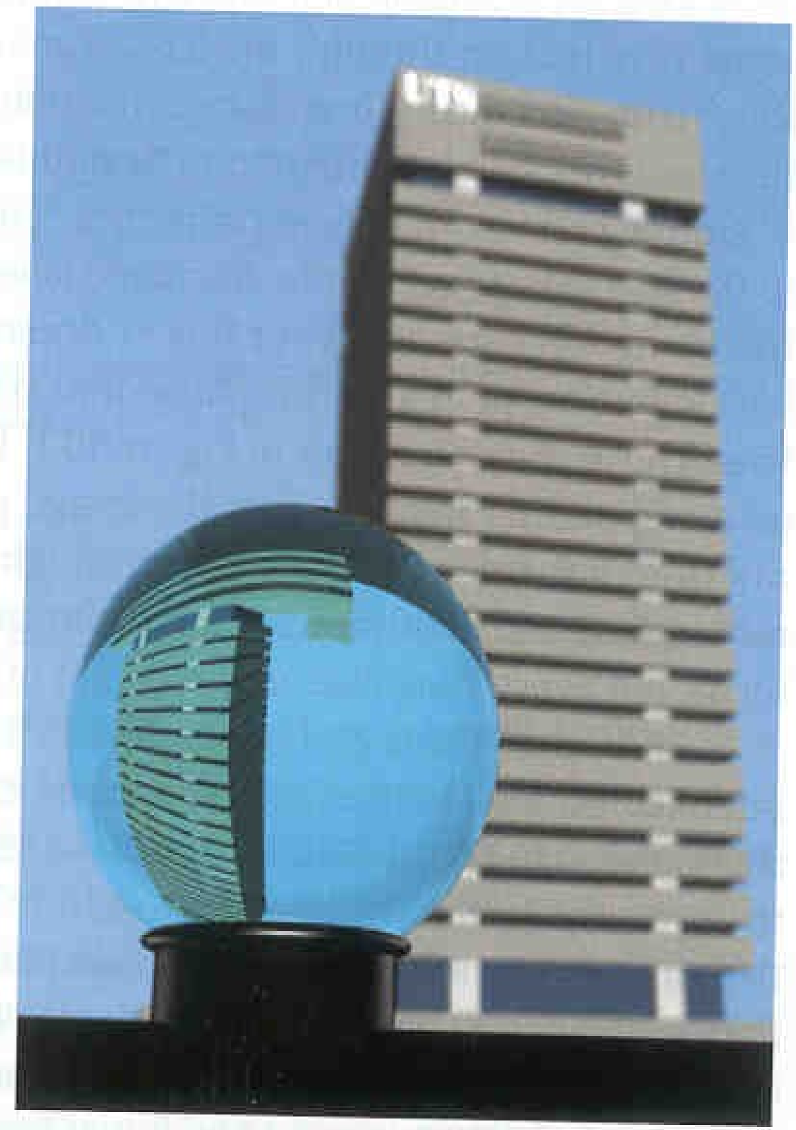


Image courtesy of Tania Humphreys

# Thin Lens Theory

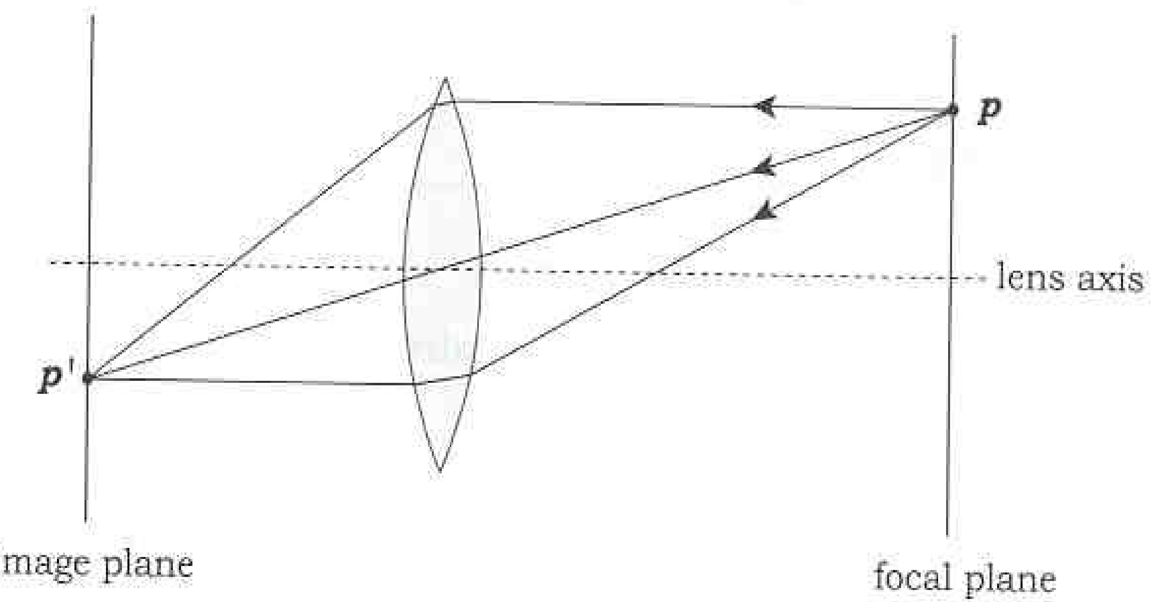



Figure 10.1. Cross section through a thin lens showing a focal plane and its corresponding image plane.

# Out of Focus Images

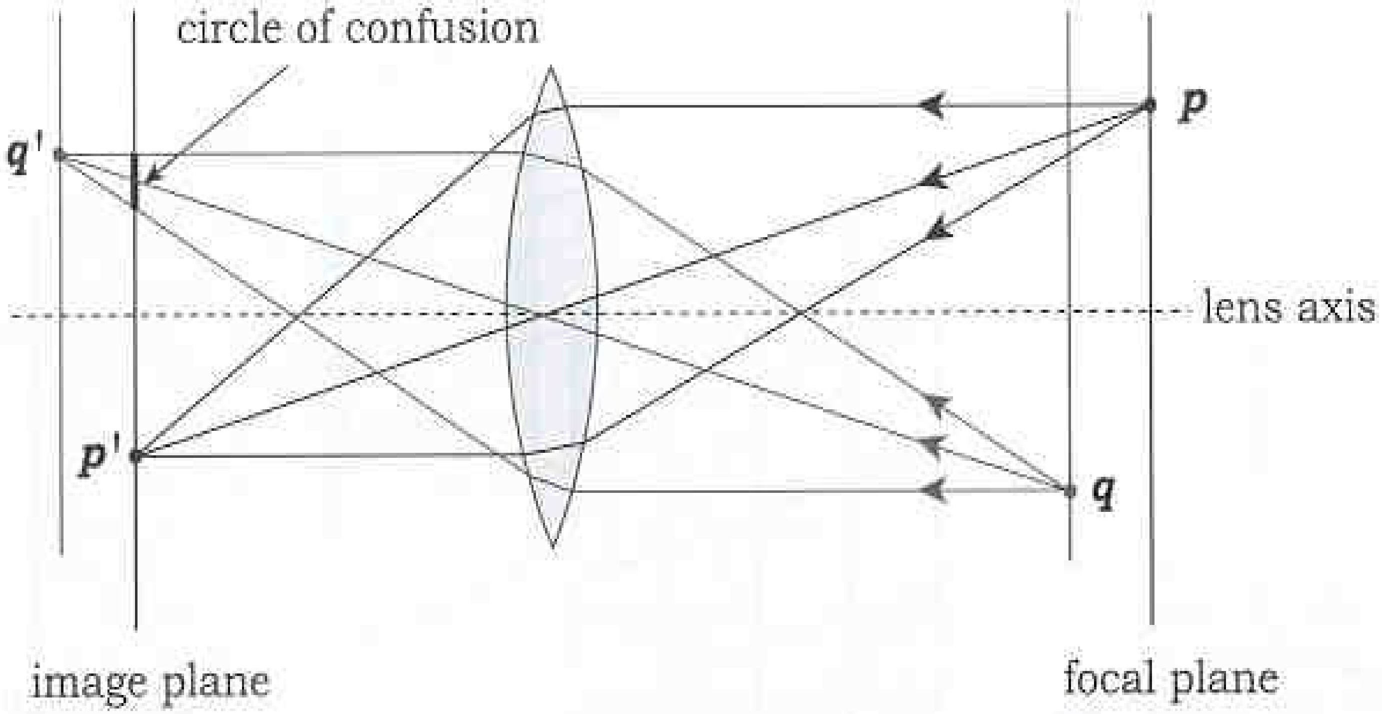
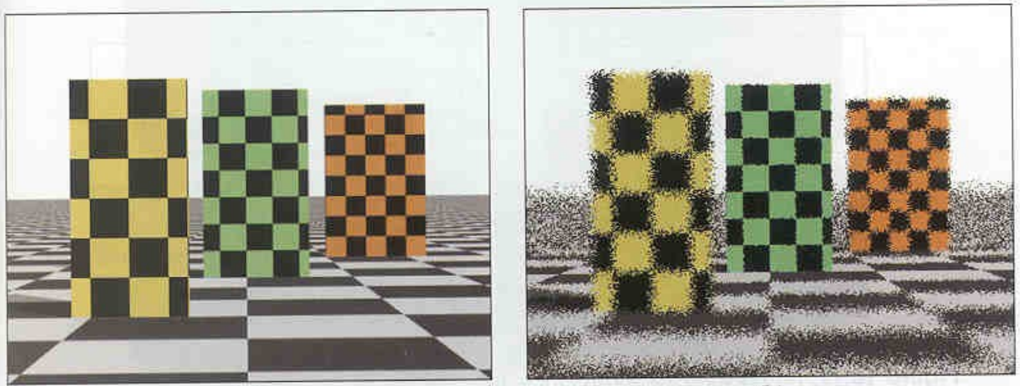



**Figure 10.2.** Rays starting a point $q$ go through the image plane of $p$ at different locations, with the result that $q$ will appear out of focus.

# Depth of Field Results



(a) (b)

**Figure 10.9.** (a) When the lens radius is zero, the image is the same as a pinhole-camera image with everything in focus; (b) noisy image from using one random sample per pixel.

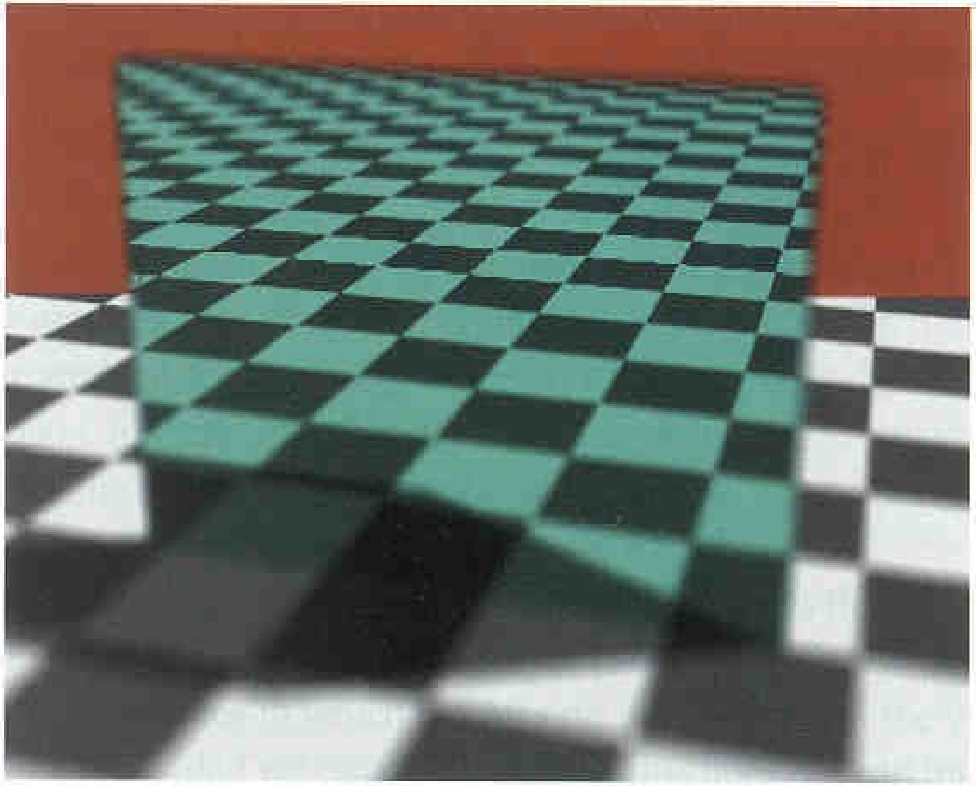


**Figure 10.12.** Mirrored surface.

# Ambient Occlusion

- Floor has a vague shadow outline
- Parts of object near floor is darker
- Ambient light is not anisotropic and uniform

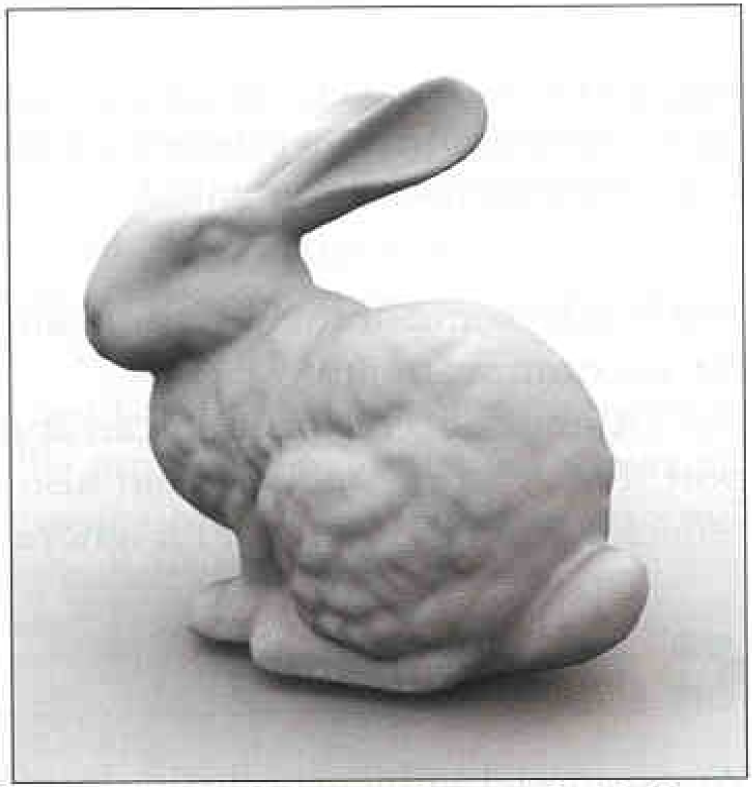


Image courtesy of Mark Howard, Stanford bunny model courtesy of Greg Turk and the Stanford University Graphics Laboratory

# Computing Ambient Occlusion

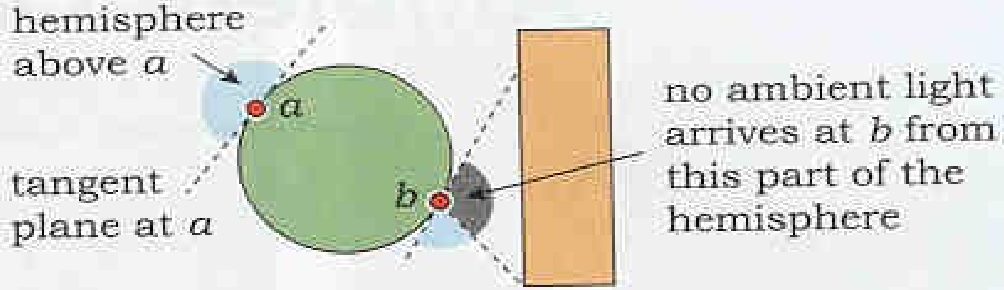



**Figure 17.1.** Point *a* on the sphere receives the maximum amount of ambient light because the box isn't visible; point *b* doesn't receive the maximum amount because the box blocks some of the incoming ambient light.

