50.017 Graphics and Visualization

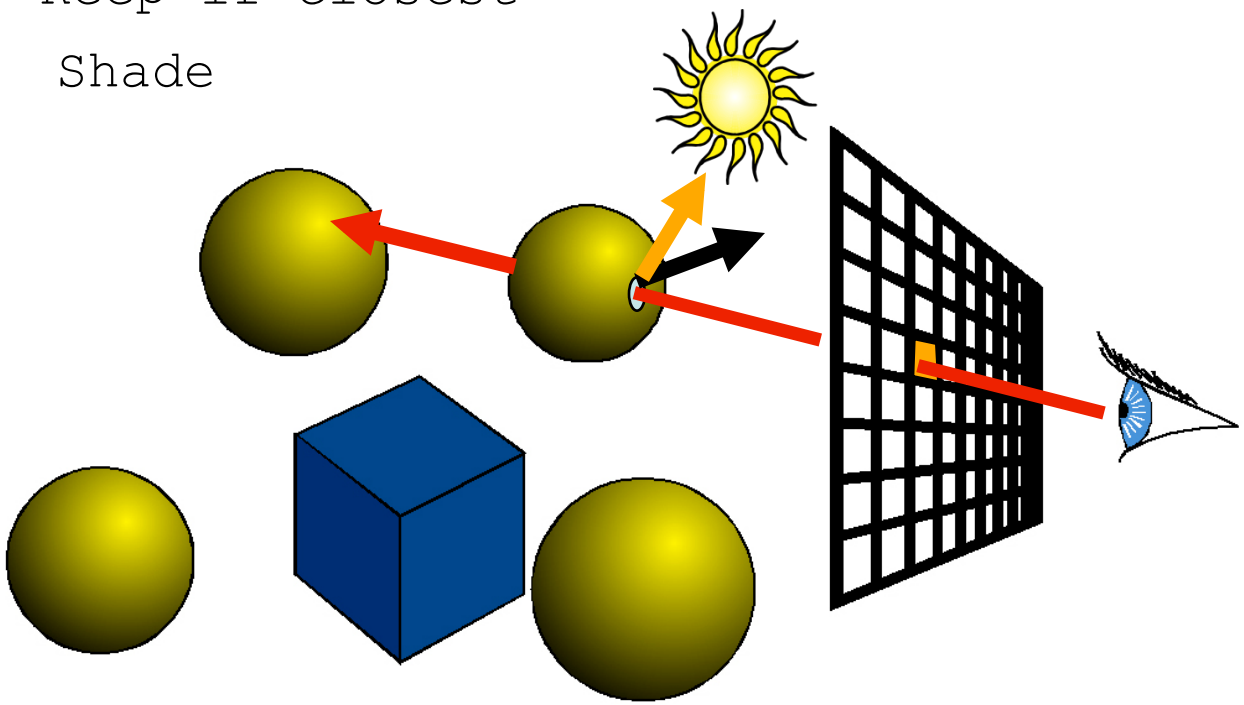
Ray Tracing

Sai-Kit Yeung SUTD ISTD

Slides from Wojciech Matusik, Jaakko Lehtinen and Fredo Durand

Ray Casting

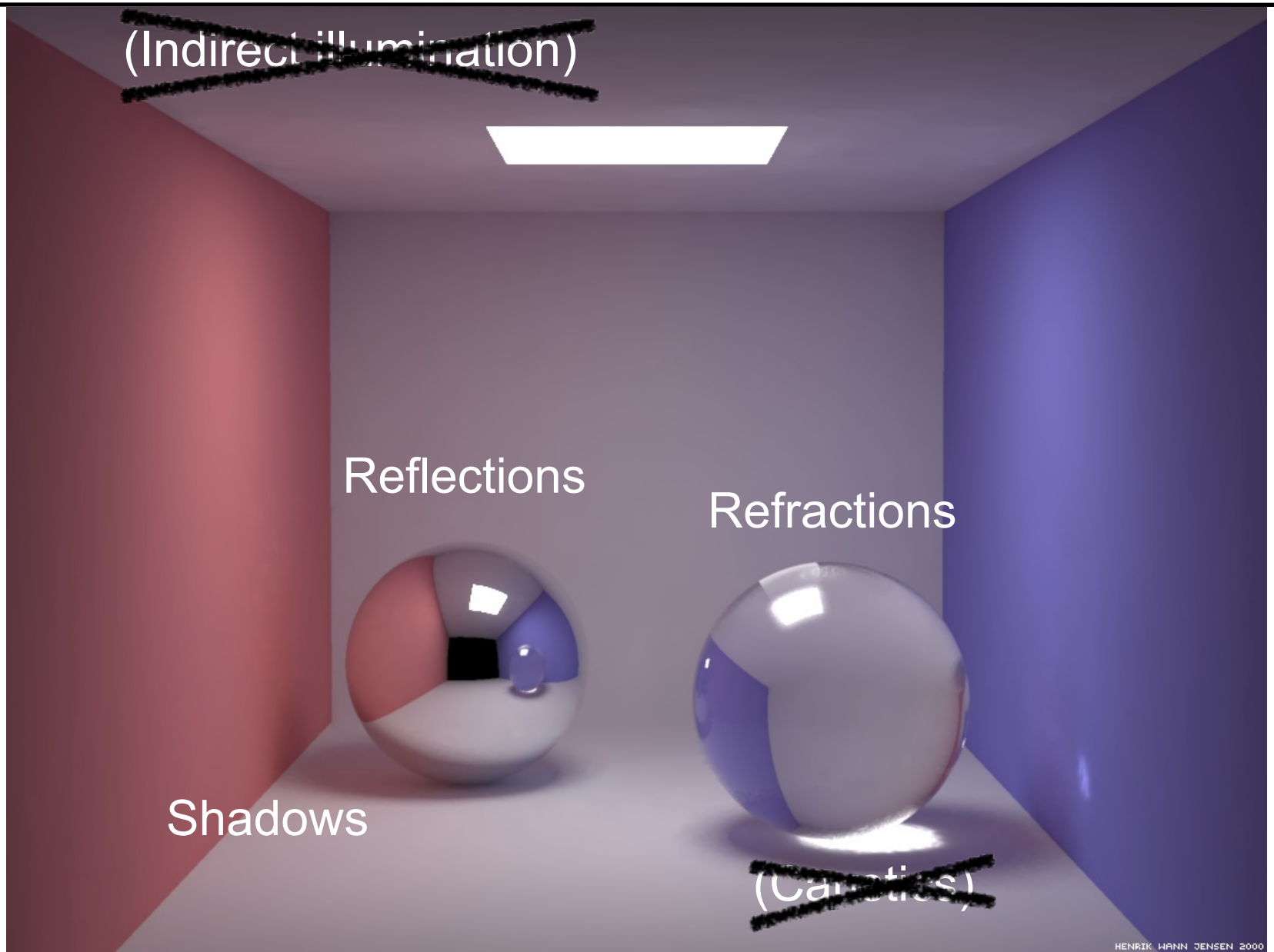
```
For every pixel
   Construct a ray from the eye
   For every object in the scene
       Find intersection with the ray
       Keep if closest
        Shade
```



Earlier

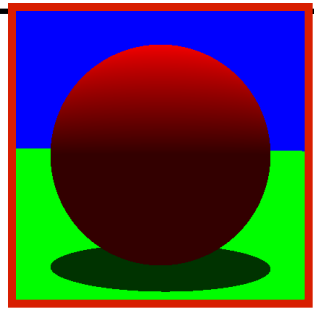
- Camera definitions
  - Perspective and orthographic
  - View coordinate system [-1,1]
  - field of view, aspect ratio, etc.
- Ray representation
  - origin + t * direction
  - Generating rays based in image coordinates
- Ray-geometry intersection
  - Planes, spheres, triangles (barycentric coordinates)
  - CSG
  - Transformations

Today – Ray Tracing

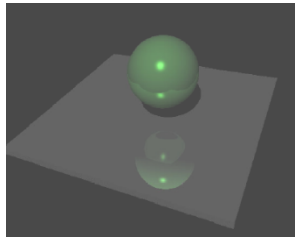


Overview of Today

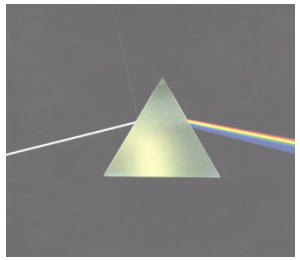
- Shadows



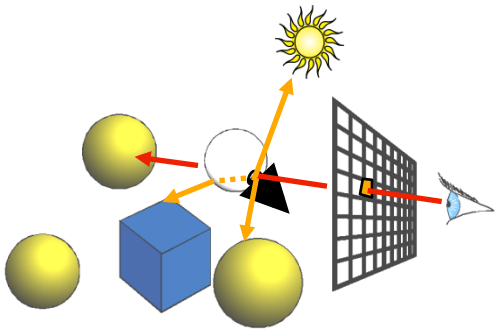
- Reflection



- Refraction

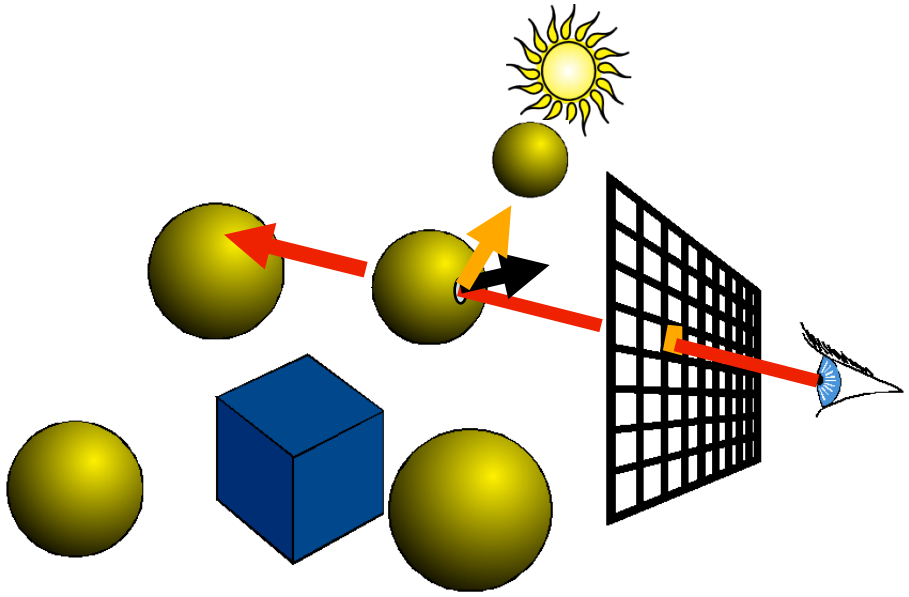


- Recursive Ray Tracing
  - "Hall of mirrors"



How Can We Add Shadows?

```
For every pixel
   Construct a ray from the eye
   For every object in the scene
       Find intersection with the ray
       Keep if closest
        Shade
```



How Can We Add Shadows?

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For every pixel
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       Find intersection with the ray
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        Shade
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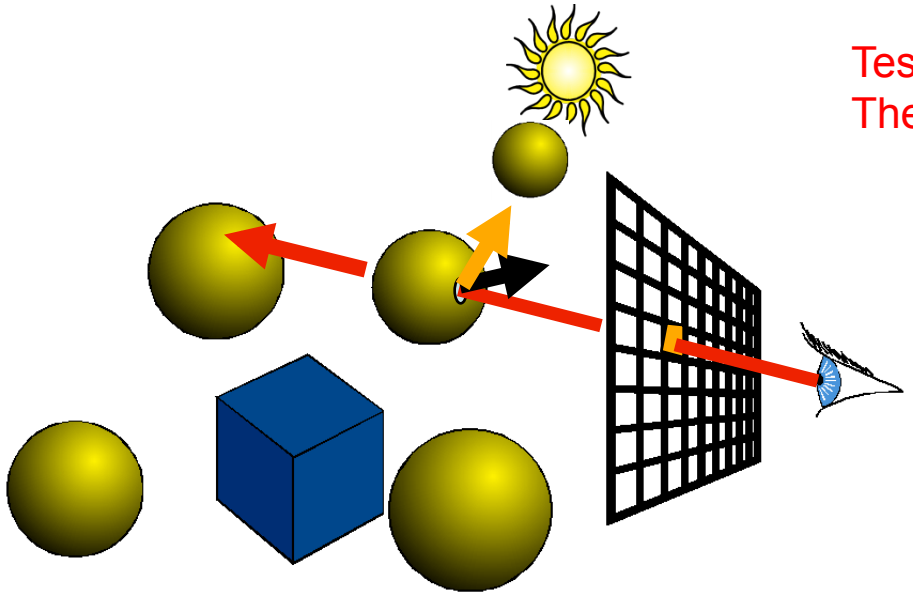
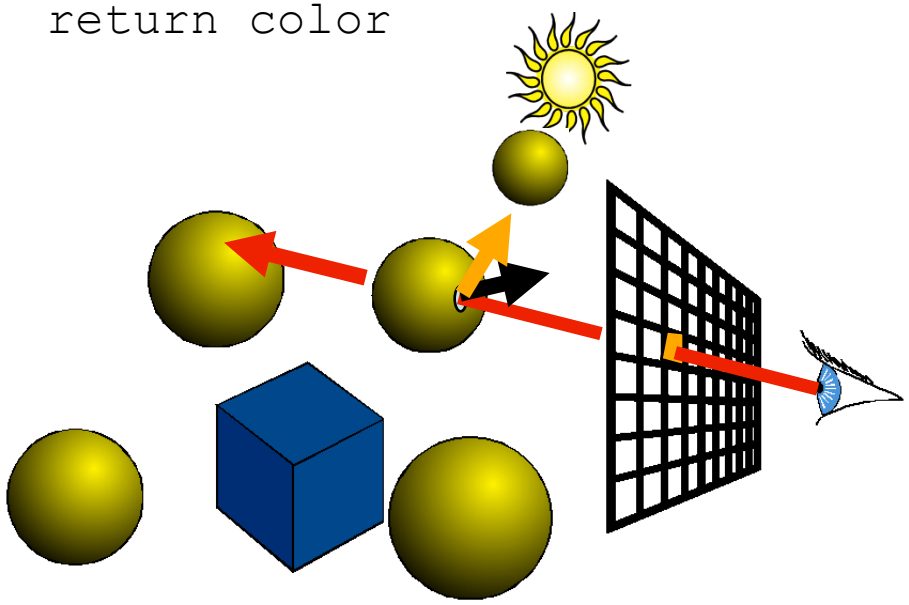
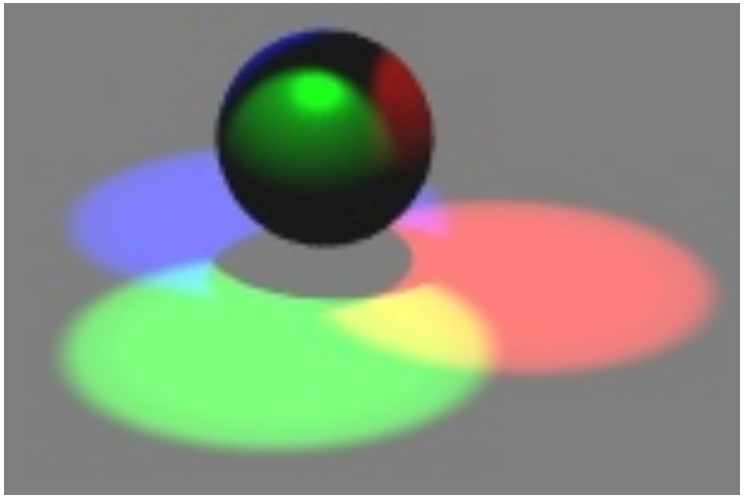


Test if there is something in between:
The line between the visible point and the light

How Can We Add Shadows?

```
color = ambient*hit->getMaterial()->getDiffuseColor()
for every light
   Ray ray2(hitPoint, directionToLight)
   Hit hit2(distanceToLight, NULL, NULL)
   For every object
      object->intersect(ray2, hit2, 0)
   if (hit2->getT() == distanceToLight)
      color += hit->getMaterial()->Shade
               (ray, hit, directionToLight, lightColor)
return color
```

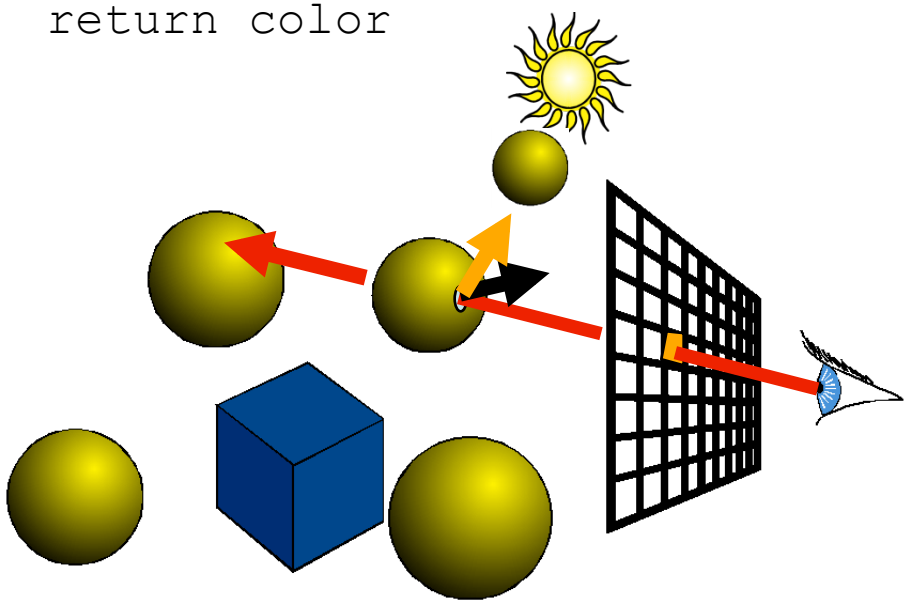


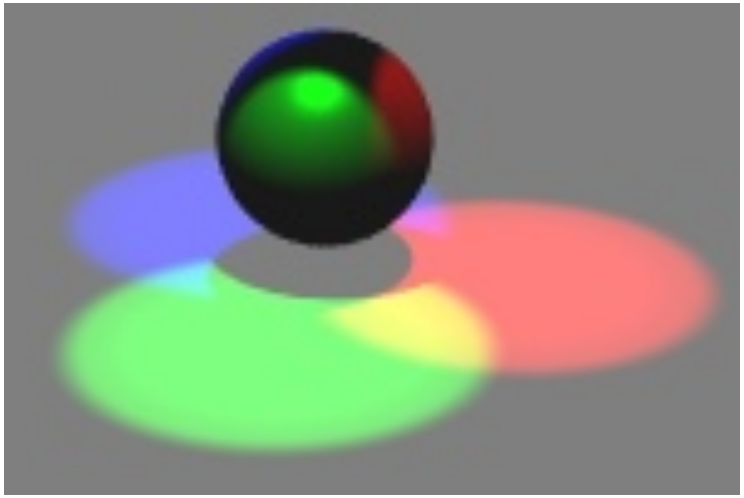


Problem: mess up the t value

```
color = ambient*hit->getMaterial()->getDiffuseColor()
for every light
   Ray ray2(hitPoint, directionToLight)
   Hit hit2(distanceToLight, NULL, NULL)
   For every object
      object->intersect(ray2, hit2, 0)
   if (hit2->getT() == distanceToLight)
      color += hit->getMaterial()->Shade
               (ray, hit, directionToLight, lightColor)
return color
```

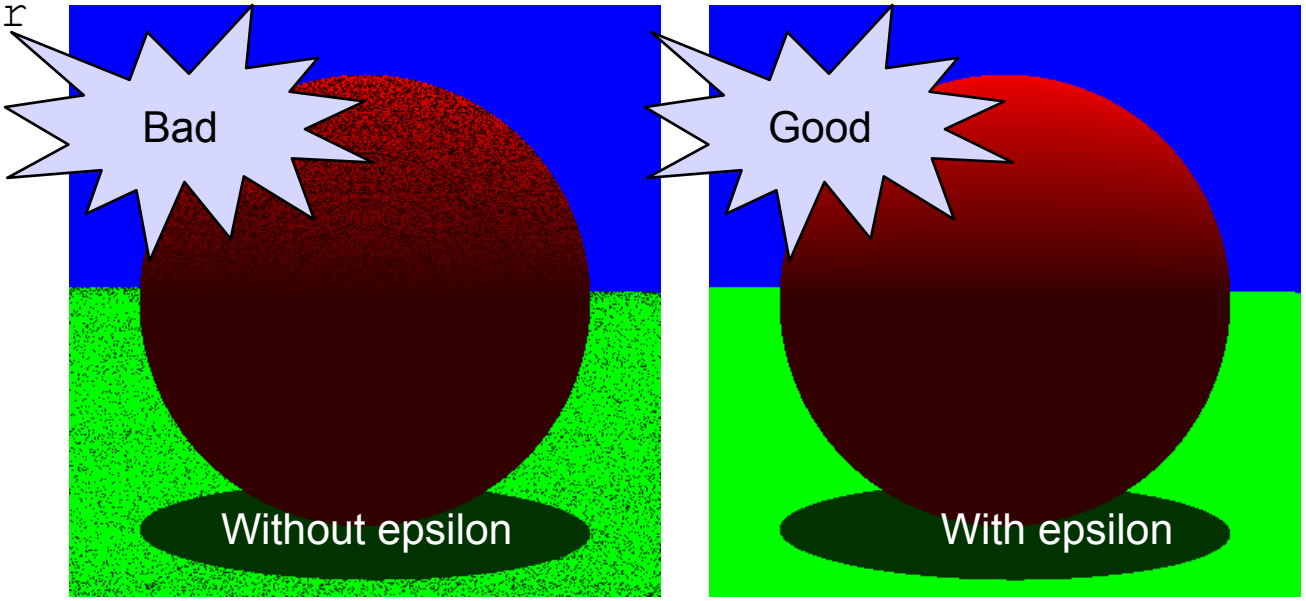
Do not mess up with the intersection from viewpoint





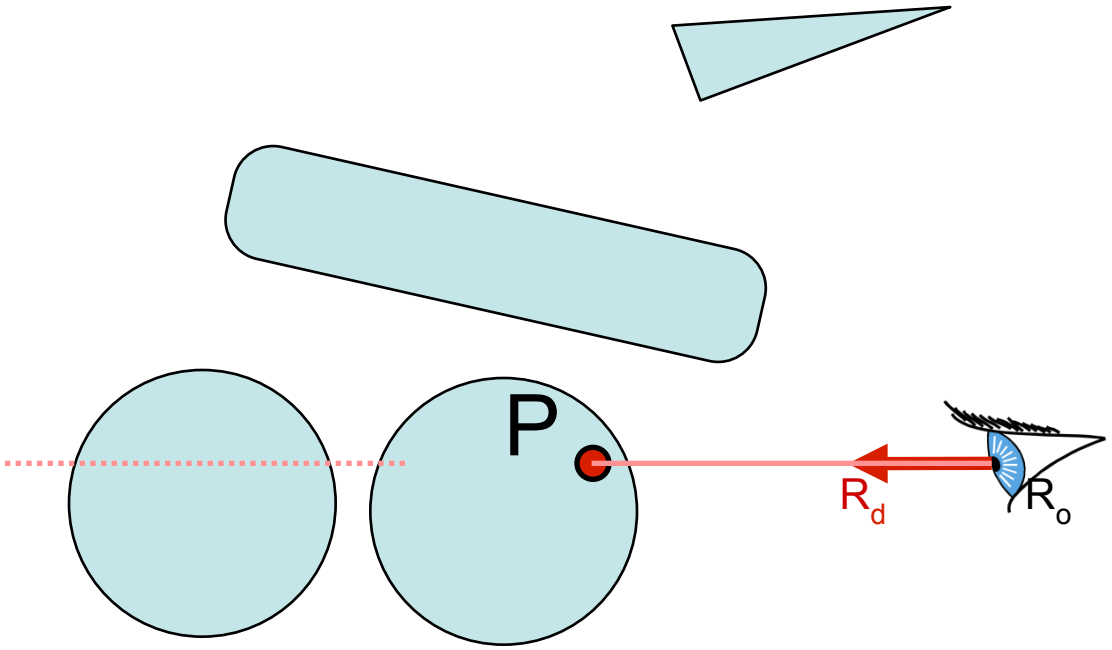
Problem: Self-Shadowing

```
color = ambient*hit->getMaterial()->getDiffuseColor()
for every light
   Ray ray2(hitPoint, directionToLight)
   Hit hit2(distanceToLight, NULL, NULL)
   For every object
      object->intersect(ray2, hit2, epsilon)
   if (hit2->getT() == distanceToLight)
      color += hit->getMaterial()->Shade
               (ray, hit, directionToLight, lightColor)
return color
```



Let's Think About Shadow Rays

- What's special about shadow rays compared to eye rays?



