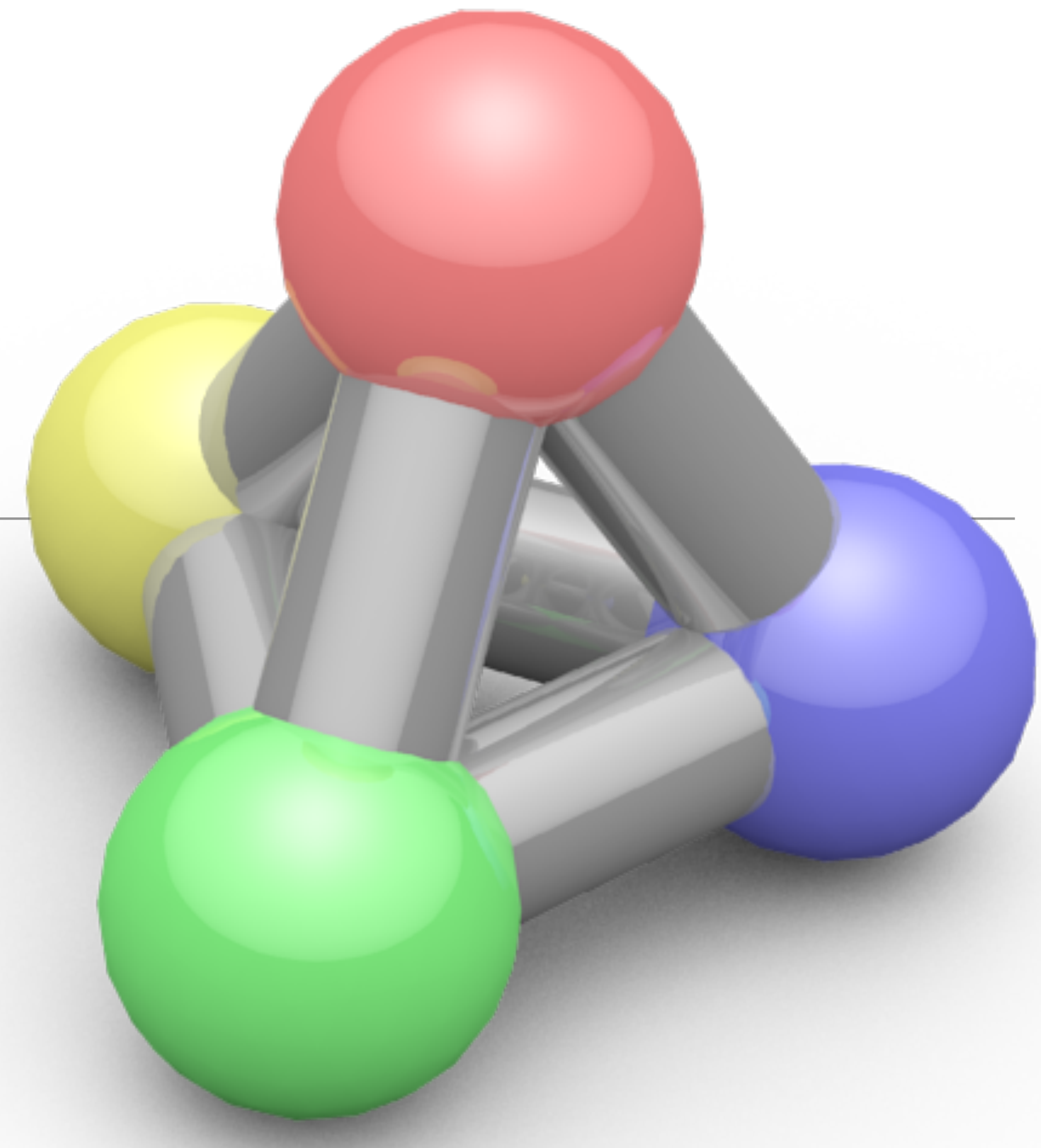
Global Illumination

CPSC 453 – Fall 2016
Sonny Chan



Outline for Today

- Motivation
- Radiometry: foundations of physically-based rendering
- Surface reflectance
- The rendering equation
- Solutions to the rendering equation

What is the primary

goal of rendering?

(photo-realistic)

The goal of photo-realistic rendering is to synthesize an image that is **indistinguishable from reality**.

Interaction of Light and Matter

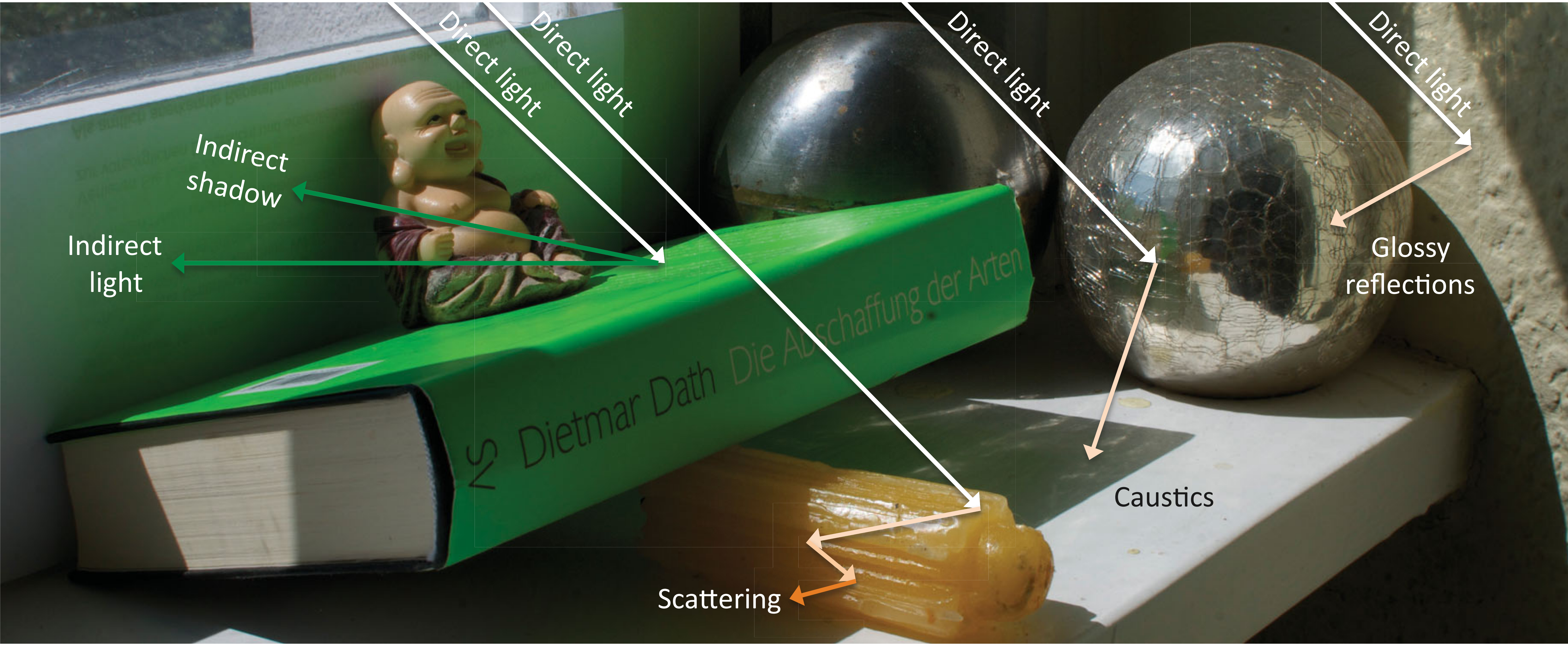
Photo by Tobias Ritschel, UCL

Interaction of Light and Matter

Photo by CPSC 453 student

Interaction of Light and Matter

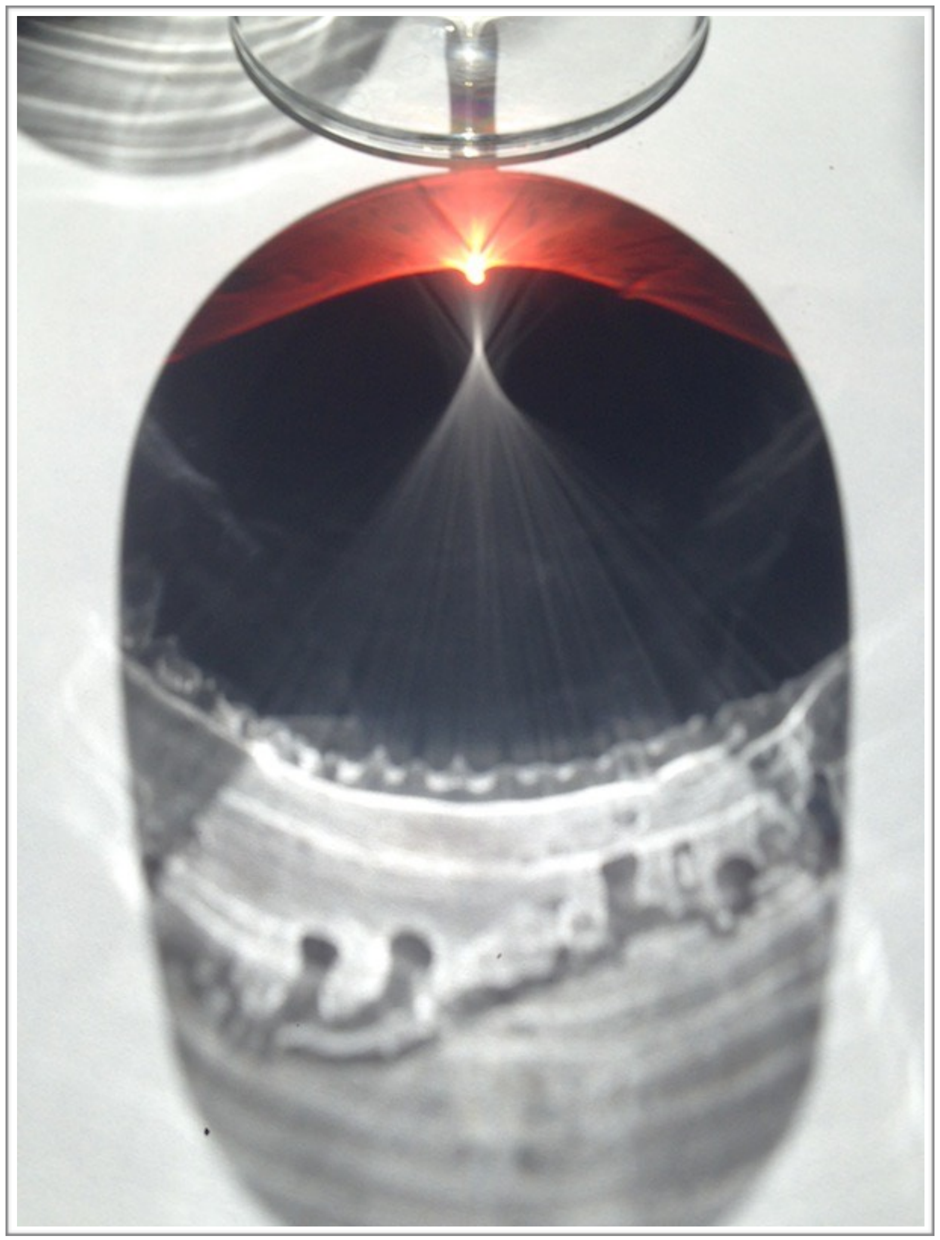
Photo by Tobias Ritschel, UCL



Interaction of Light and Matter

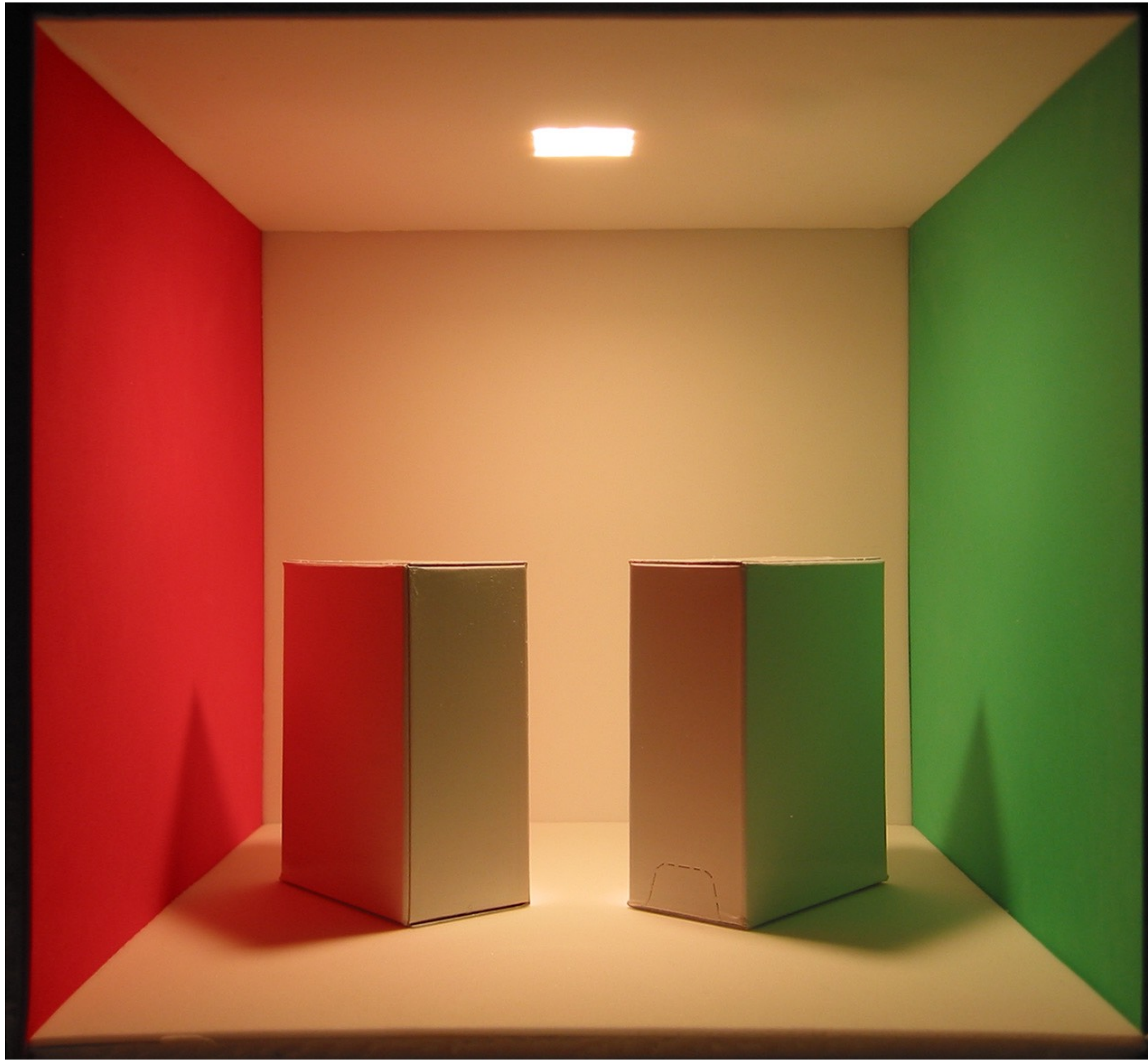
Photo by Tobias Ritschel, UCL

Caustics



 [from K. Breeden, Stanford University]