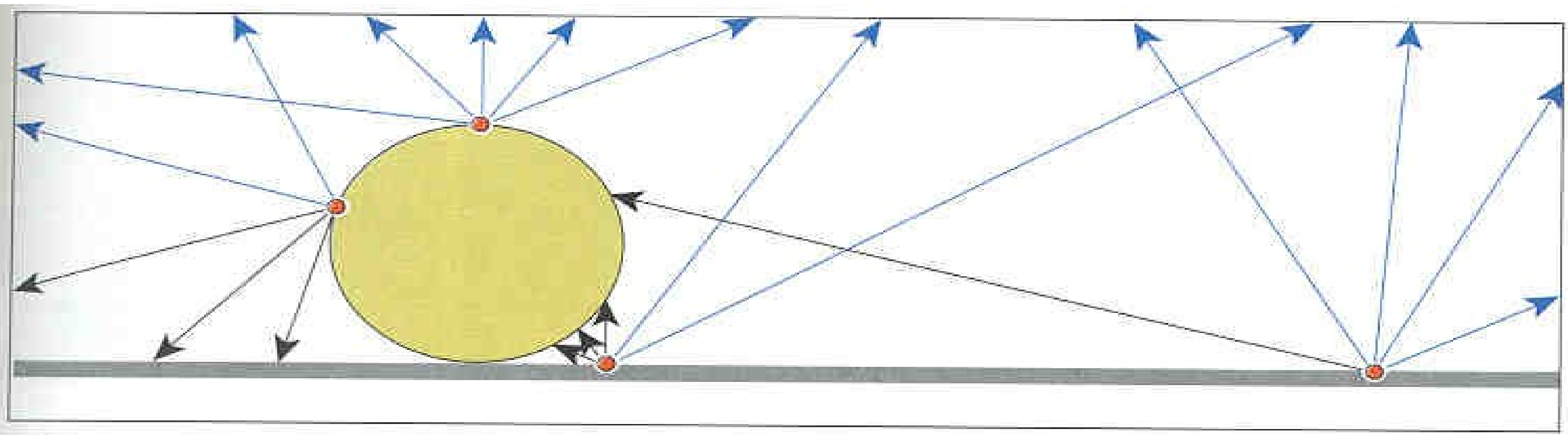


**Figure 17.2.** Various hit points on the plane and the sphere, with sample shadow rays.

# Ambient Occlusion Results

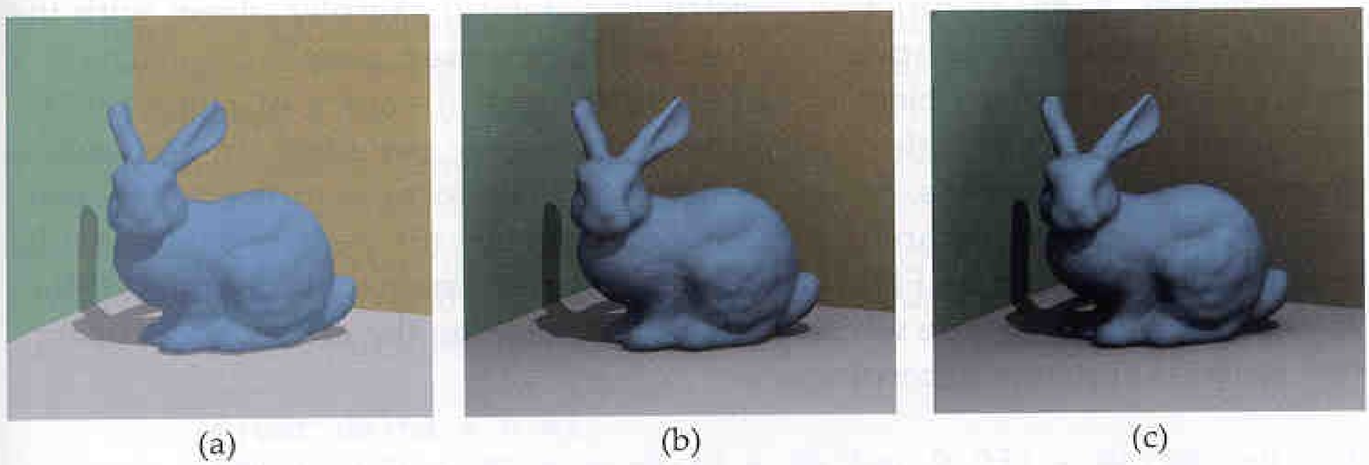



**Figure 17.12.** Bunny scene rendered with 256 samples per pixel: (a) `min_amount = 1`; (b) `min_amount = 0.25`; (c) `min_amount = 0`.

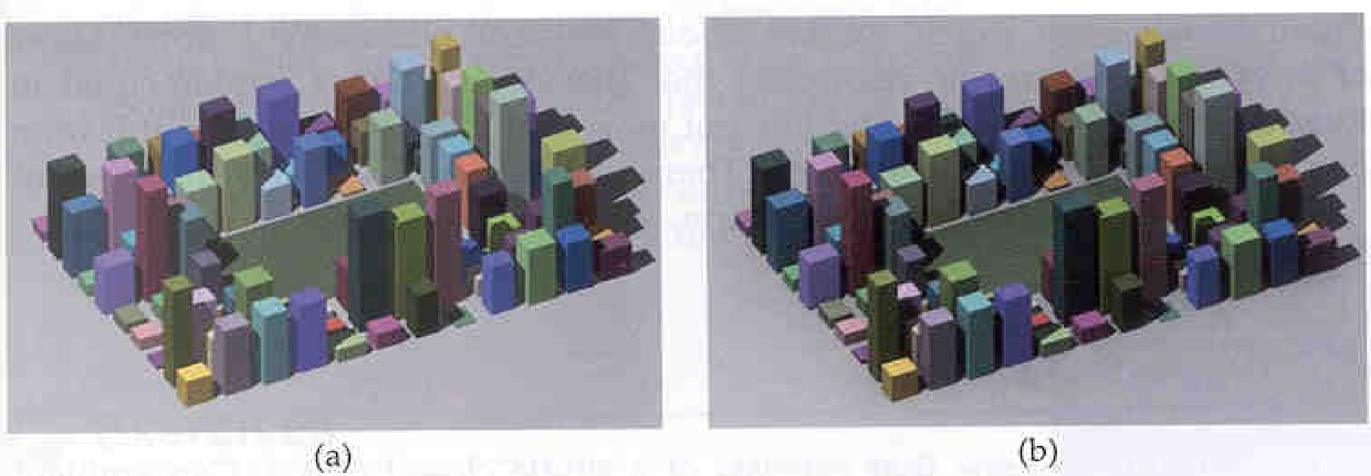



**Figure 17.13.** Random boxes rendered with 64 samples per pixel: (a) `min_amount = 1.0`; (b) `min_amount = 0.25`.

# Mirror Reflection

- Mirror reflections are a signature of ray tracing
  - Shiny objects
    - Glass
    - Metal
  - Multiple reflections may occur
- Occurs naturally in ray tracing
- Requires tracing ray through multiple bounces
- Adds significant effort

Reflective spheres by Burt Flugleman, Rundle Street Mall, Adelaide. Photograph by Kevin Suffern.

# Conservation of Energy

- Mirrors reflect almost all the energy
- Retains beam geometry

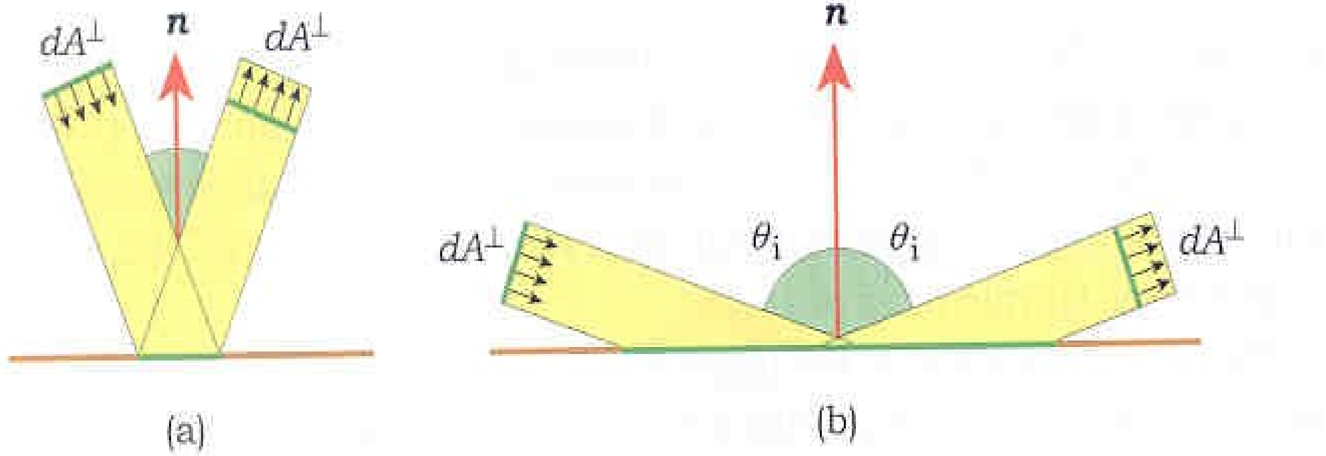
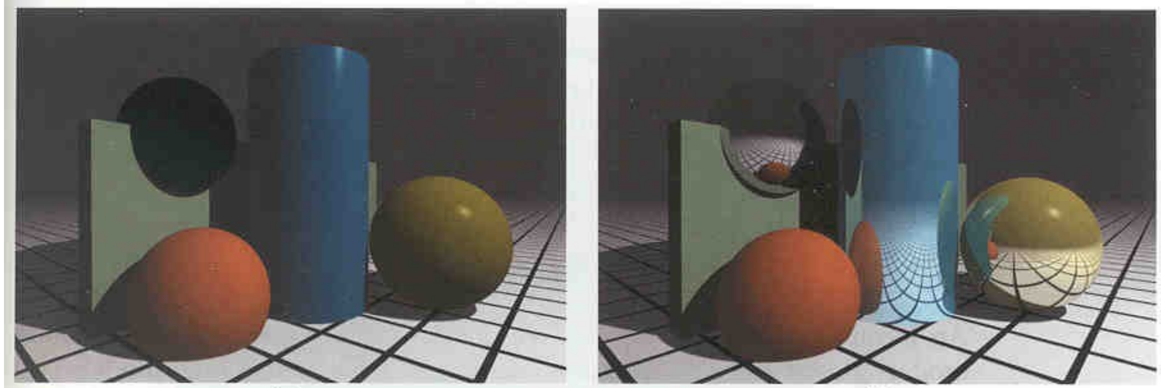



Figure 24.3. When a beam of light is reflected from a perfect mirror, its cross section area is unchanged after reflection and is therefore independent of the angle of incidence $\theta_i$.

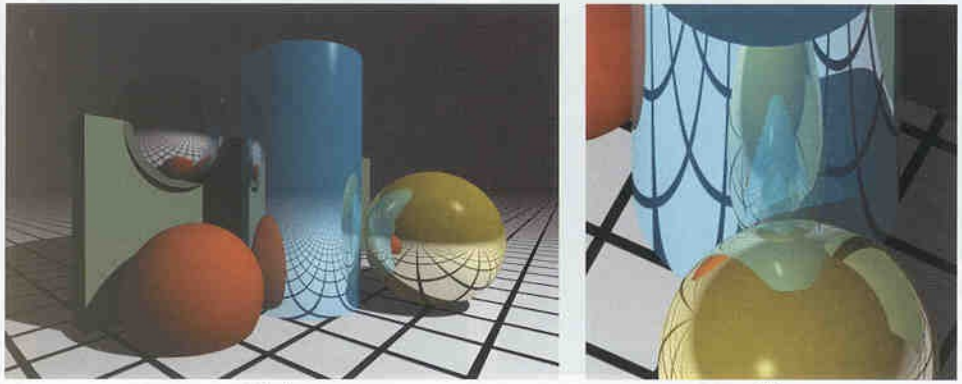
# Number of Reflections

- 0 dull
- 1 “simple” mirror
- >1 “hall of mirrors”
- Effort grows with number of bounces



(a) (b)

**Figure 24.6.** A scene rendered with `max_depth` = 0 (a) and `max_depth` = 1 (b).



(a) (b)

**Figure 24.7.** (a) The scene from Figure 24.6 rendered with `max_depth` = 10; (b) close-up view of the yellow-green sphere and the cylinder from a different viewpoint than in (a).

# Hall of Mirrors
(Showcases Ray Tracing)

(a) (b)

**Figure 24.18.** (a) Hall of mirrors with `max_depth` = 19; (b) close-up view of the multiple reflections between the floor mirror and the sphere.