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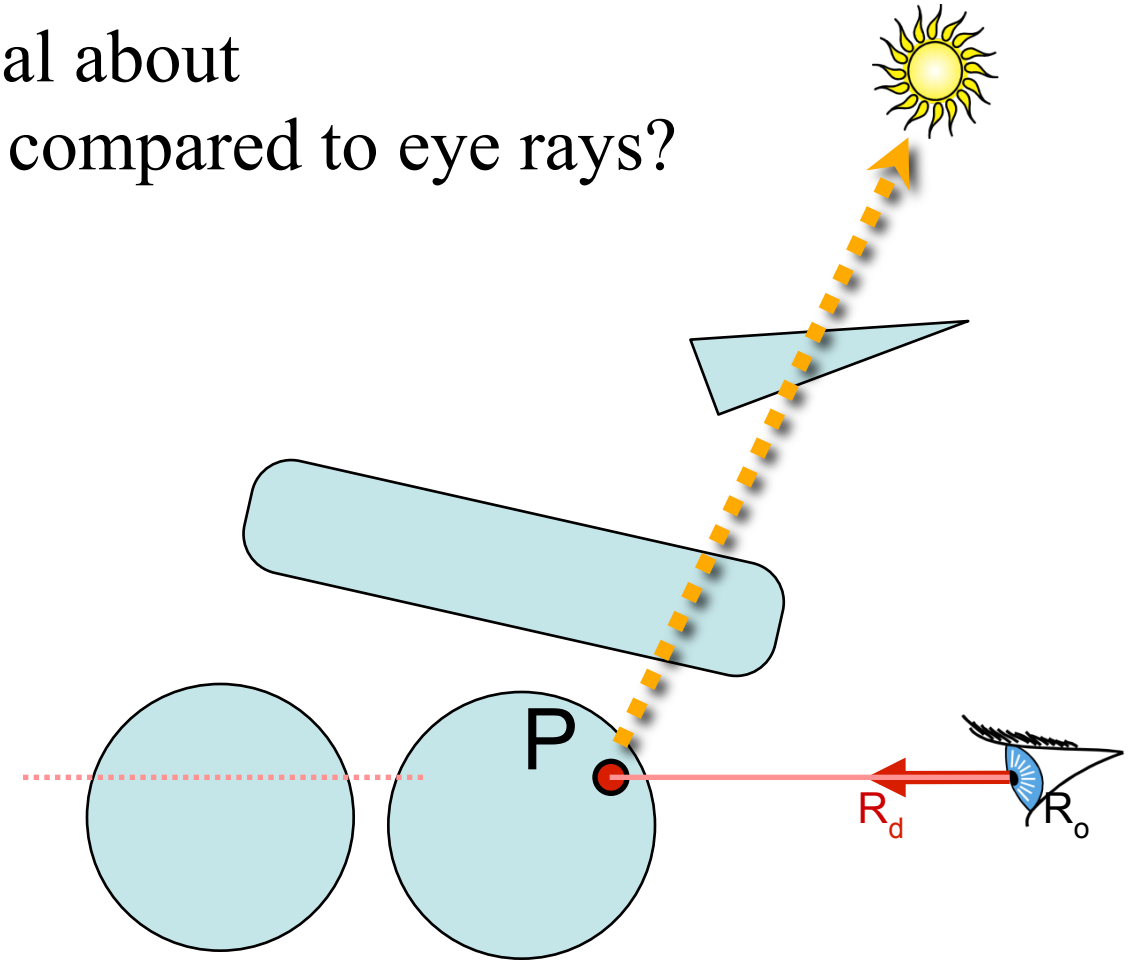

Let's Think About Shadow Rays

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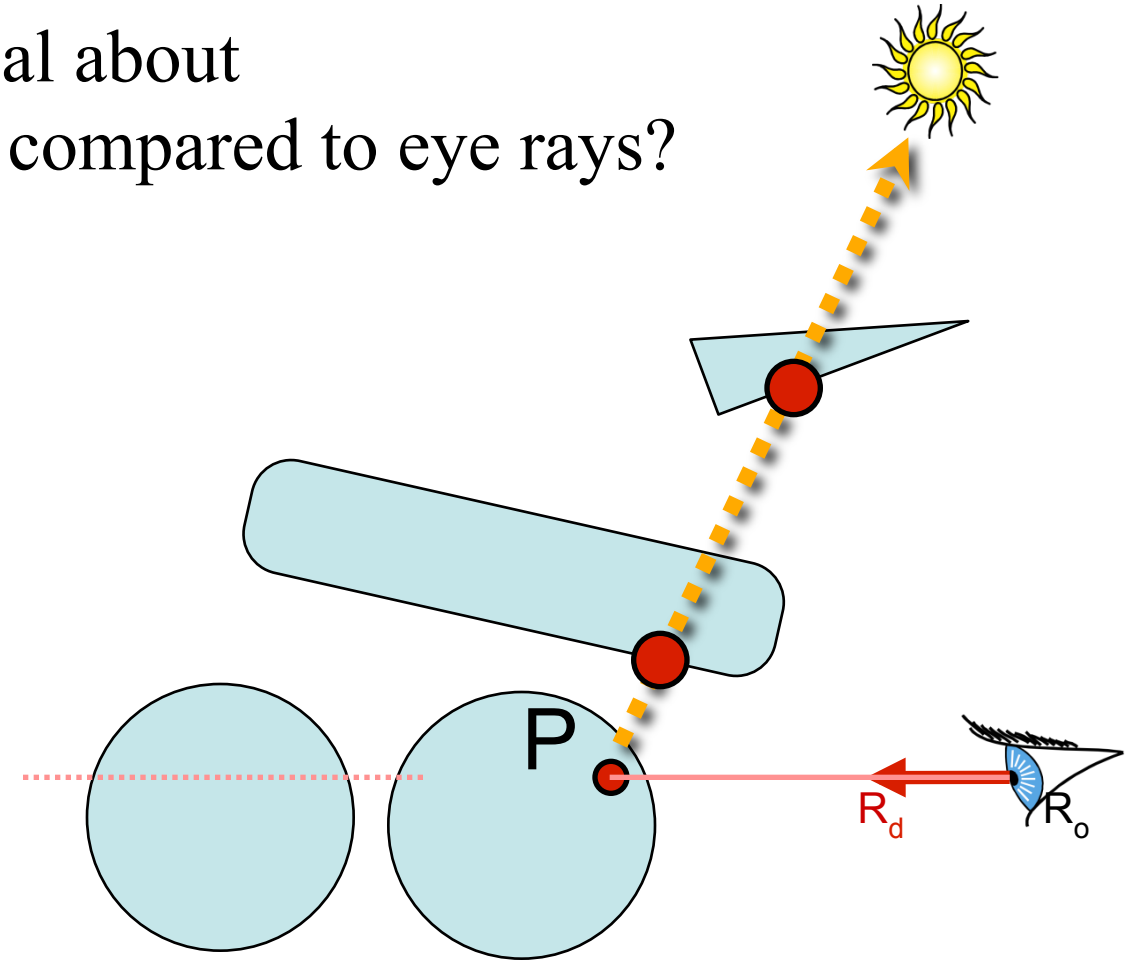
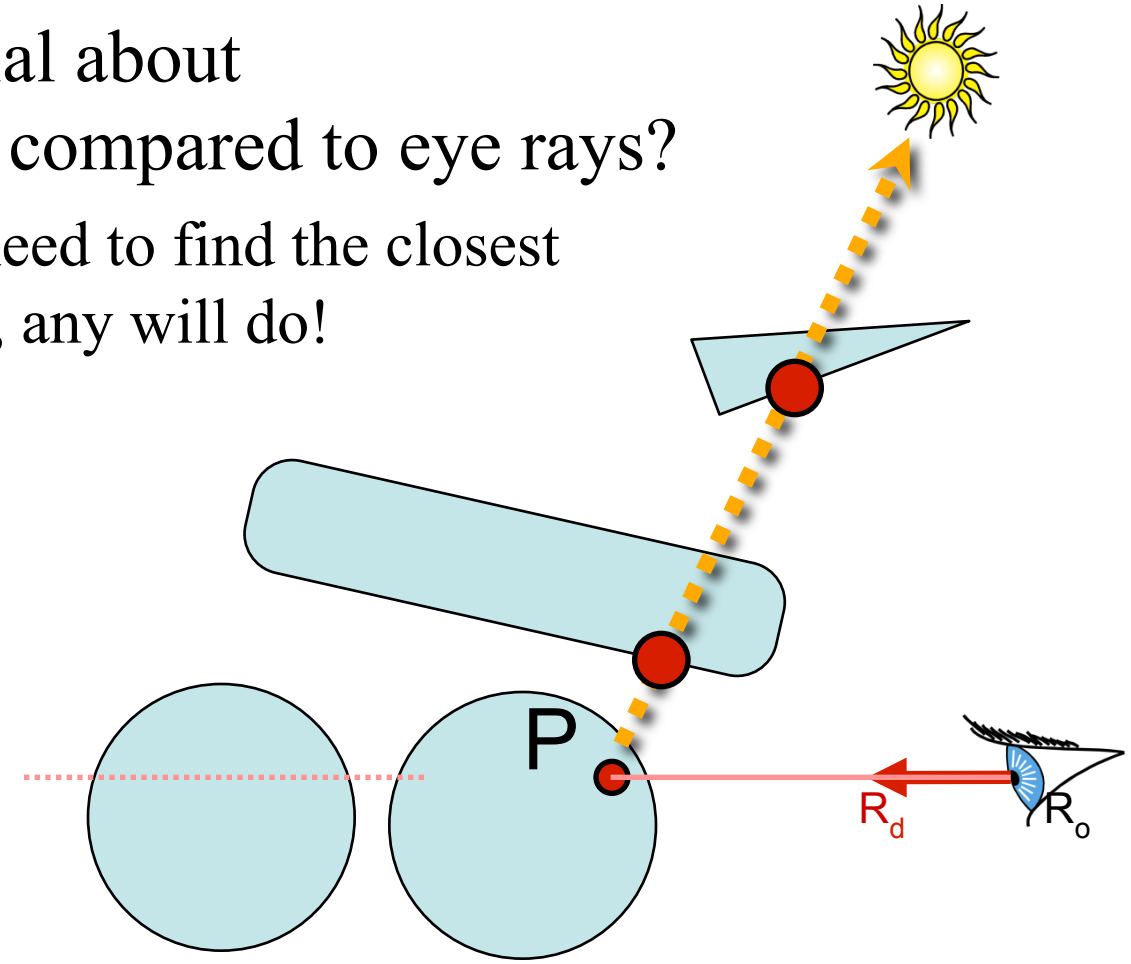


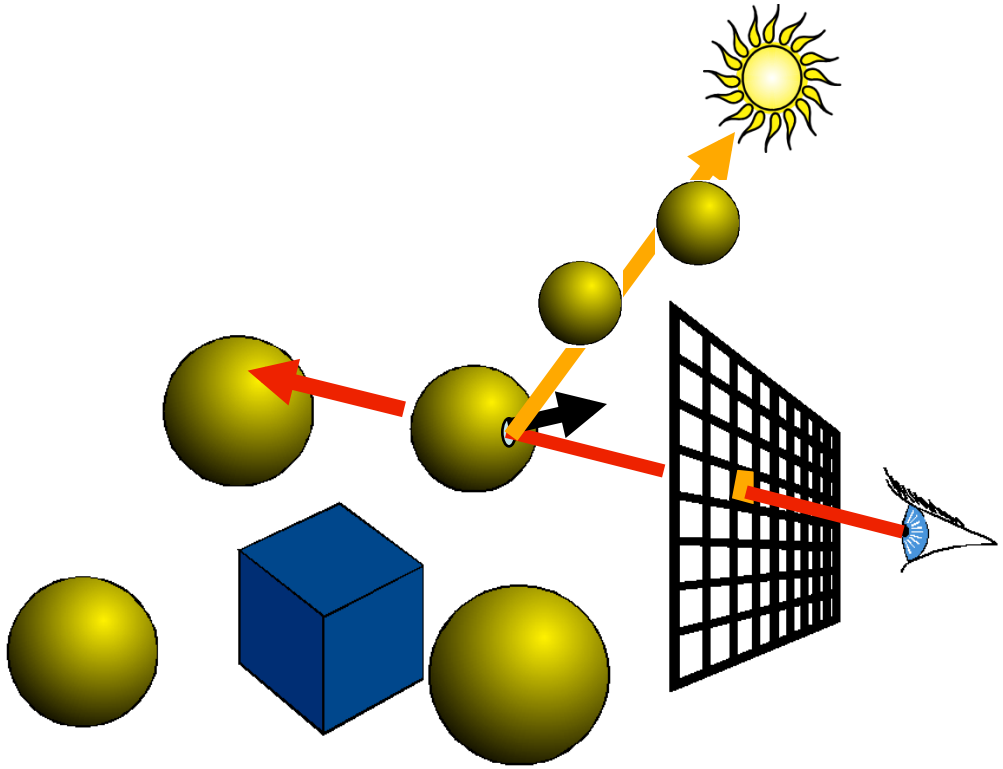
Let's Think About Shadow Rays

- What's special about shadow rays compared to eye rays?
  - We do not need to find the closest intersection, any will do!

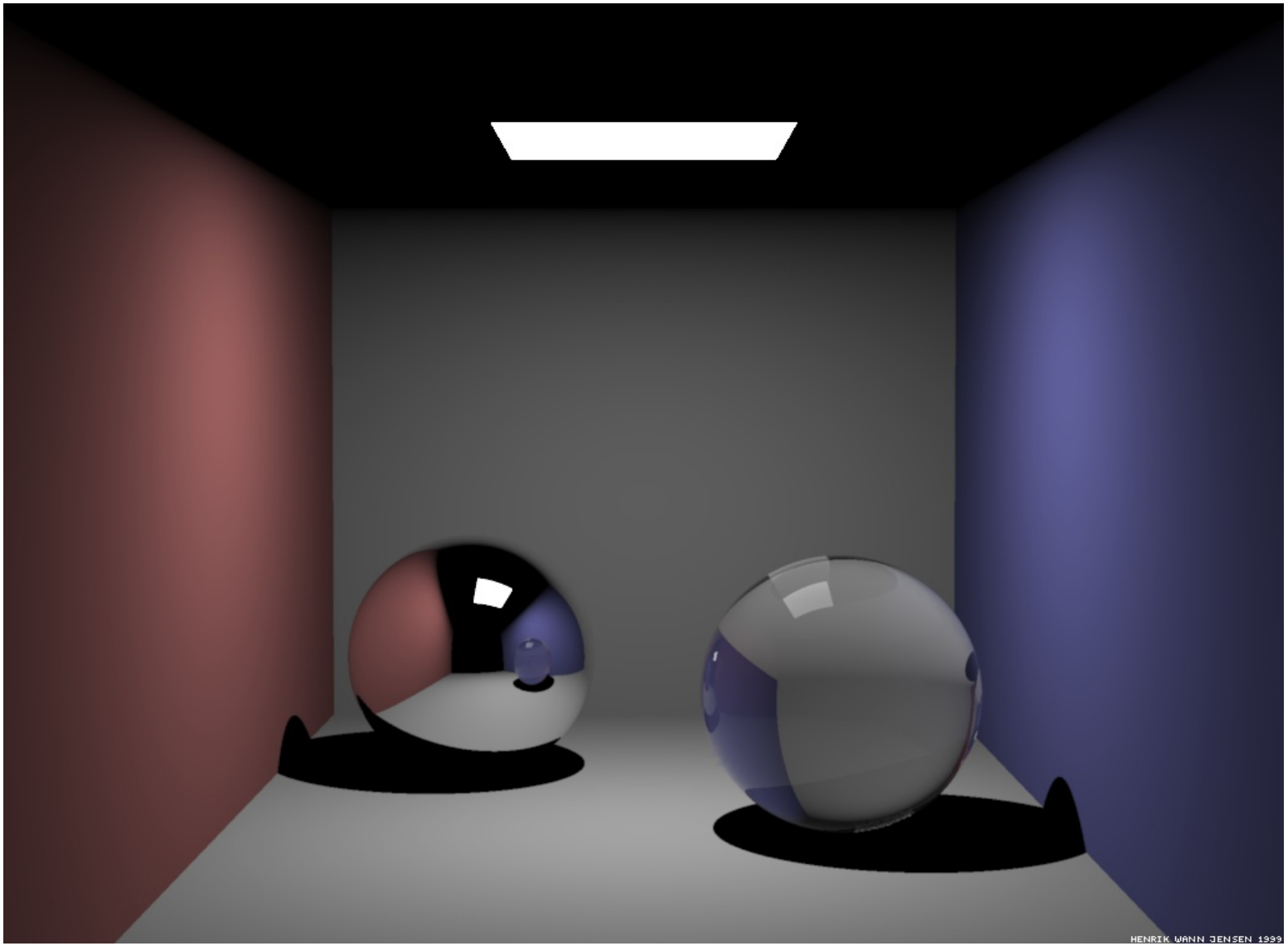


Shadow Optimization

- We only want to know whether there is an intersection, not which one is closest
- Special routine `Object3D::intersectShadowRay()`
  - Stops at first intersection



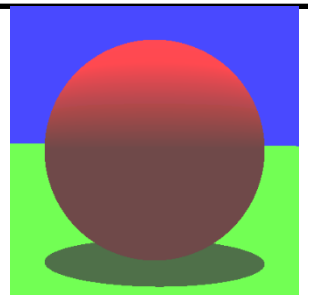
Questions?

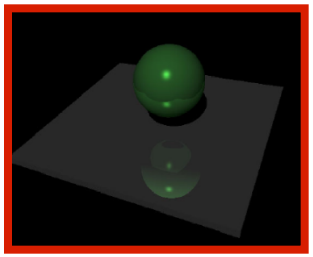


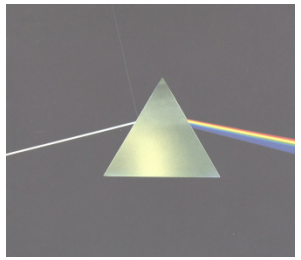
Henrik Wann Jensen

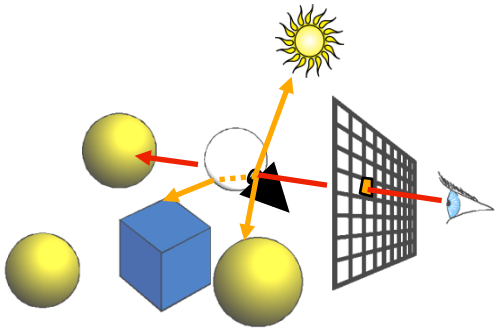
Overview of Today

- Shadows
- Reflection
- Refraction
- Recursive Ray Tracing



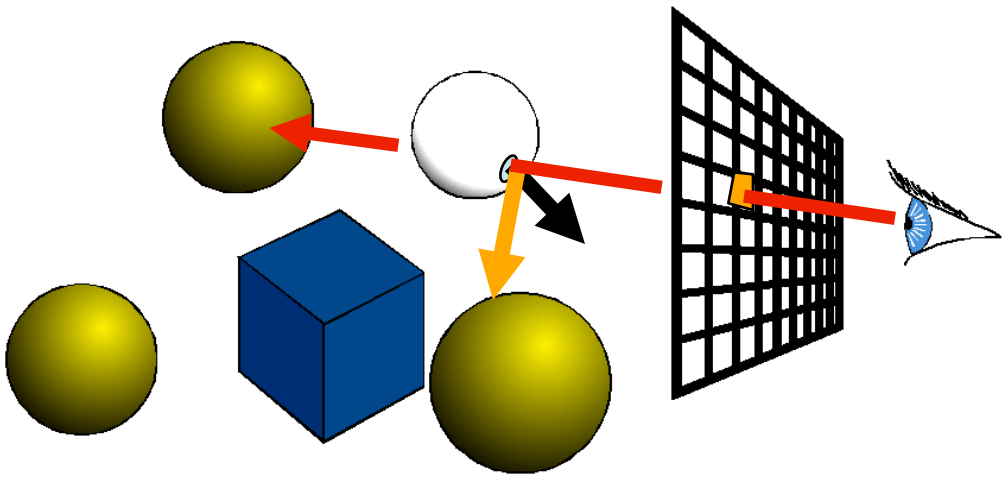


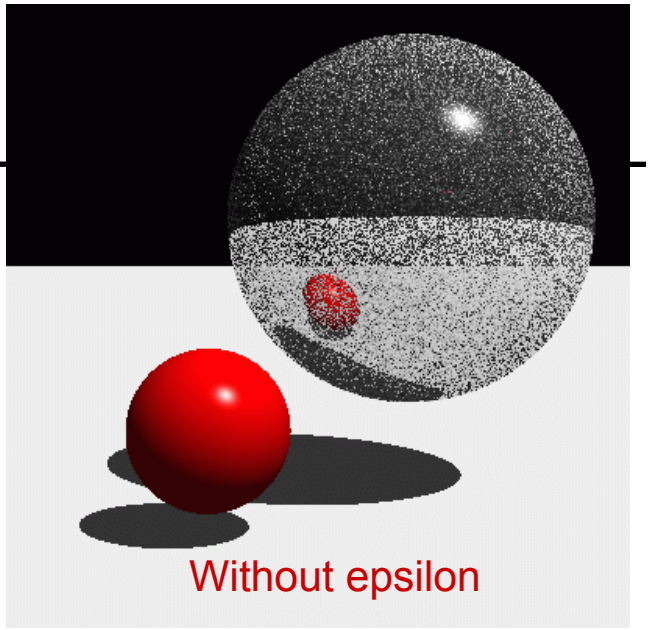


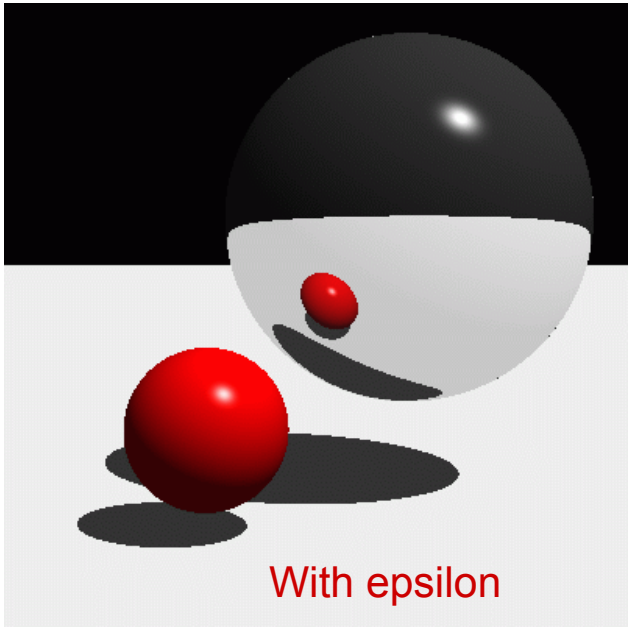


Mirror Reflection

- Cast ray symmetric with respect to the normal
- Multiply by reflection coefficient k_s (color)
- Don't forget to add epsilon to the ray!