Radiosity



[construction and photograph by Richard Rosenman]

Shadows

[from learnmyshot.com]

How can we synthesize these

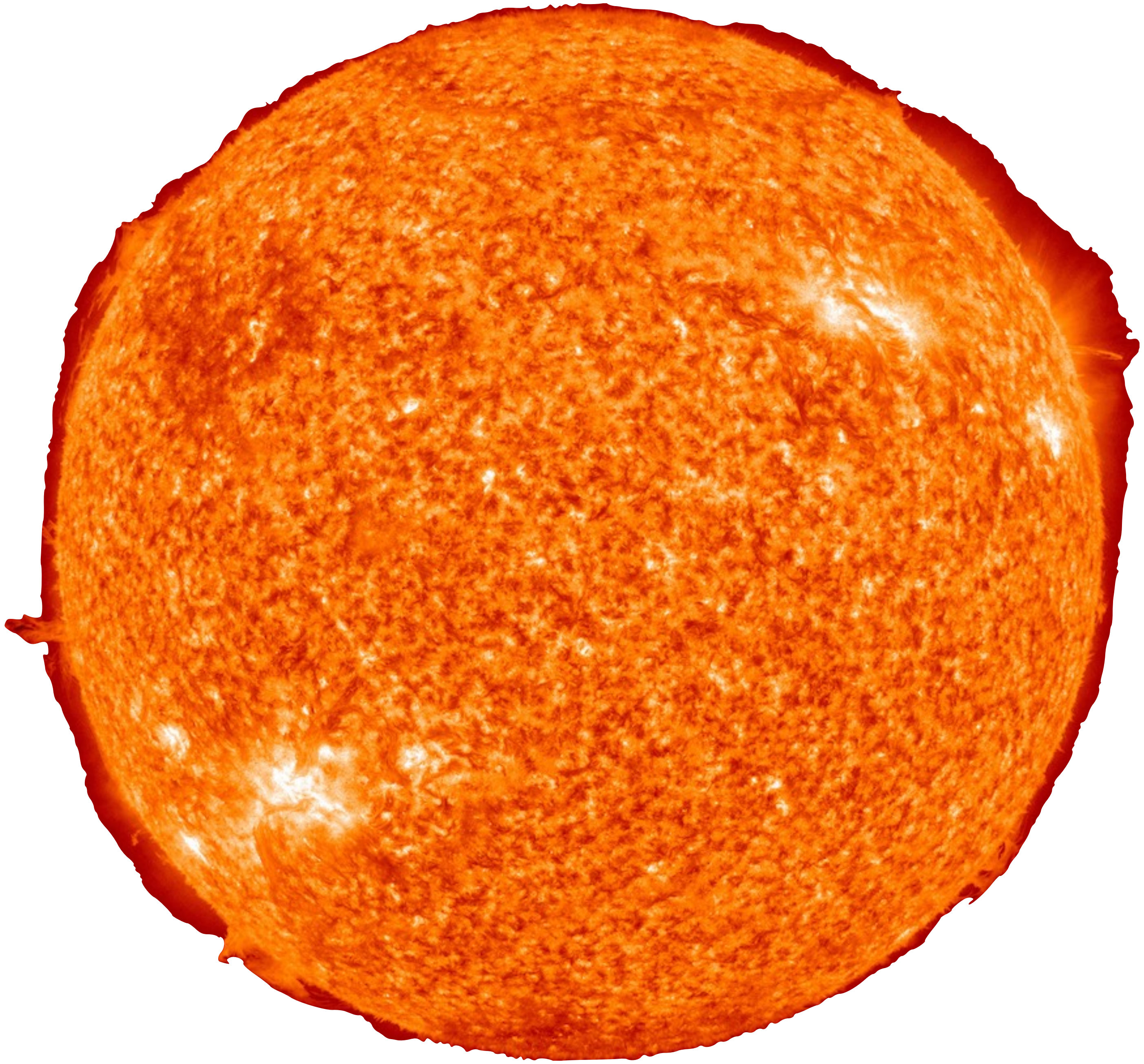
illumination effects?

Radiometry

The foundations for physically-based image synthesis

How bright is

the sun?



What is a

lumen?

Radiometry and Photometry

- Measurement of spatial properties of light:
  - radiant power
  - radiant intensity
  - irradiance
  - radiance
  - radiant exitance (radiosity)
- Physically-based rendering performs lighting calculations in a physically correct way

Radiant Energy and Power

- **Power** is energy flux:

$$\Phi = \frac{dQ}{dt}$$

  - measured in **watts** (radiometry)
  - or **lumens** (photometry)

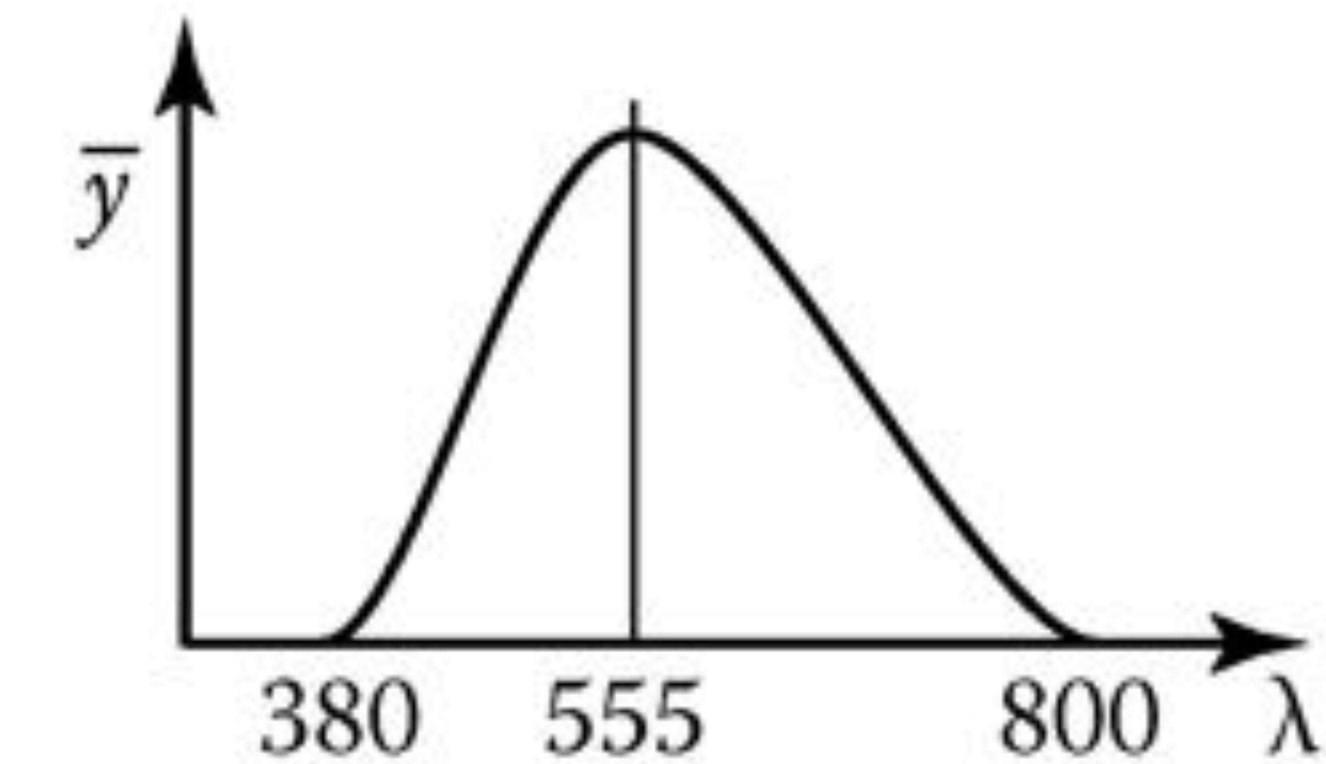
- **Energy** is a fundamental physical quantity
  - measured in **joules** (radiometry)
  - or **talbots** (photometry)

What is the difference between

radiometry and **photometry?**

Luminous Efficiency

Photometry is concerned only with measurements in the human-visible light spectrum.



Radiant Intensity

- The radiant (or luminous) intensity is the power per unit solid angle emanating from a light source

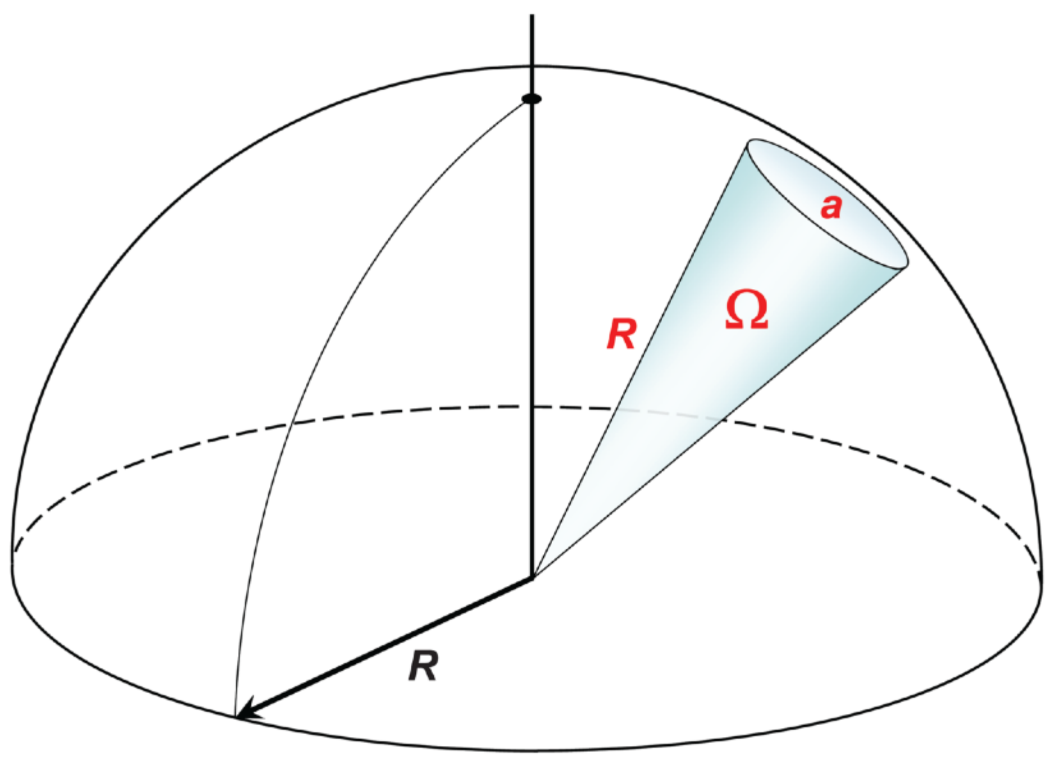
$$I(\omega) = \frac{d\Phi}{d\omega}$$

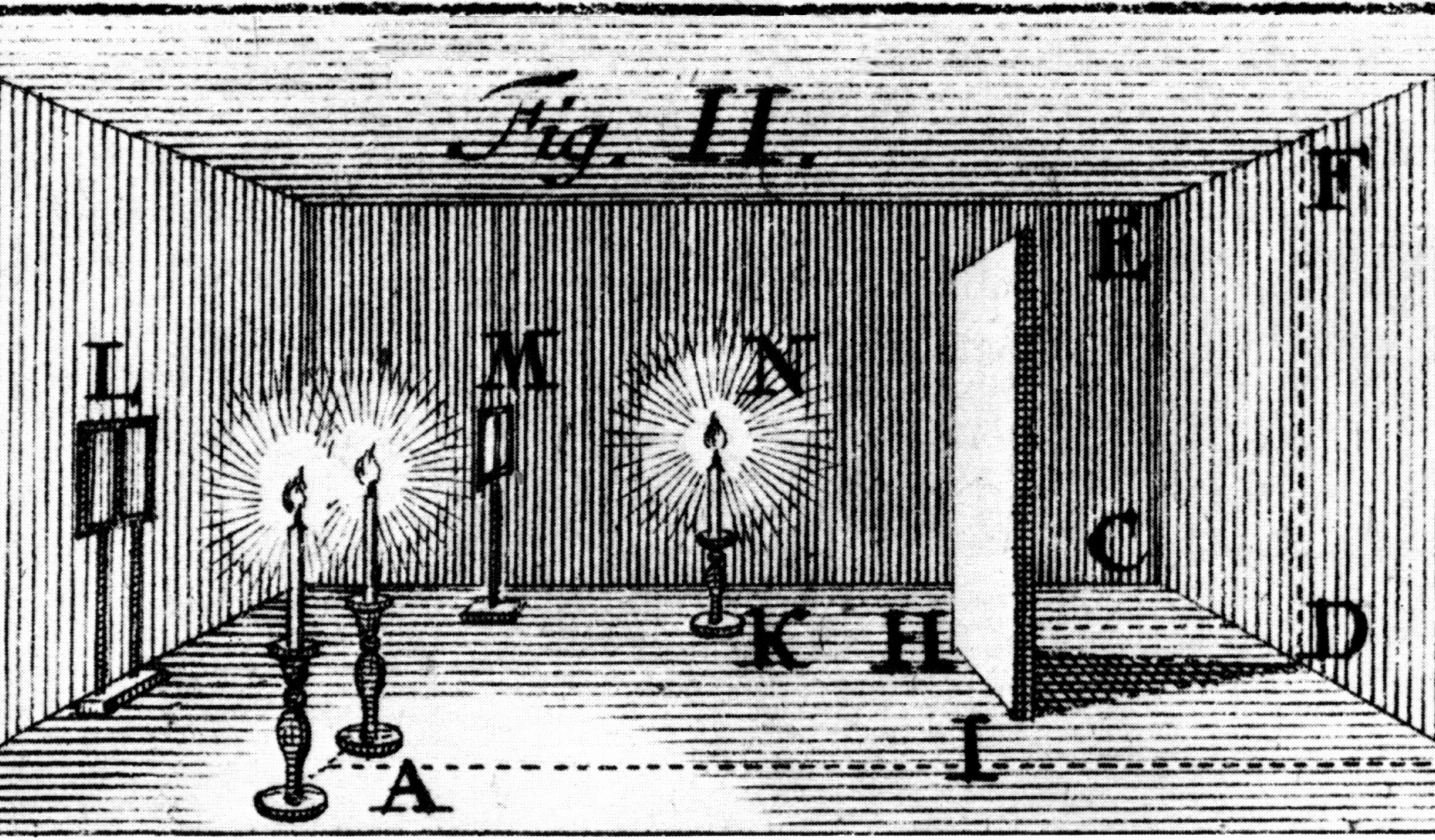
  - measured in **watts / steradian** (radiometry)
  - or lumens / steradian = **candelas** (photometry)
- What the heck is a steradian?
- What does this quantity allow us to describe?