# Mirror vs Glossy Reflection

- Mirror reflections are "perfect"
- Glossy reflections are "imperfect"
  - Reflected ray = 2(N•V)N – V + $\varepsilon$
  - Super-sample for many values of $\varepsilon$

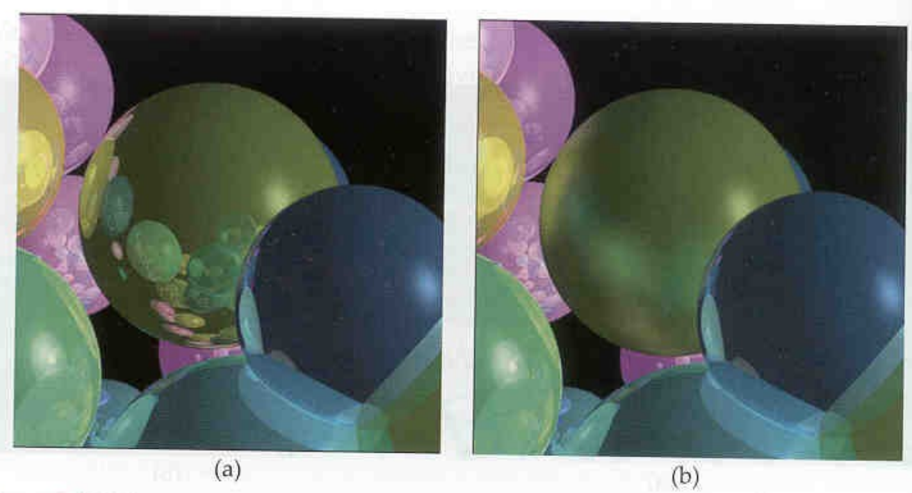



**Figure 24.8.** The green sphere has glossy specular highlights and perfect mirror reflections (a) and glossy reflections (b).

# Degrees of perfection

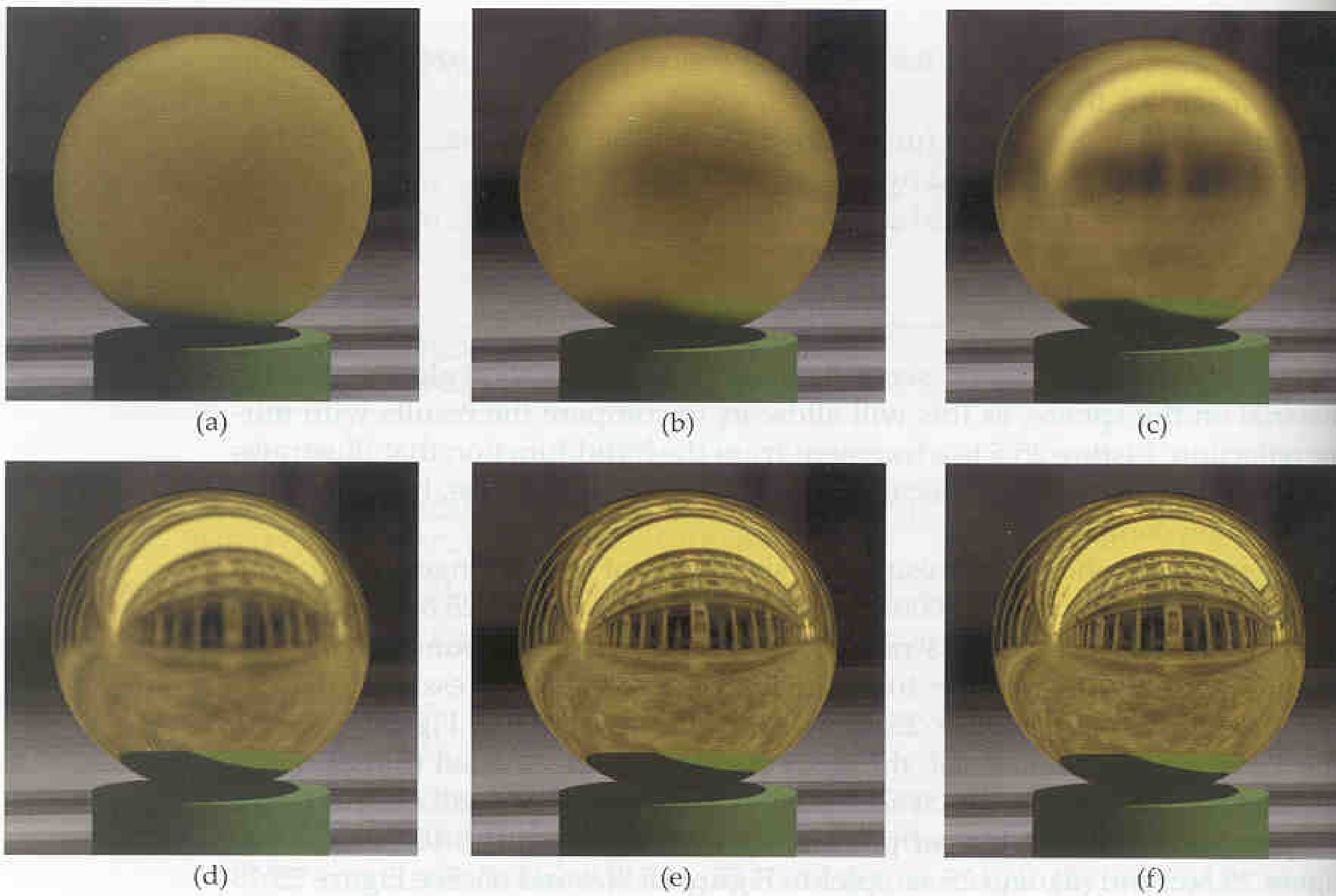



**Figure 25.8.** Glossy sphere surrounded by the Uffizi image and rendered with the following values of $e$: (a) 1.0; (b) 10.0; (c) 100.0; (d) 1000.0; (e) 10000.0; (f) 100000.0.

# Simple Transparency

- Light passes through objects
- Light changes through object
  - Rays are bent
  - Colors are changed
- Rays multiply
  - Reflected
  - Transmitted


Photograph courtesy of Steve Agland

# Refraction

- Index of refraction $\eta = c/v$
  - Vacuum 1
  - Air 1.0003
  - Water 1.33
  - Glass 1.5
  - Diamond 2.42
- Snell's law
  - $\sin\theta_i / \sin\theta_t = \eta$

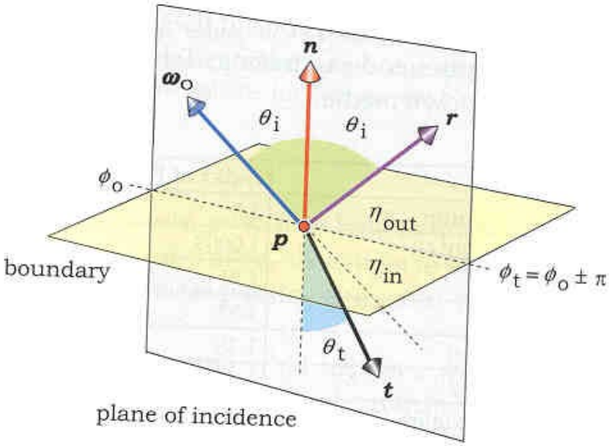



Figure 27.2. Reflected and transmitted rays at the boundary between two transparent media.

# Media Transitions

- Direction of bend depends on whether the refrection index increases or decreases
  - Air η is very low
  - Angles decrease into liquids
  - Angles increase out of liquids

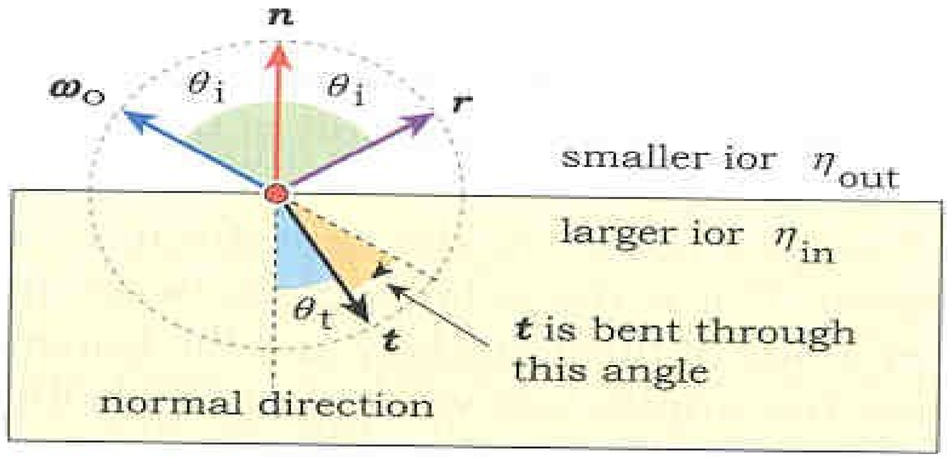



Figure 27.3. Direction change of $t$ when $\eta > 1$.

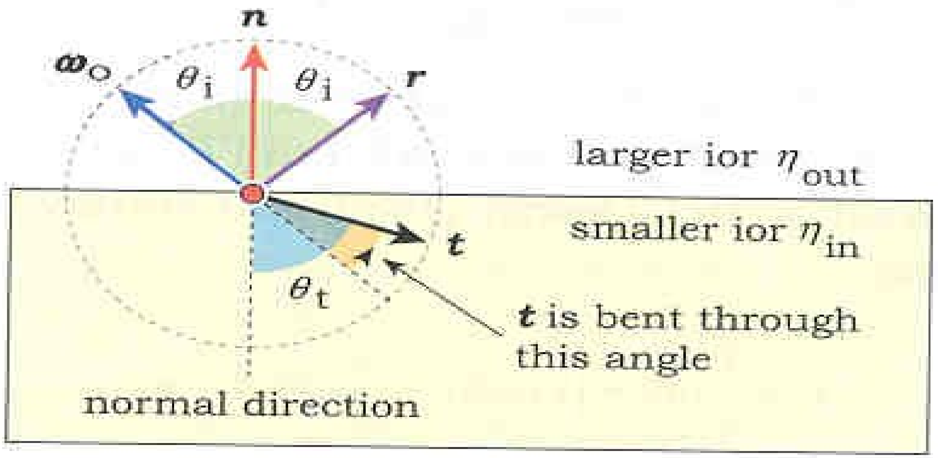



Figure 27.4. Direction change of $t$ when $\eta < 1$.

# Internal reflections

- Critical angle
  - Refraction bends ray back into medium
- Higher η contrast causes larger critical angle
  - That is why diamonds are so sparkly

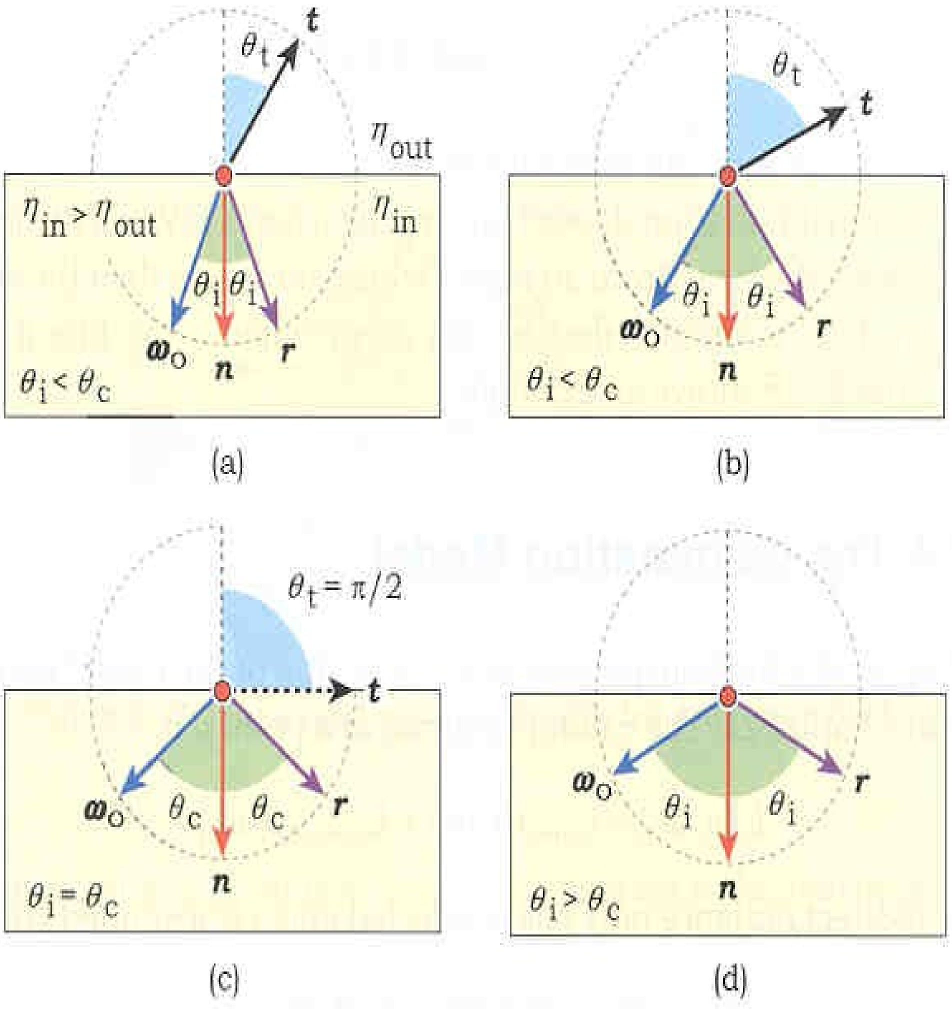



**Figure 27.5.** Total internal reflection: (a) and (b) $\theta_i < \theta_c$; (c) $\theta_i = \theta_c$; (d) $\theta_i > \theta_c$.