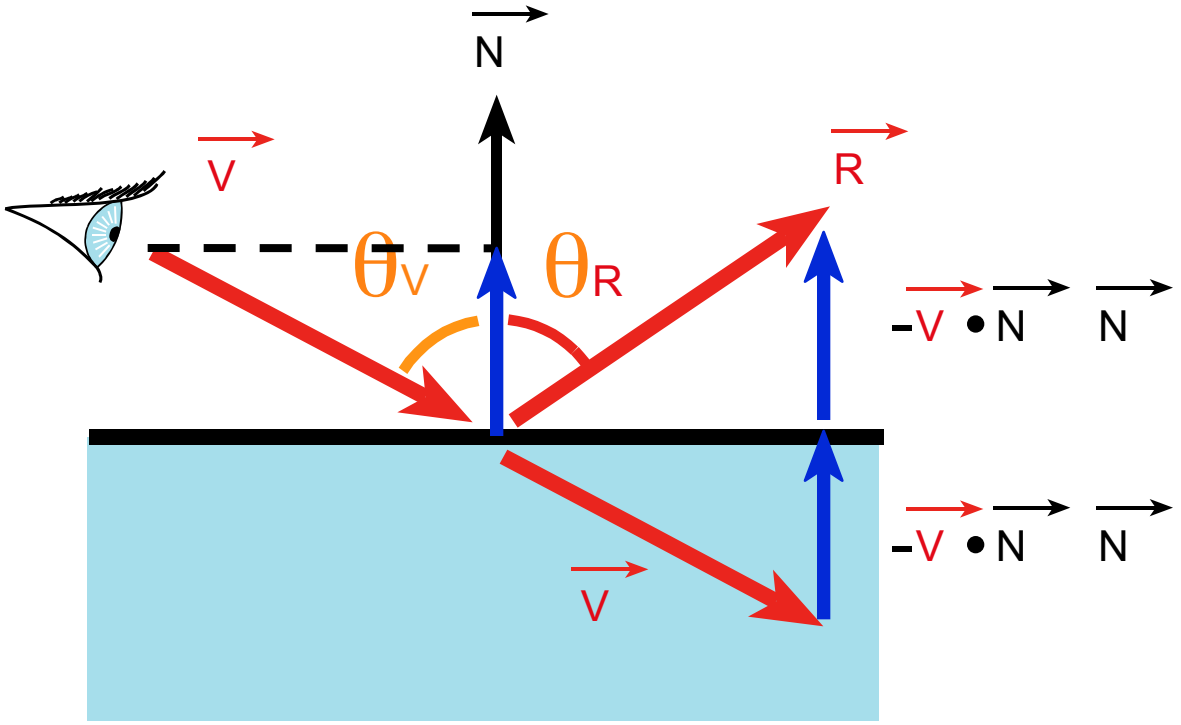






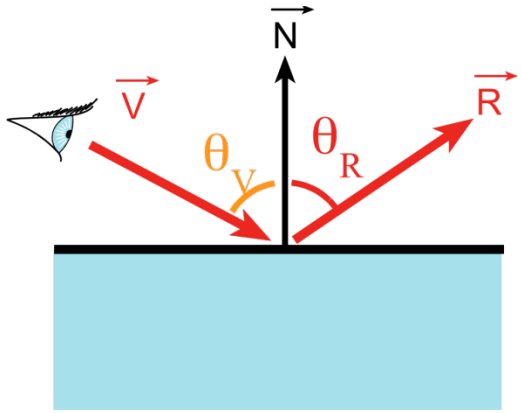
Perfect Mirror Reflection

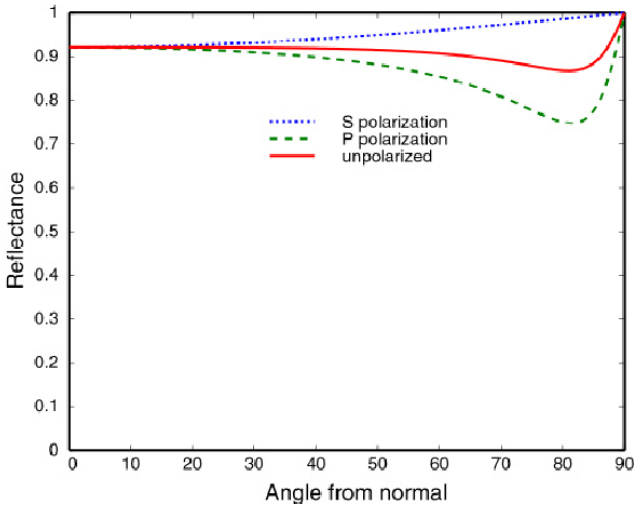
- Reflection angle = view angle
  - Normal component is negated
- $R = V - 2\,(V \cdot N)\,N$



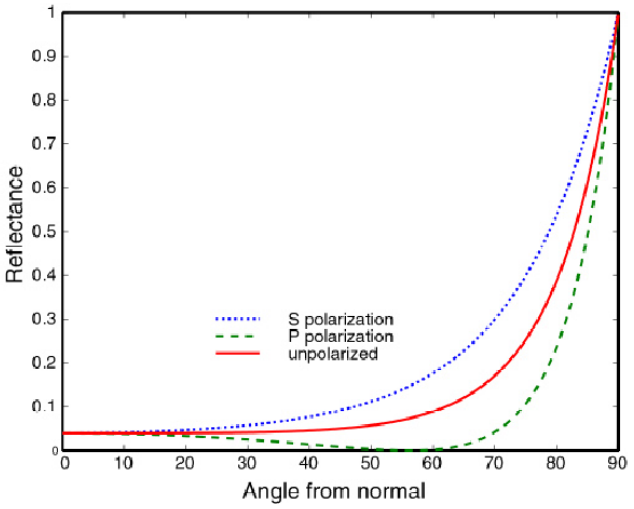
Amount of Reflection

- Traditional ray tracing (hack)
  - Constant k_s
- More realistic (we'll do this later):
  - Fresnel reflection term (more reflection at grazing angle)
  - Schlick's approximation: $R(\theta)=R_0+(1-R_0)(1-\cos\theta)^5$
- Fresnel makes a big difference!





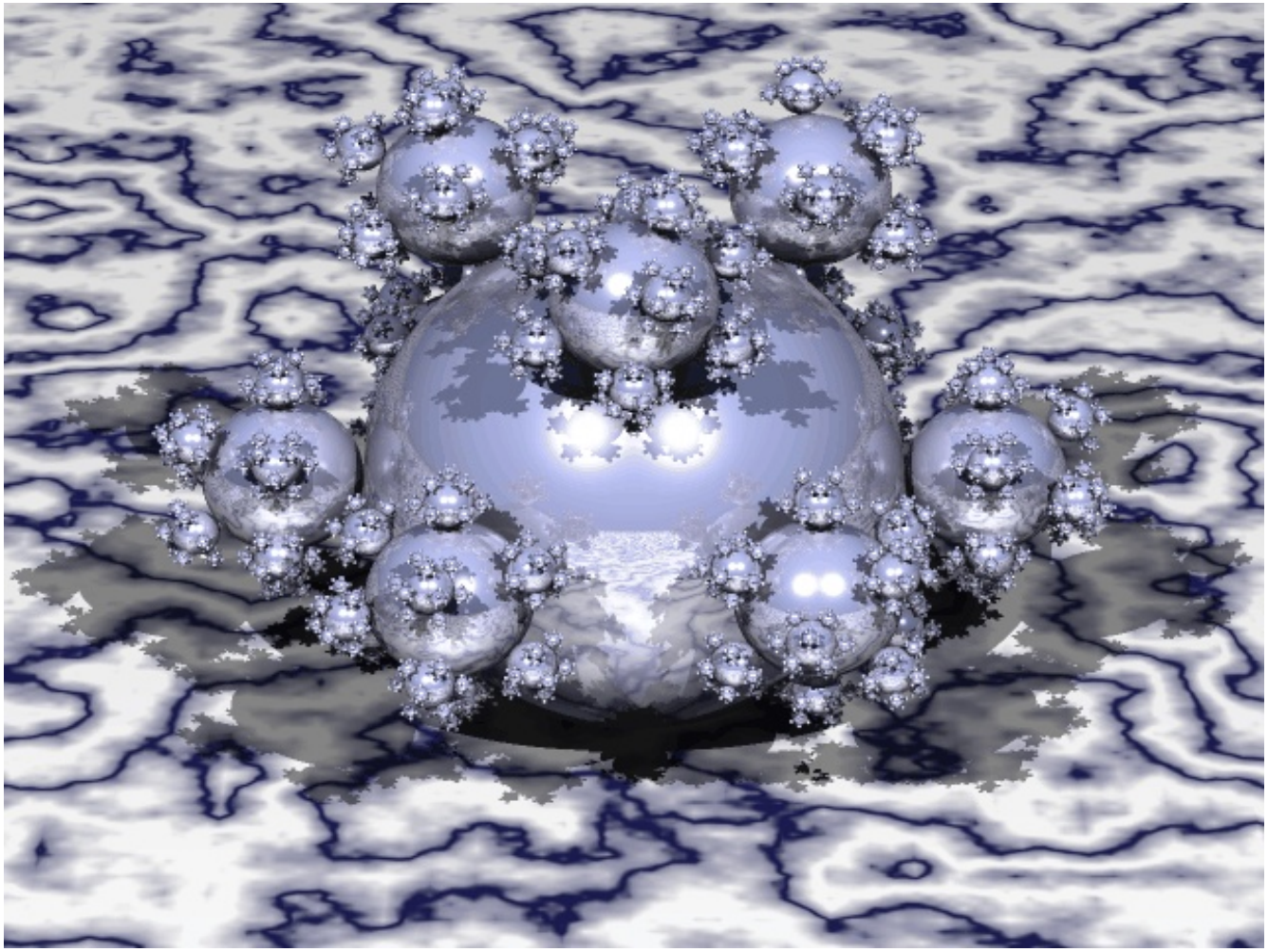
metal



Dielectric (glass)

Questions?

"Sphereflake" fractal



Henrik Wann Jensen

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- Shadows
- Reflection
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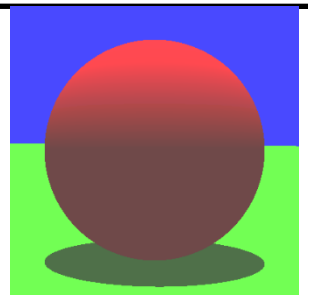
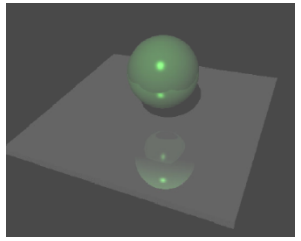
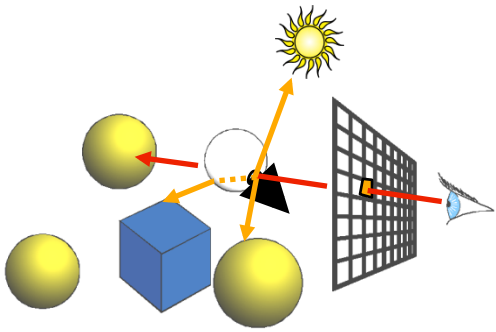
- Recursive Ray Tracing

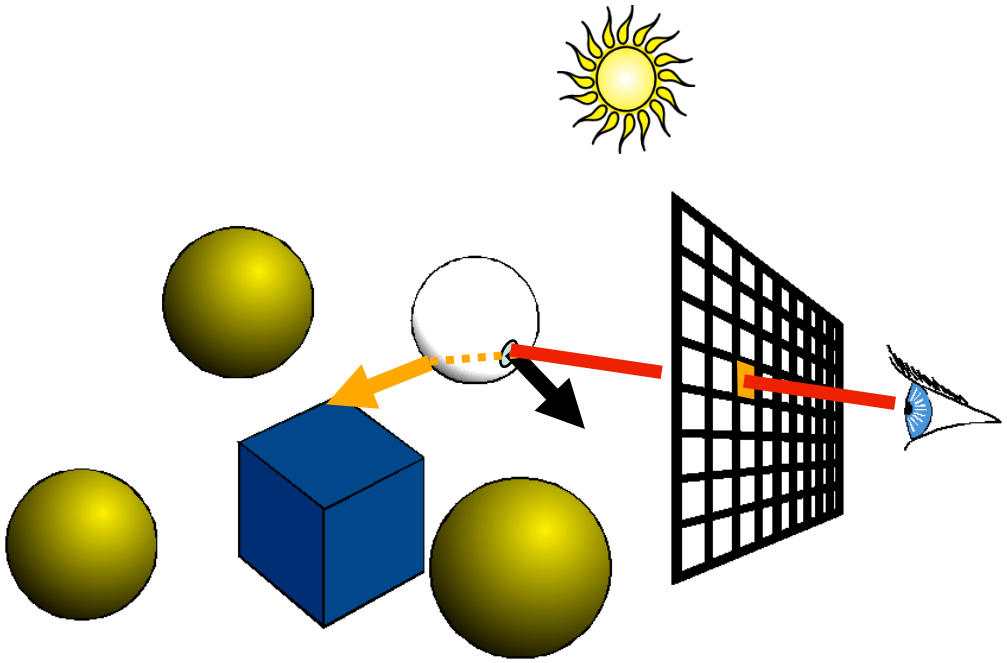




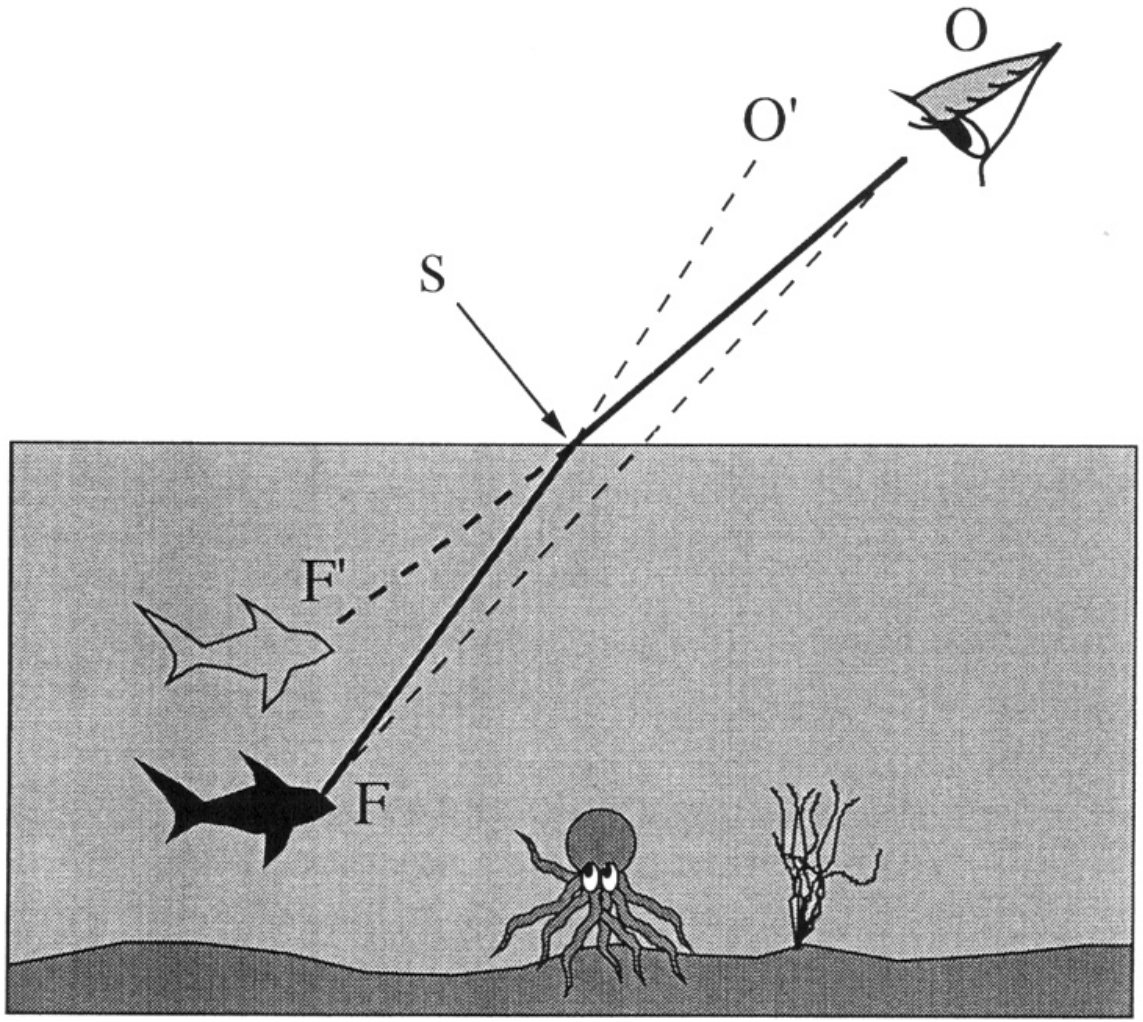


Transparency (Refraction)

- Cast ray in refracted direction
- Multiply by transparency coefficient k_t (color)

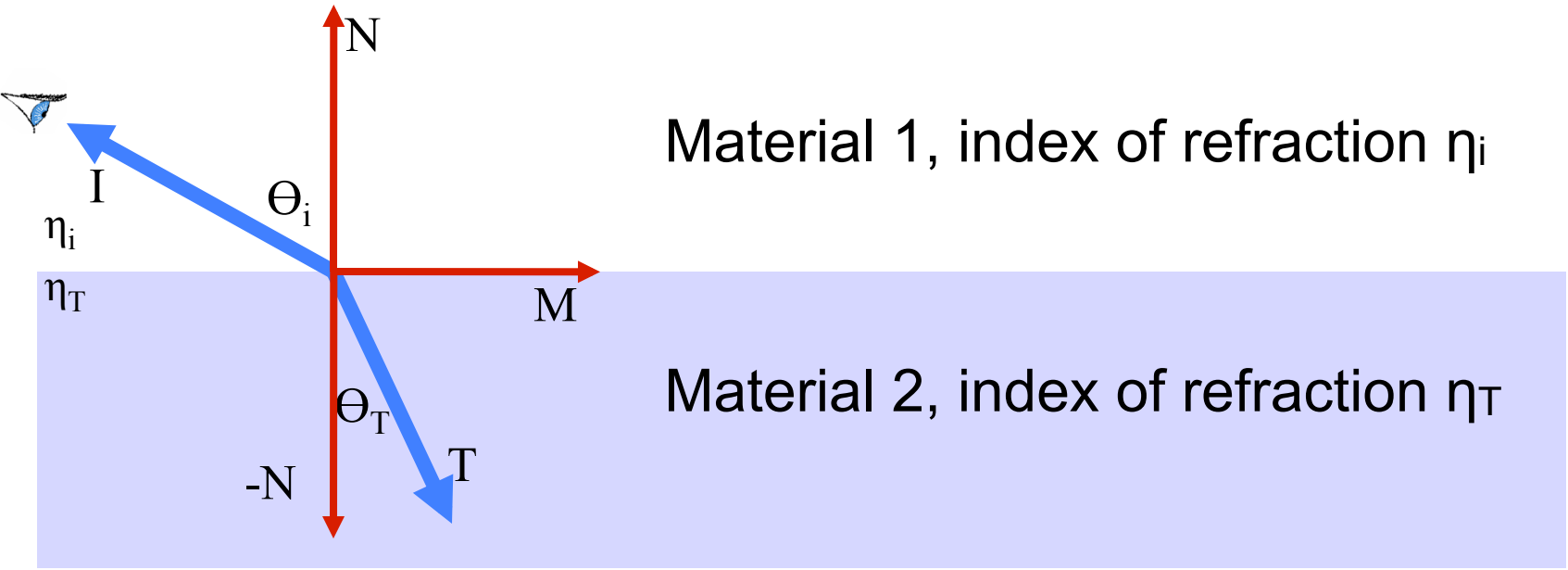


Qualitative Refraction



From “Color and Light in Nature” by Lynch and Livingston

Refraction



Snell-Descartes Law:

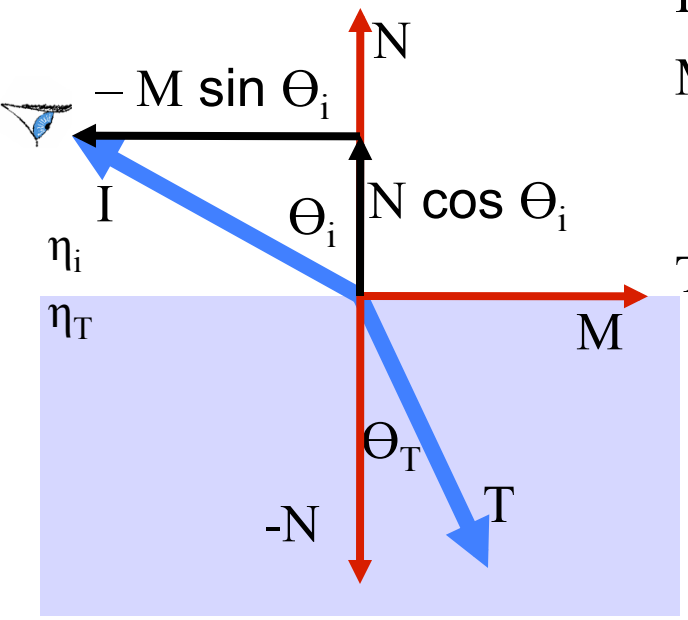
$$n_i \sin\theta_i = n_T \sin\theta_T$$

Refracted direction T?

$$\sin\theta_T / \sin\theta_i = n_i / n_T = n_r$$

Relative index of refraction

Refraction



$$I = N \cos \Theta_i - M \sin \Theta_i$$

$$M = (N \cos \Theta_i - I) / \sin \Theta_i$$

$$T = -N \cos \Theta_T + M \sin \Theta_T$$

$$= -N \cos \Theta_T + (N \cos \Theta_i - I) \sin \Theta_T / \sin \Theta_i \quad \text{Plug M}$$

$$= -N \cos \Theta_T + (N \cos \Theta_i - I)\, \eta_r \quad \text{let's get rid of the cos \& sin}$$

$$= [\, \eta_r \cos \Theta_i - \cos \Theta_T \,] N - \eta_r I$$

$$= [\, \eta_r \cos \Theta_i - \sqrt{1 - \sin^2 \Theta_T} \,] N - \eta_r I$$

$$= [\, \eta_r \cos \Theta_i - \sqrt{1 - \eta_r^2 \sin^2 \Theta_i} \,] N - \eta_r I$$

$$= [\, \eta_r \cos \Theta_i - \sqrt{1 - \eta_r^2 (1 - \cos^2 \Theta_i)} \,] N - \eta_r I$$