Solid Angles

- Angle is ratio of arc length to radius: $\theta = \dfrac{l}{r}$
  - a circle has 2π radians
- Solid angle is ratio of area to squared radius: $\Omega = \dfrac{A}{r^2}$
  - measured in steradians (sr)
- How many steradians does a sphere have?

4π





What is a candela?

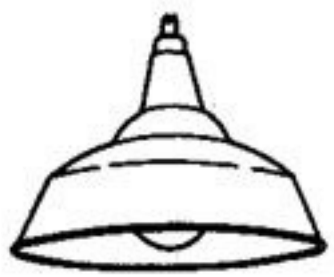
Pierre Bouguer, ca. 1725

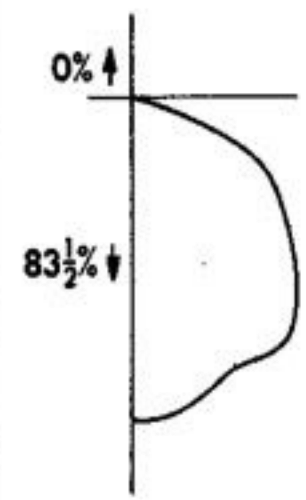
Luminous Intensity

- The candela is one of seven SI base units!
- Originally defined as the amount of light from one standard candle
- Now a monochromatic light source of 555 nm with intensity 1/683 W/sr

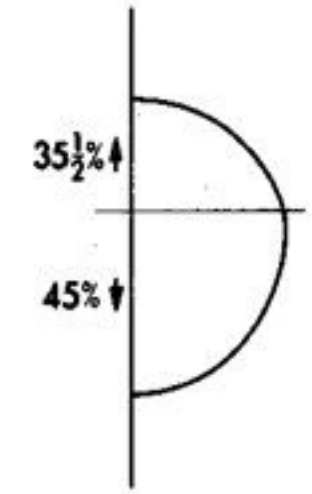
Light Source Goniometric Diagrams

3



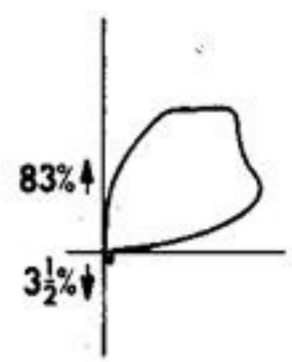


Porcelain-enameled ventilated standard dome with incandescent lamp

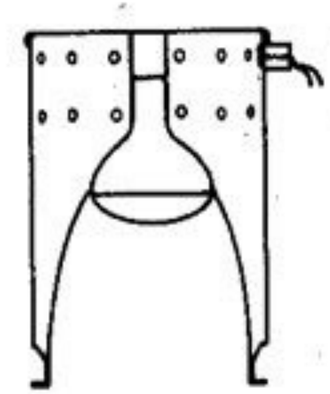


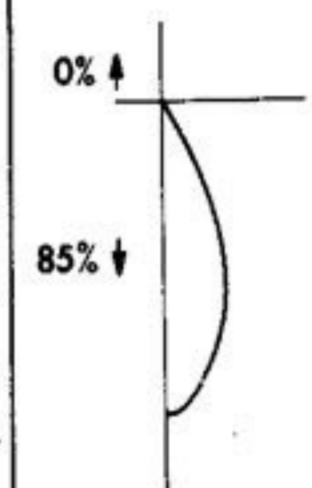
Pendant diffusing sphere with incandescent lamp

2



Concentric ring unit with incandescent silvered-bowl lamp





R-40 flood with specular anodized reflector skirt; 45° cutoff

[courtesy of P. Hanrahan, Stanford University]

Irradiance

- The irradiance (illuminance) is the power for unit area incident on a surface.

$$E(x) = \frac{d\Phi_i}{dA}$$

  - measured in **watts / square metre** (radiometry)
  - or lumens / square metre = **lux** (photometry)

- What does this quantity allow us to describe?

- Radiant exitance (luminosity) is defined the same way

Radiance

- The surface radiance (luminance) is the intensity per unit area leaving a surface
  - measured in **watts / steradian m^2** (radiometry)
  - or lumens / steradian m^2 = **nit** (photometry)

$$L(x, \omega) = \frac{d^2\Phi}{d\omega\, dA}$$

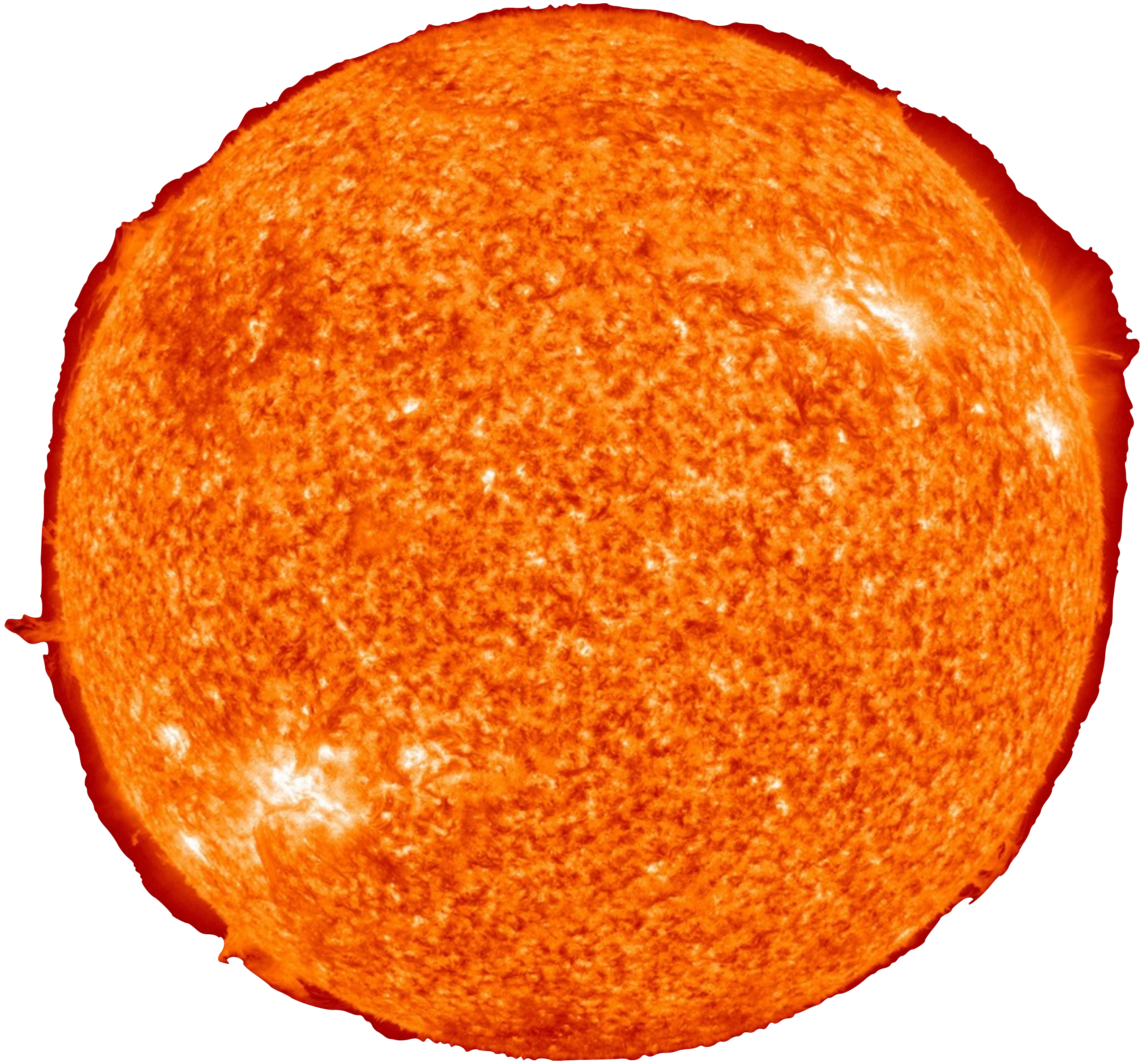
- What can we describe with this quantity?

Light Beams!

Radiance is perhaps the most important measure for physically based rendering.

How bright is

the sun?



Typical Values of Luminance

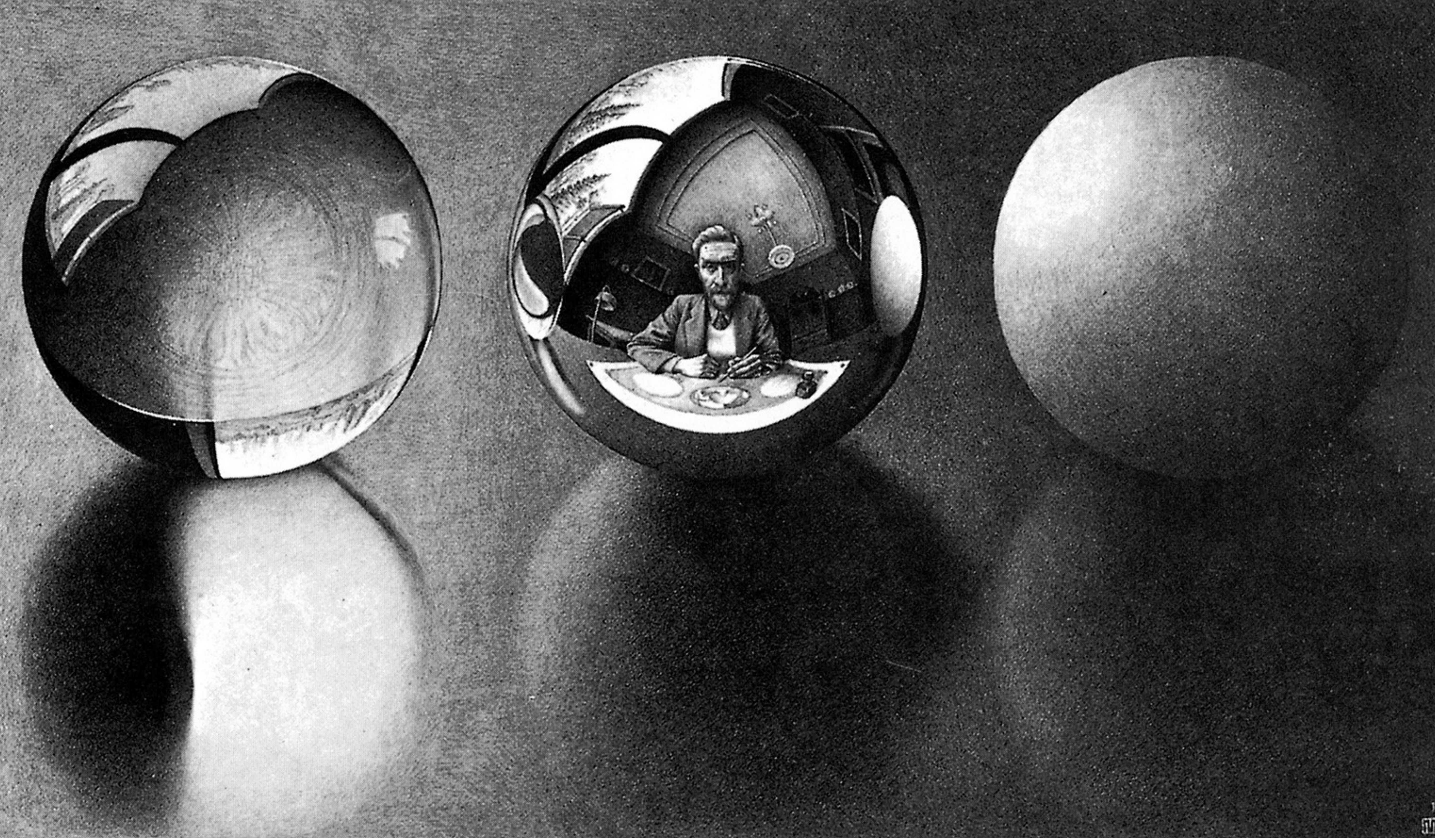
	nit (candela/m^2)
Surface of the sun	2 000 000 000
Sunlight clouds	30 000
Clear sky	3000
Overcast sky	300
Moon	0.03

[courtesy of P. Hanrahan, Stanford University]

Typical Values of Illuminance

	lux (lumens/m^2)
Direct sunlight plus skylight	100000
Sunlight plus skylight (overcast)	10000
Interior near window (daylight)	1000
Artificial light (minimum)	100
Moonlight (full)	0.01
Starlight	0.0003