# Transparency require bifurcating rays

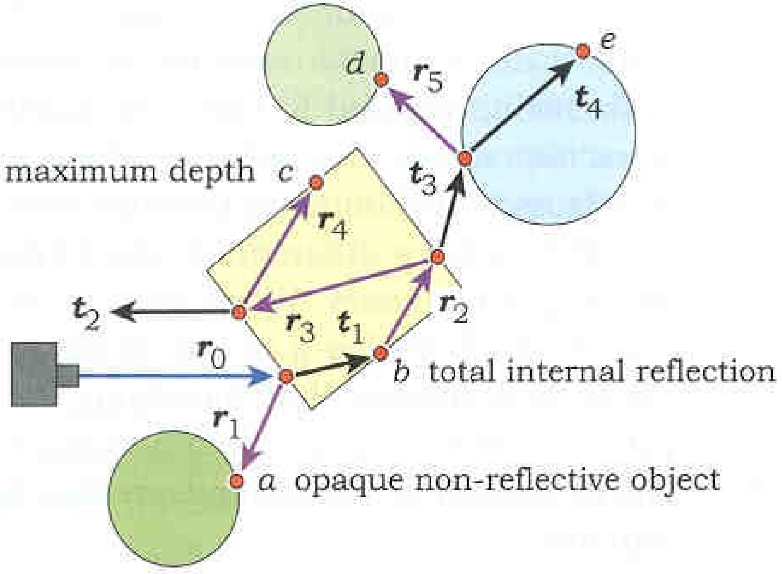



Figure 27.6. Transparent objects with reflected and transmitted rays.

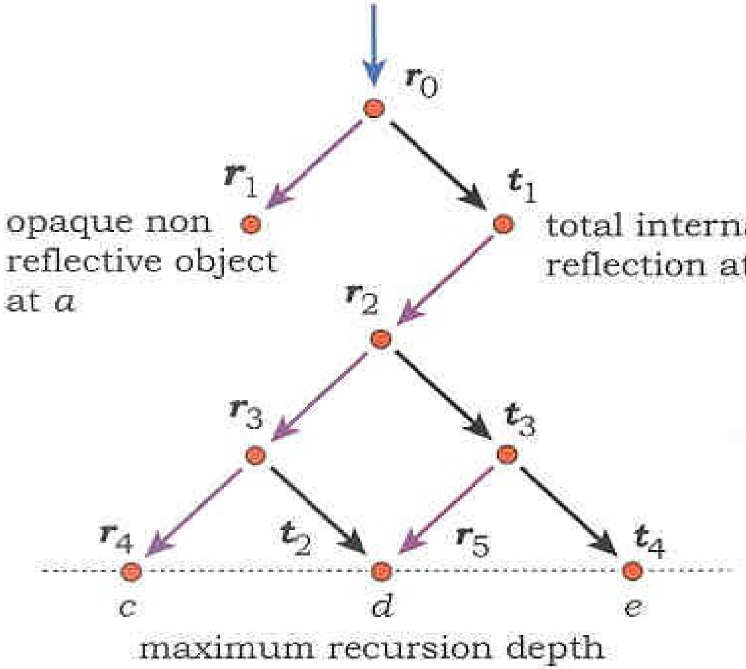



Figure 27.7. The ray tree that corresponds to Figure 27.6.

# Objects Appearance

- Object inside other material
  - Objects are magnified when not viewed parallel to the normal
  - Object's apparent position is displaced
- Objects on other side
  - Objects apparent position is displaced

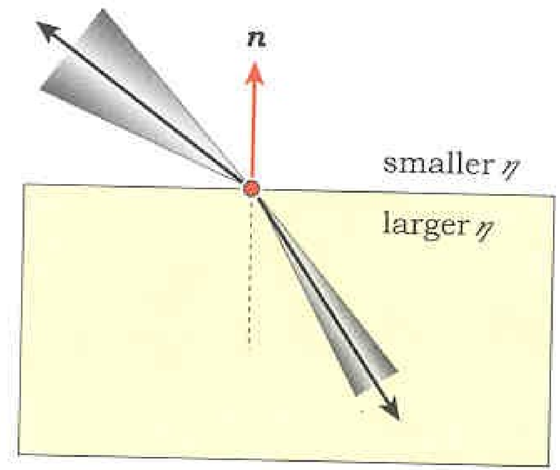



**Figure 27.8.** The angle of a differential cone of incident radiance changes as it crosses the boundary between two dielectrics.

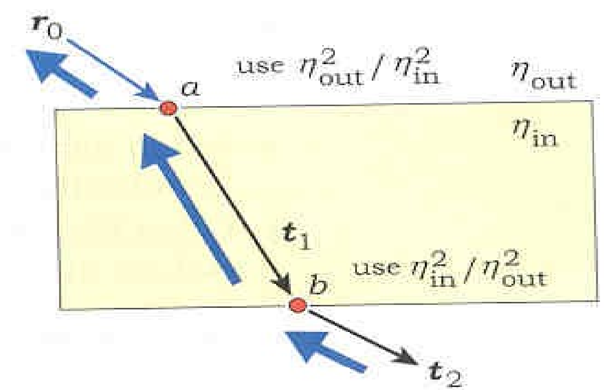


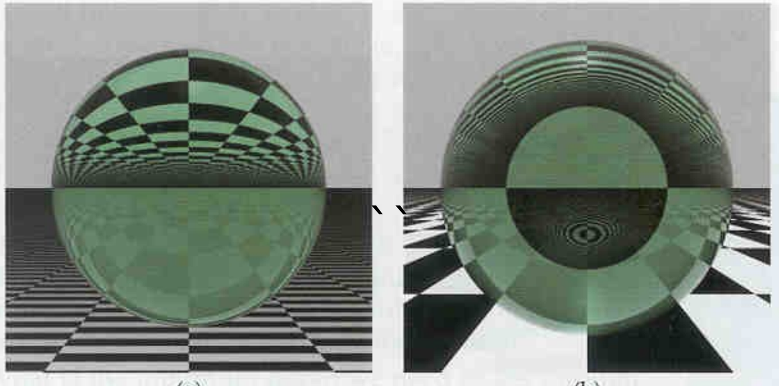

**Figure 27.9.** Ray and radiance-transfer directions through a transparent object.

# Distortion by Glass Spheres

- Sphere as a lens


Figure 27.22. Transparent sphere in front of text.

- Eye position is critical



(a) (b)

Figure 27.23. A transparent sphere with the camera far from the sphere (a) and close to the sphere (b).

# Light movement through sphere

- Magnification

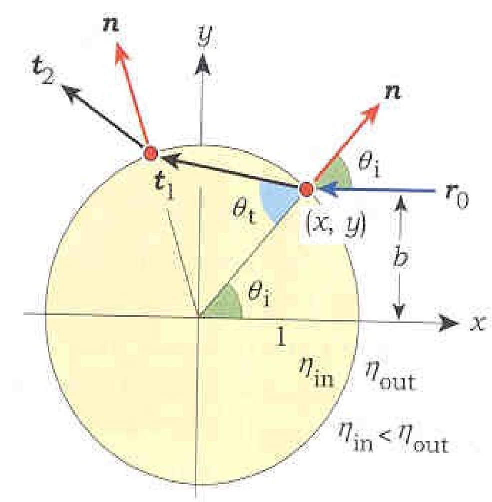



Figure 27.17. Reflected and transmitted rays generated by a ray $r_0$ that hits a unit sphere with impact parameter $b$, where the sphere has $\eta < 1$.

- Internal reflection

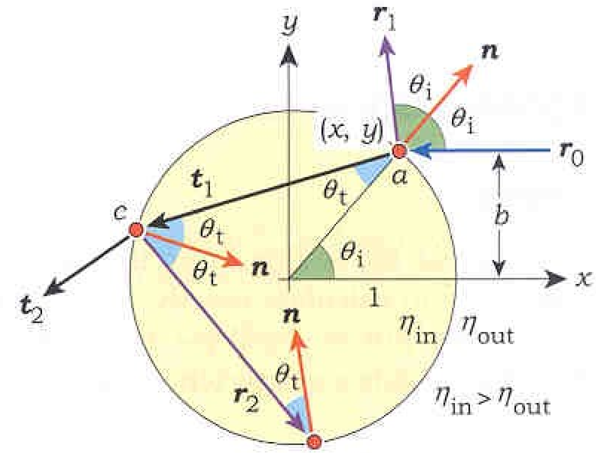



Figure 27.11. Reflected and transmitted rays generated by a ray $r_0$ that hits a unit sphere with impact parameter $b$. The lengths of the (unit) normals and the sphere are not drawn on the same scale.

# Realistic Transparency

- Three η's
  - Air
  - Glass
  - Water
- Colored liquid
- Beveled edges
  - Glass
  - Meniscus
- Mixed transparency
  - Foam is opaque