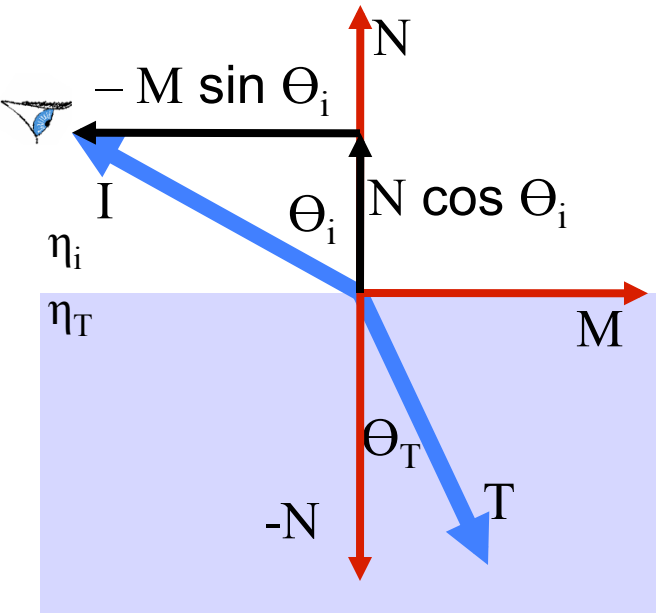
$$= [\, \eta_r (N \cdot I) - \sqrt{1 - \eta_r^2 (1 - (N \cdot I)^2)} \,] N - \eta_r I$$

Snell-Descartes Law:

$$n_i \sin\theta_i = n_T \sin\theta_T$$

$$\sin\theta_T / \sin\theta_i = n_i / n_T = n_r$$

Refraction



$$I = N \cos \Theta_i - M \sin \Theta_i$$

$$M = (N \cos \Theta_i - I) / \sin \Theta_i$$

- Total internal reflection when the square root is imaginary (no refraction, just reflection)

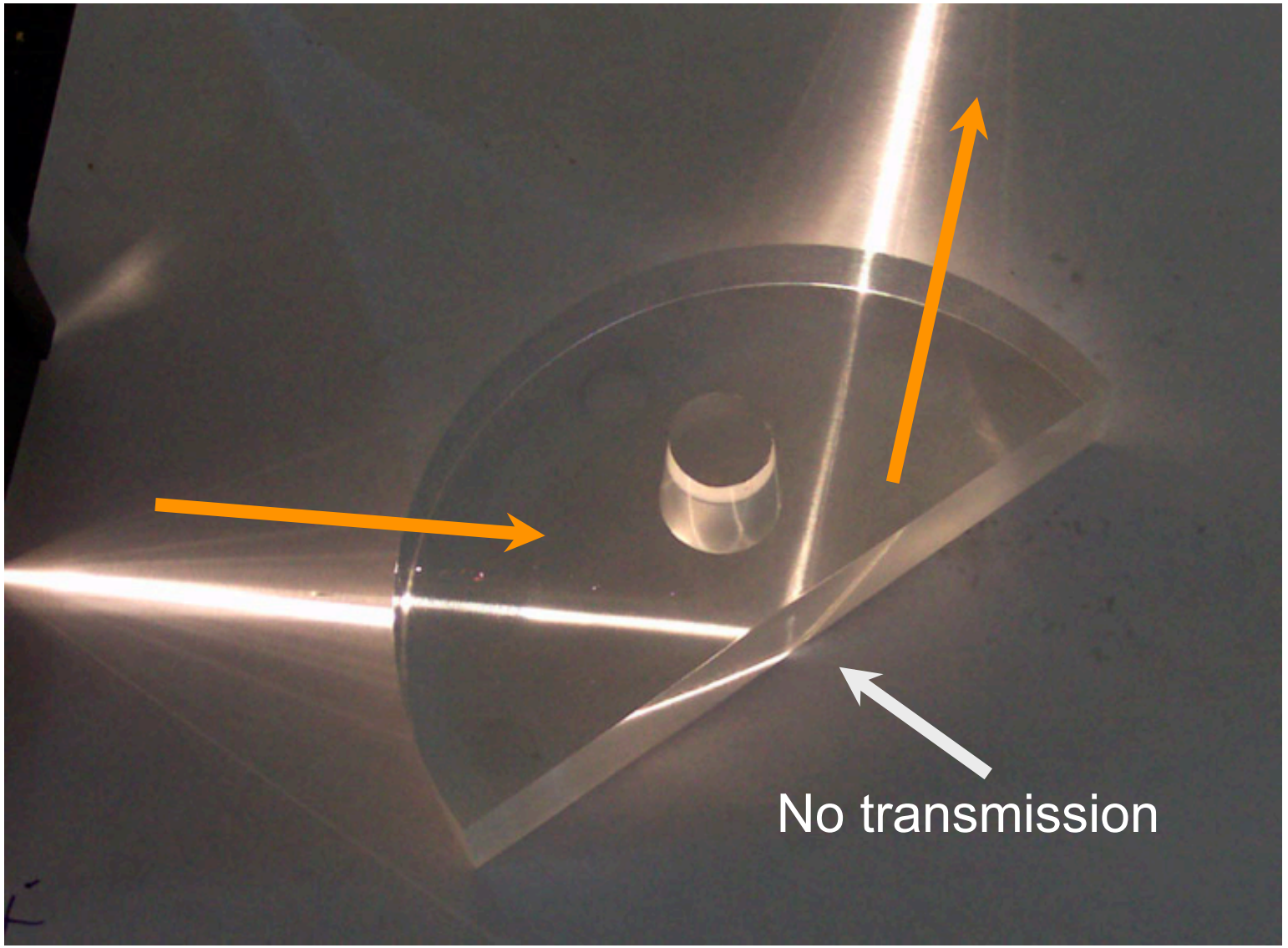
Snell-Descartes Law:

$$n\downarrow i \sin\theta\downarrow i = n\downarrow T \sin\theta\downarrow T$$

$$\sin\theta\downarrow T / \sin\theta\downarrow i = n\downarrow i / n\downarrow T = n\downarrow r$$

$$= [\, \eta_r (N \cdot I) - \sqrt{1 - \eta_r^2 (1 - (N \cdot I)^2)} \,] N - \eta_r I$$

Total Internal Reflection



Wikipedia user Fir0002

Total Internal Reflection

Fig. 3.7A The optical manhole. From under water, the entire celestial hemisphere is compressed into a circle only 97.2° across. The dark boundary defining the edges of the manhole is not sharp due to surface waves. The rays are analogous to the crepuscular type seen in hazy air, Section 1.9. (Photo by D. Granger)

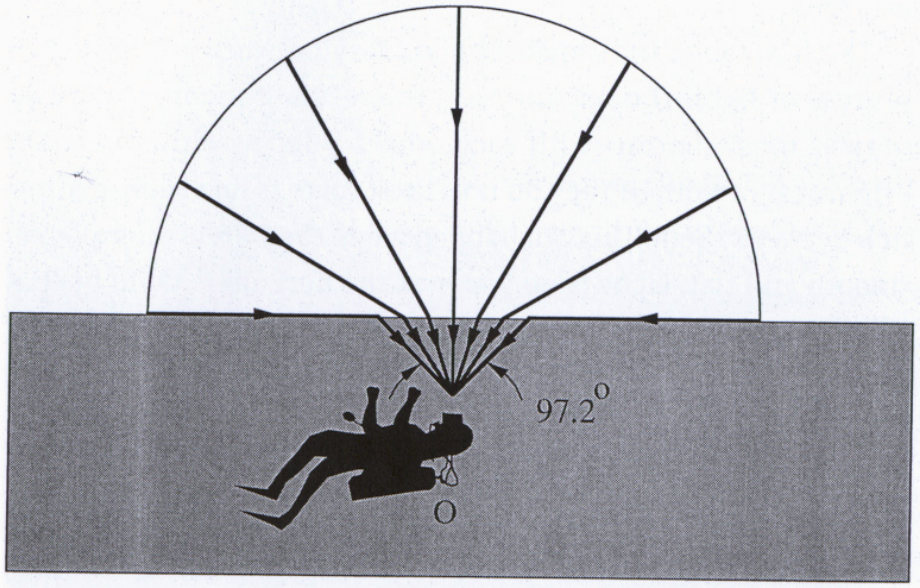
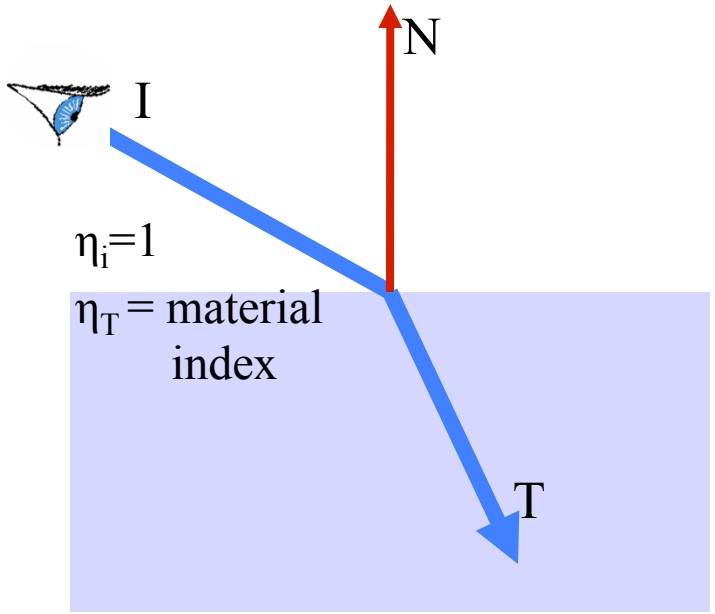


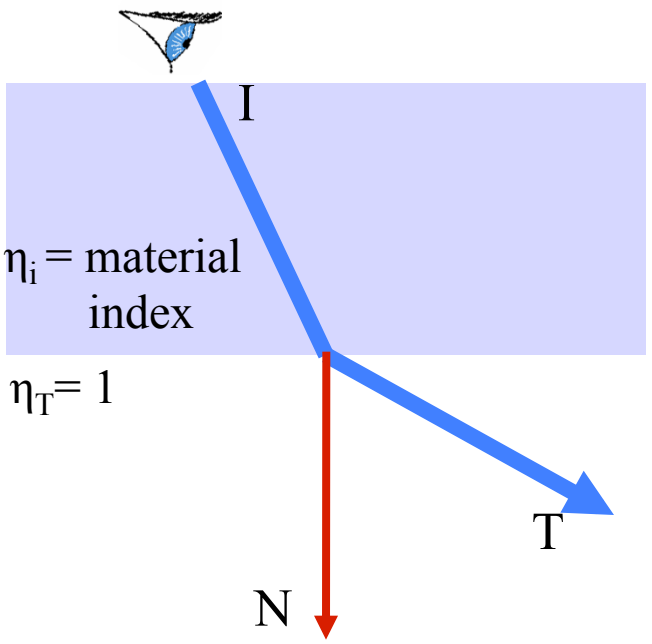
Fig. 3.7B The optical manhole. Light from the horizon (angle of incidence = 90°) is refracted downward at an angle of 48.6°. This compresses the sky into a circle with a diameter of 97.2° instead of its usual 180°.

From "Color and Light in Nature" by Lynch and Livingston

Refraction & Sidedness of Objects

- Make sure you know whether you're entering or leaving the transmissive material:





Sign of dot product

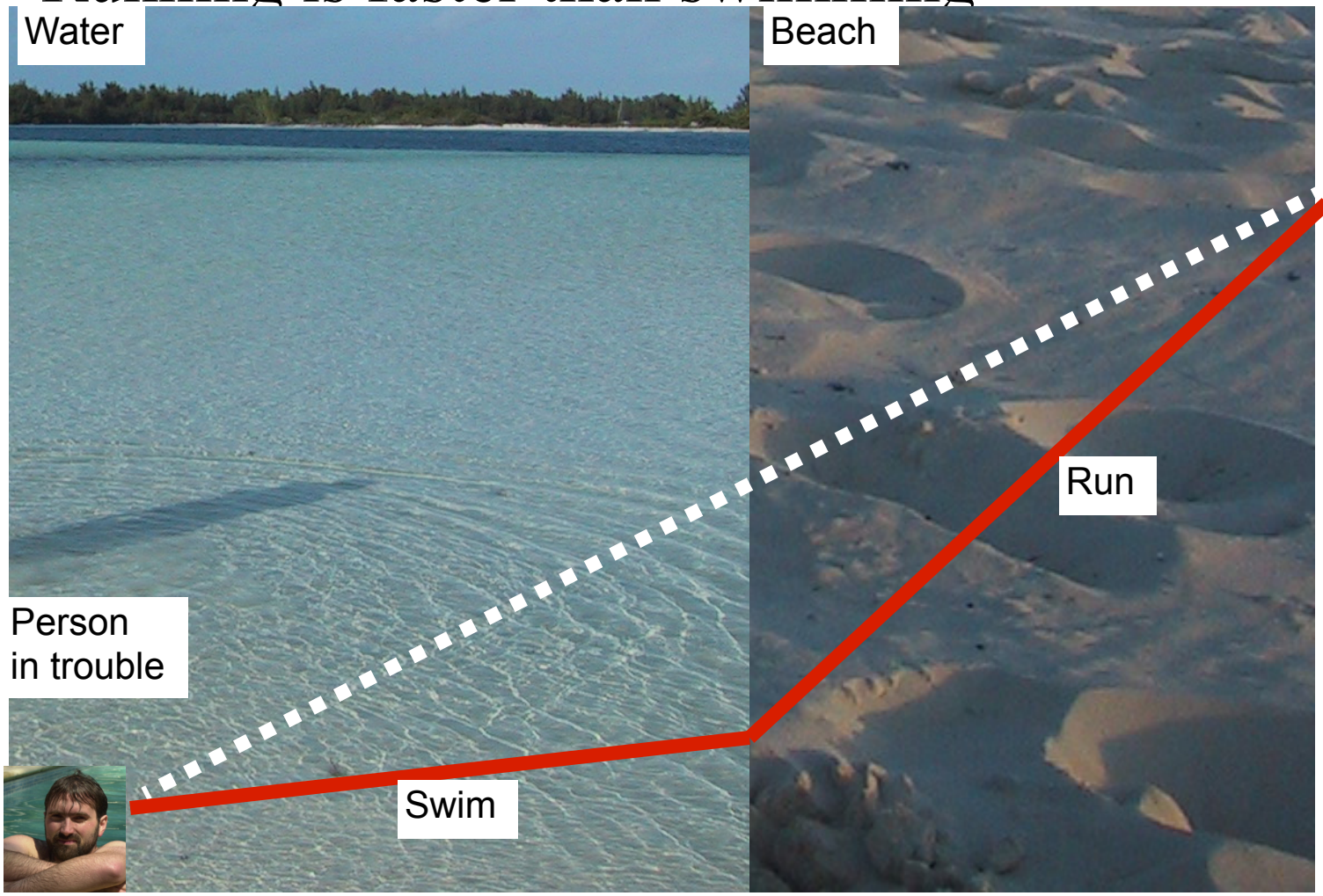
- Note: We won't ask you to trace rays through intersecting transparent objects :-)

Cool Refraction Demo

- Enright, D., Marschner, S. and Fedkiw, R., SIGGRAPH 2002

Refraction and the Lifeguard Problem

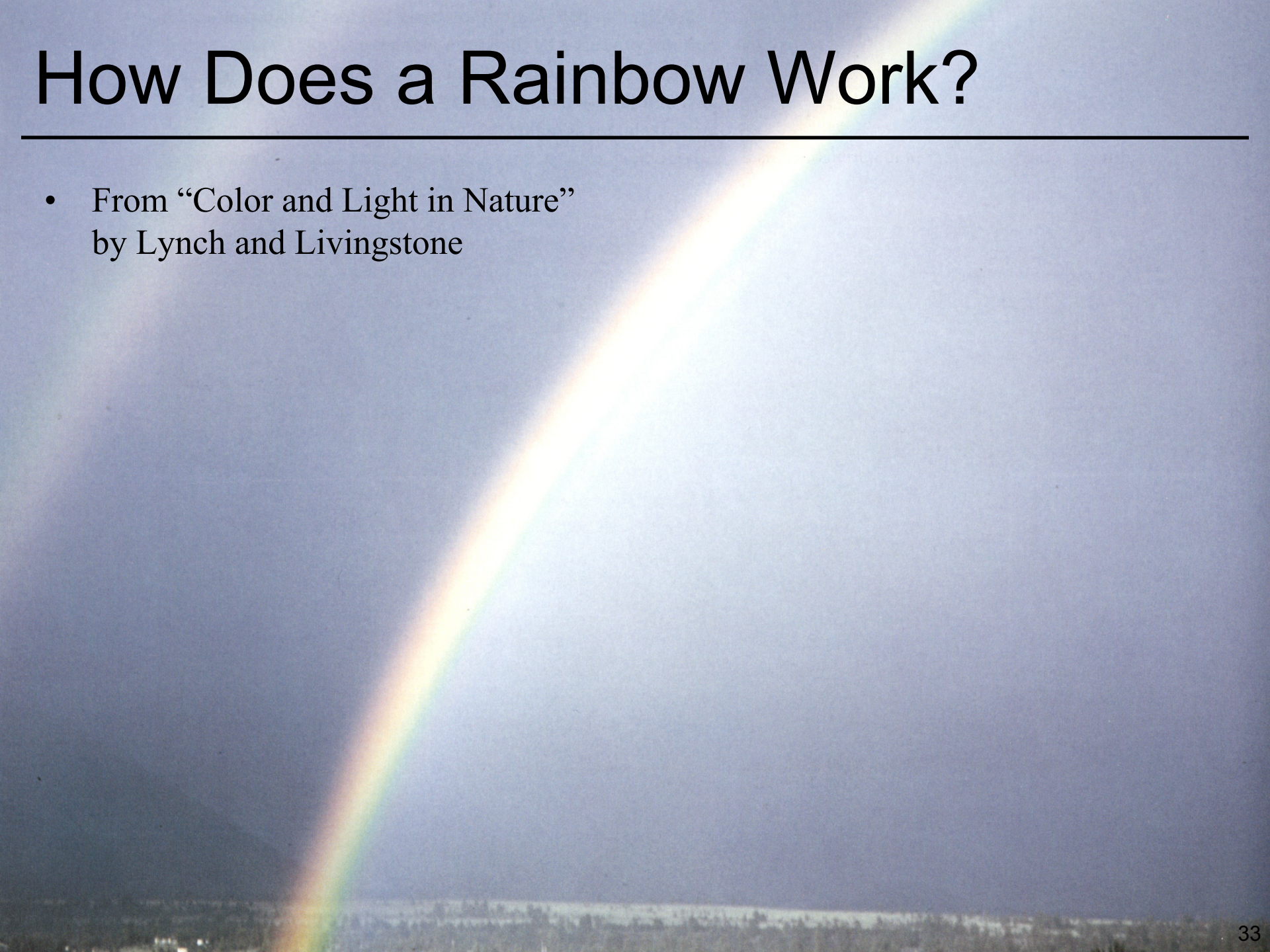
- Running is faster than swimming



Lifeguard

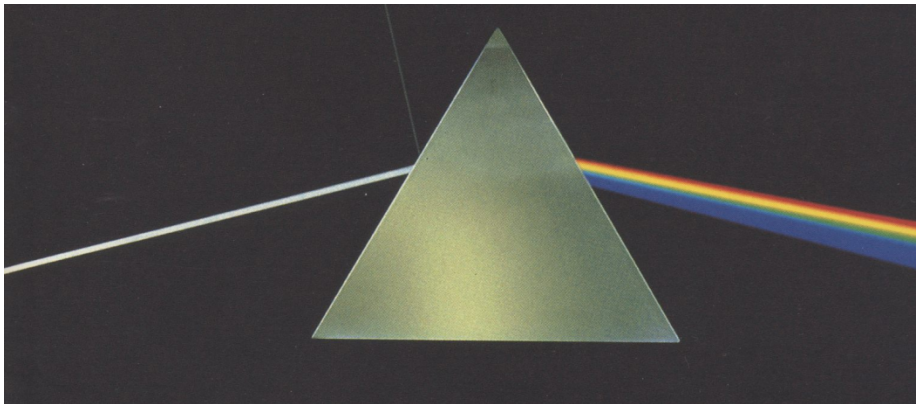
How Does a Rainbow Work?

- From “Color and Light in Nature” by Lynch and Livingstone



Wavelength

- Refraction is wavelength-dependent (dispersion)
  - Refraction increases as the wavelength of light decreases
  - violet and blue experience more bending than orange and red
- Newton's prism experiment
- Usually ignored in graphics

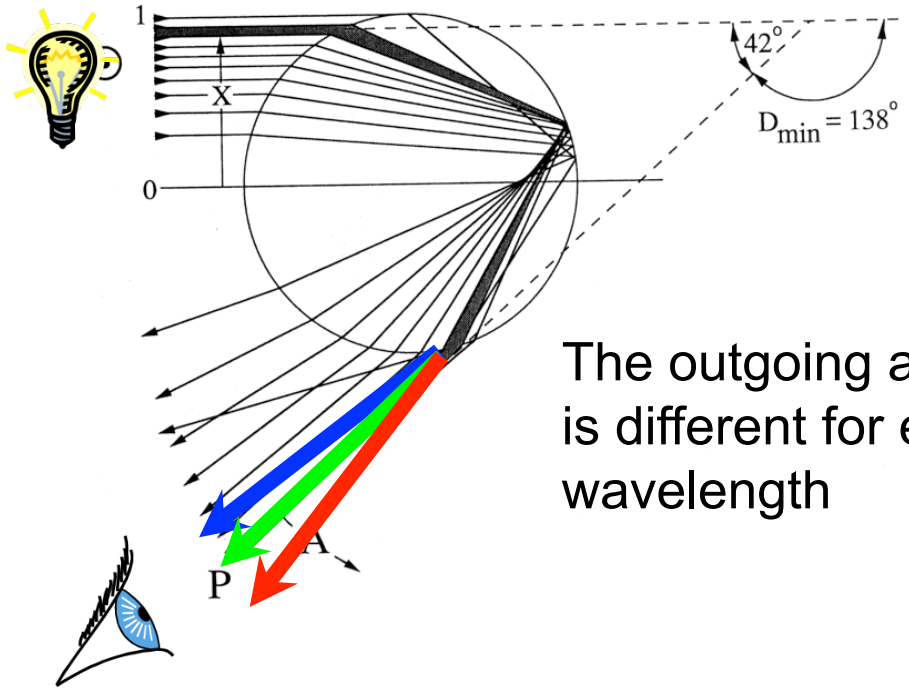


Pink Floyd, The Dark Side of the Moon

Pittoni, 1725, Allegory to Newton

Rainbow

- Rainbow is caused by
  refraction + internal reflection + refraction
- Maximum for angle around 42 degrees
- Refraction depends on wavelength (dispersion)