[courtesy of P. Hanrahan, Stanford University]



Surface Reflectance

M.C. Escher, 1946

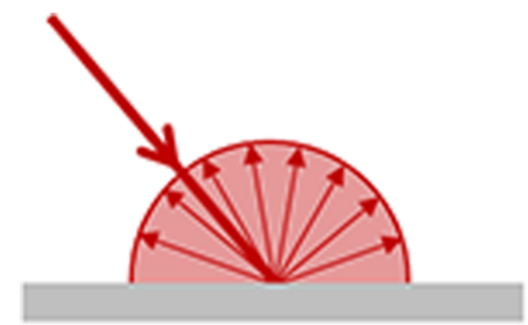
Reflection Models

- Reflection is the process by which light incident on a surface interacts with the surface such that it leaves on the incident side without change in frequency
- Characterizes many material properties:
  - spectra and colour
  - directional distribution
  - polarization

Types of Surface Reflectance

- Ideal specular (mirror)
  - reflection law

- Ideal diffuse (matte)
  - Lambert’s law

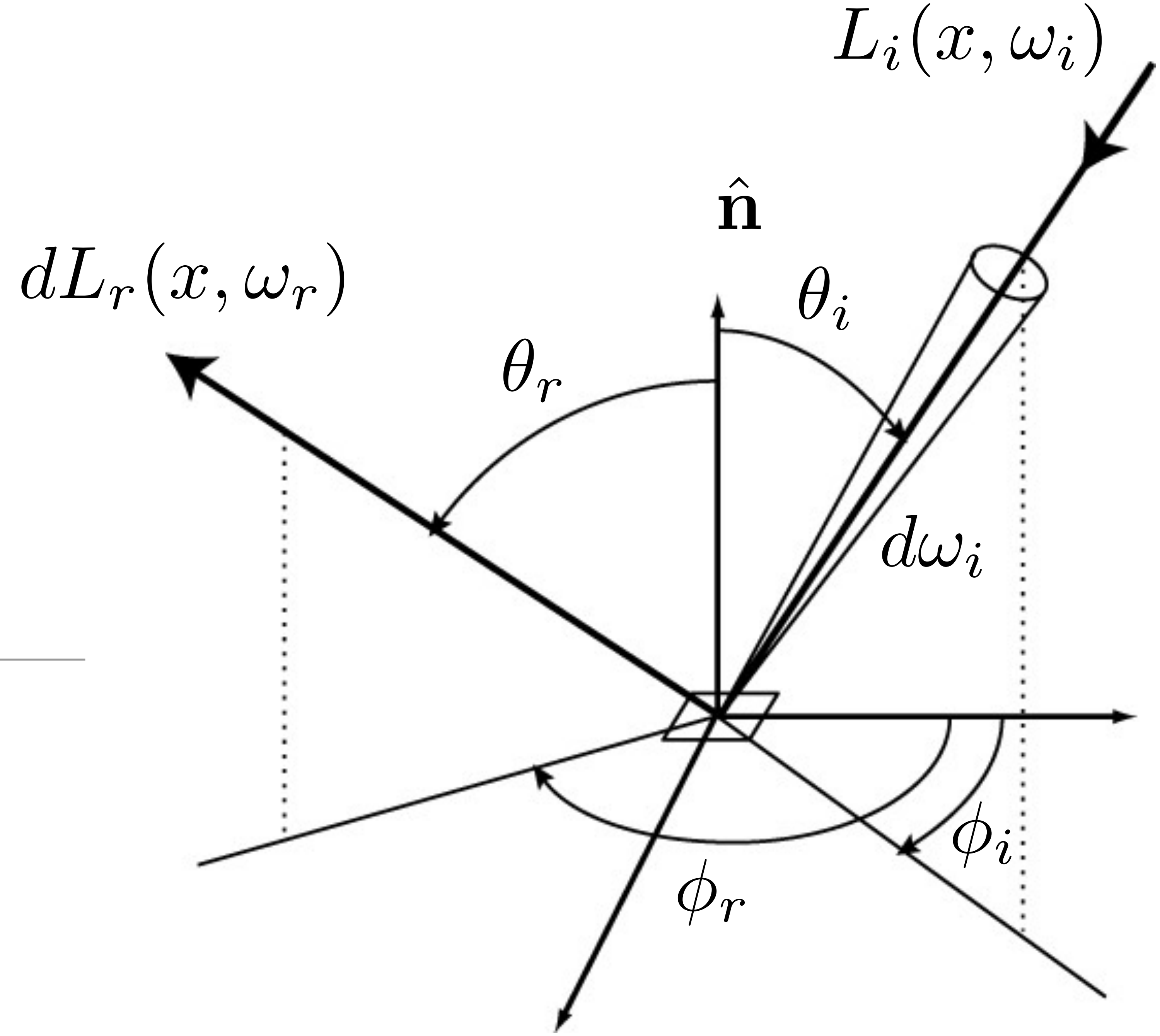


- Specular (glossy)
  - directional diffuse

- Can we make a function to characterize these and more?

The BRDF

Bidirectional Reflectance
Distribution Function

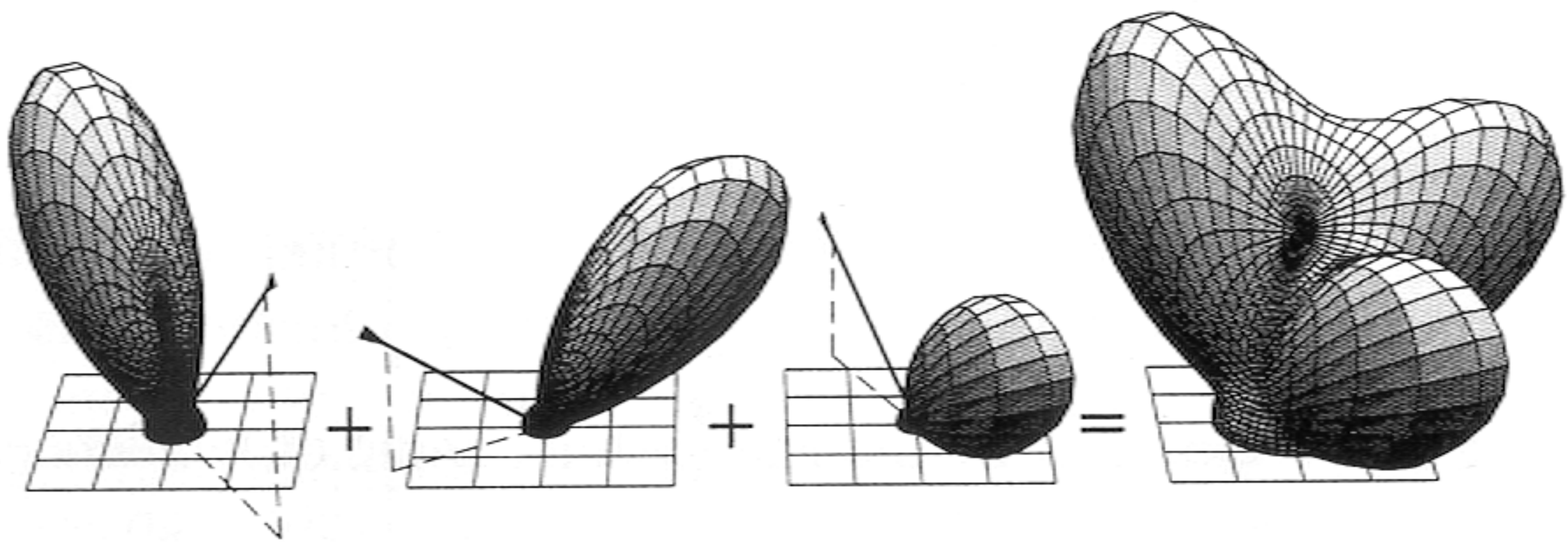


$$f_r(\omega_i \to \omega_r) = \frac{dL_r(\omega_i \to \omega_r)}{dE_i}$$

[courtesy of P. Hanrahan, Stanford University]

Properties of the BRDF

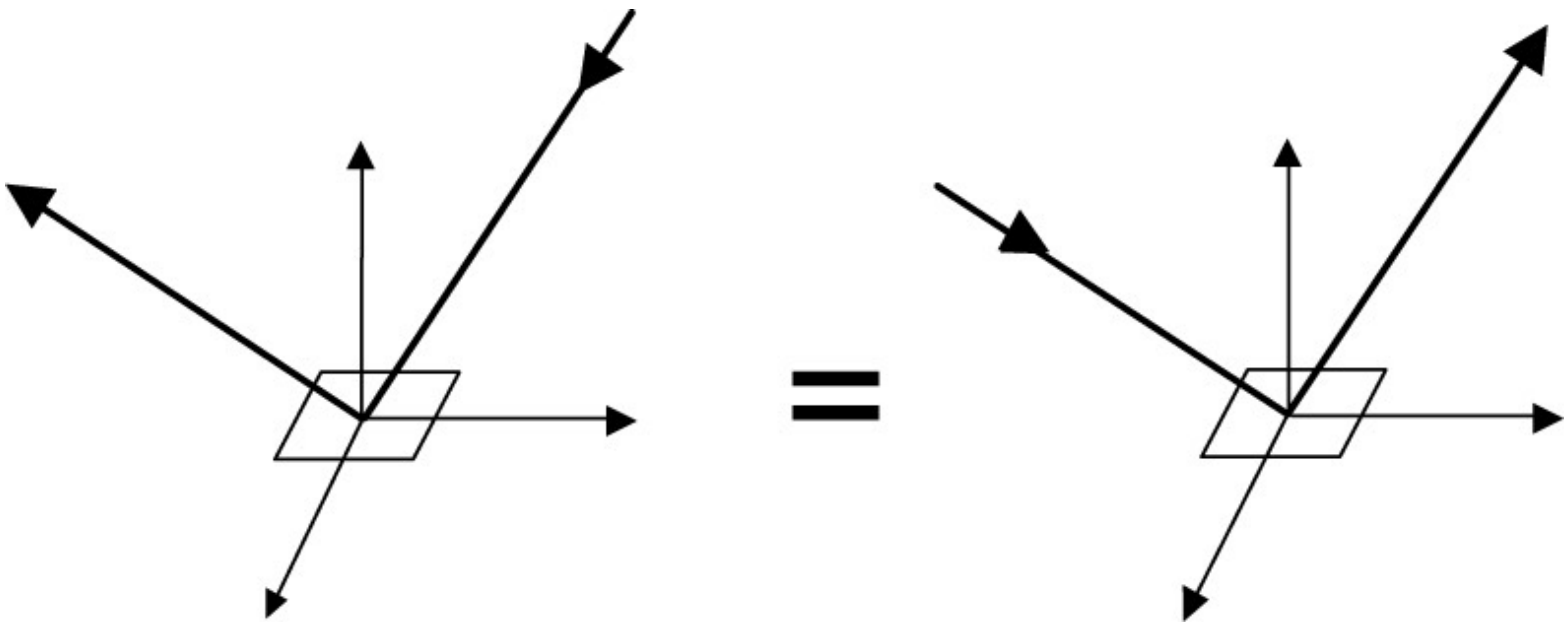
- **Linearity:** directional distributions can be additively combined



[from F. Sillion *et al.*, *Proc. ACM SIGGRAPH*, 1991]

Properties of the BRDF

- **Reciprocity:** reflectance is unchanged if the incoming and reflected directions are reversed



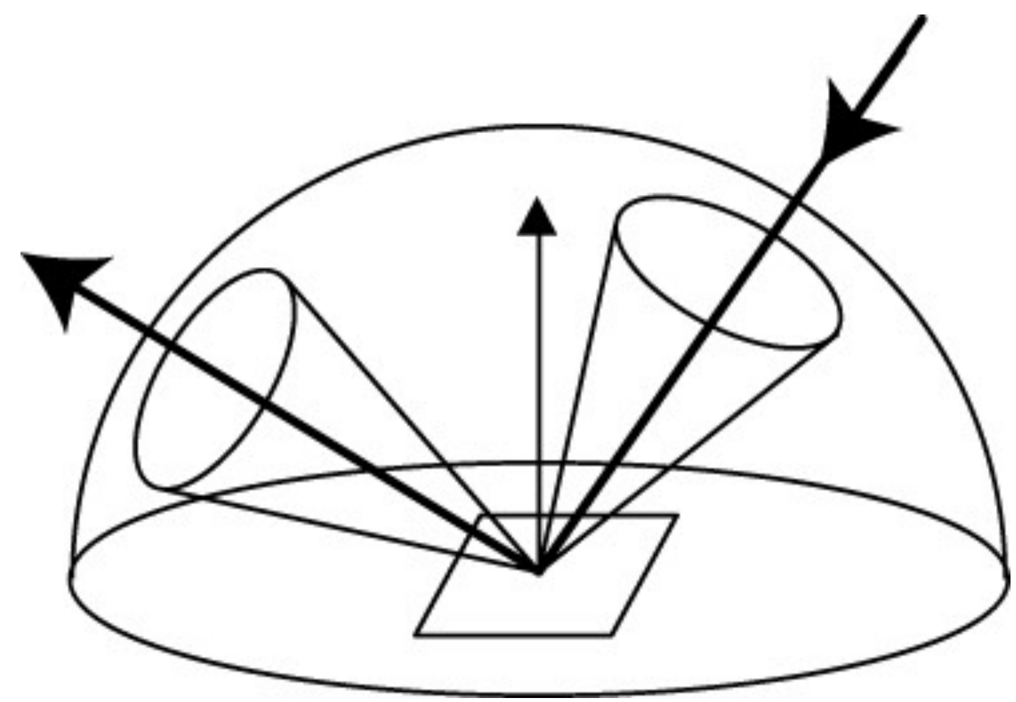
$$f_r(\omega_i \to \omega_r) = f_r(\omega_r \to \omega_i)$$

[courtesy of P. Hanrahan, Stanford University]

Properties of the BRDF

- **Energy conservation:** total reflected radiant flux must not exceed total incoming radiant flux

$$\frac{d\Phi_r}{d\Phi_i} \leq 1$$



[courtesy of P. Hanrahan, Stanford University]