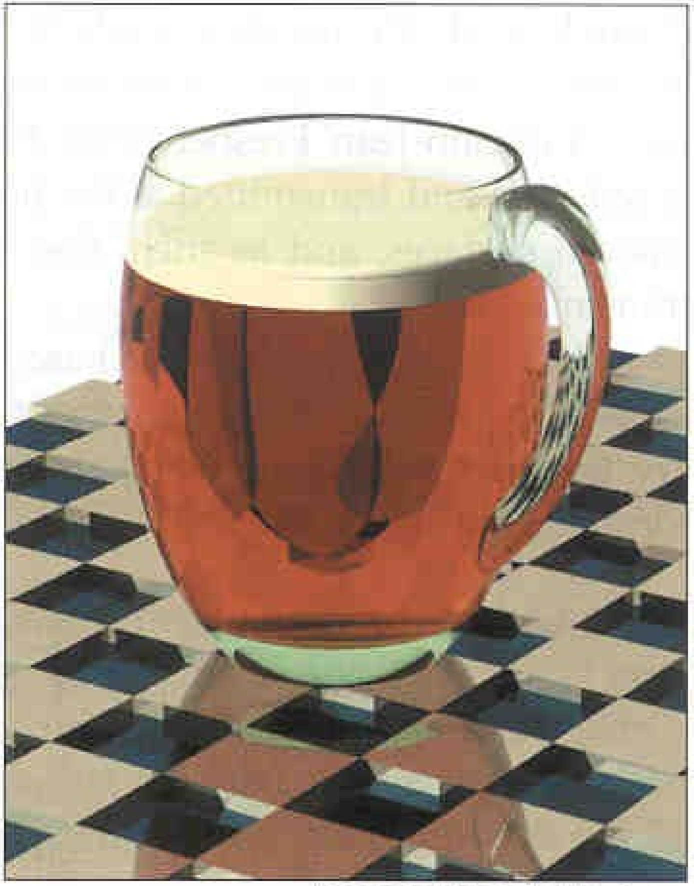


Image courtesy of John Avery

# Reflectance and Attenuation

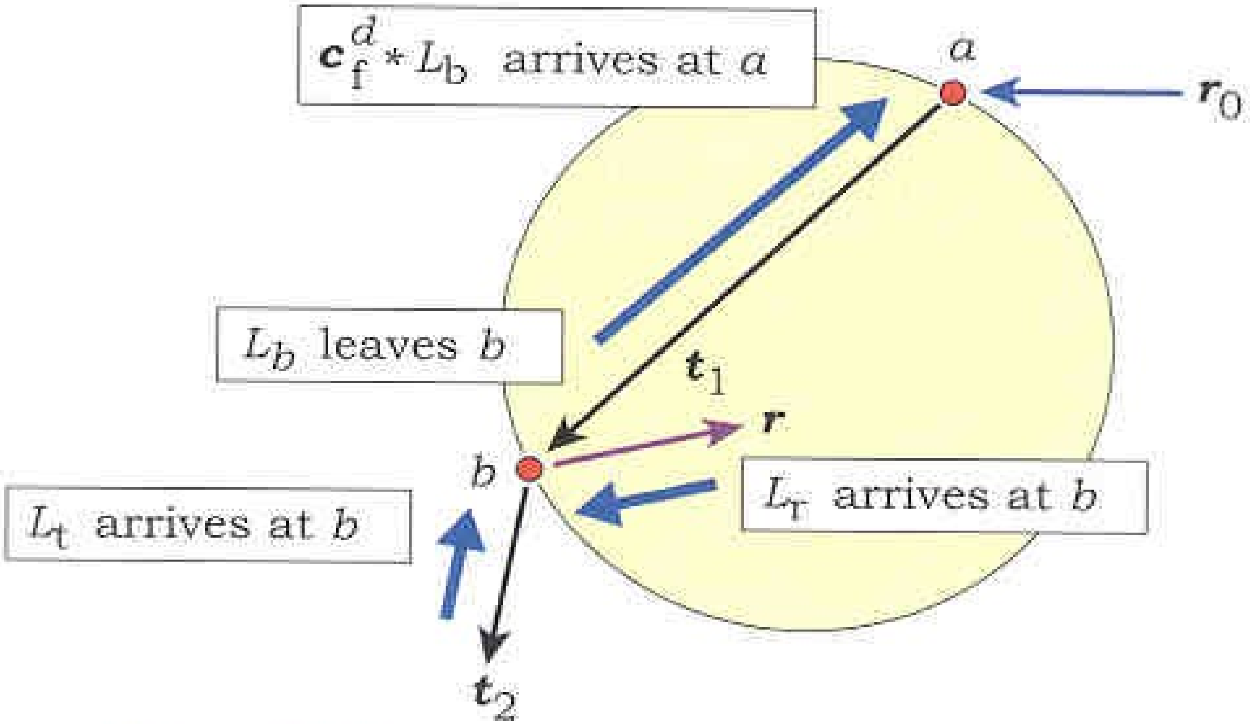



**Figure 28.4.** Radiance attenuation in a dielectric.

# Multiple Internal Reflections

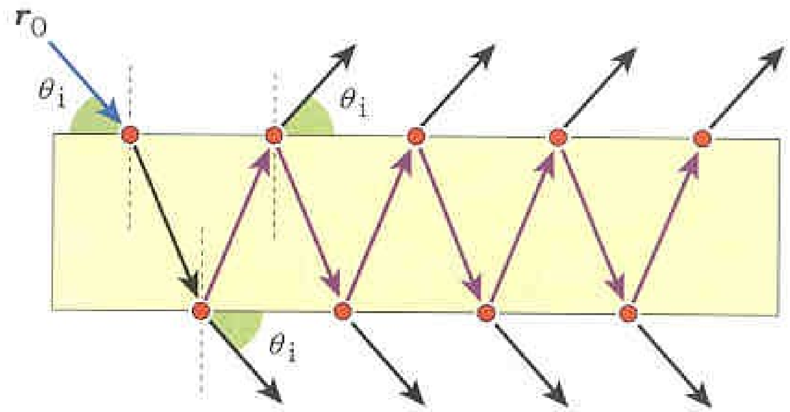



**Figure 28.19.** A transparent box with multiple reflected and transmitted rays.

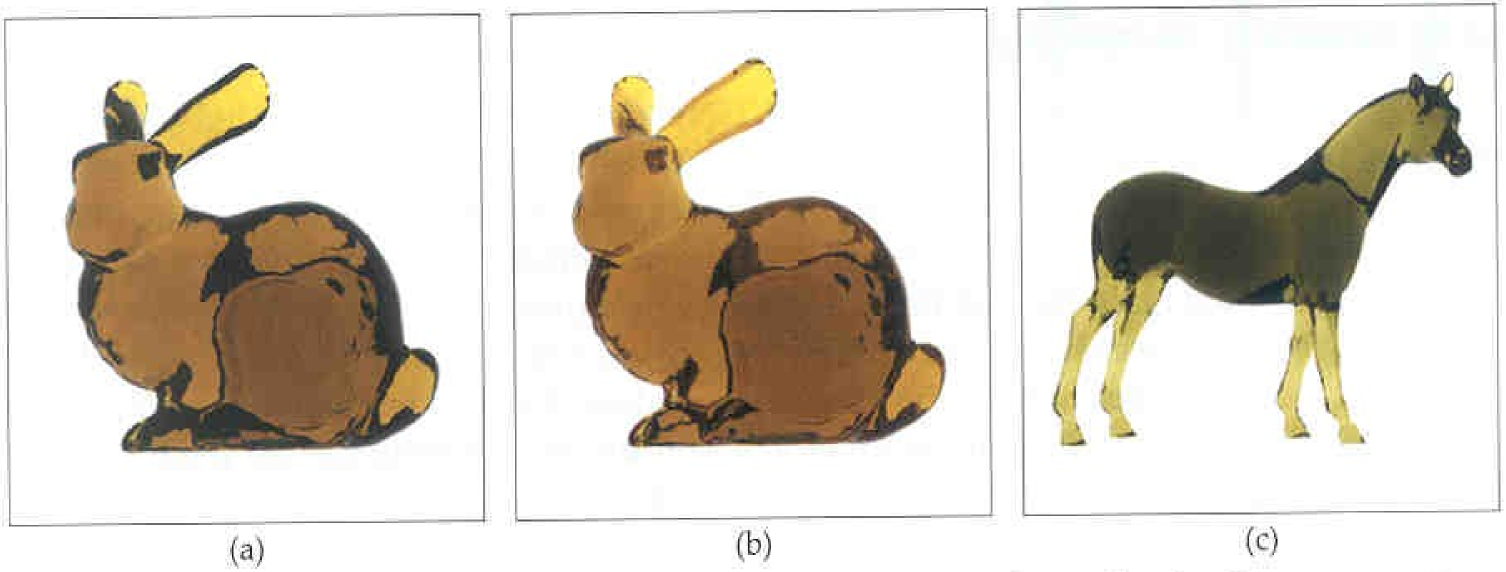



**Figure 28.12.** (a) Stanford bunny rendered with $c_f$ = (0.65, 0.45, 0) and max_depth = 2; (b) max_depth = 10; (c) horse model rendered with $c_f$ = (0.65, 0.65, 0.1) and max_depth = 10.

# Colored Beaker

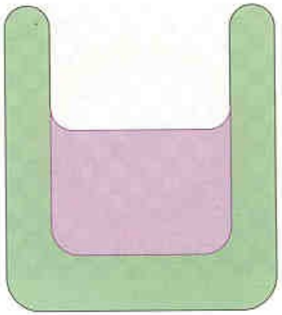
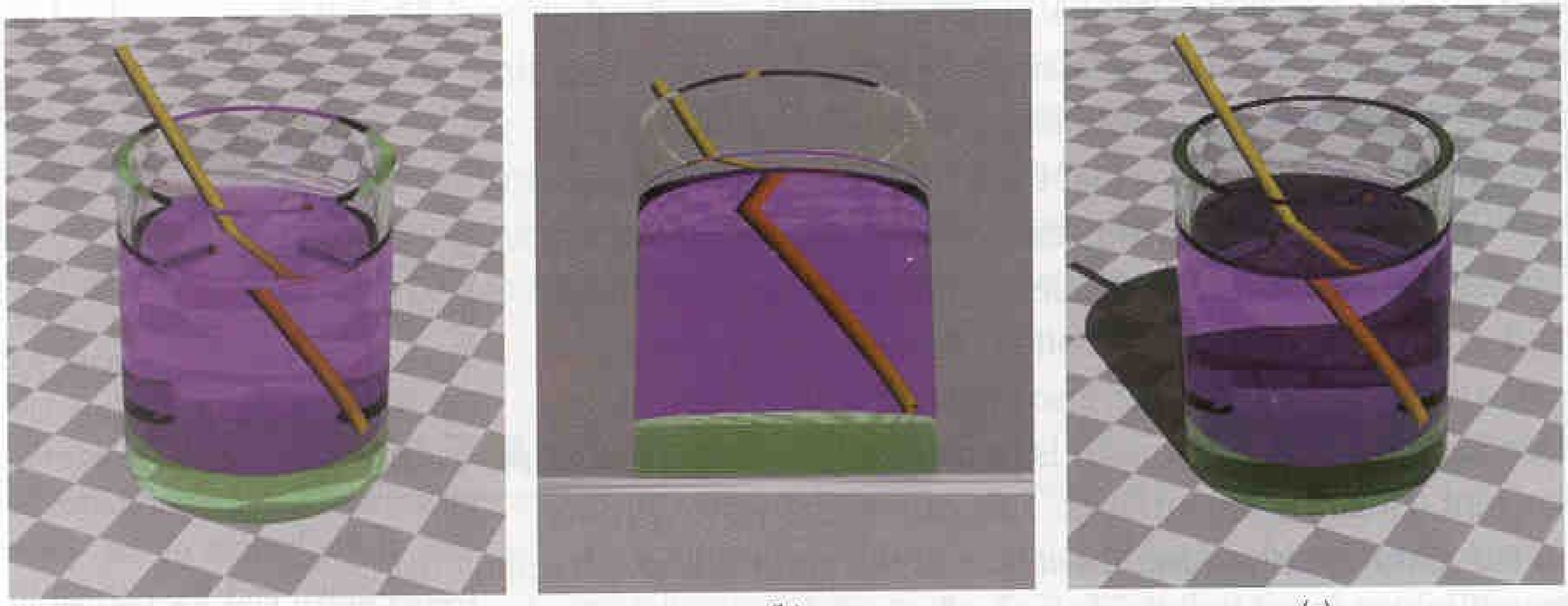


Figure 28.37. A more sophisticated glass of water has a curved top, rounded edges, and a meniscus for the water.



(a) (b) (c)

Figure 28.38. Glass of water and straw rendered with: (a) no shadows; (b) camera looking up; (c) shadows and direct illumination on the straw.

# The Fish Bowl

- Making it real
  - Complex shape
  - Three media
  - Colored media
  - Beveled edges
- Challenges
  - Multiple reflections
  - Refraction

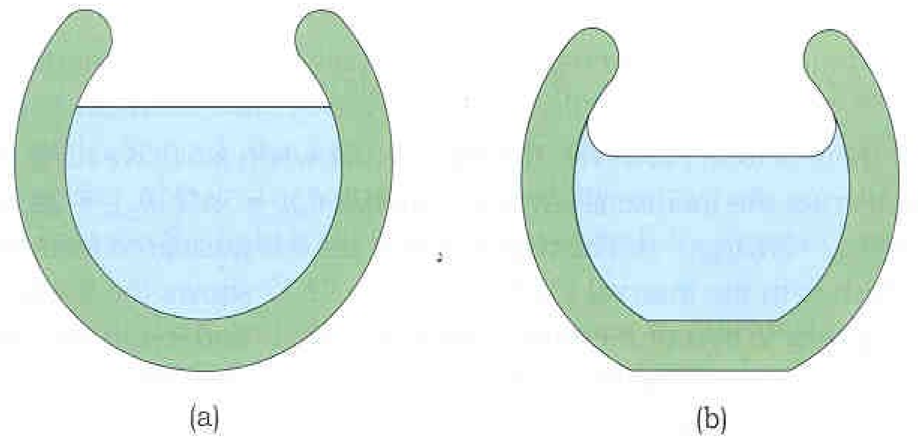


**Figure 28.39.** (a) Basic fishbowl; (b) fishbowl with flat base and meniscus.

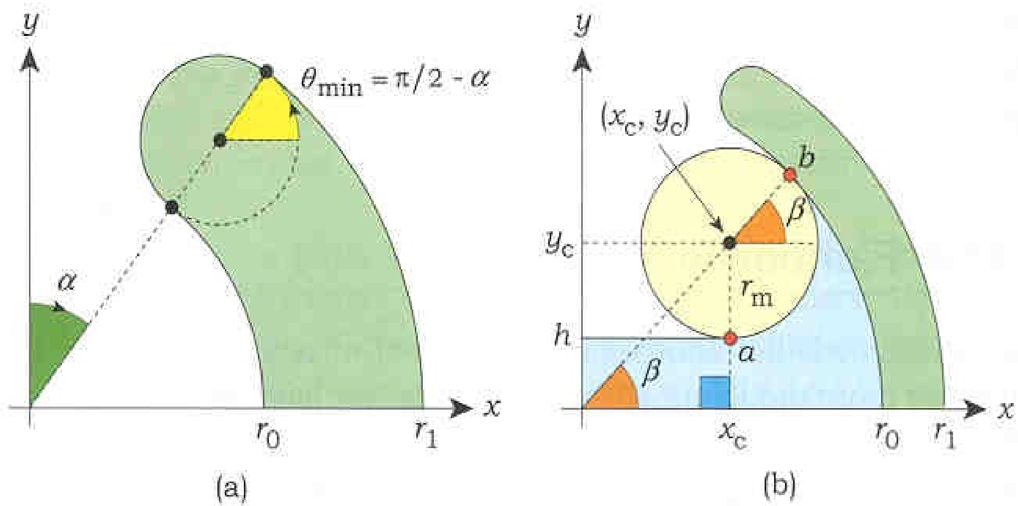
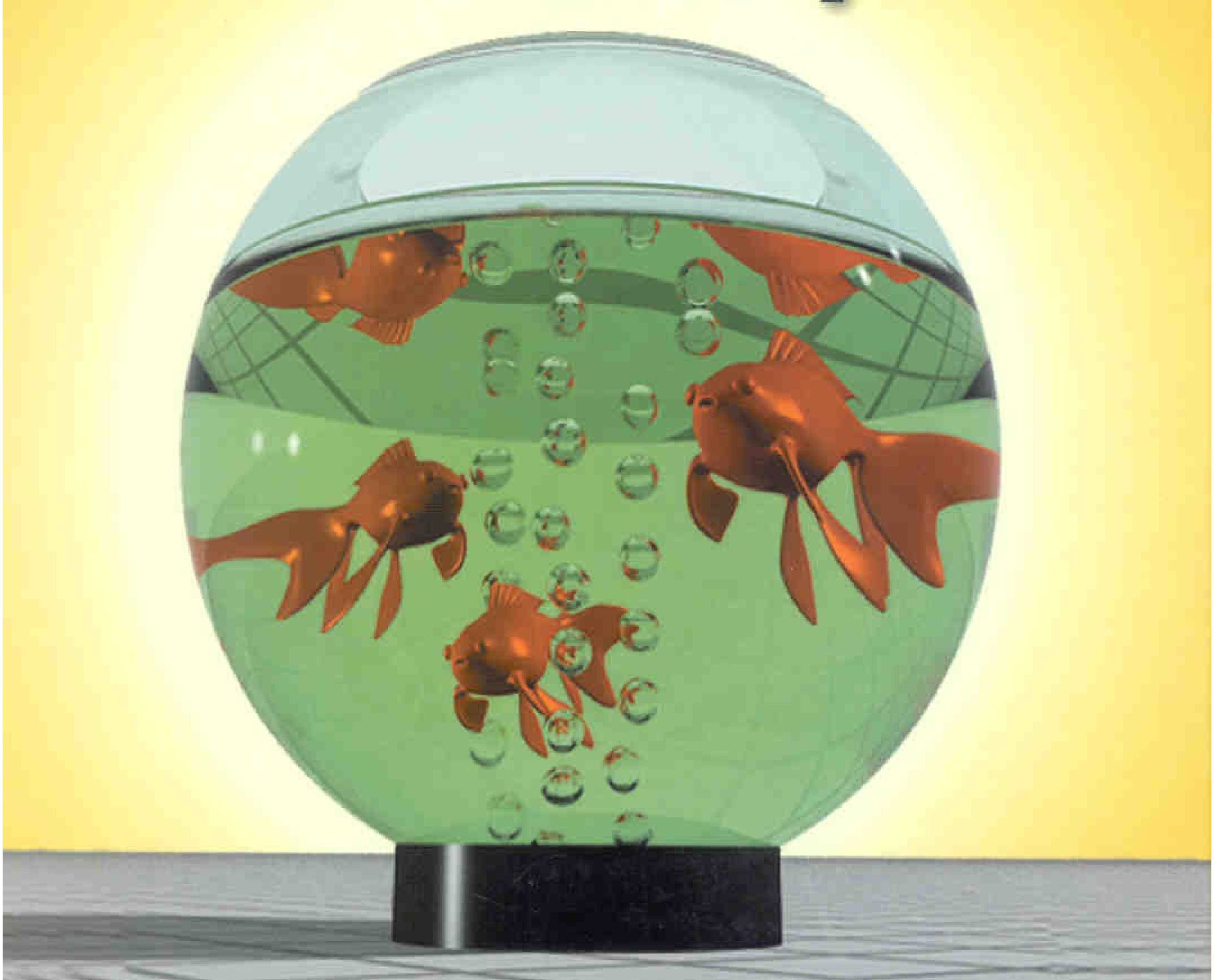


**Figure 28.40.** (a) Construction of the rim; (b) construction of the meniscus.



# Adding Textures

- Per pixel modification of surface appearance
- Use texture coordinates to map textures to objects
  - When ray tracing, you have to do this yourself
- Textures modify ray color on each bounce