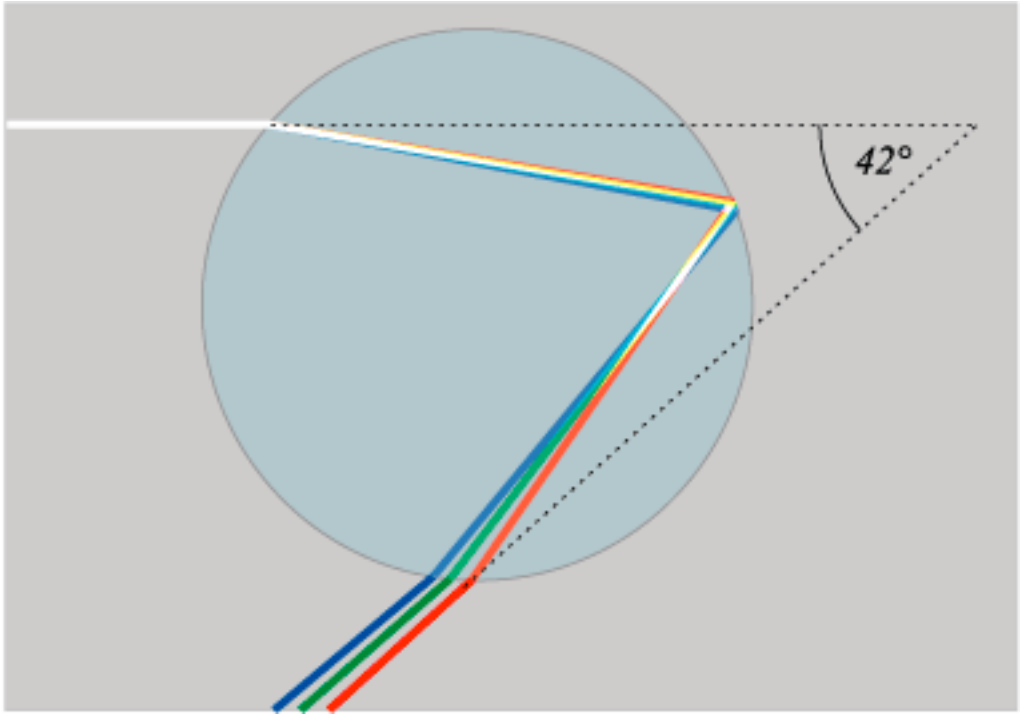


The outgoing angle is different for each wavelength

"Color and Light in Nature" by Lynch and Livingstone

Rainbow

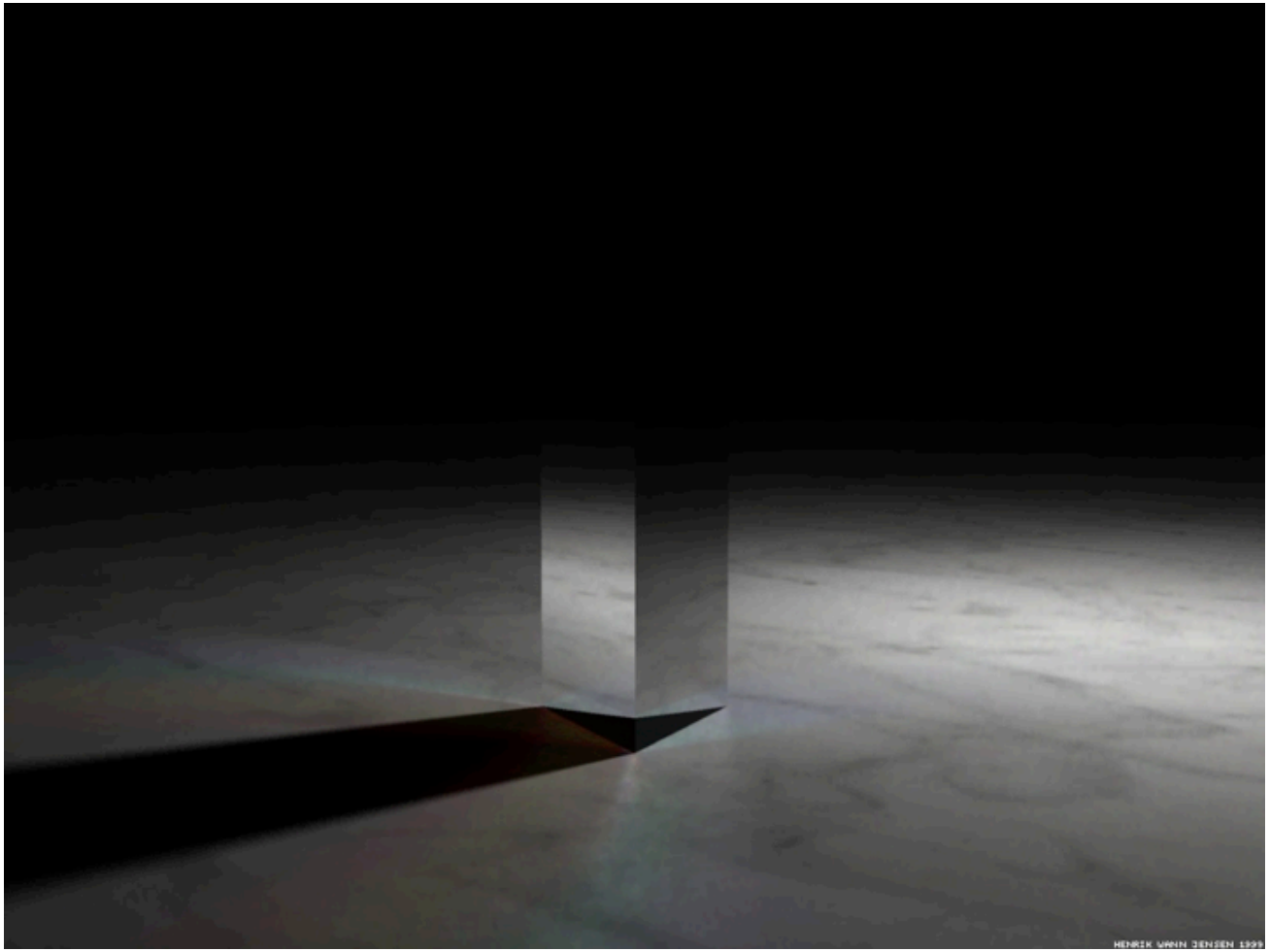
- Rainbow is caused by refraction + internal reflection + refraction
- Maximum for angle around 42 degrees
- Refraction depends on wavelength (dispersion)



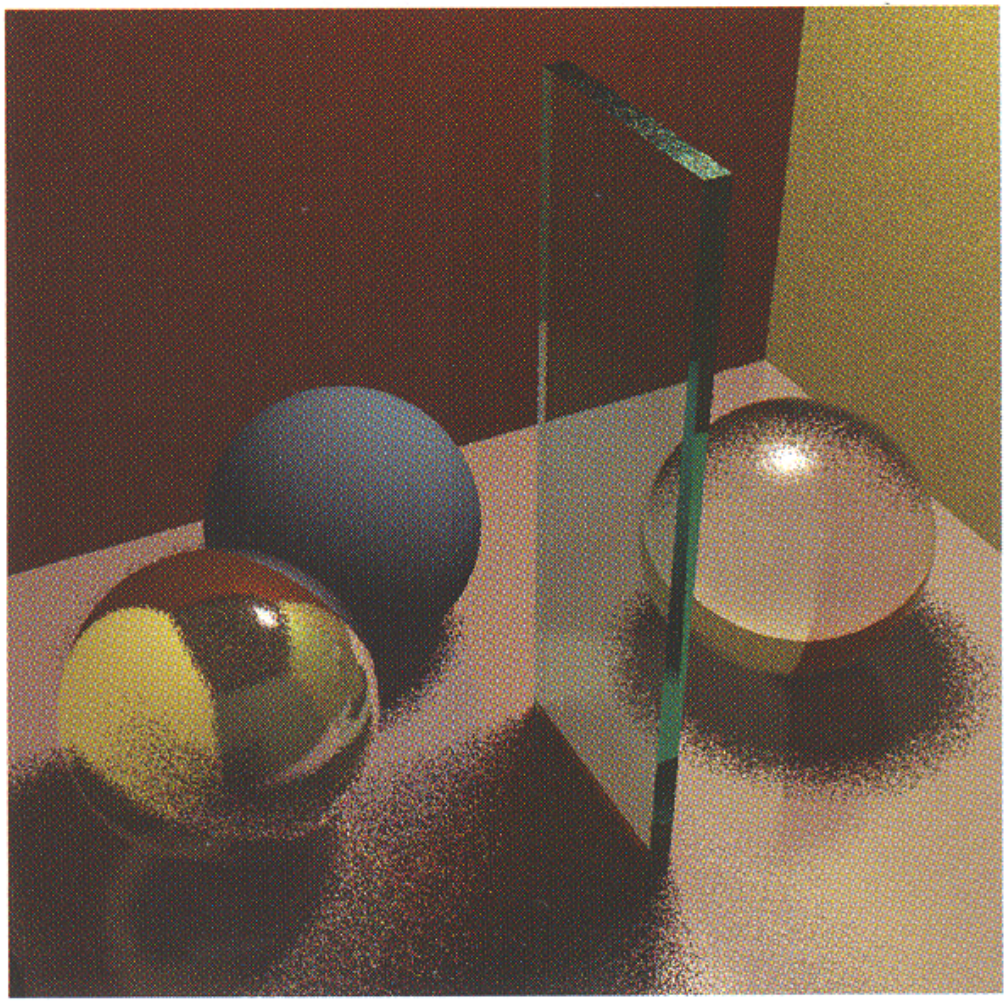
Wikipedia

Dispersion

- Image by Henrik Wann Jensen using Photon Mapping



Questions?



Application: CAD for lenses

- Has revolutionized lens design
  - E.g. zoom lenses are good now

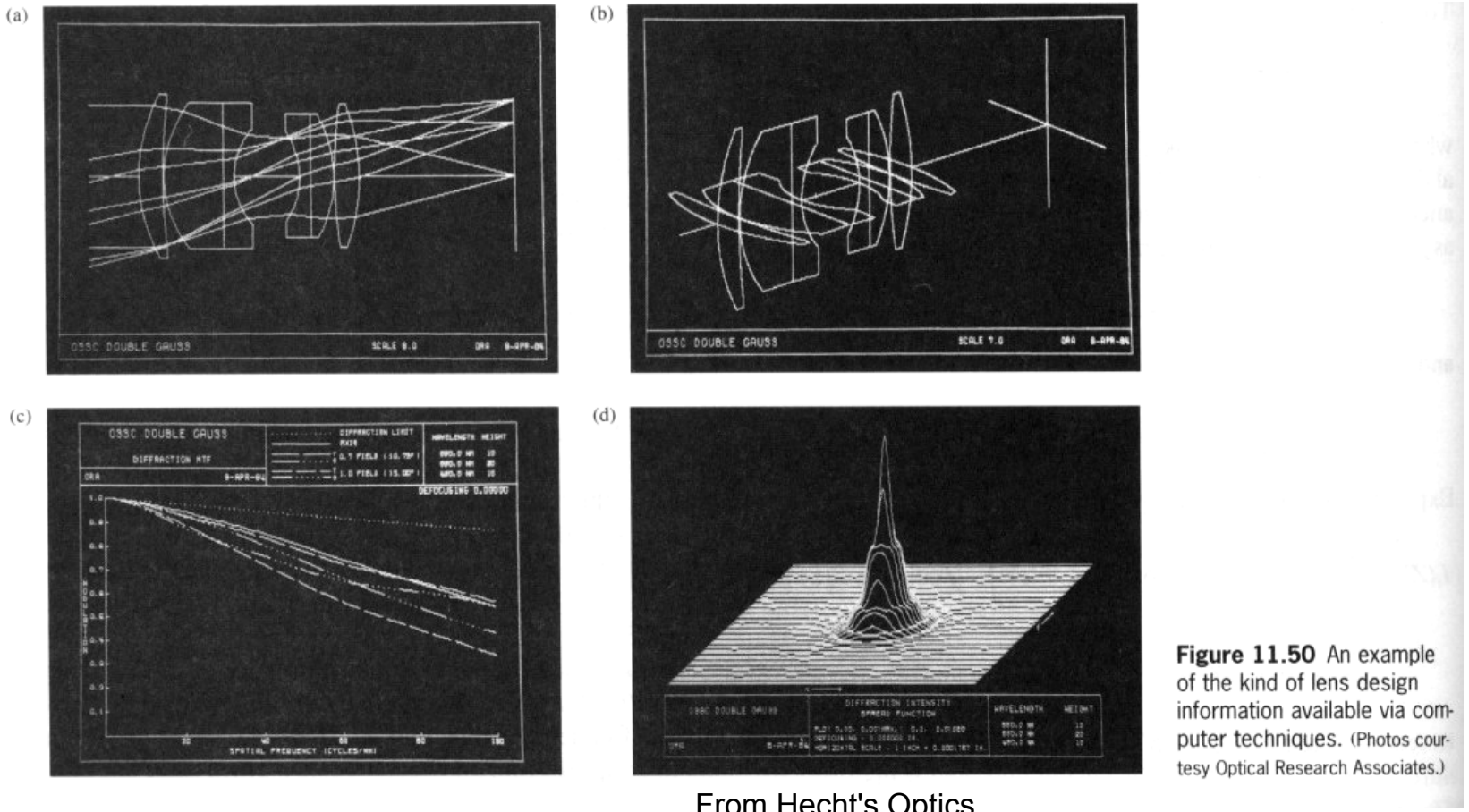


Figure 11.50 An example of the kind of lens design information available via computer techniques. (Photos courtesy Optical Research Associates.)

From Hecht's Optics

Lens design by Ray Tracing

- Used to be done manually, by rooms full of engineers who would trace rays.
- Now software, e.g. Zemax

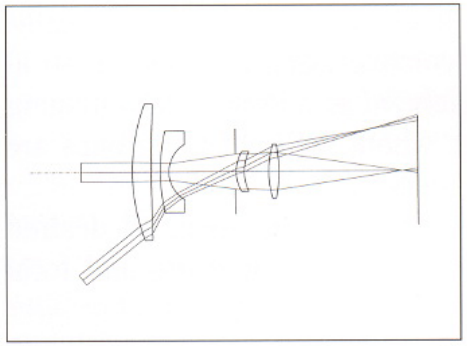


Figure-5

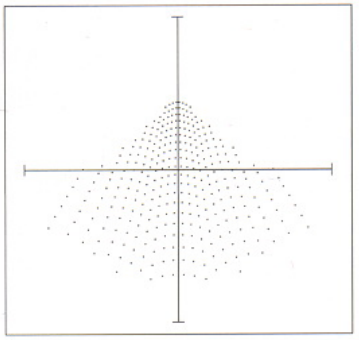


Figure-8

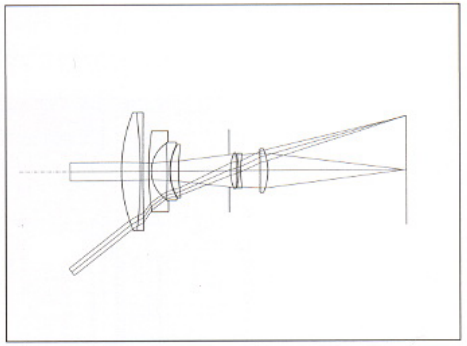


Figure-6

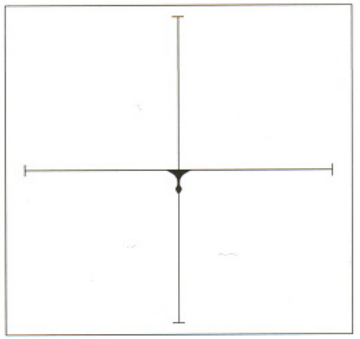


Figure-9

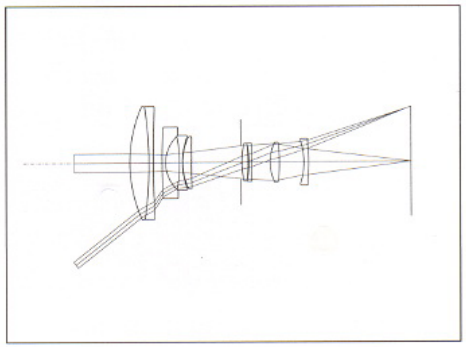


Figure-7

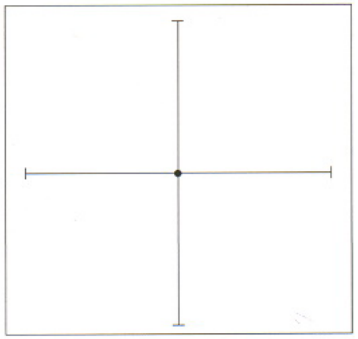
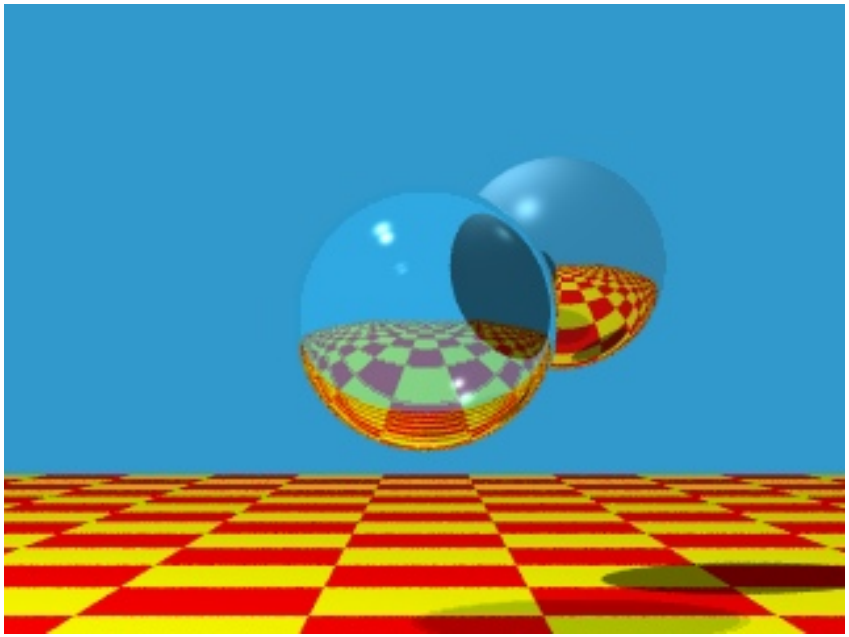


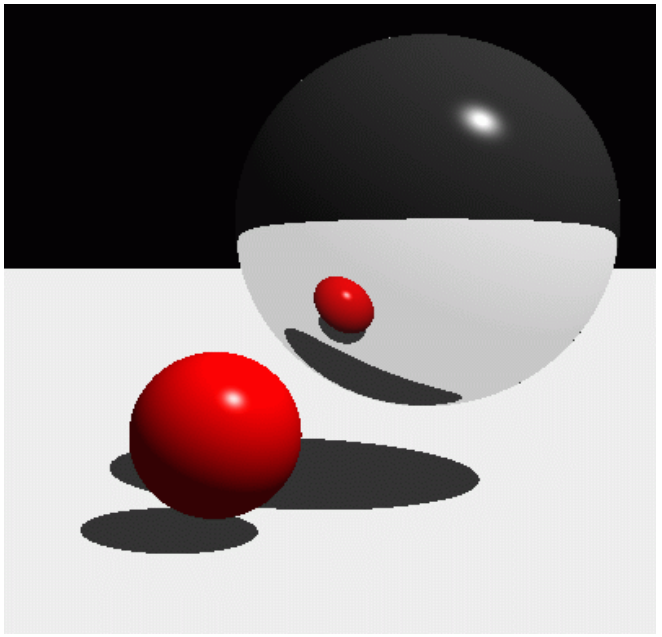
Figure-10

source: canon red book

Let's Pause for a Moment...

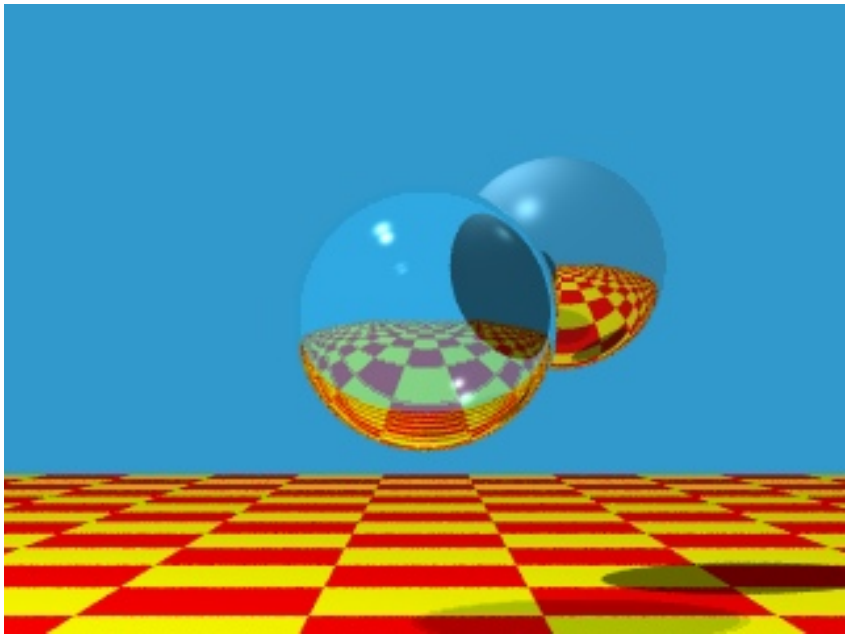
- Do these pictures look real?

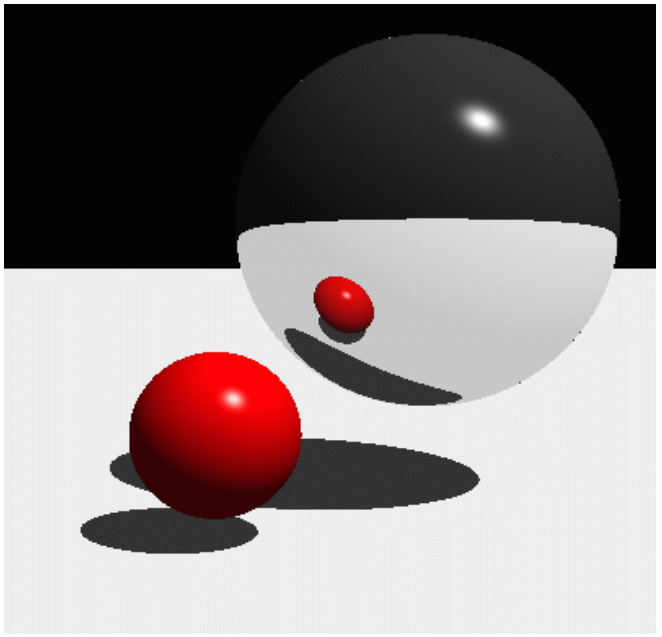




What's Wrong then?