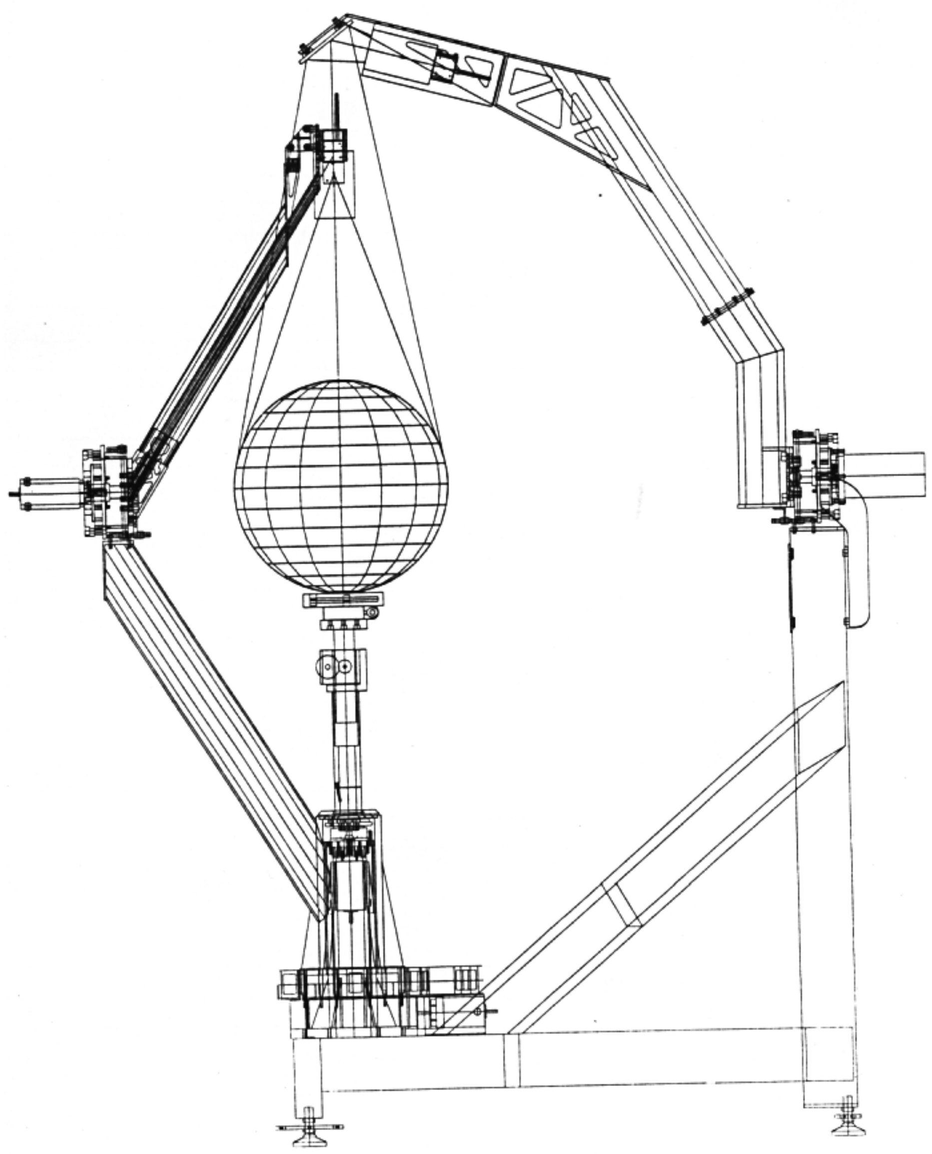
Recall our heuristic shading equation…

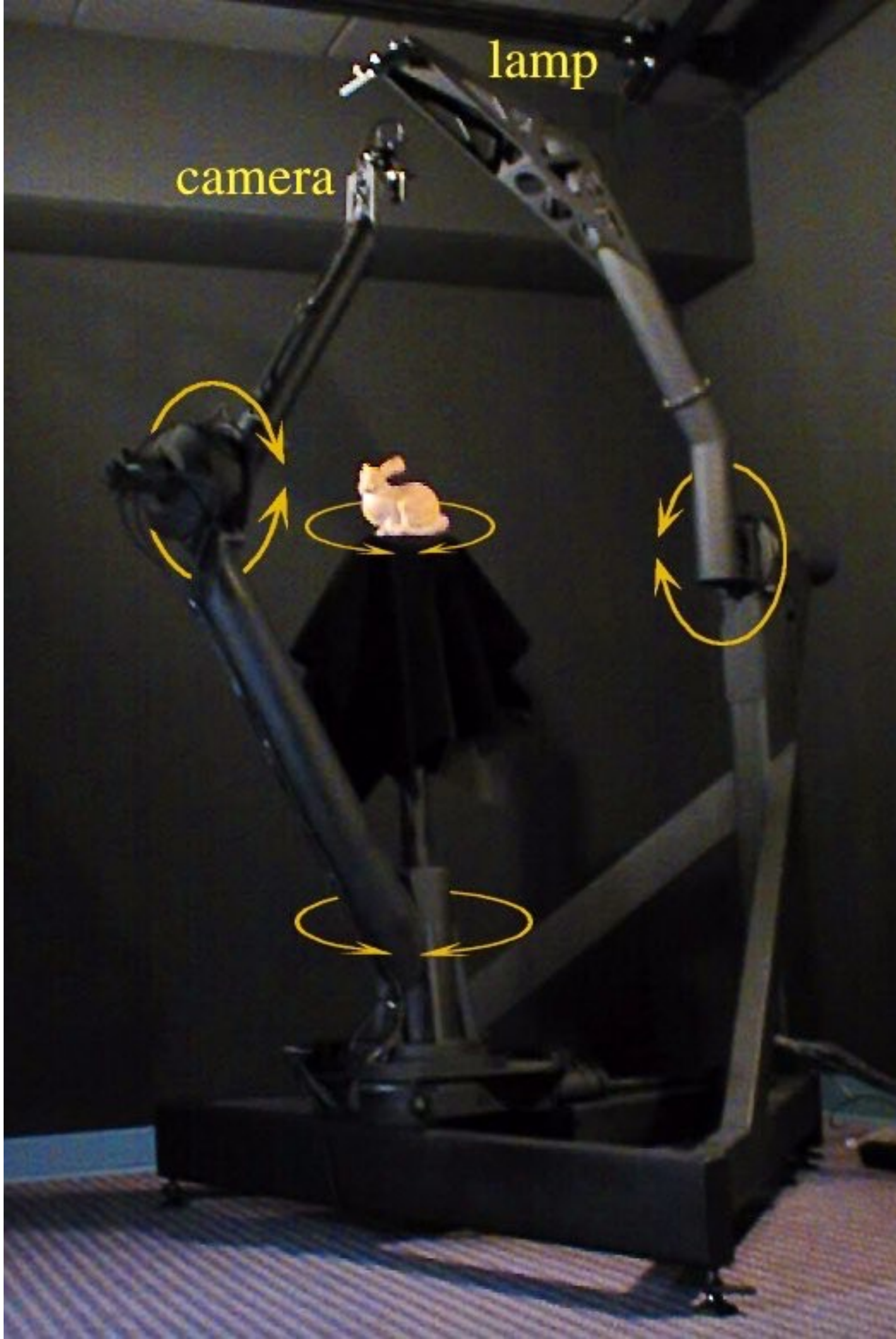
- with ambient, diffuse, and specular terms:

$$c = c_r \left(c_a + c_l \max(0, \hat{\mathbf{n}} \cdot \hat{\mathbf{l}}) \right) + c_l \, c_p \left(\hat{\mathbf{h}} \cdot \hat{\mathbf{n}} \right)^p$$

- Is this a valid BRDF?
- (not quite, but it’s possible to turn it into one)
- Where else might we be able to obtain BRDFs?

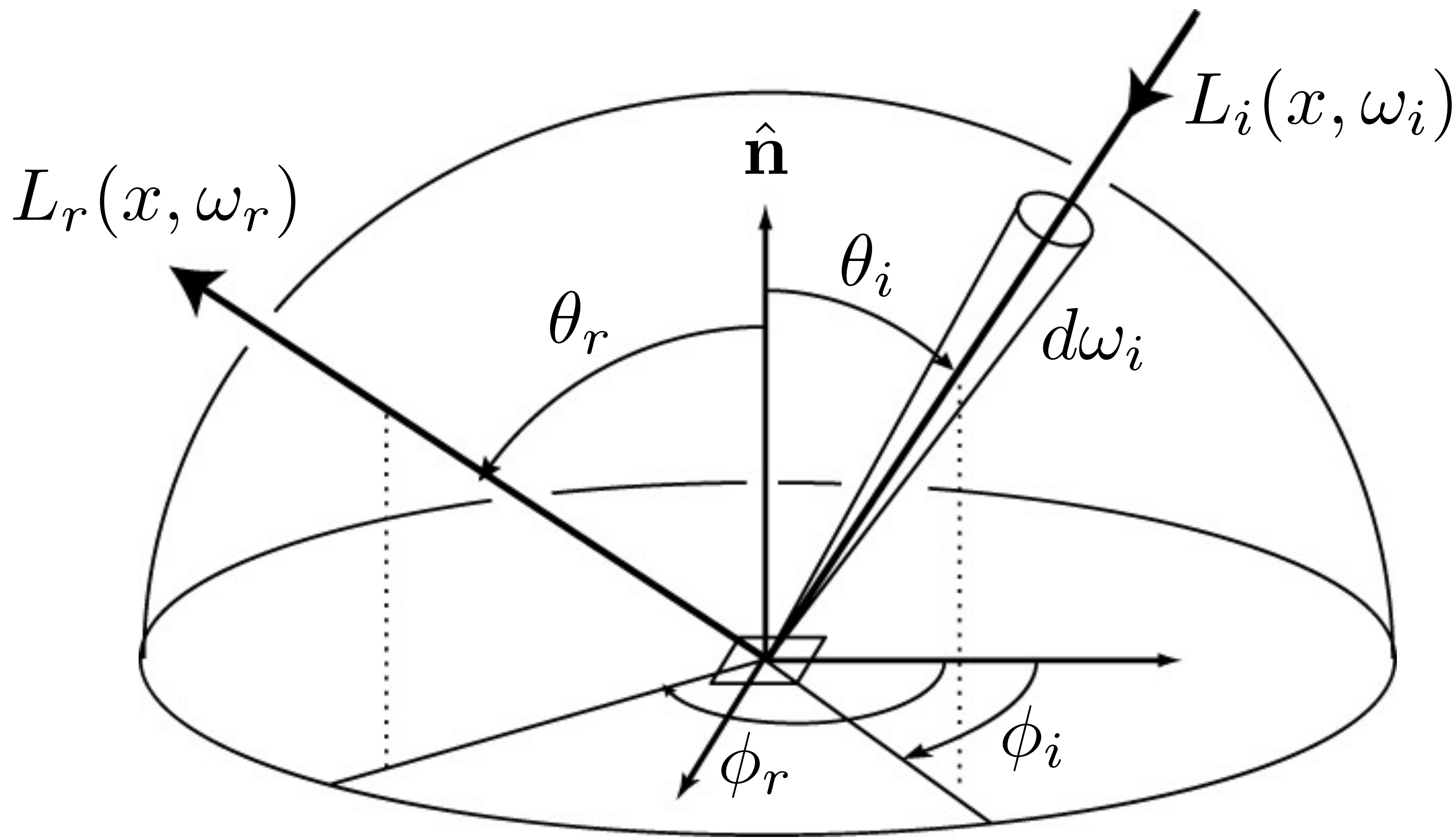
Gonioreflectometer





 [from Marc Levoy, Stanford University]

The Reflection Equation



$$L_r(x,\omega_r) = \int_{\mathcal{H}^2} f_r(x,\omega_i \to \omega_r) L_i(x,\omega_i) \cos\theta_i \; d\omega_i$$

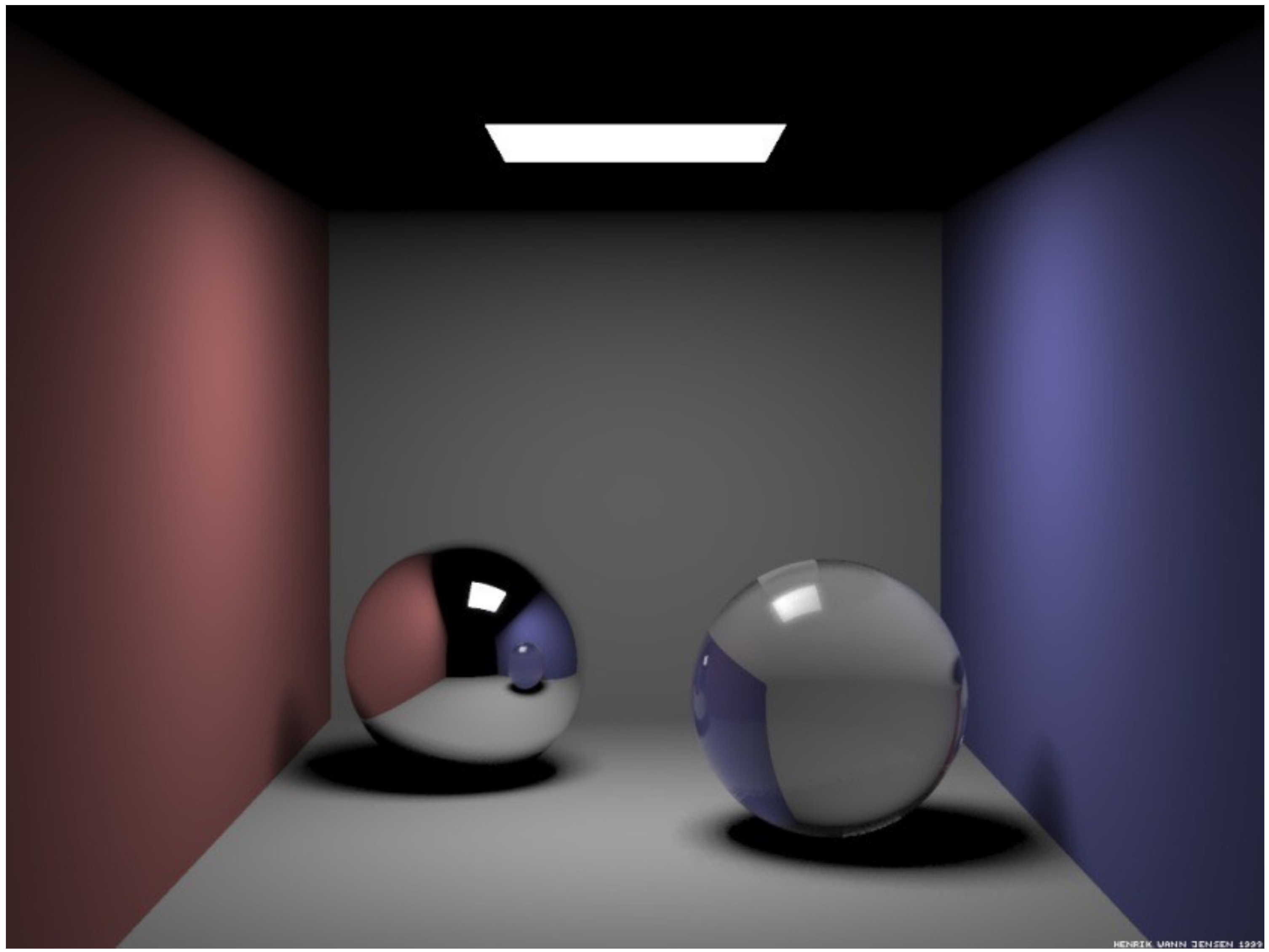
[courtesy of P. Hanrahan, Stanford University]