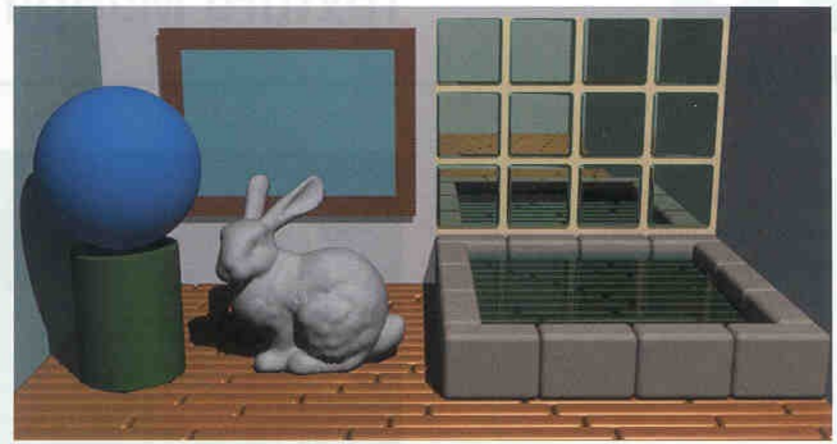
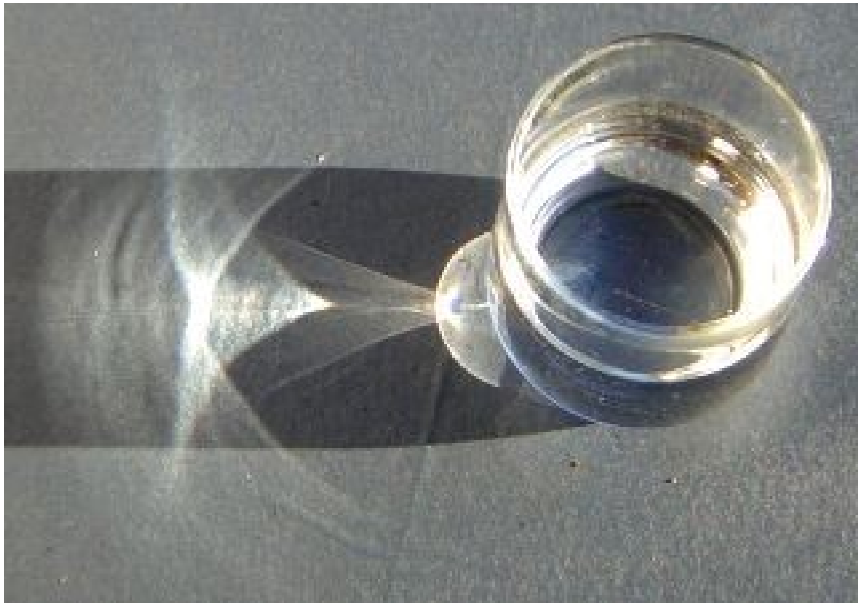
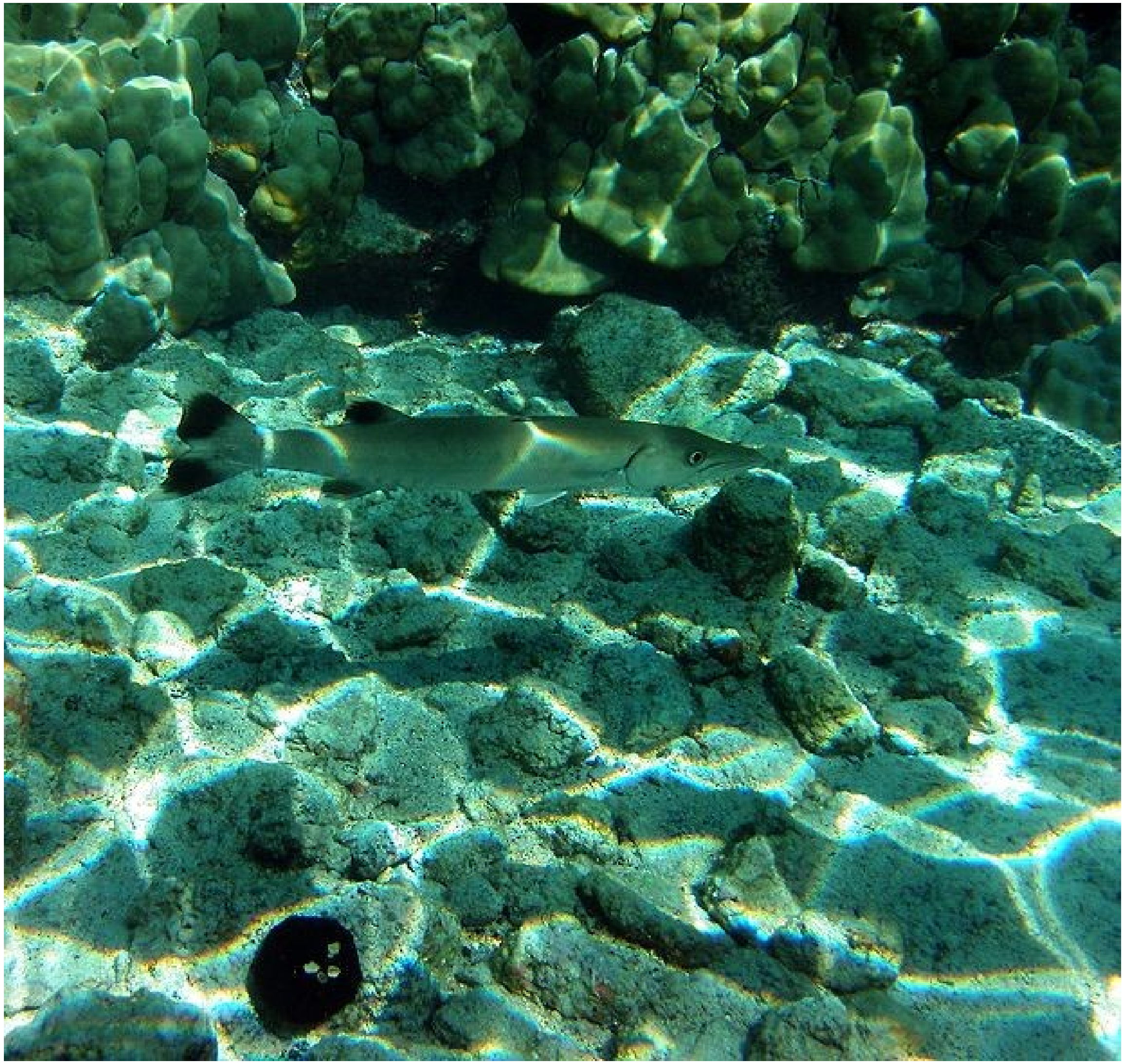


**Figure 29.1.** Interior scene rendered with no textures.

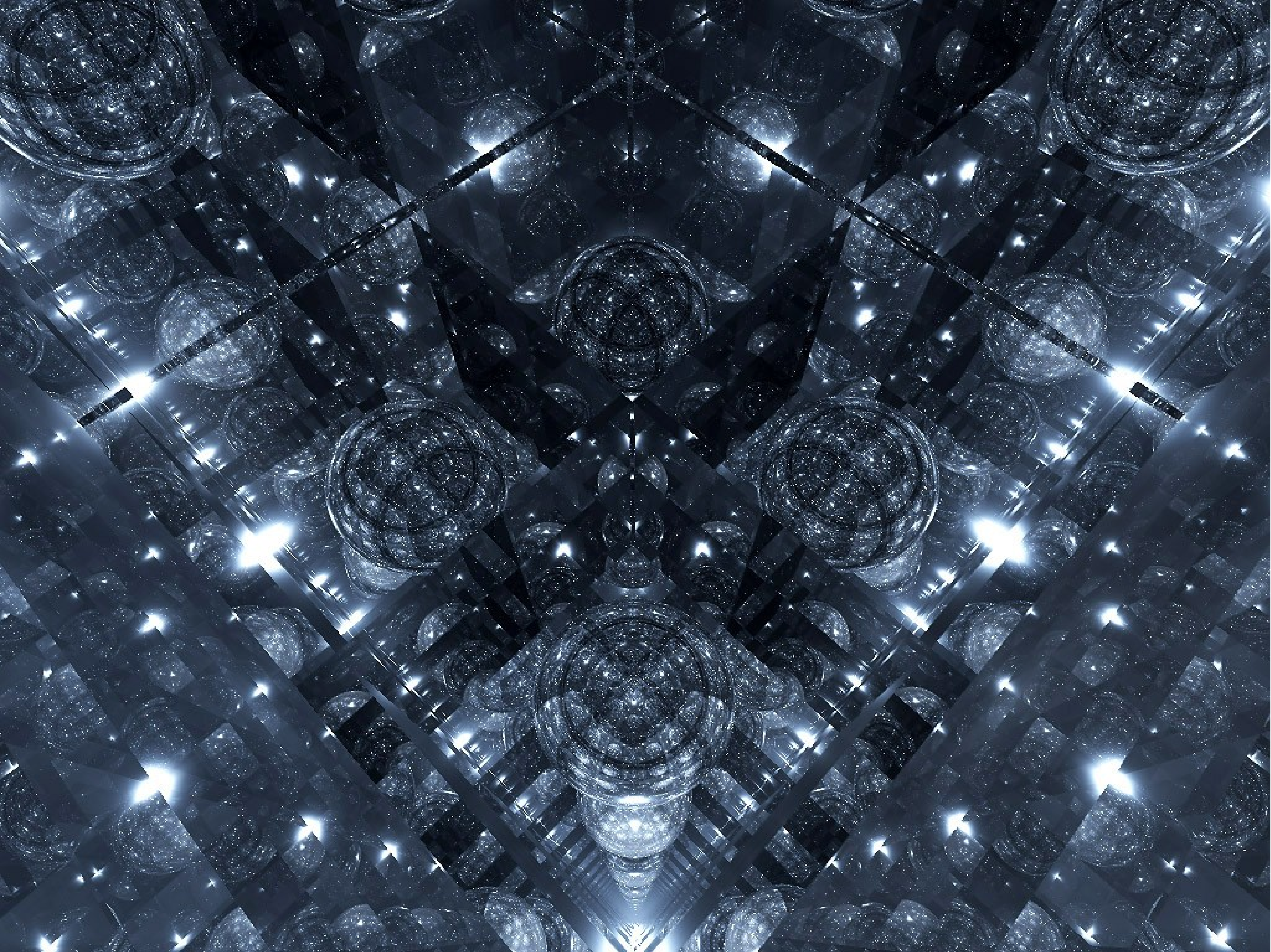
**Figure 29.2.** Same scene as in Figure 29.1 but rendered with a variety of textures. The water surface is Ken Musgrave's water bump map, as described in Musgrave (2003b).