- No surface is a perfect mirror,
  no material interface is perfectly smooth





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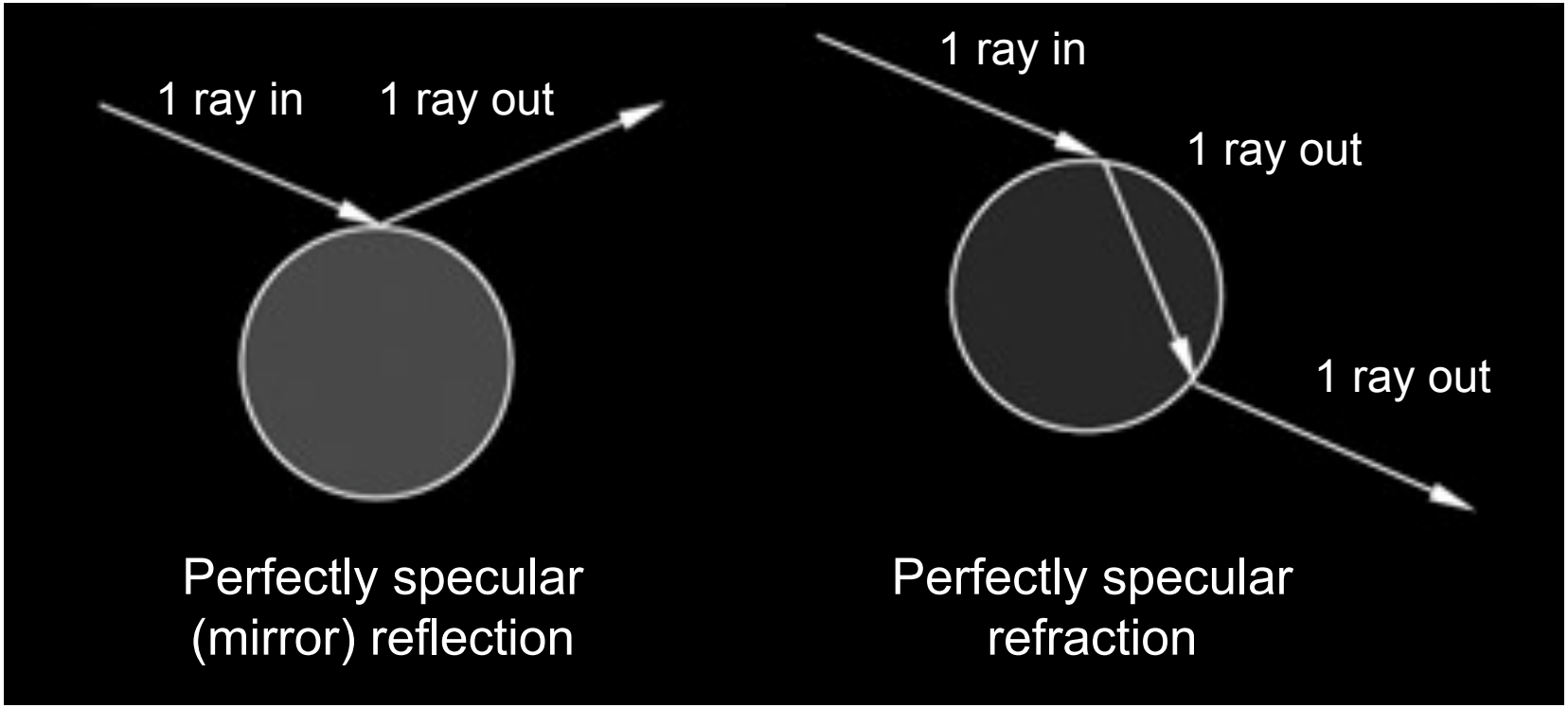
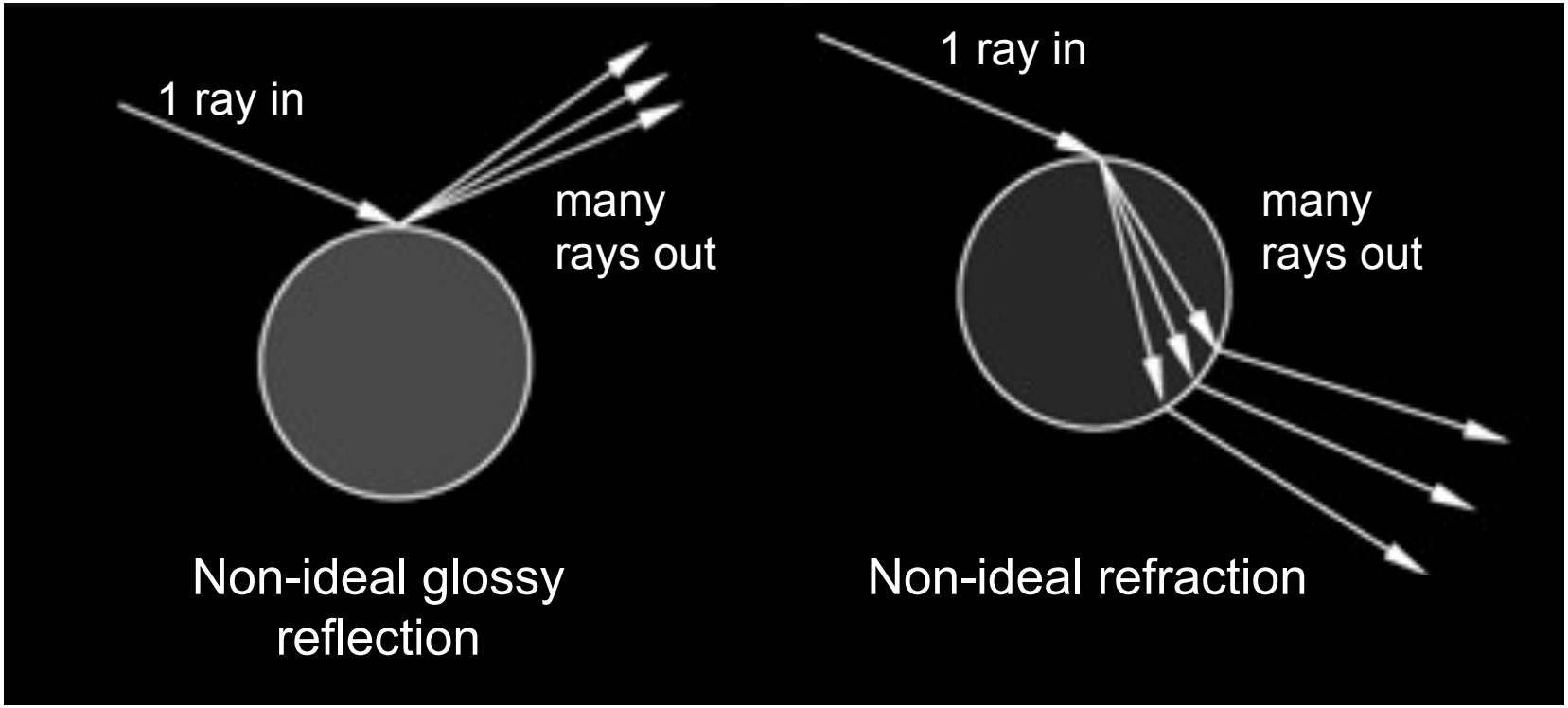


Adapted from blender.org

Non-Ideal Reflection/Refraction

- No surface is a perfect mirror,
  no material interface is perfectly smooth



Adapted from blender.org

Non-Ideal Reflection/Refraction

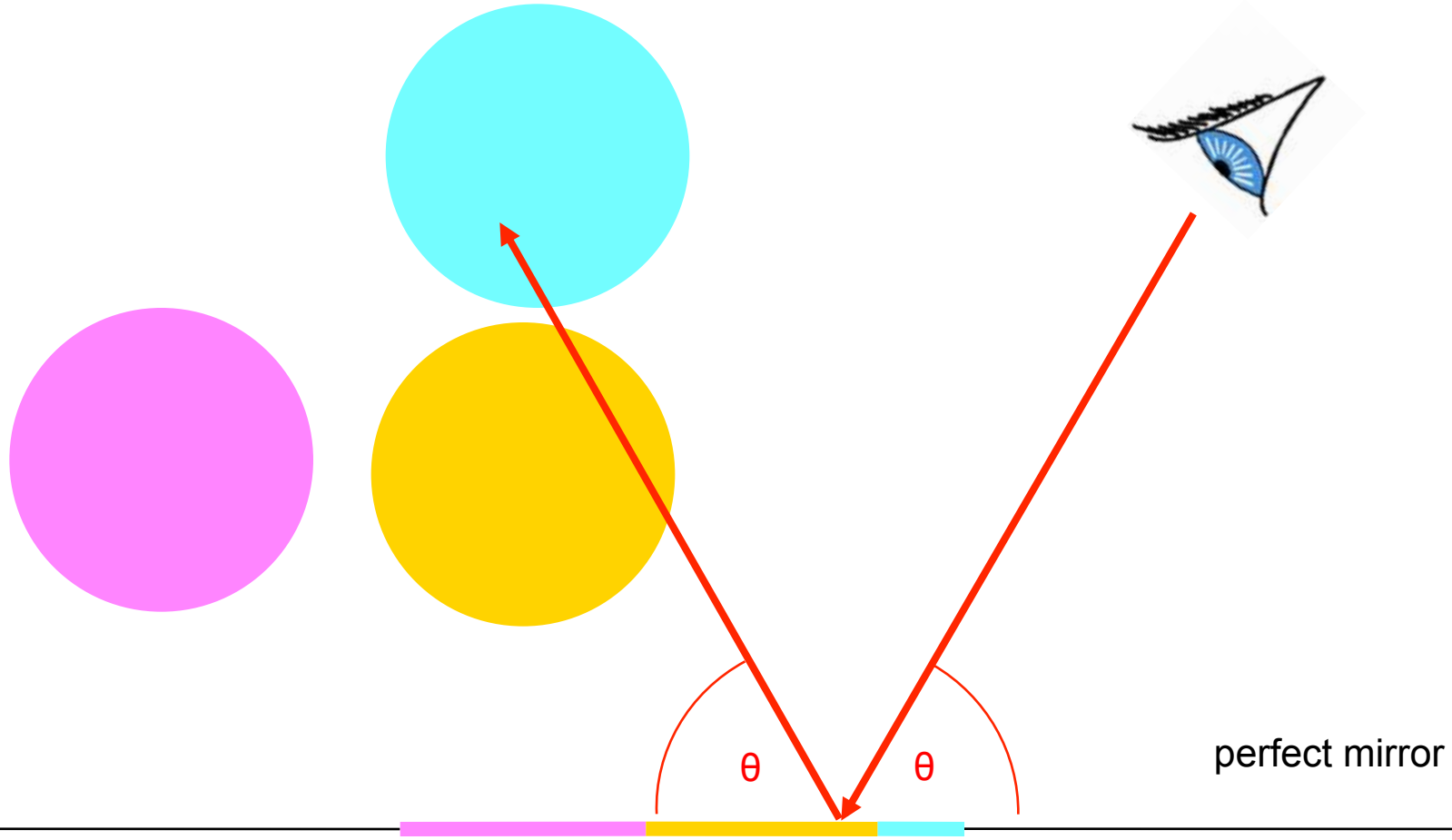
Glossy (as opposed to mirror) reflection

Glossy (as opposed to perfect) refraction

images from blender.org

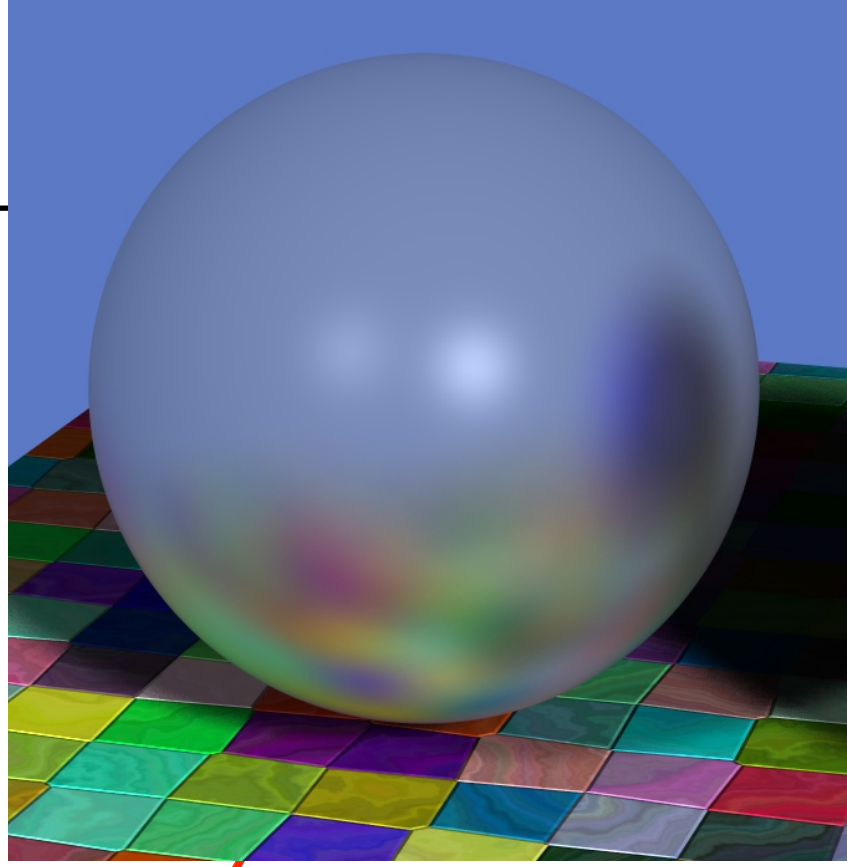
Reflection

- One reflection ray per intersection

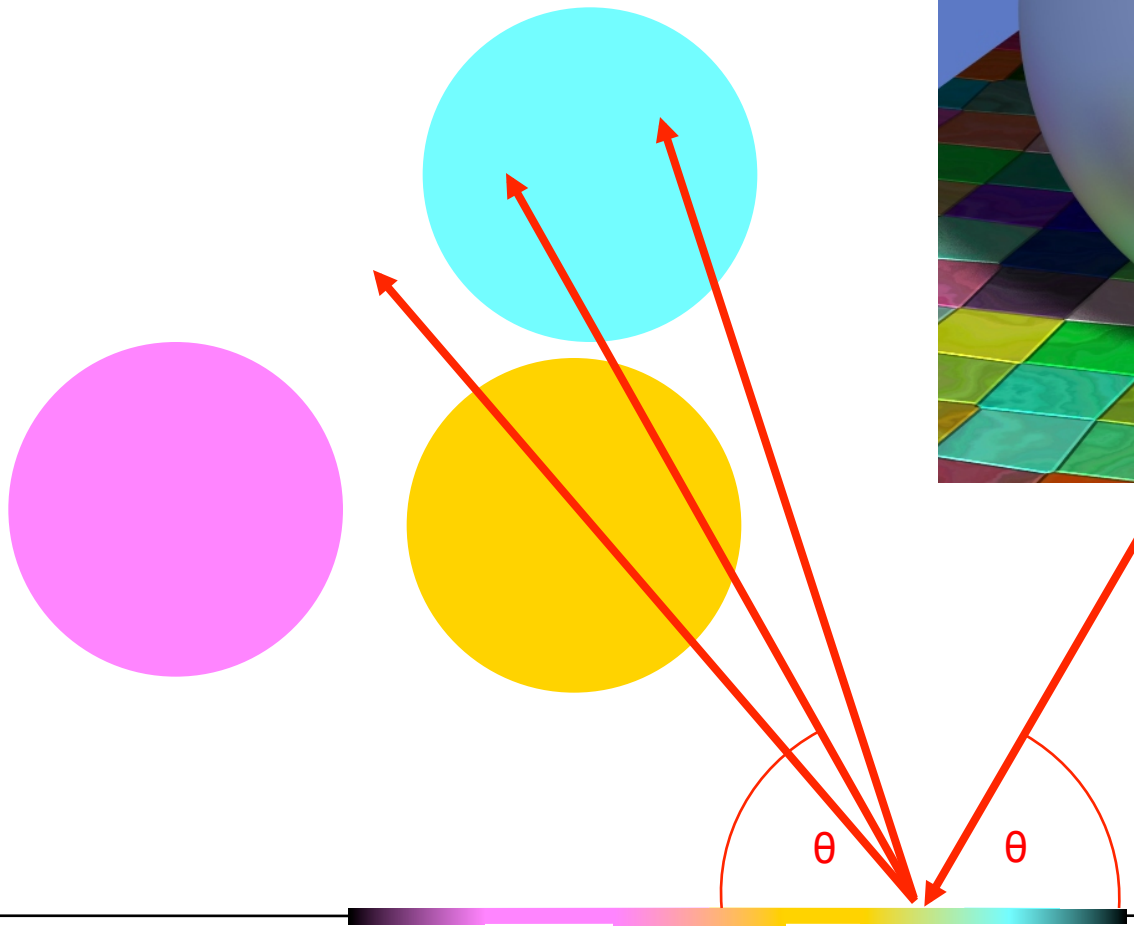


Glossy Reflection

- Multiple reflection rays

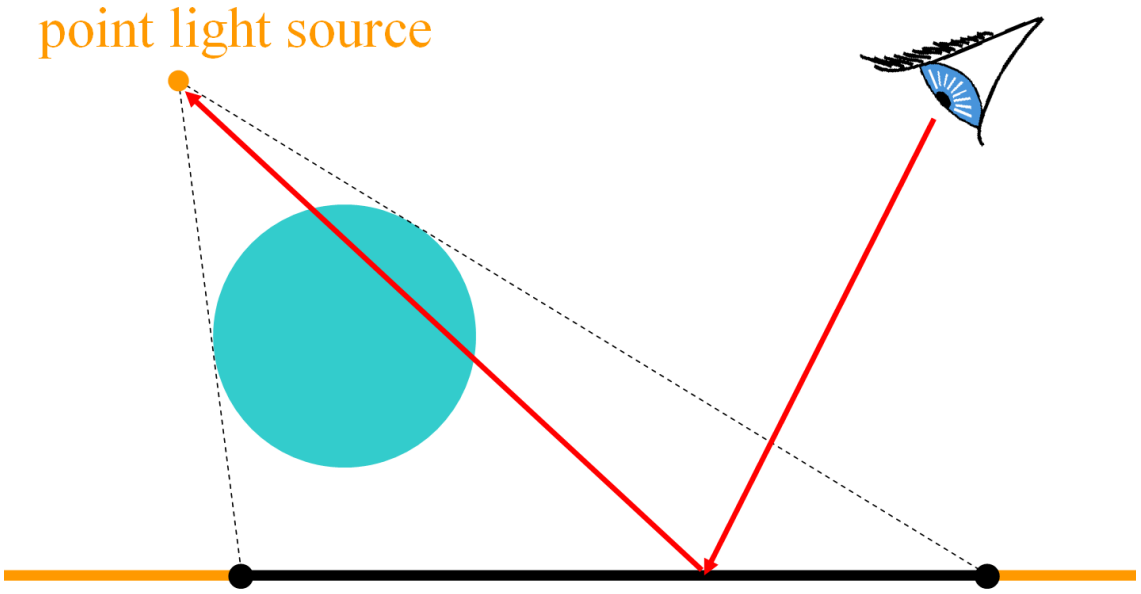


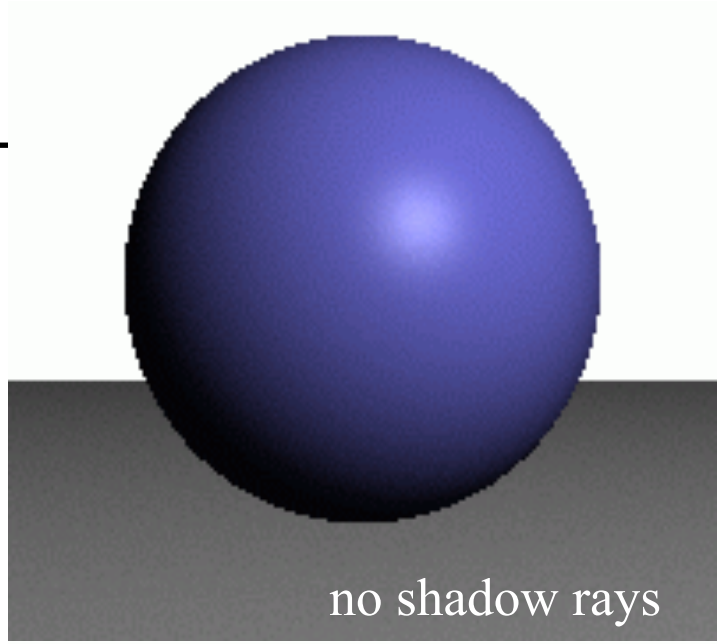
Justin Legakis

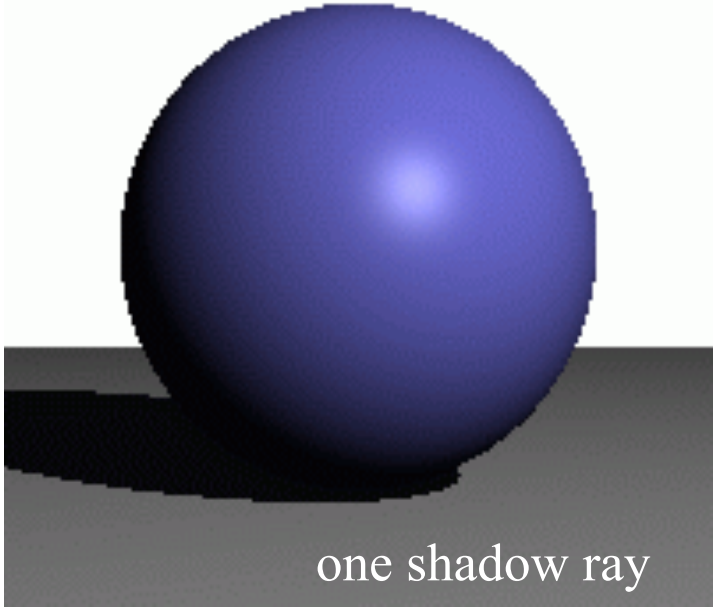


Shadows

- One shadow ray per intersection per point light source



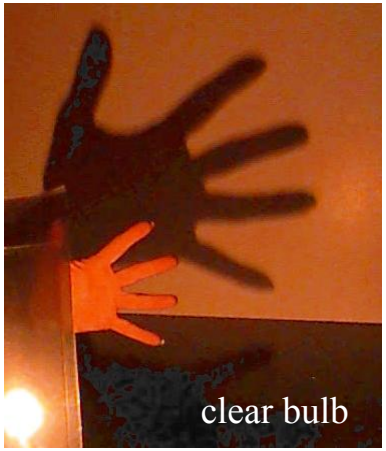


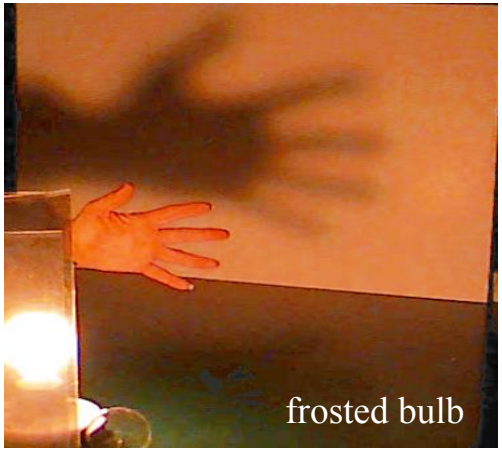


Shadows & Light Sources

http://3media.initialized.org/photos/2000-10-18/index_gall.htm

http://www.davidfay.com/index.php

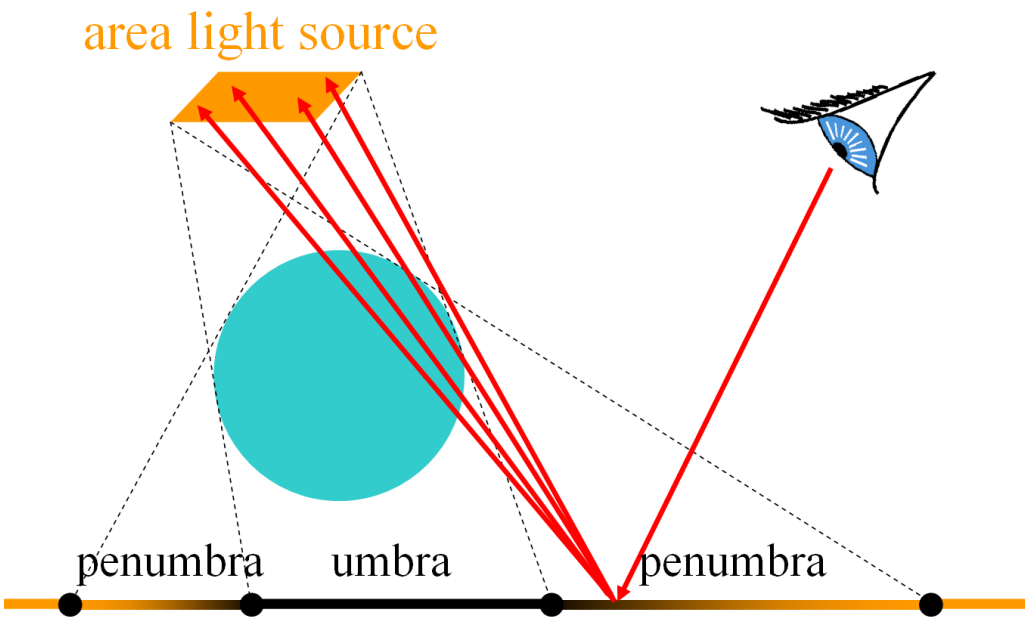


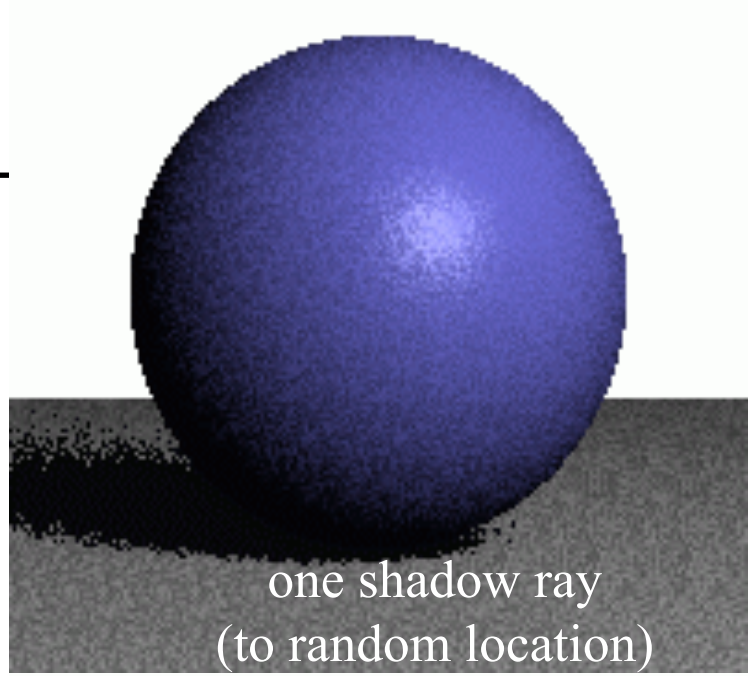


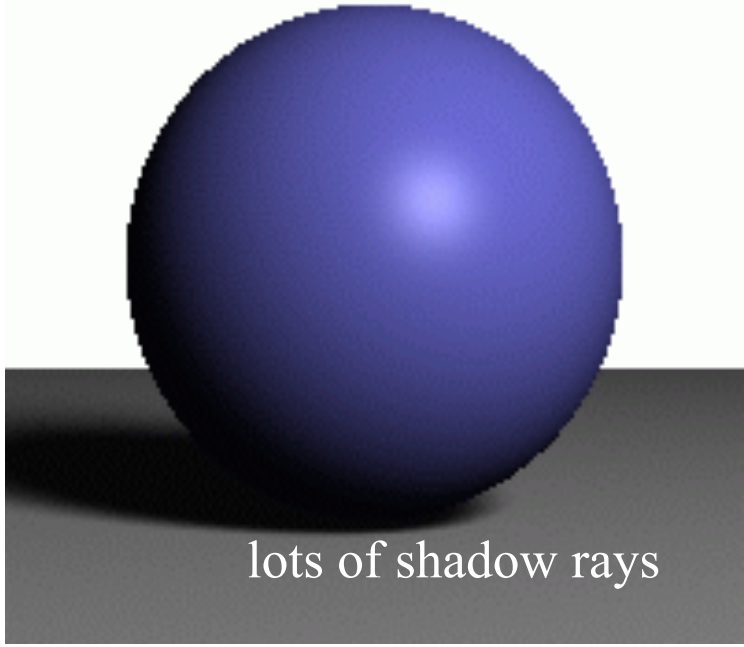
http://www.pa.uky.edu/~sciworks/light/preview/bulb2.htm