The Rendering Equation

The Rendering Equation

- Goal is to compute direct and indirect illumination
- **Direct (local)** illumination:
  - incoming radiance from light sources only; no shadows
- **Indirect (global)** illumination:
  - hard and soft shadows
  - diffuse inter-reflections (radiosity)
  - glossy inter-reflections (caustics)

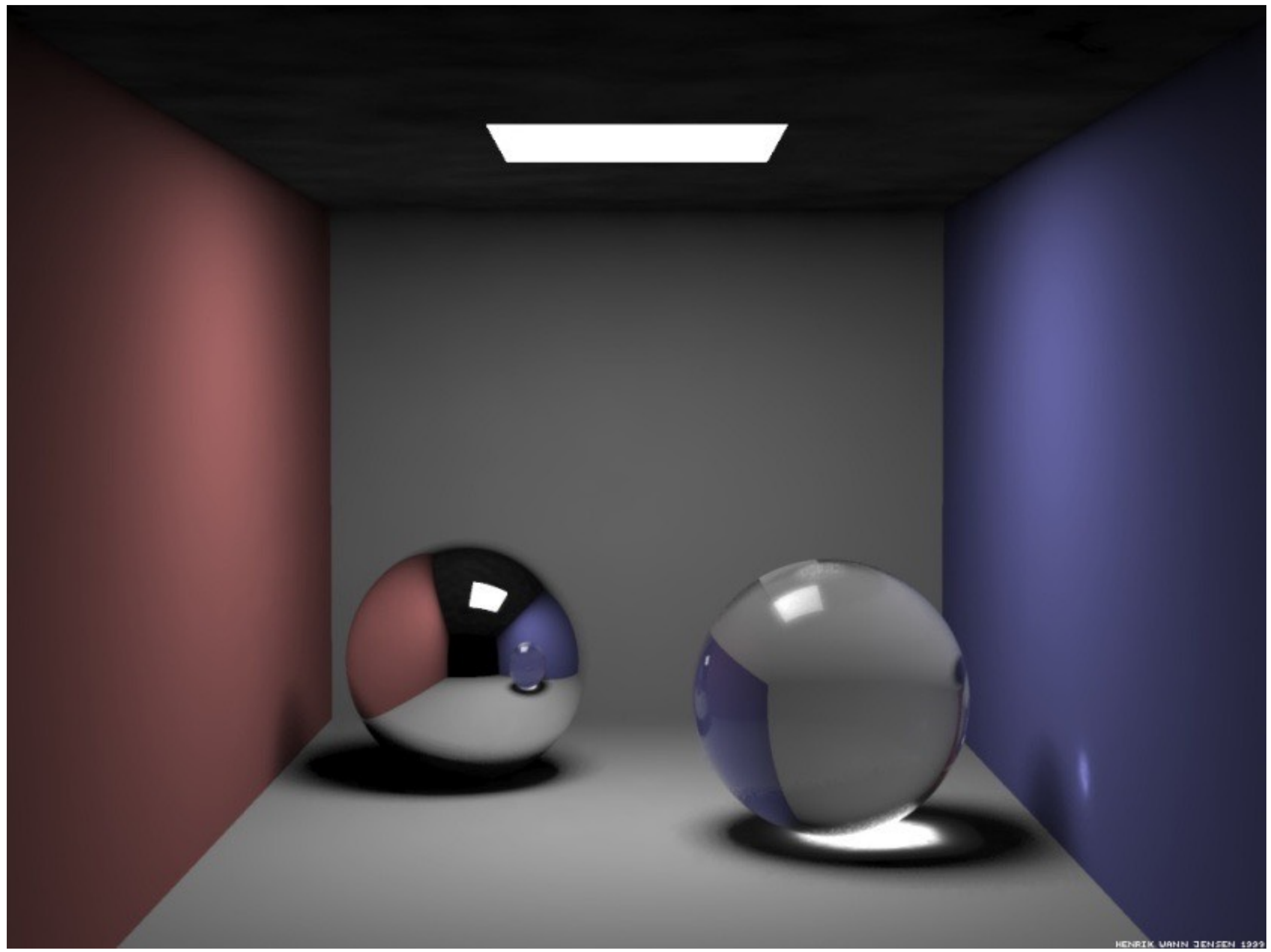
Global Illumination Effects



hard and soft shadows

[image by Henrik Wann Jensen, UCSD]

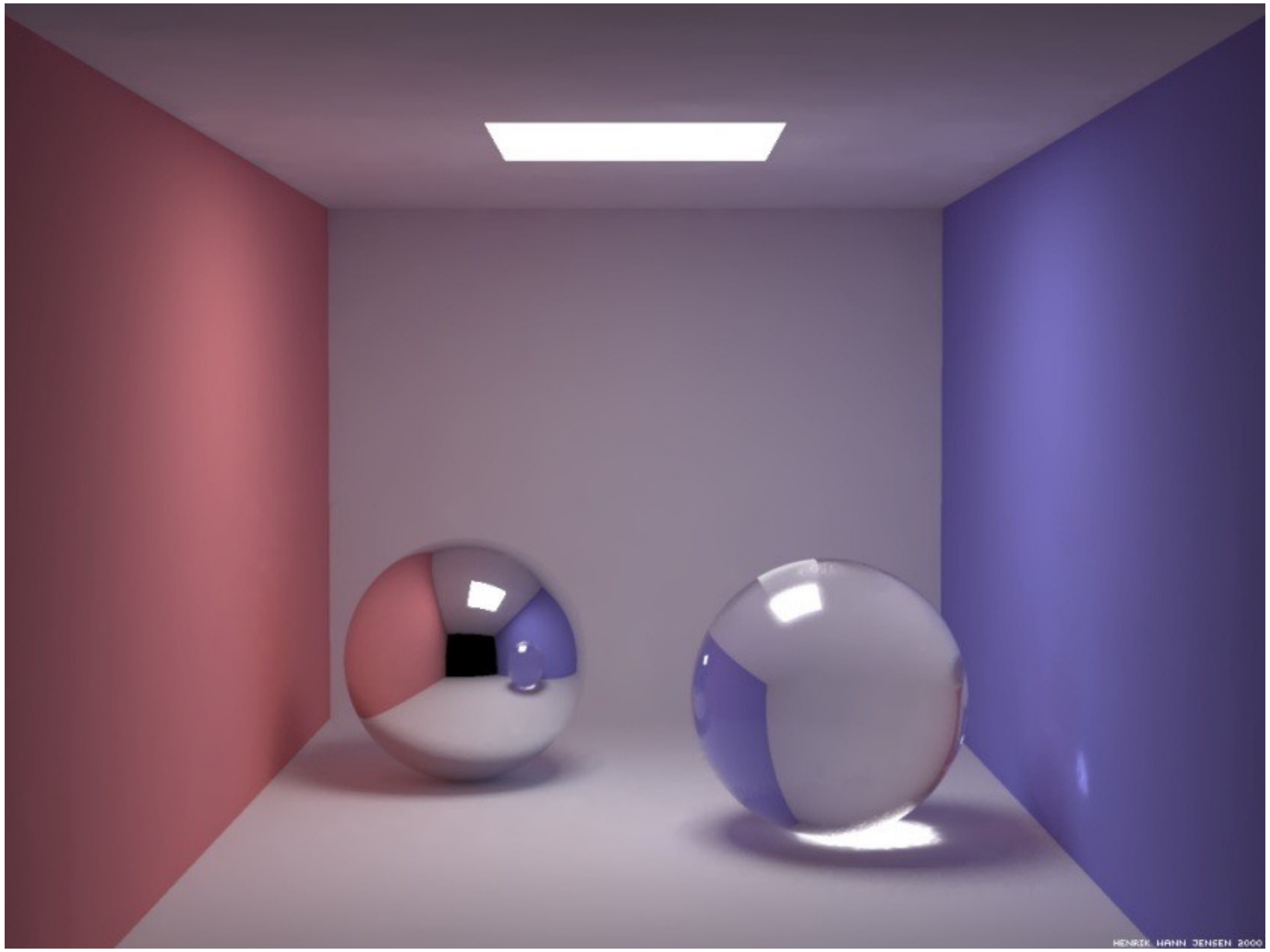
Global Illumination Effects



shadows + caustics

[image by Henrik Wann Jensen, UCSD]

Global Illumination Effects

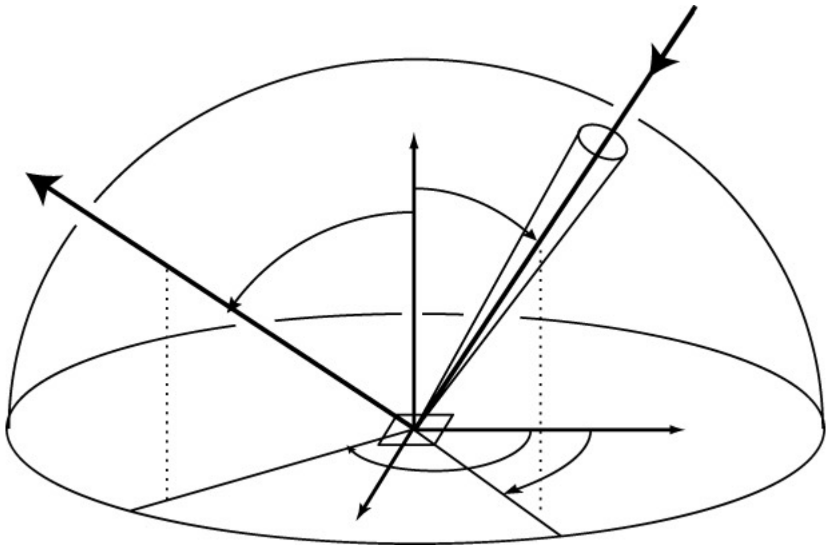


shadows + caustics + radiosity

[image by Henrik Wann Jensen, UCSD]

The Main Challenge

- To evaluate the **reflection equation**,
  - the **incoming radiance** must be known



- To evaluate the **incoming radiance**,
  - the **reflected radiance** must be known

Light Energy Balance

- What are the conditions for equilibrium flow of light in an environment?
- **Globally:** The total light energy put into the system must equal the energy leaving the system
  - correct solution must account for all possible light paths!
- **Locally:** The energy flowing into a small region of phase space equal the energy flowing out
  - outgoing – incoming irradiance = emitted – absorbed

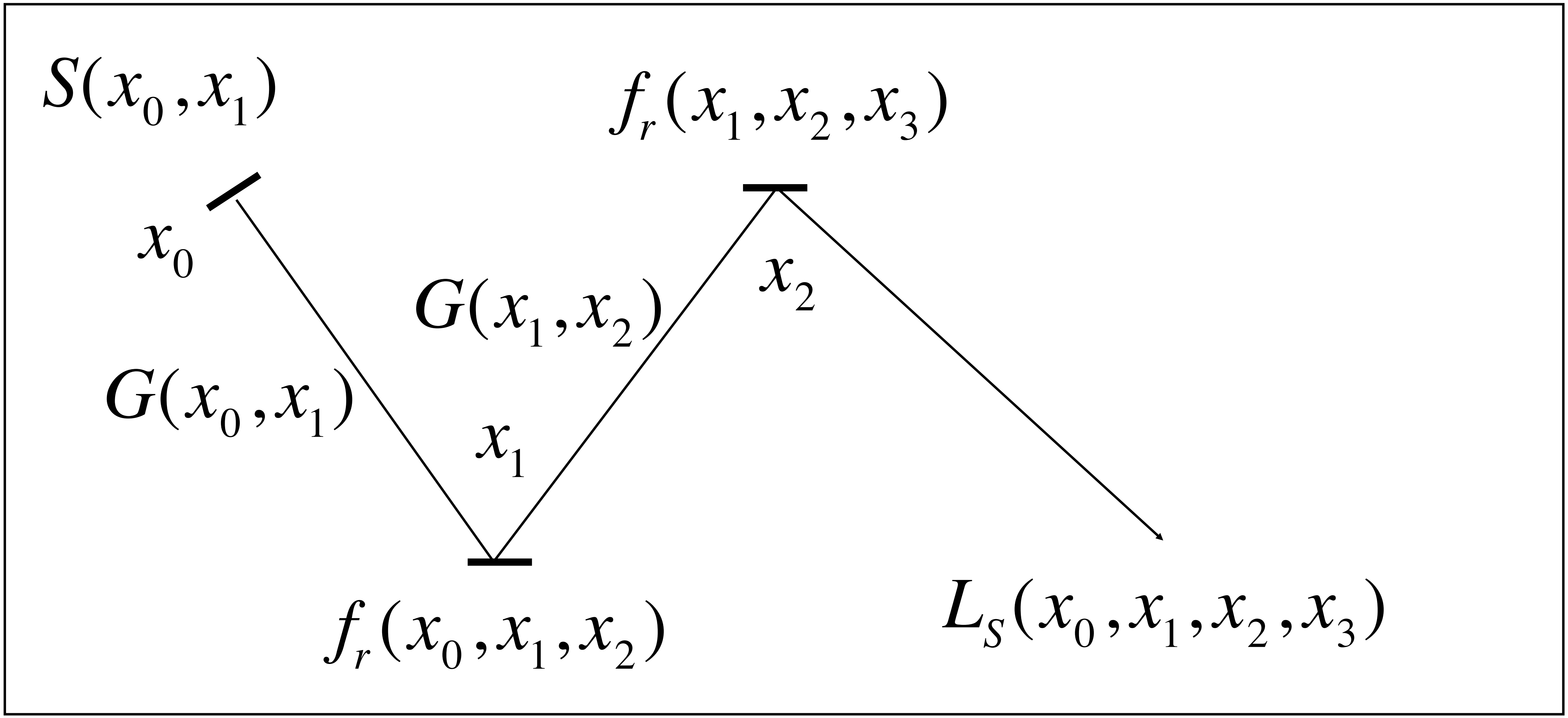
The Surface Rendering Equation

- Outgoing radiance in a given direction is equal to the sum of the emitted and reflected radiance in that direction:

$$
\begin{aligned}
L_o(x, \omega_o) &= L_e(x, \omega_o) + L_r(x, \omega_o) \\
&= L_e(x, \omega_o) + \int_{\mathcal{H}^2} f(x, \omega_i \to \omega_o) L_i(x, \omega_i) \cos\theta_i \; d\omega_i
\end{aligned}
$$