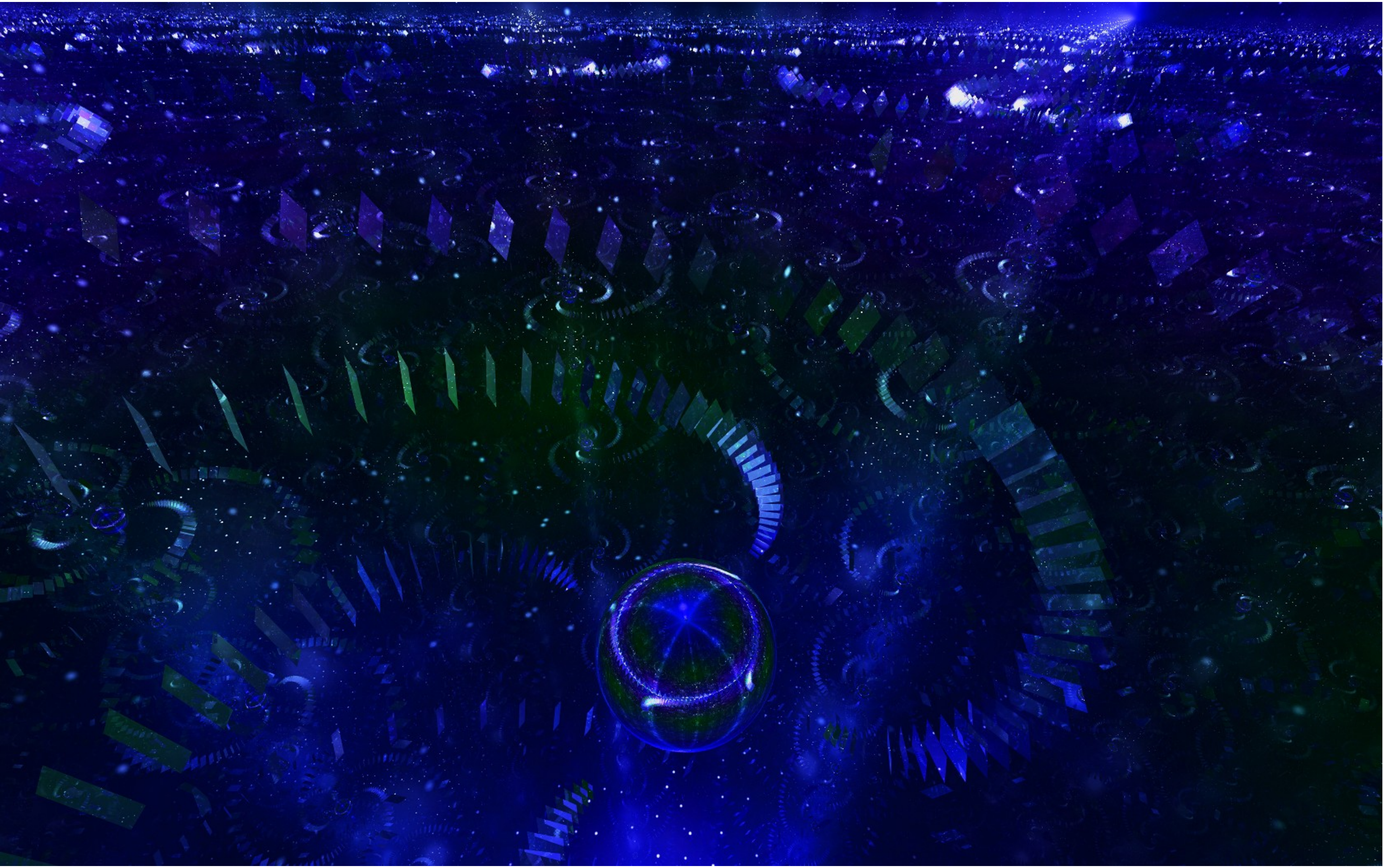
# Caustics

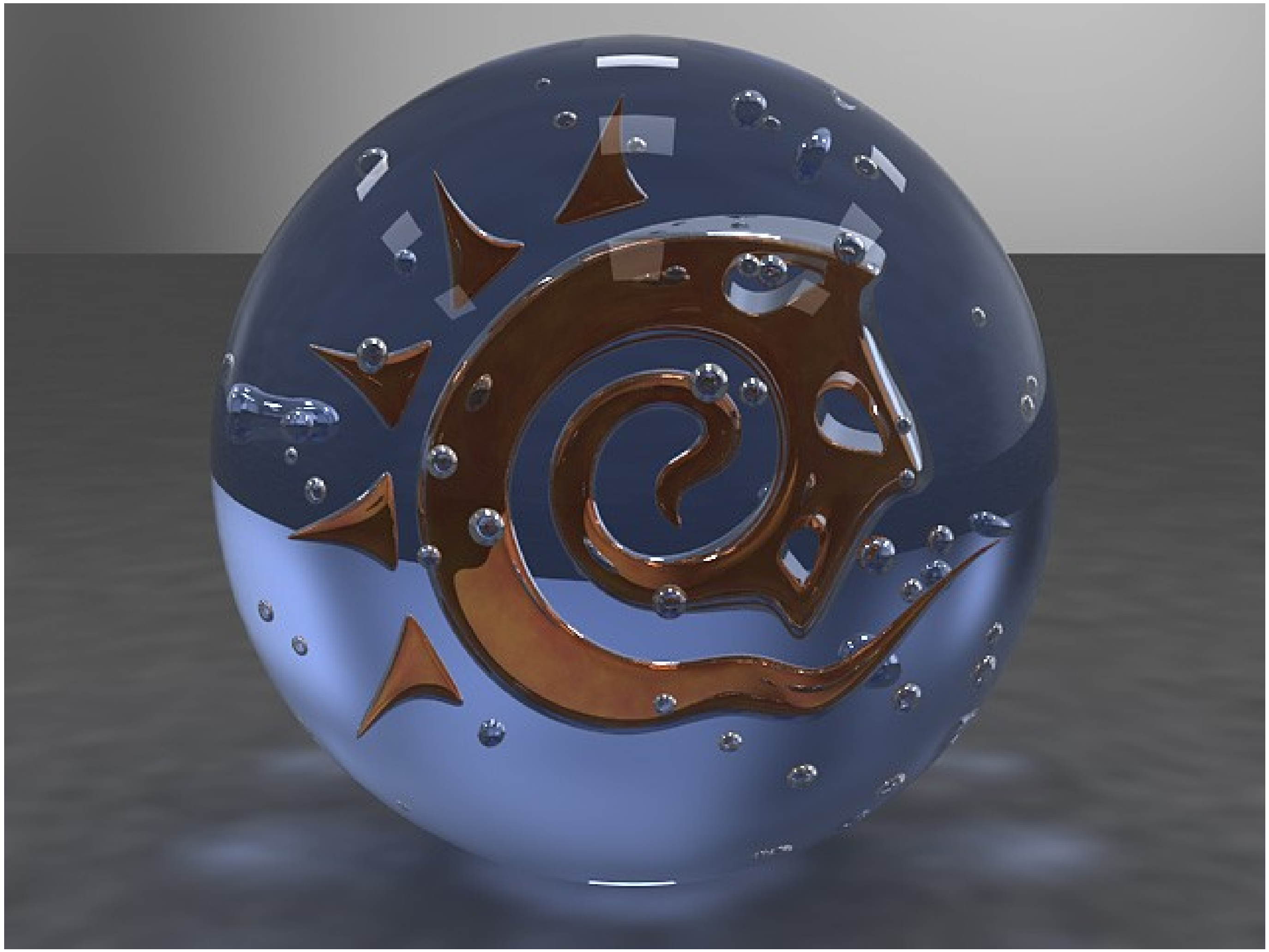




# Tim Dunn's Gallery

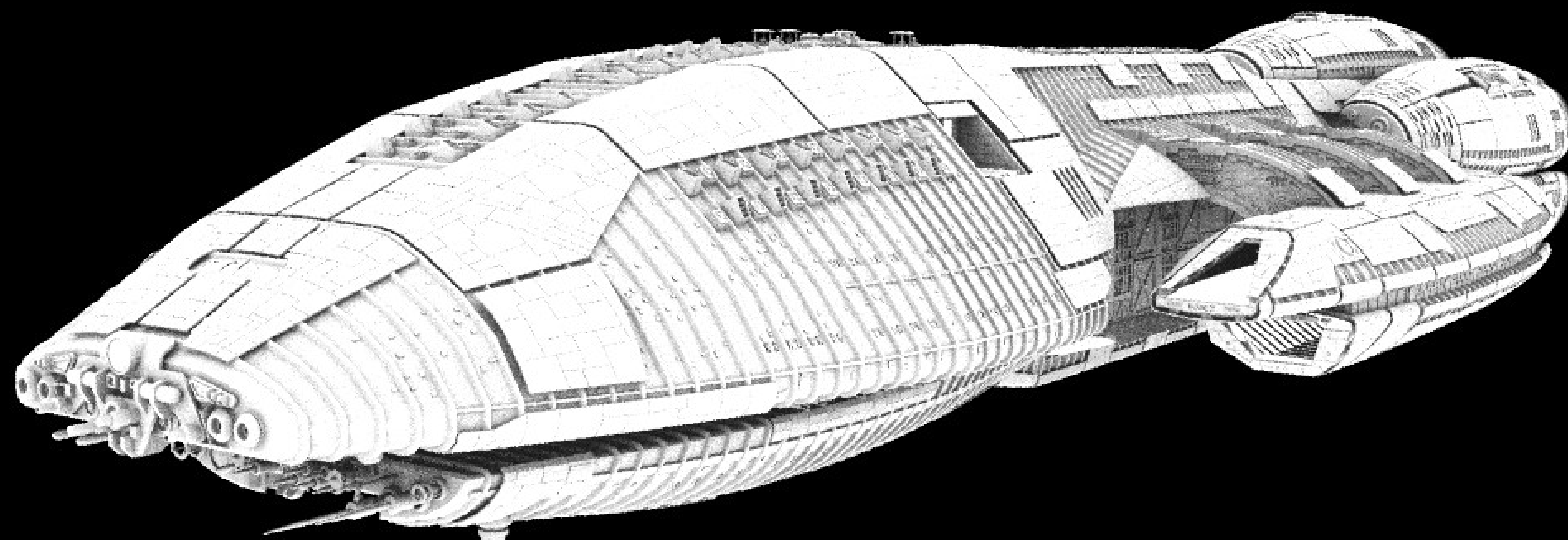




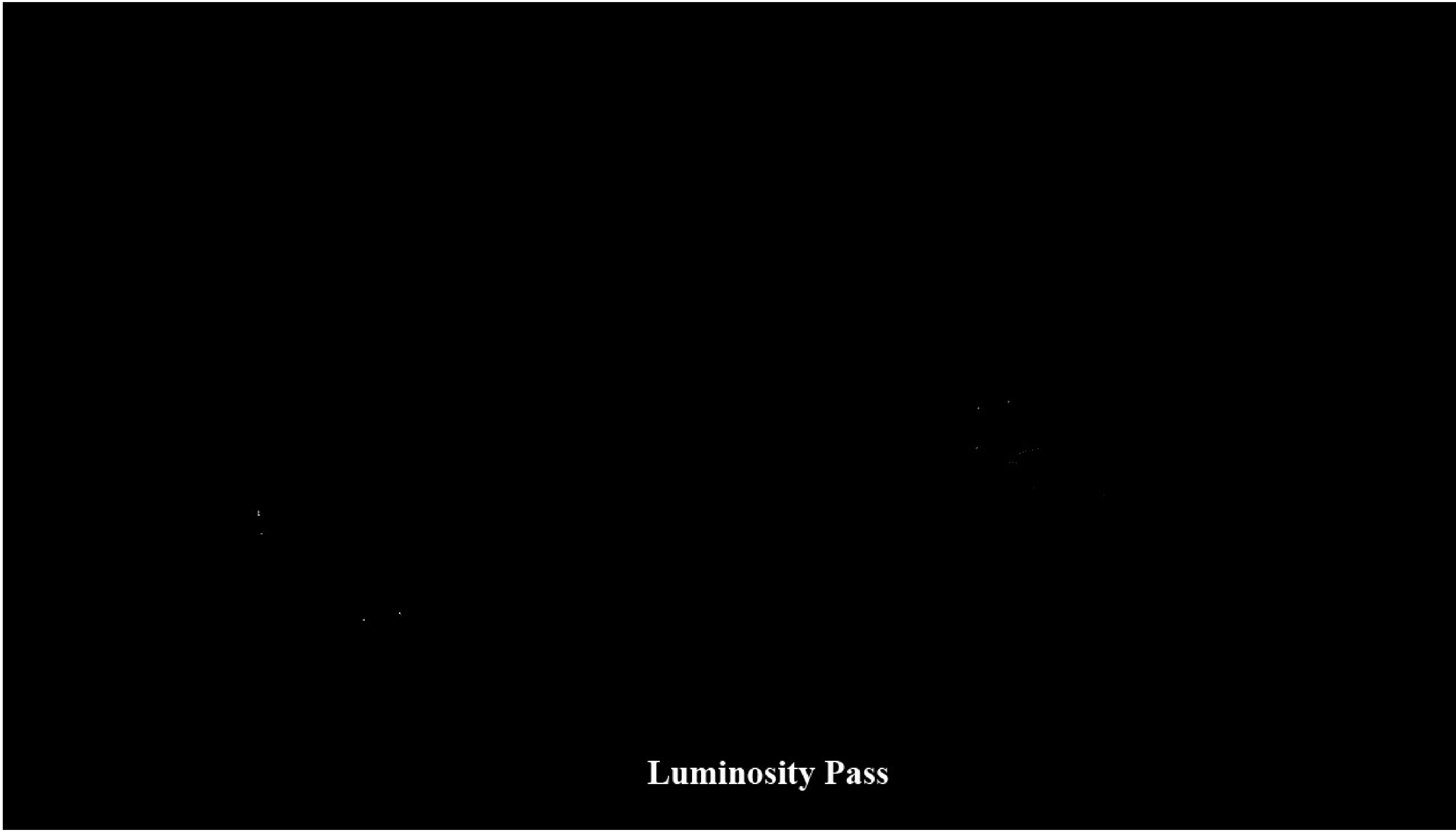


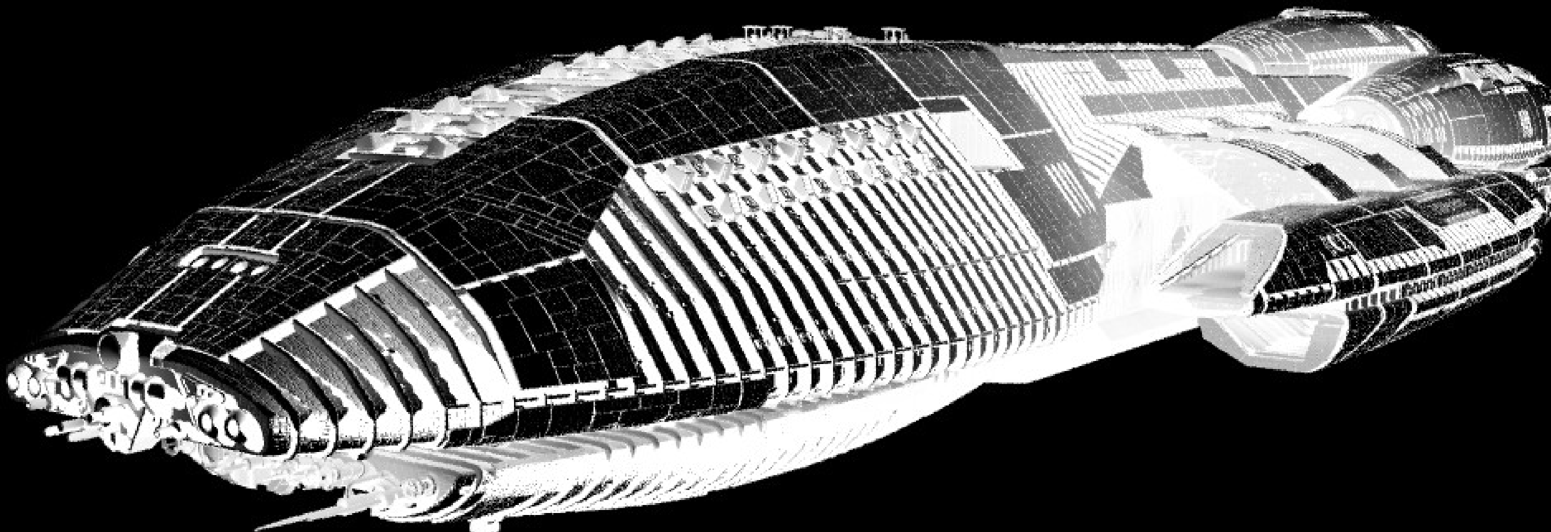
# Production Ray Tracing
Tim Dunn

Raw Render Pass

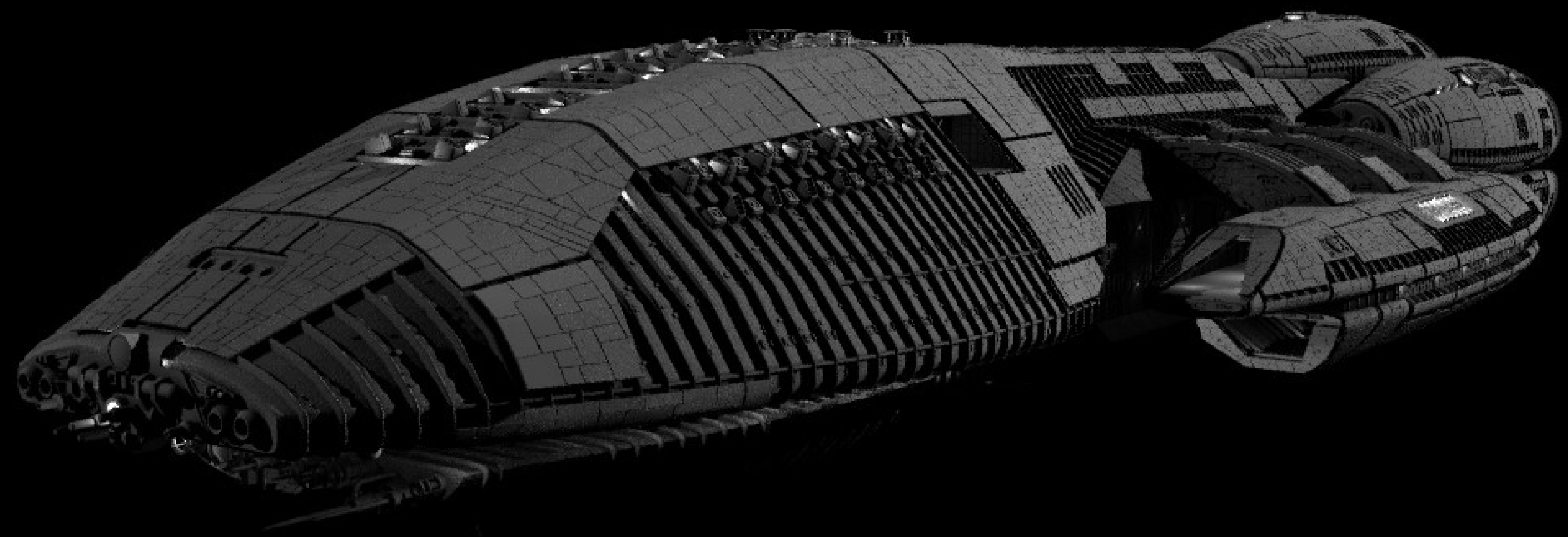


Ambient Occculsion Pass


Luminosity Pass



Shadow Pass

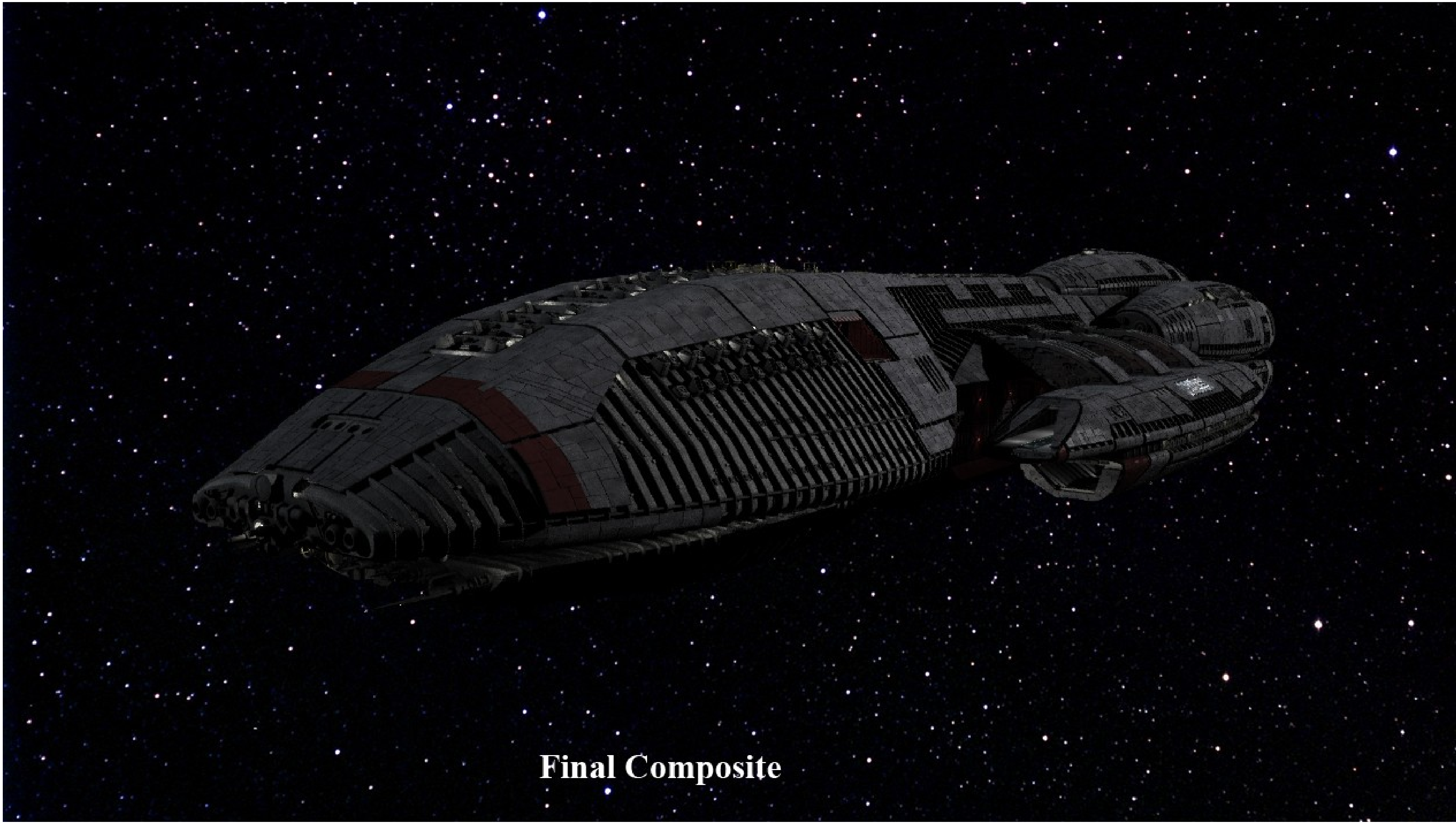


**Diffuse Pass**

**Dissue Lighting Pass**

**Specular Color Pass**


Background Plate Pass



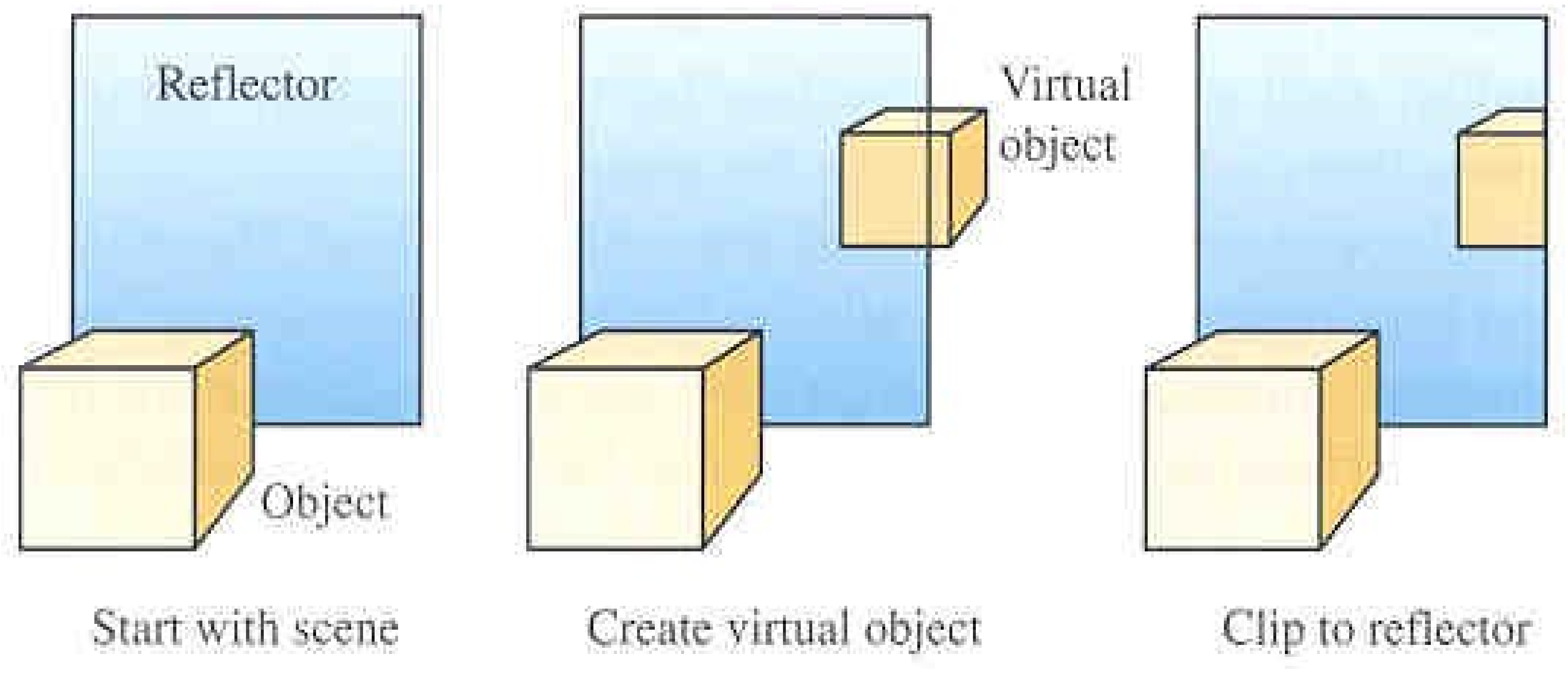
**Final Composite**

# Reflections in Raster Methods

- Two possible approaches
  - Textures (image space)
  - Virtual objects (object space)
- Both approaches requires rendering the scene multiple times
- Mirrors can be planar or curved
- Mirrors are “windows” to the virtual scene

# Virtual Objects

- Draw object where they seem to appear
- Clip to reflector



# Planar Reflection Equation

- Point on mirror *P*
- Normal vector *V*