Soft Shadows

- Multiple shadow rays to sample area light source



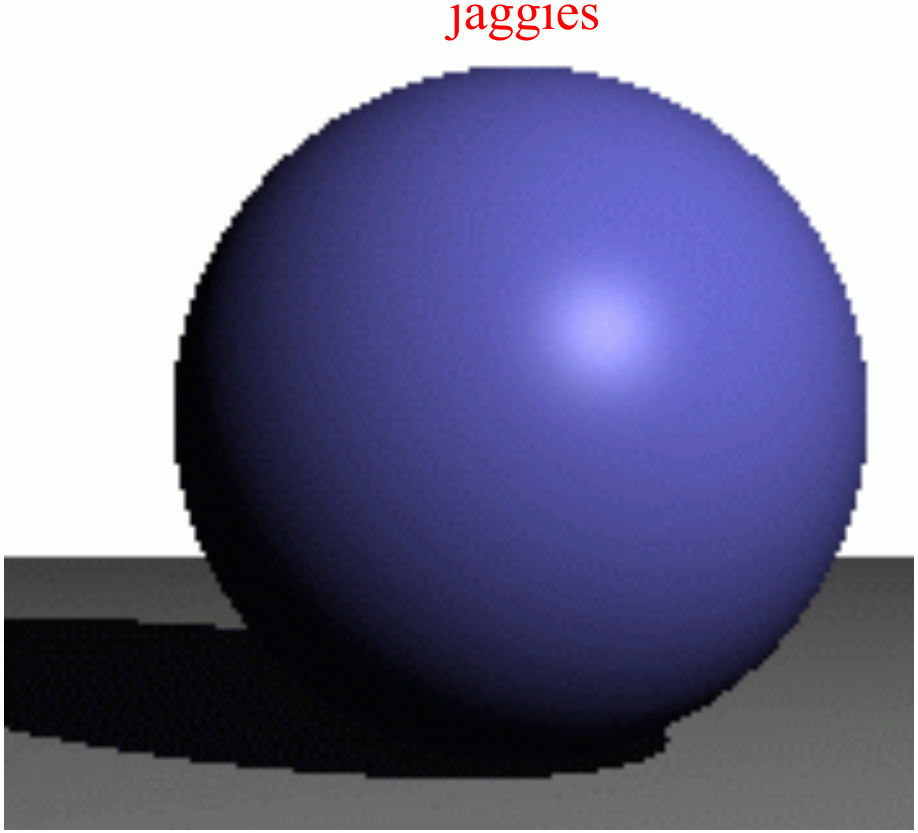




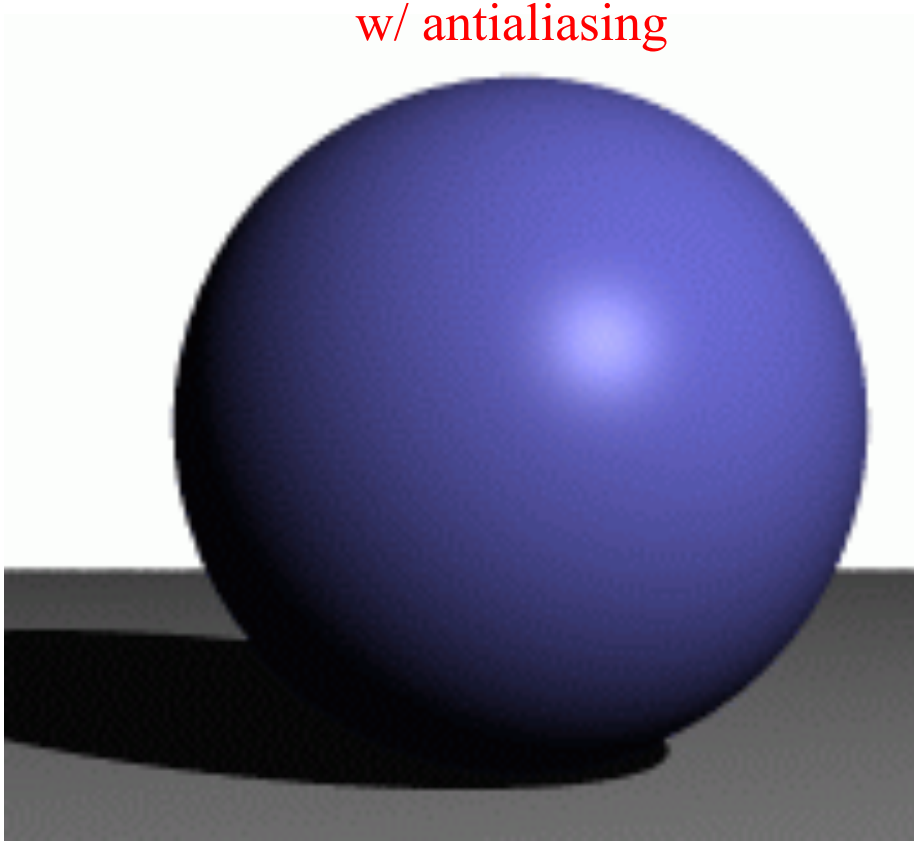
Antialiasing – Supersampling

- Multiple rays per pixel

jaggies

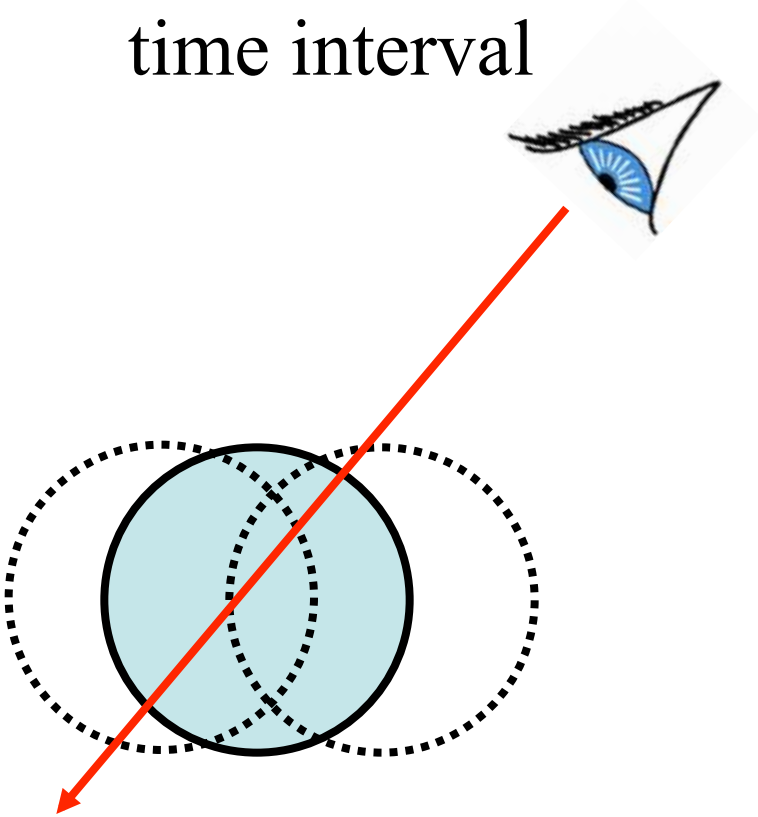


w/ antialiasing



Motion Blur

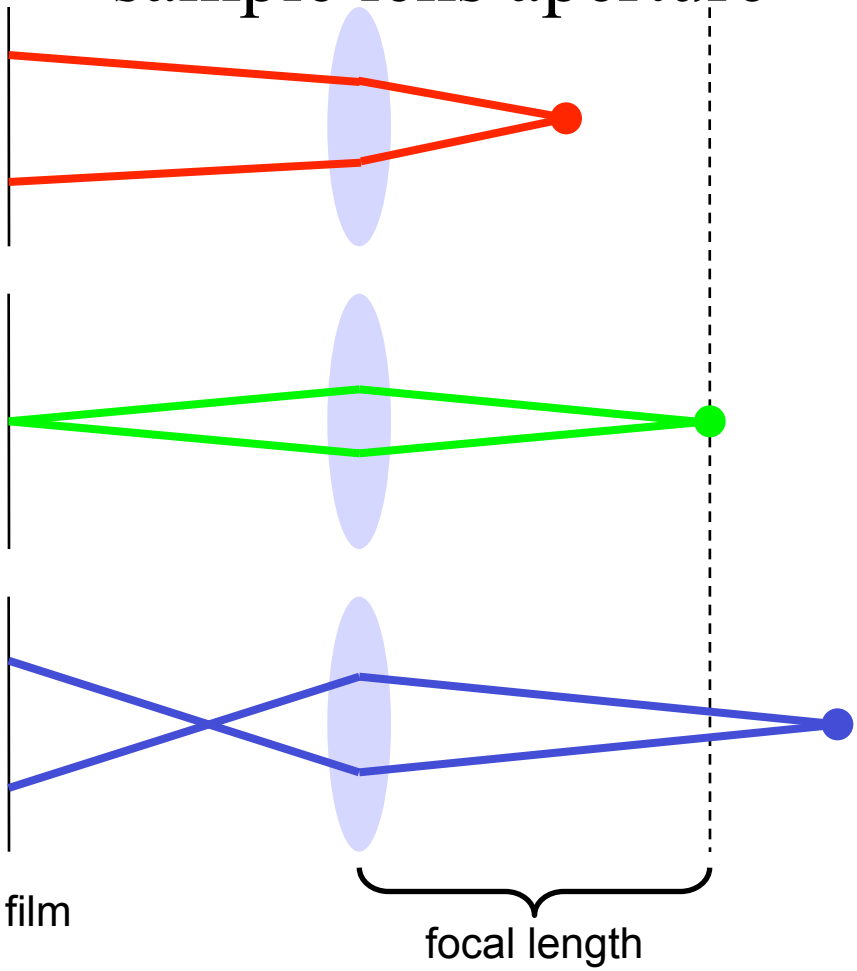
- Sample objects temporally over time interval

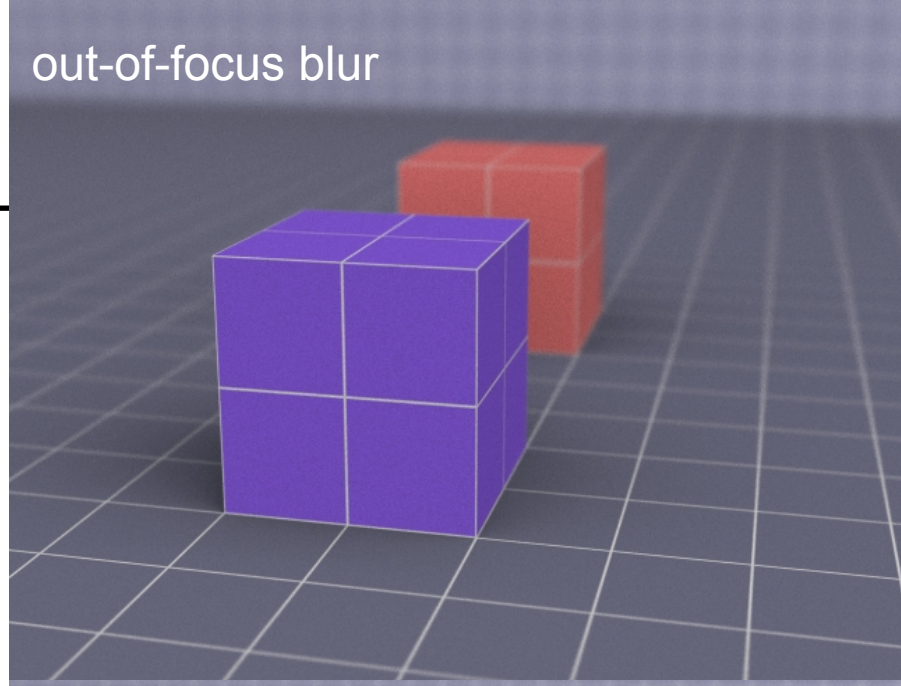


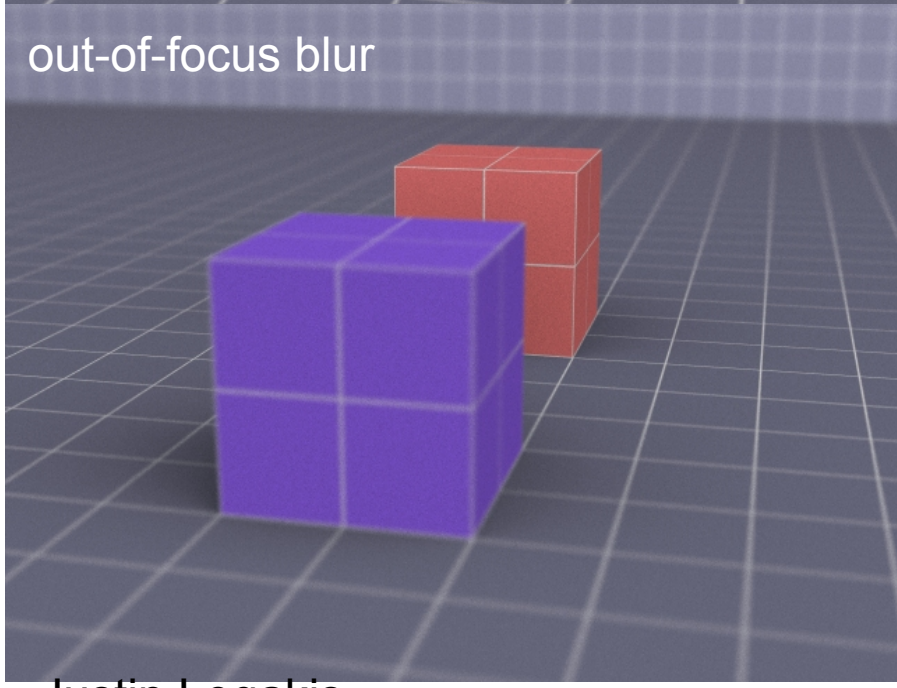
Rob Cook

Depth of Field

- Multiple rays per pixel: sample lens aperture







Justin Legakis

Distribution ray tracing

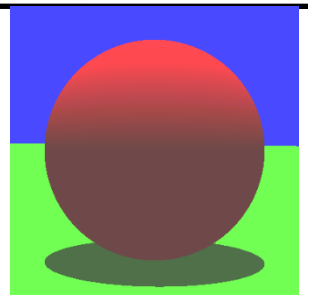
- Basic idea: one single ray → many rays vary in some dimensions
  - Time
  - Lens
  - Light source area
  - Reflected direction
  - Refracted direction, etc..

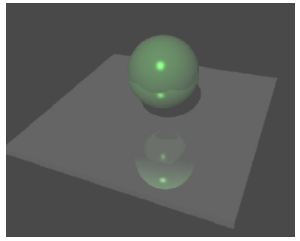
Questions?

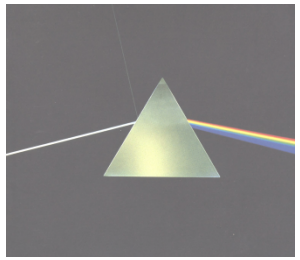
Henrik Wann Jensen

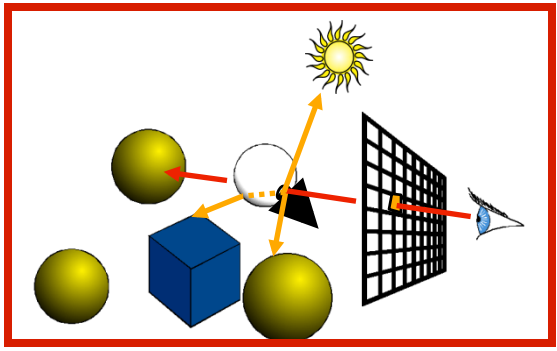
Overview of Today

- Shadows
- Reflection
- Refraction
- Recursive Ray Tracing





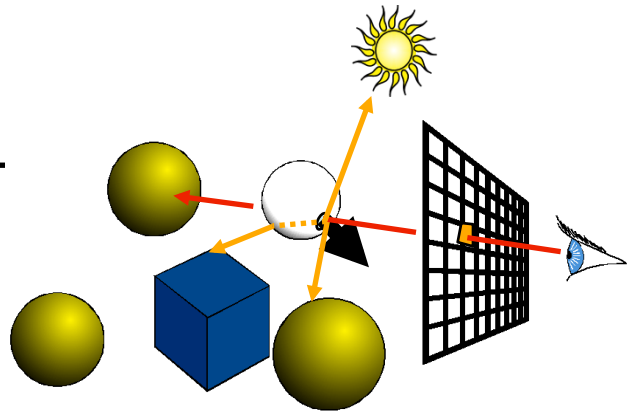




Recap: Ray Tracing

```
trace ray
    Intersect all objects
    color = ambient term
    For every light
        cast shadow ray
        color += local shading term
    If mirror
        color += color_refl *
                 trace reflected ray
    If transparent
        color += color_trans *
                 trace transmitted ray
```

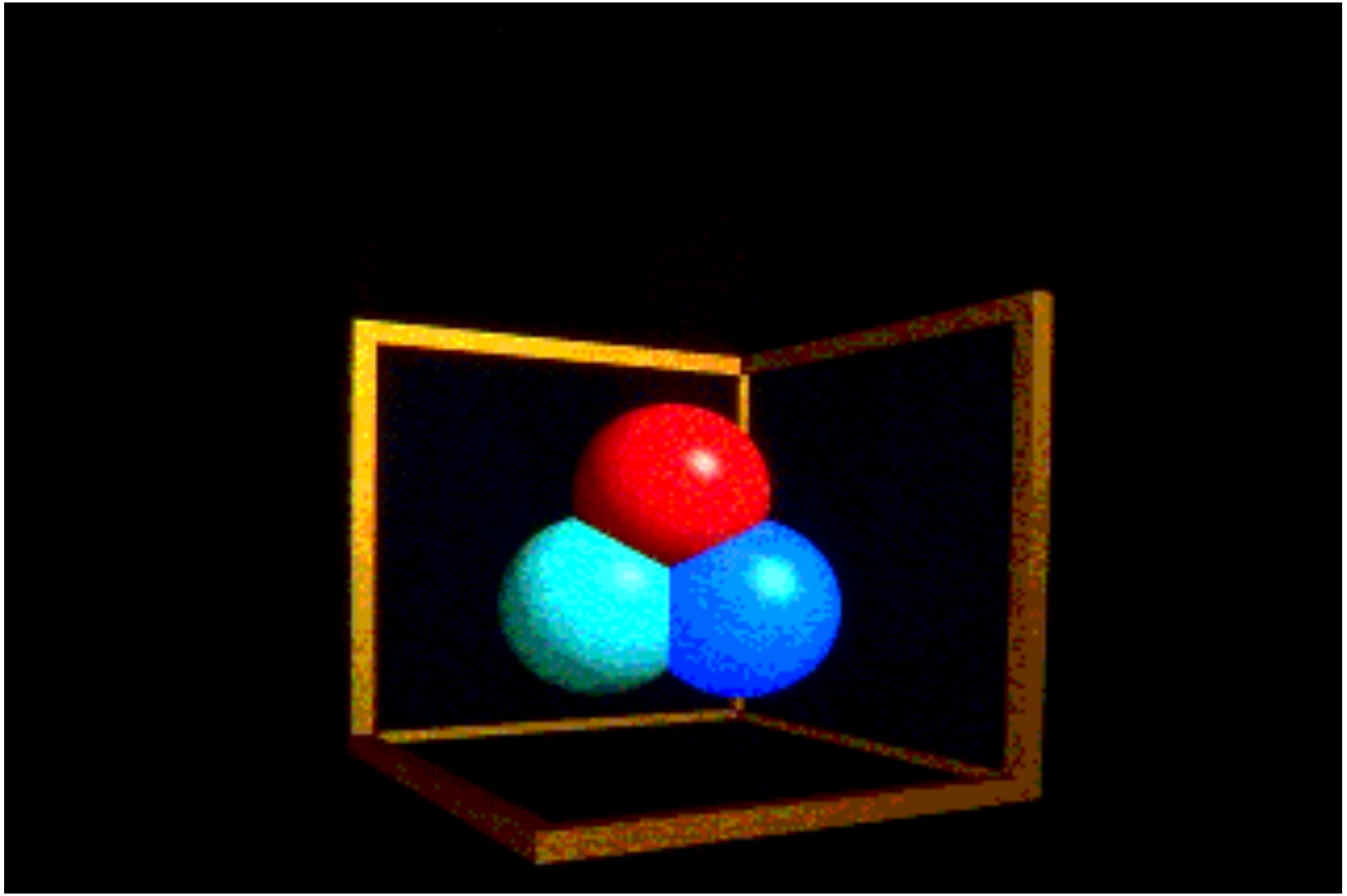
- Does it ever end?