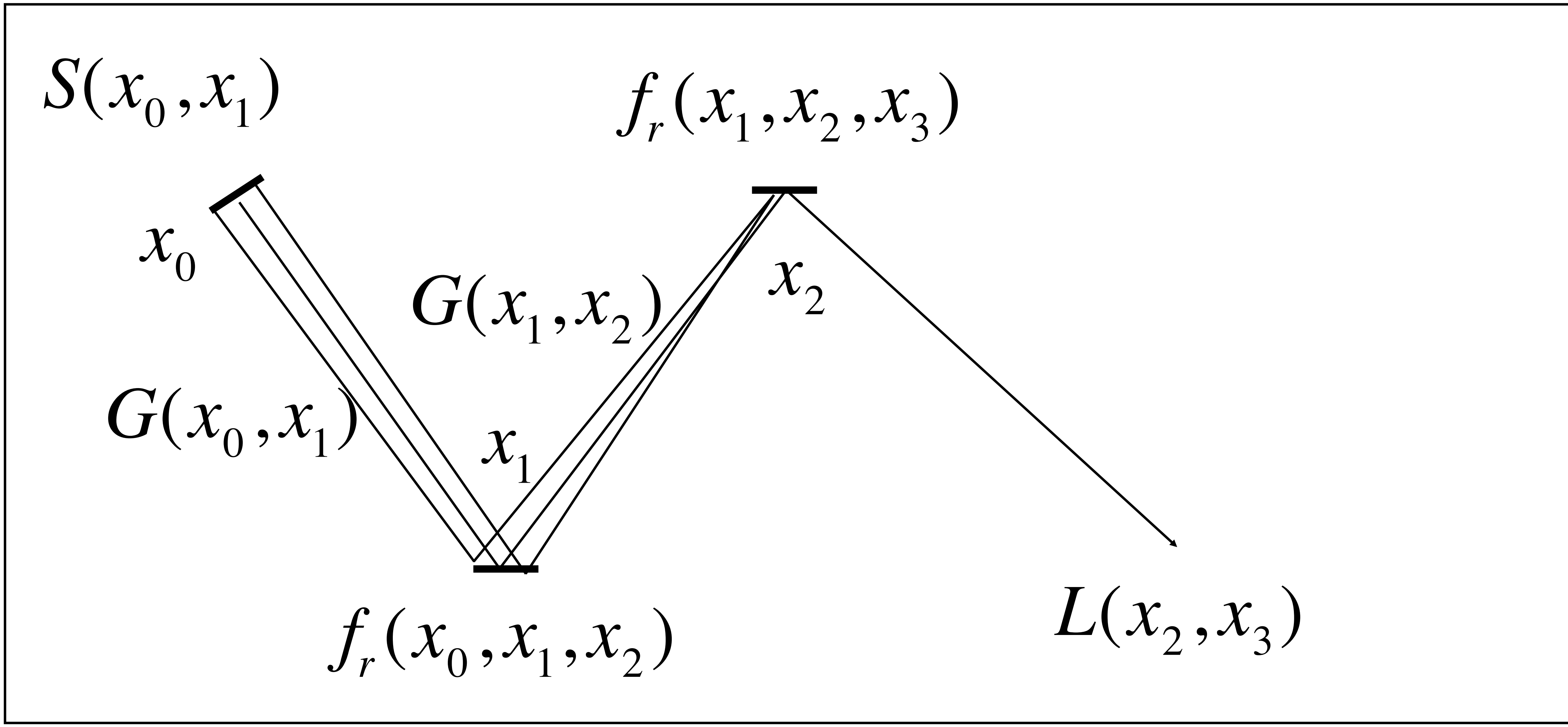
- How the heck do we solve this thing???

A Light Path



[courtesy of P. Hanrahan, Stanford University]

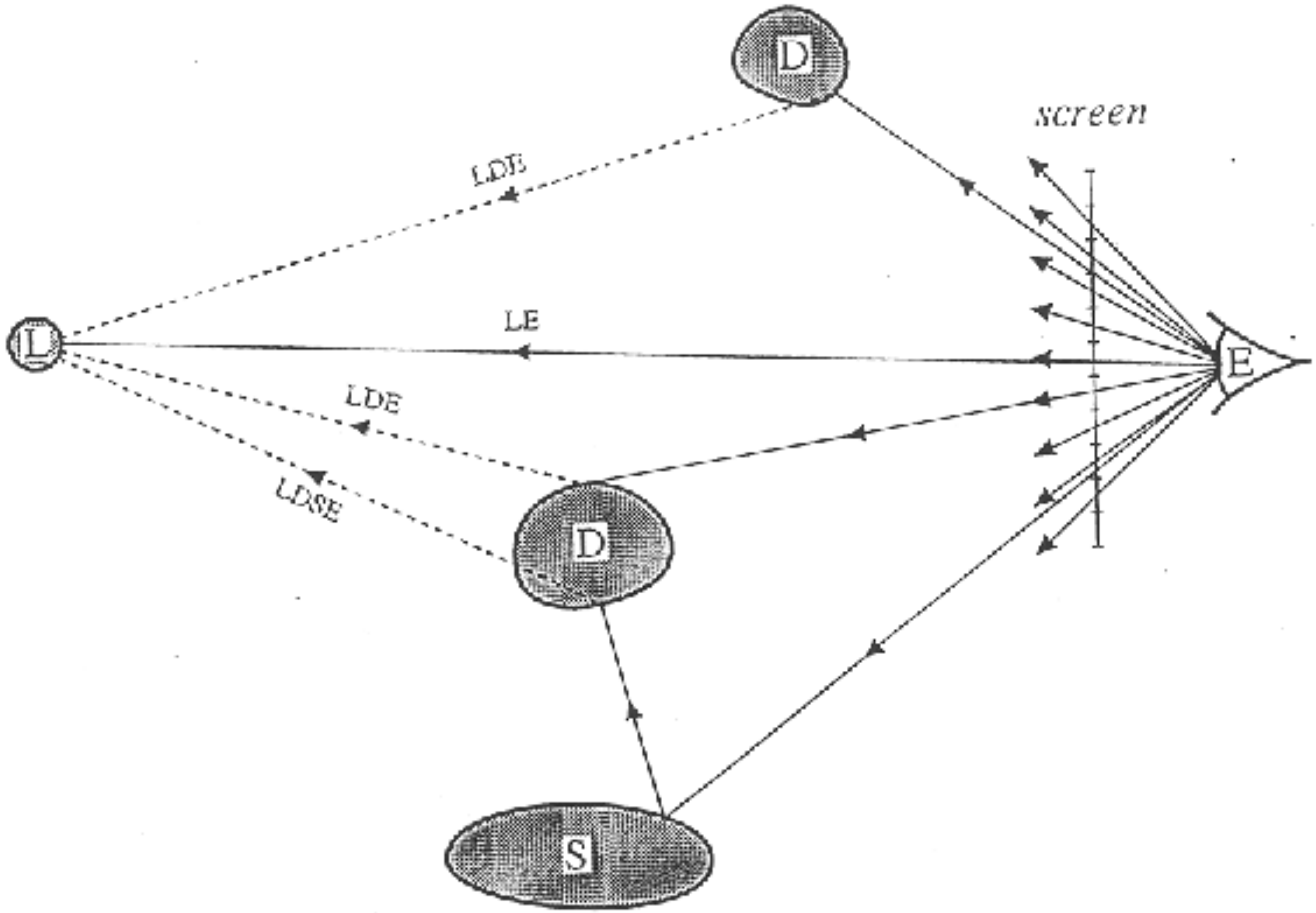
Light Paths



How many light paths contribute to the ray *L*?

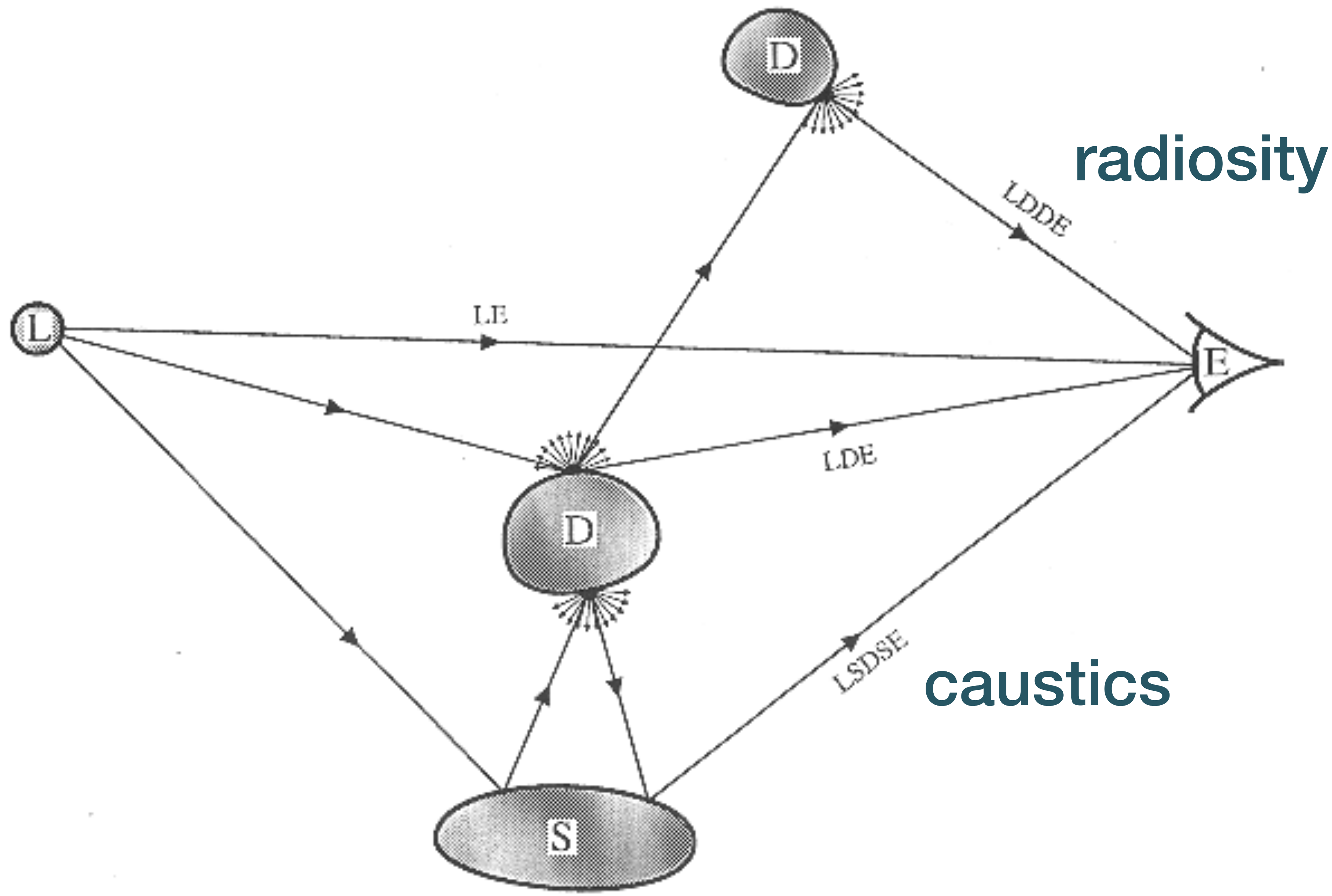
[courtesy of P. Hanrahan, Stanford University]

Light paths you traced in Assignment #4…



[diagram by Paul Heckbert]

Photon Paths



[diagram by Paul Heckbert]

Simulation of Light Transport

- Integrate over **all paths of all lengths**

$$L(x_{k-1}, x_k) = \sum_{k=1}^{\infty} \int_{M^2} \cdots \int_{M^2} L_S(x_0, \cdots, x_{k-2}, x_{k-1}, x_k) dA(x_0) \cdots dA(x_{k-2})$$

- Key challenges of physically-based rendering:
  - How do we generate all the possible light paths?
  - How do we sample the space of paths efficiently?