$$R = \begin{pmatrix} 1-2V_x^2 & -2V_xV_y & -2V_xV_z & 2(P\cdot V)V_x \\ -2V_xV_y & 1-2V_y^2 & -2V_yV_z & 2(P\cdot V)V_y \\ -2V_xV_z & -2V_yV_z & 1-2V_z^2 & 2(P\cdot V)V_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

# Rendering Order

- Reflections are difficult when the mirror is an object inside the scene
  - Mirror on wall is easier

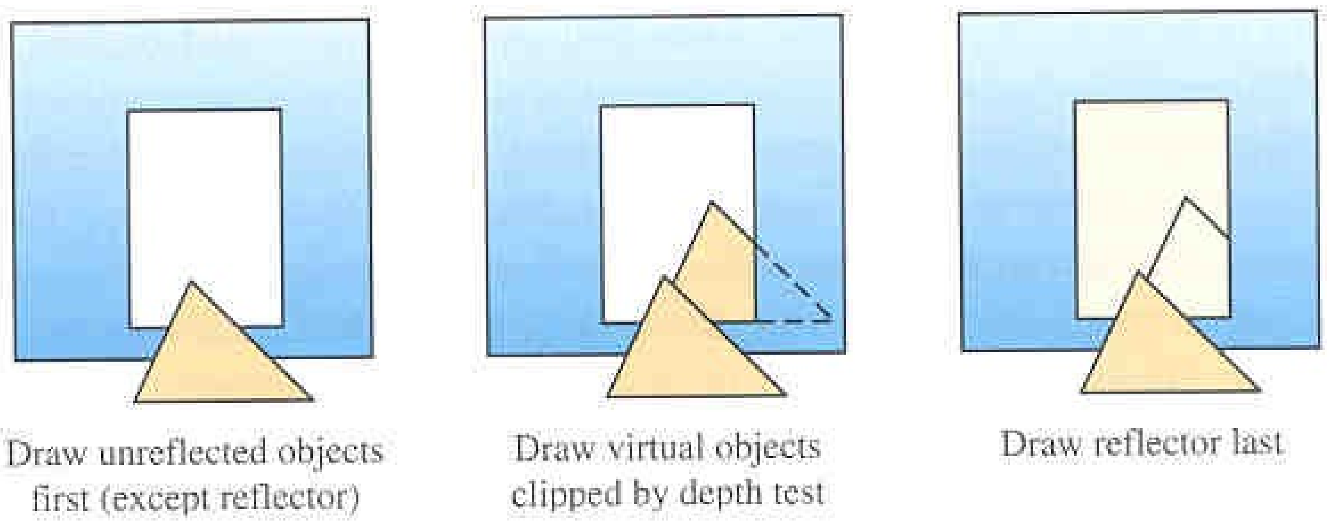



Figure 17.3 Masking reflections with depth buffering.

# Limiting the Reflector

- User defined clipping volume
  - Front and back clipping planes
  - Frustrum
- Stencil buffer
- Special cases
  - Scissors test
  - Alpha blending

# Reflections using Textures

- Quads
  - Simple mirrors
- Environment maps
  - Cube map
  - Sphere map

Figure 17.4 Masking reflections using projective texture.

# Reflections from Curved Surfaces

- Cannot be done using virtual objects
- Readily done by distorting textures

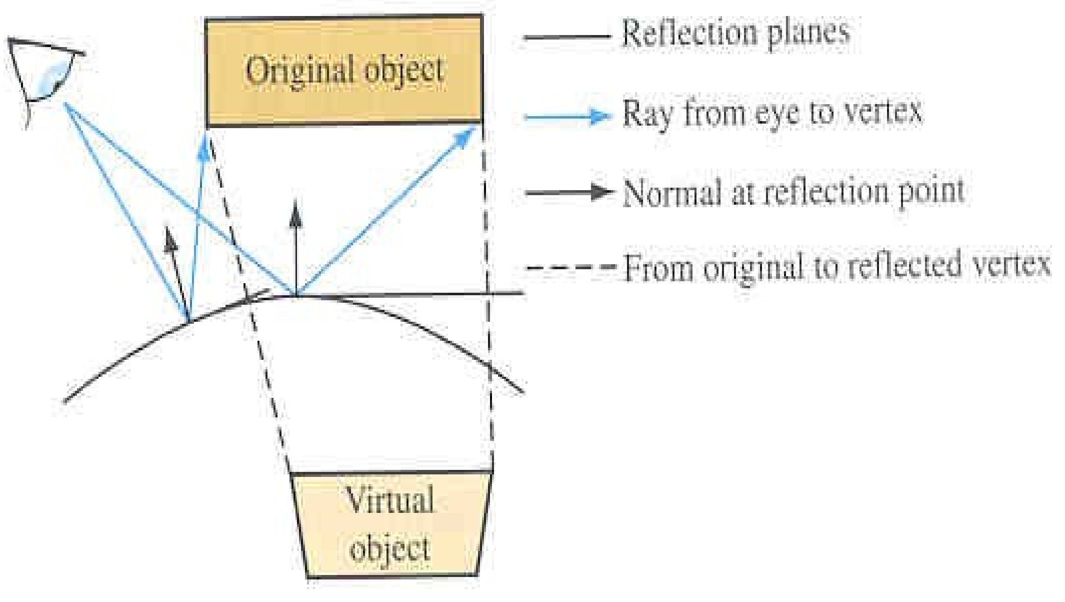



Figure 17.5 Normals and reflection vectors in curved reflectors.

# Inter-reflections

- Hall of mirrors requires multiple passes
  - Similar to max-levels

Figure 17.13 Clipping multiple interreflections with stencil.