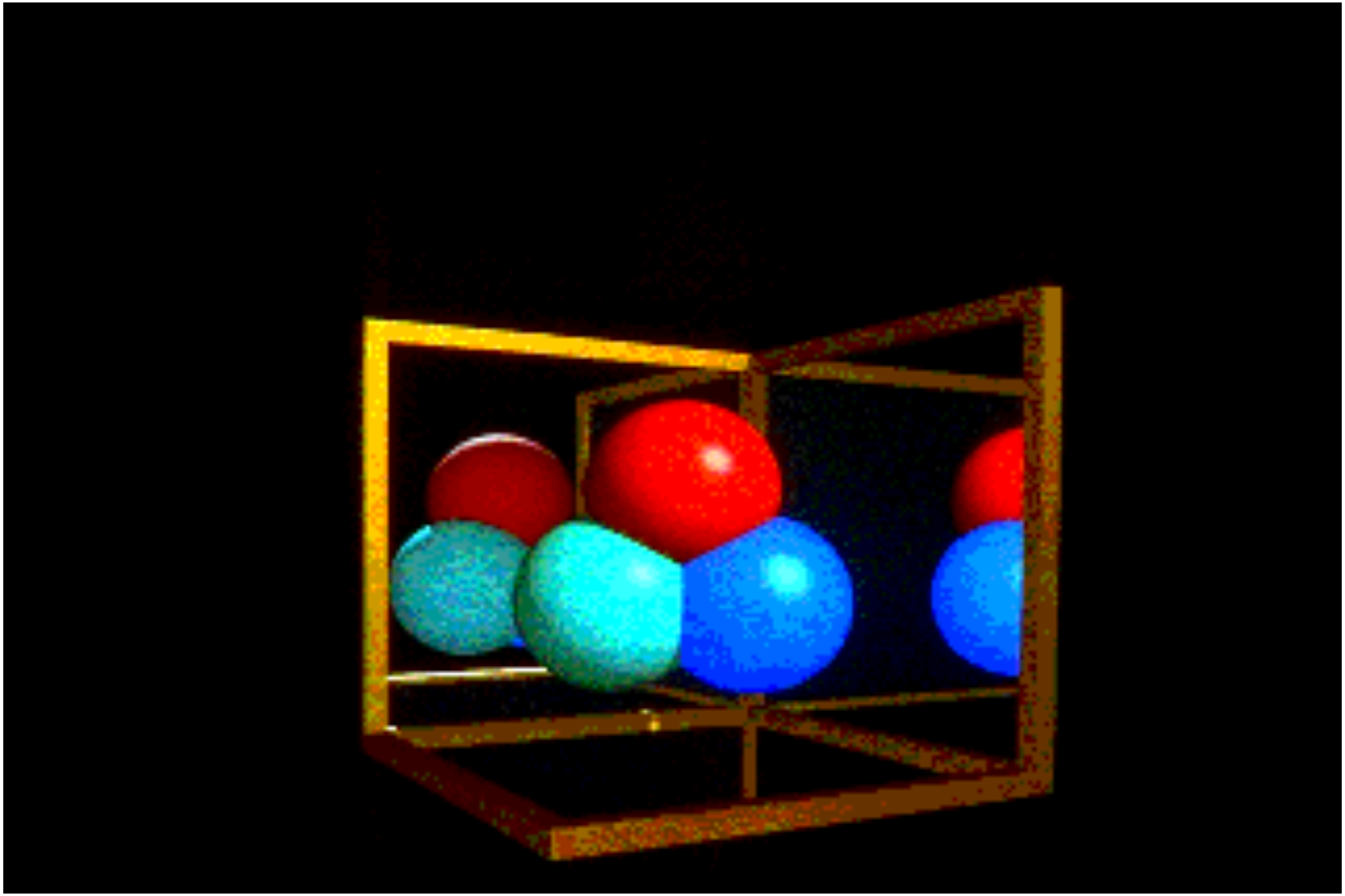
Stopping criteria:

- Recursion depth
  - Stop after a number of bounces
- Ray contribution
  - Stop if reflected / transmitted contribution becomes too small

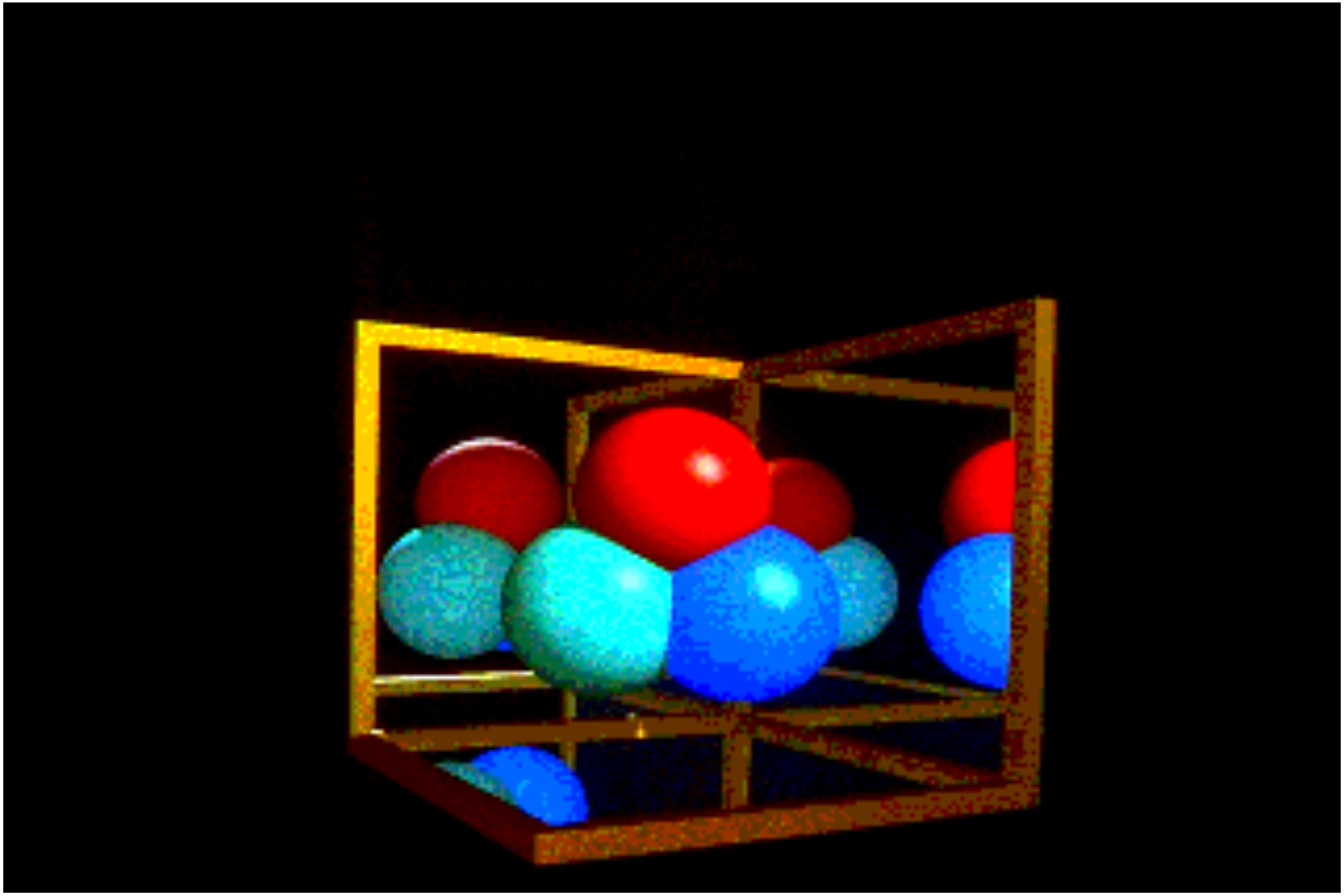
Recursion For Reflection: None



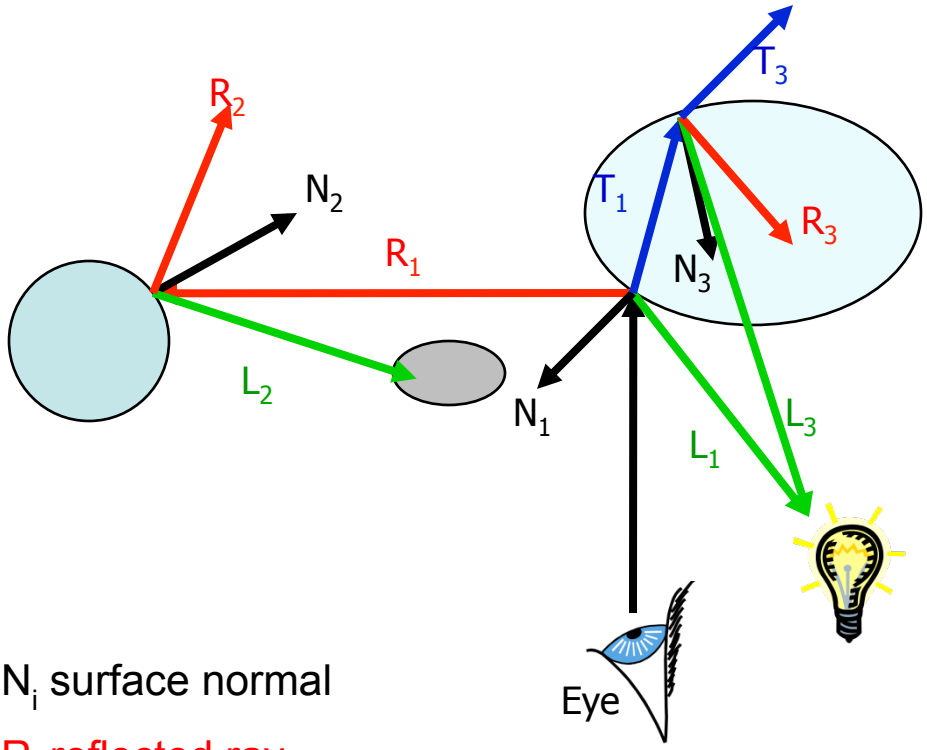
Recursion For Reflection: 1



Recursion For Reflection: 2



The Ray Tree

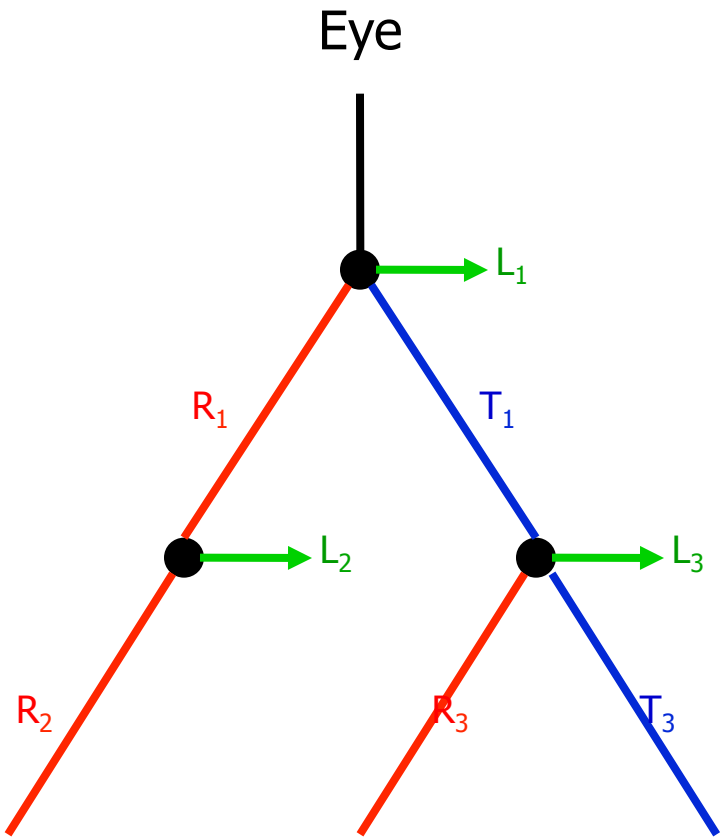


N_i surface normal

R_i reflected ray

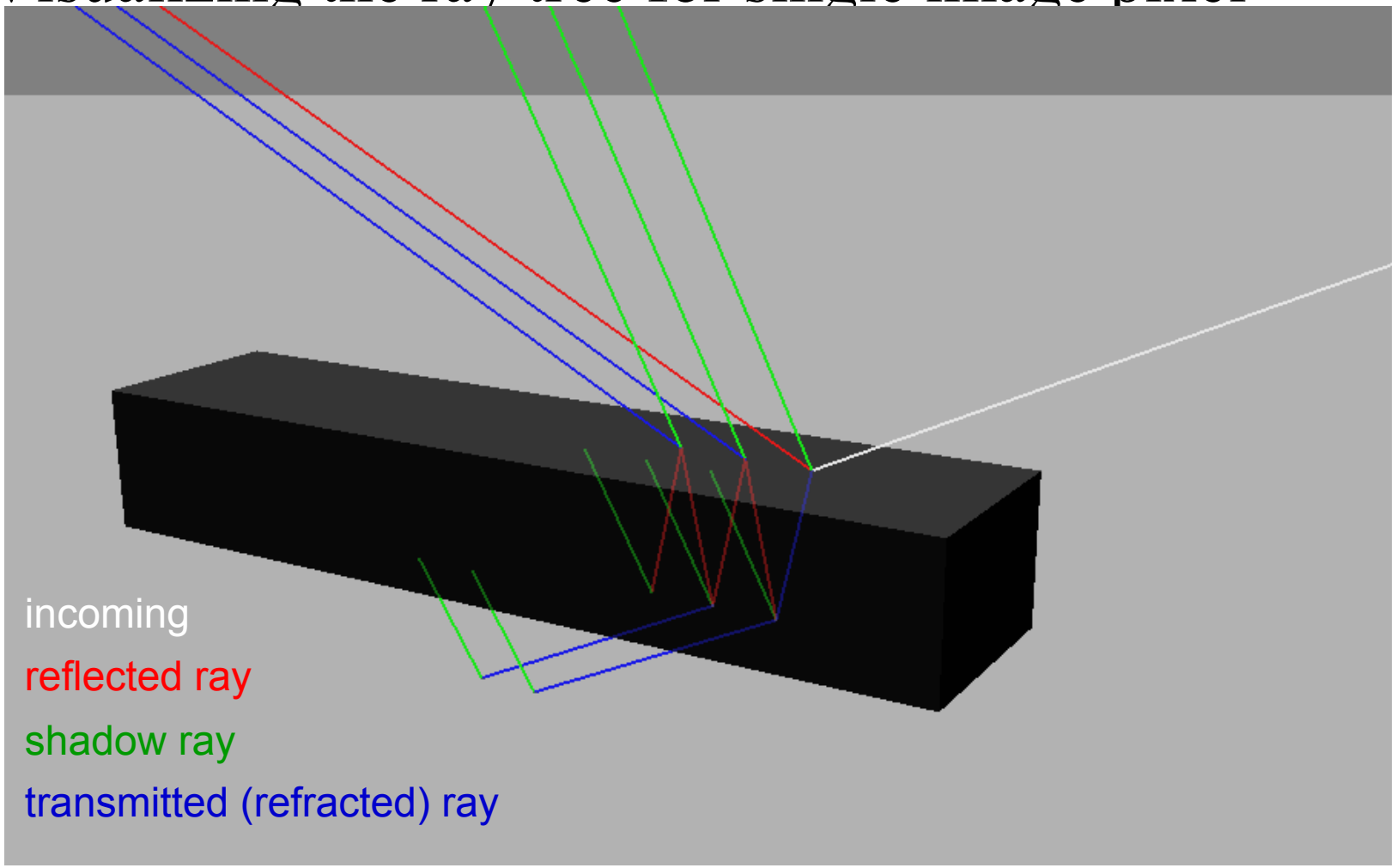
L_i shadow ray

T_i transmitted (refracted) ray



Ray tree

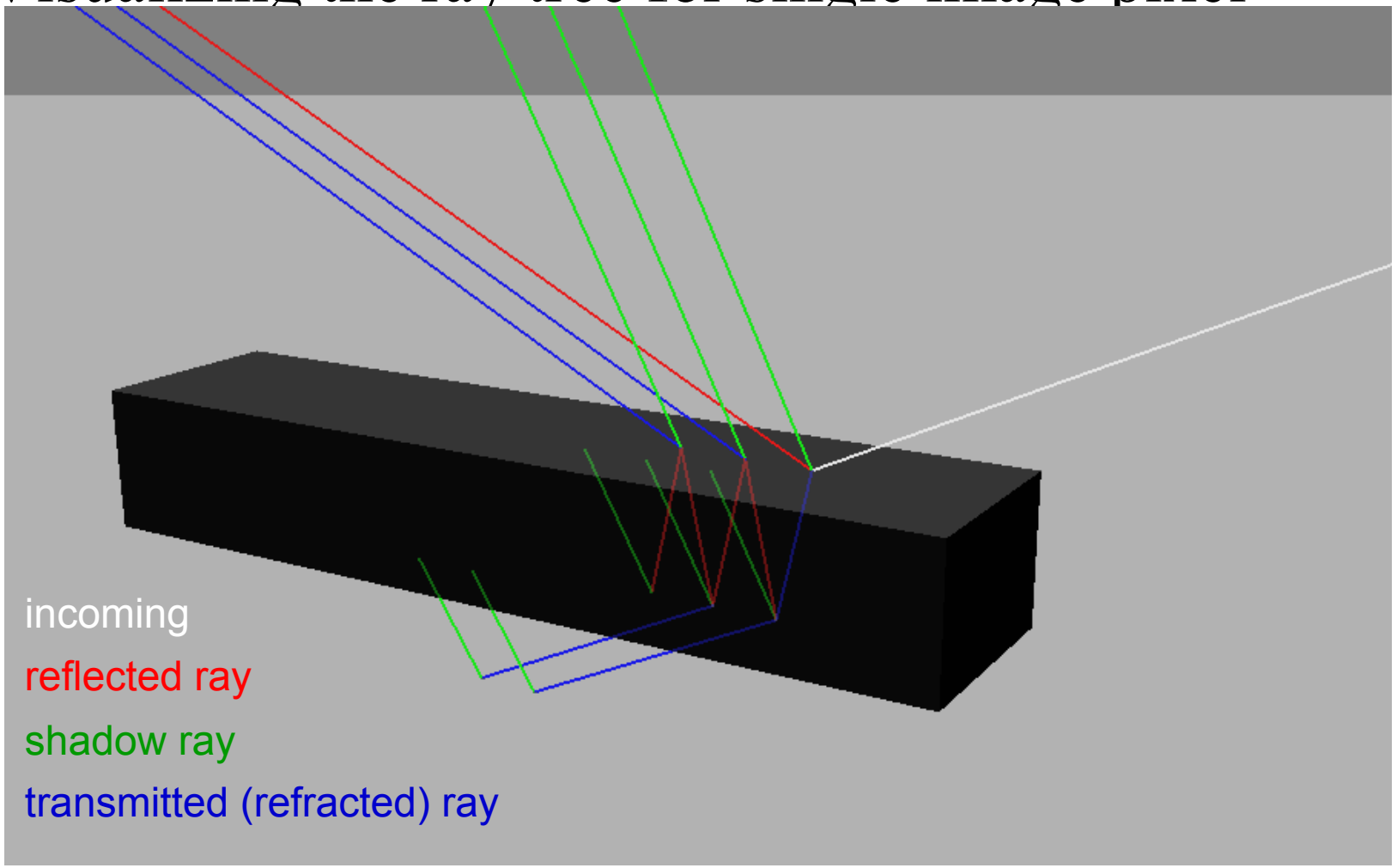
- Visualizing the ray tree for single image pixel

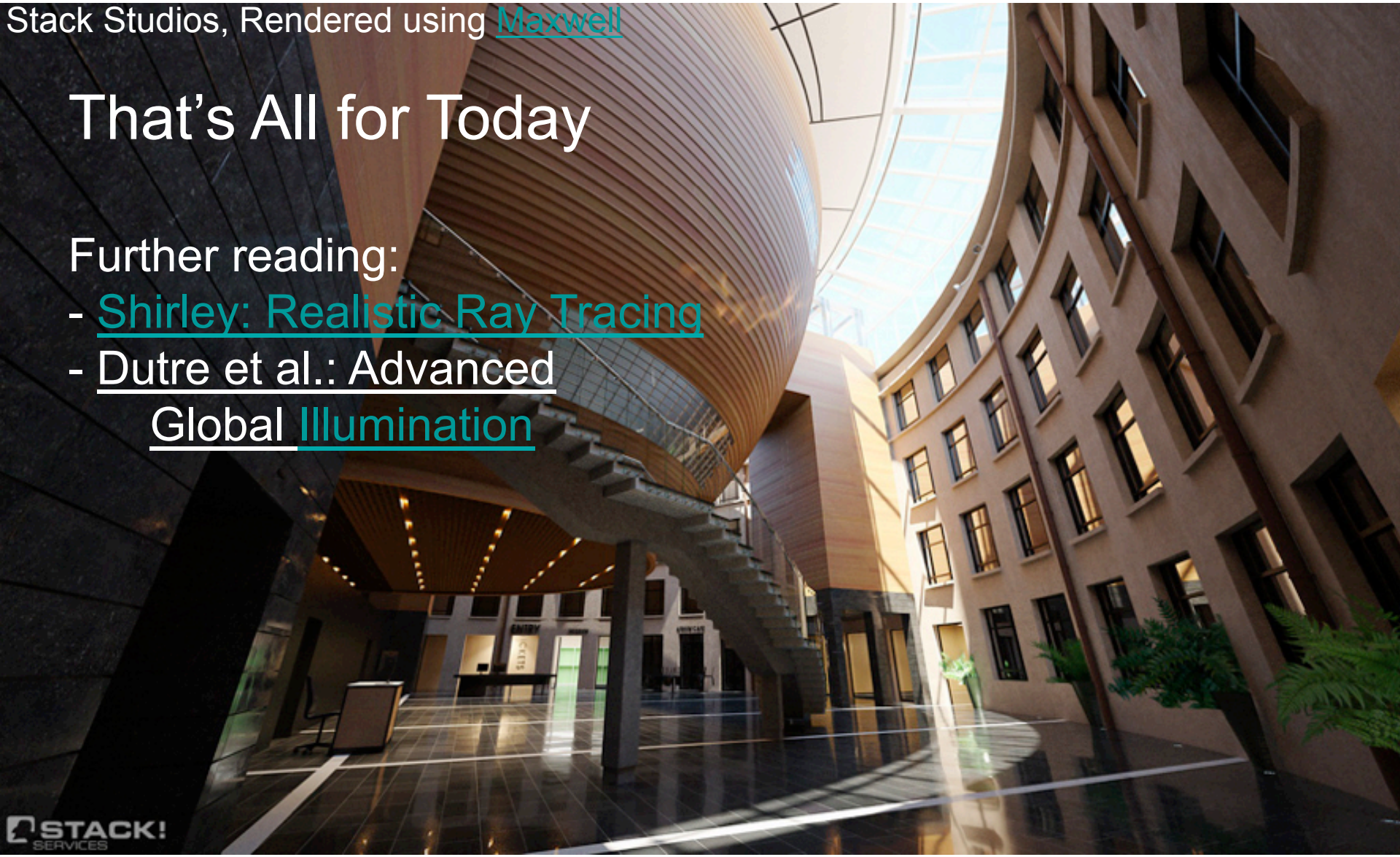


Ray tree

This gets pretty complicated pretty fast!

- Visualizing the ray tree for single image pixel





That's All for Today

Further reading:

- Shirley: Realistic Ray Tracing
- Dutre et al.: Advanced Global Illumination