Monte Carlo Integration

Monte Carlo Integration

- Define a random variable on the integration domain
- Sample the variable and evaluate the integrand
- Integral estimate is the average of samples:

$$\int f(x)dx \quad \Rightarrow \quad F_N = \frac{1}{N}\sum_{i=1}^{N} f(X_i)$$

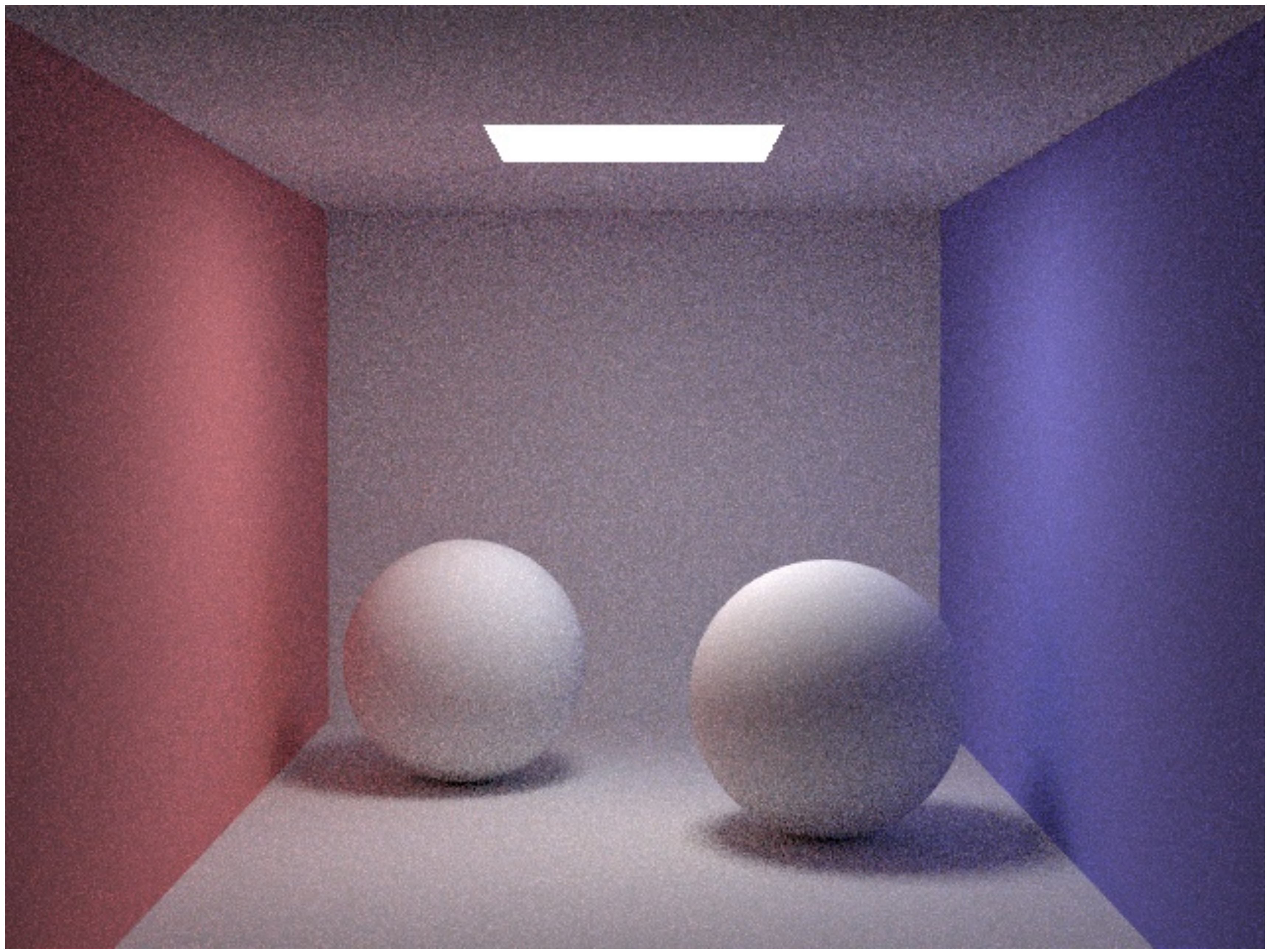
Monte Carlo Integration

- **Advantages**:
  - easy to implement
  - robust with complex integrands
  - efficient for high dimensional integrals
- **Disadvantages**:
  - noisy results
  - slow (many samples needed for convergence)

Monte Carlo Path Tracing

- Choose a source ray (x, ω)
- Find ray-surface intersection $x = x^* (x, \omega)$
    - if light source, return $L_e(x, \omega)$
    - check ray termination condition
    - choose a new ray direction ω drawn from BRDF
    - repeat with new ray (x, ω)

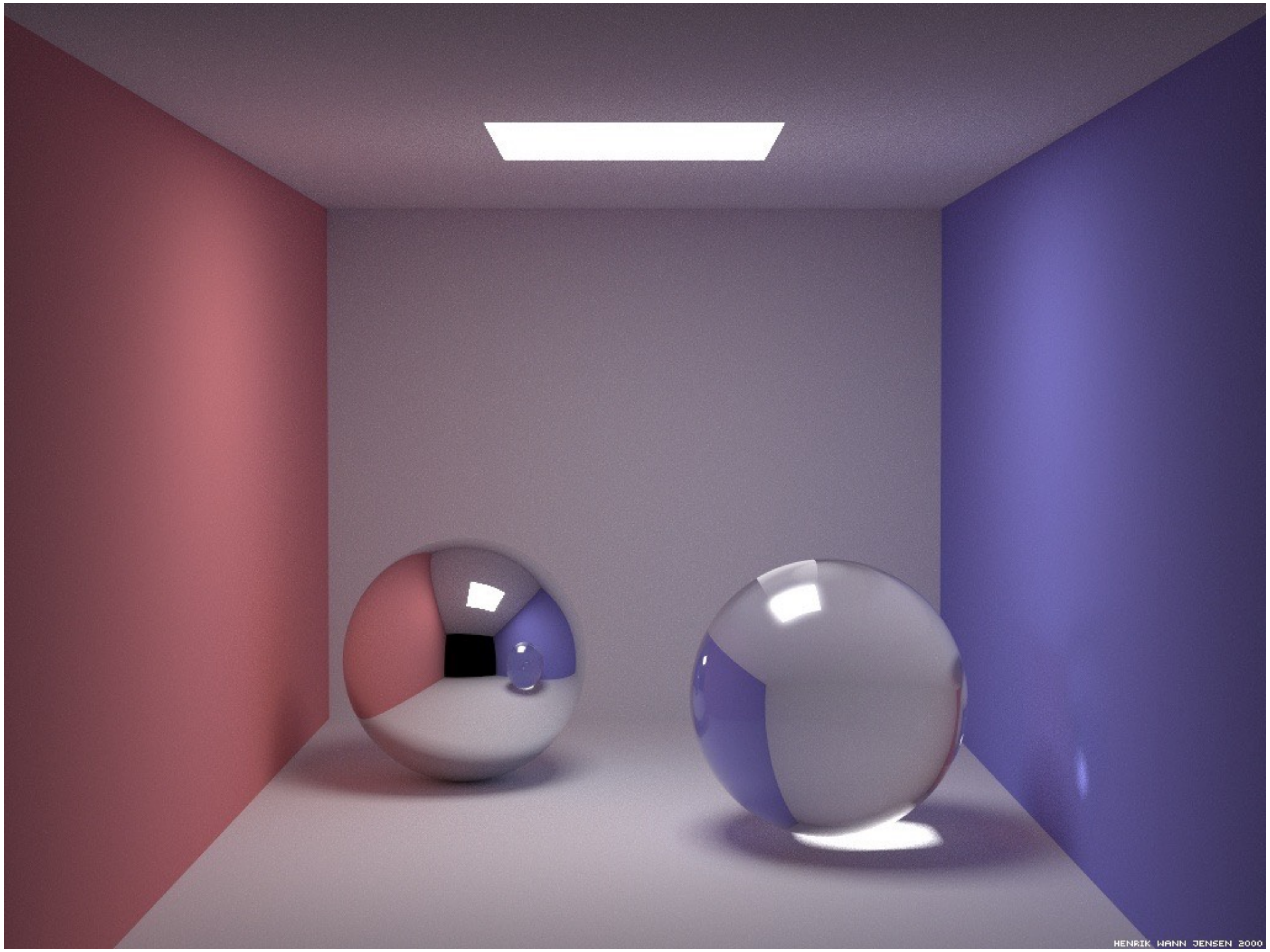
Monte Carlo Path Tracing



10 paths / pixel

[image by Henrik Wann Jensen, UCSD]

Monte Carlo Path Tracing



1000 paths / pixel

[image by Henrik Wann Jensen, UCSD]

What scenes can path tracing

render well?

Large, Hemispherical Light

Marcos Fajardo, 1997

Ambient Occlusion: Pre-Baked Global Illumination

Diffuse Only Ambient Occlusion Combined

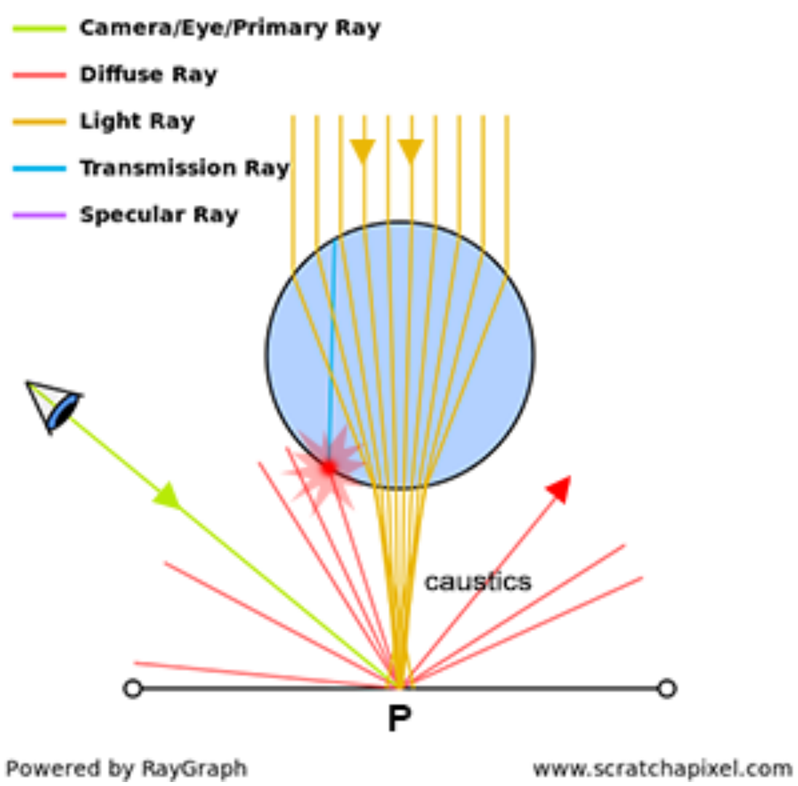
ARNOLD render:

16 paths/pixel, 2 bounces, 250000 faces, 18 min / dual 800 Mhz

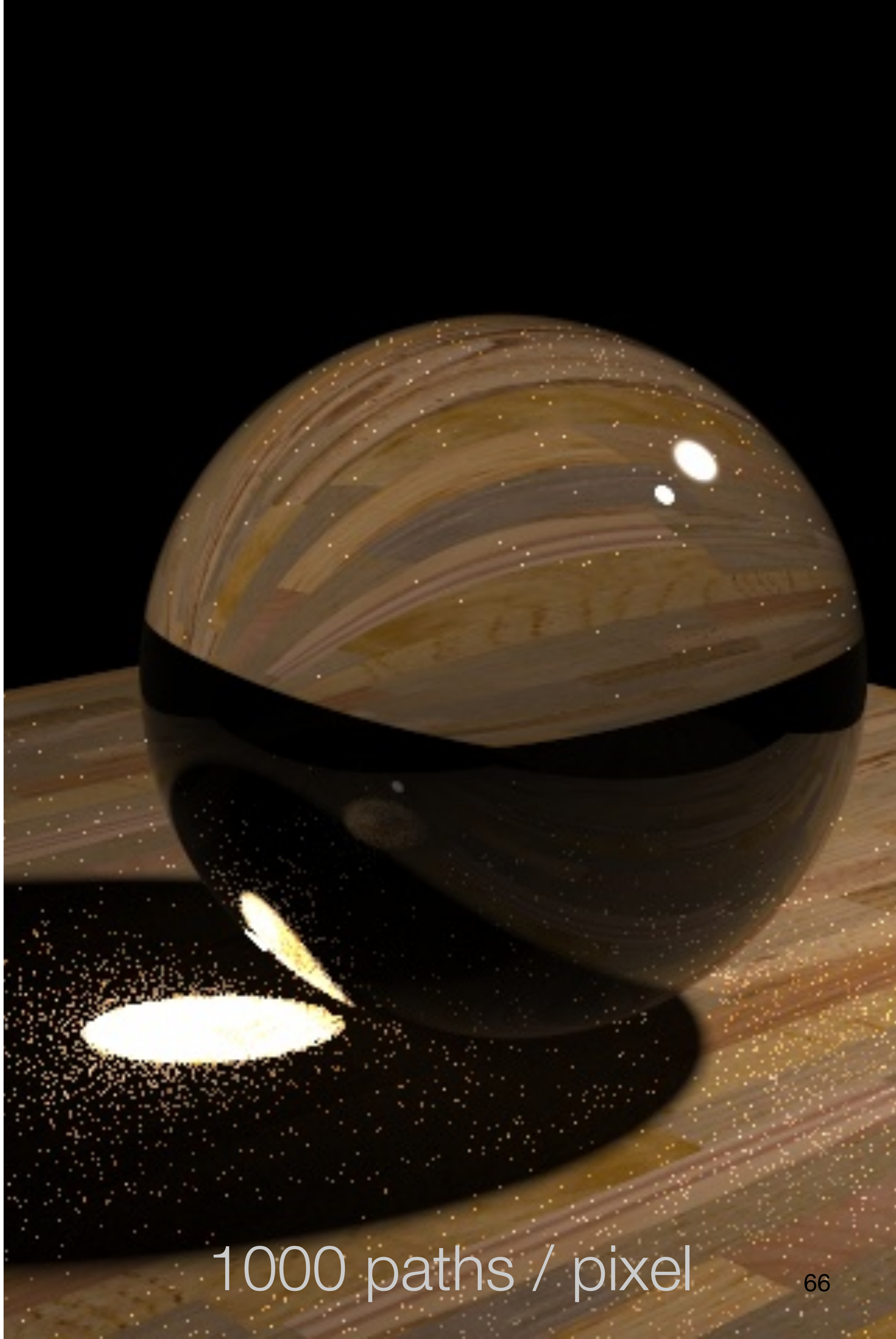
What scenes does path tracing

render poorly?

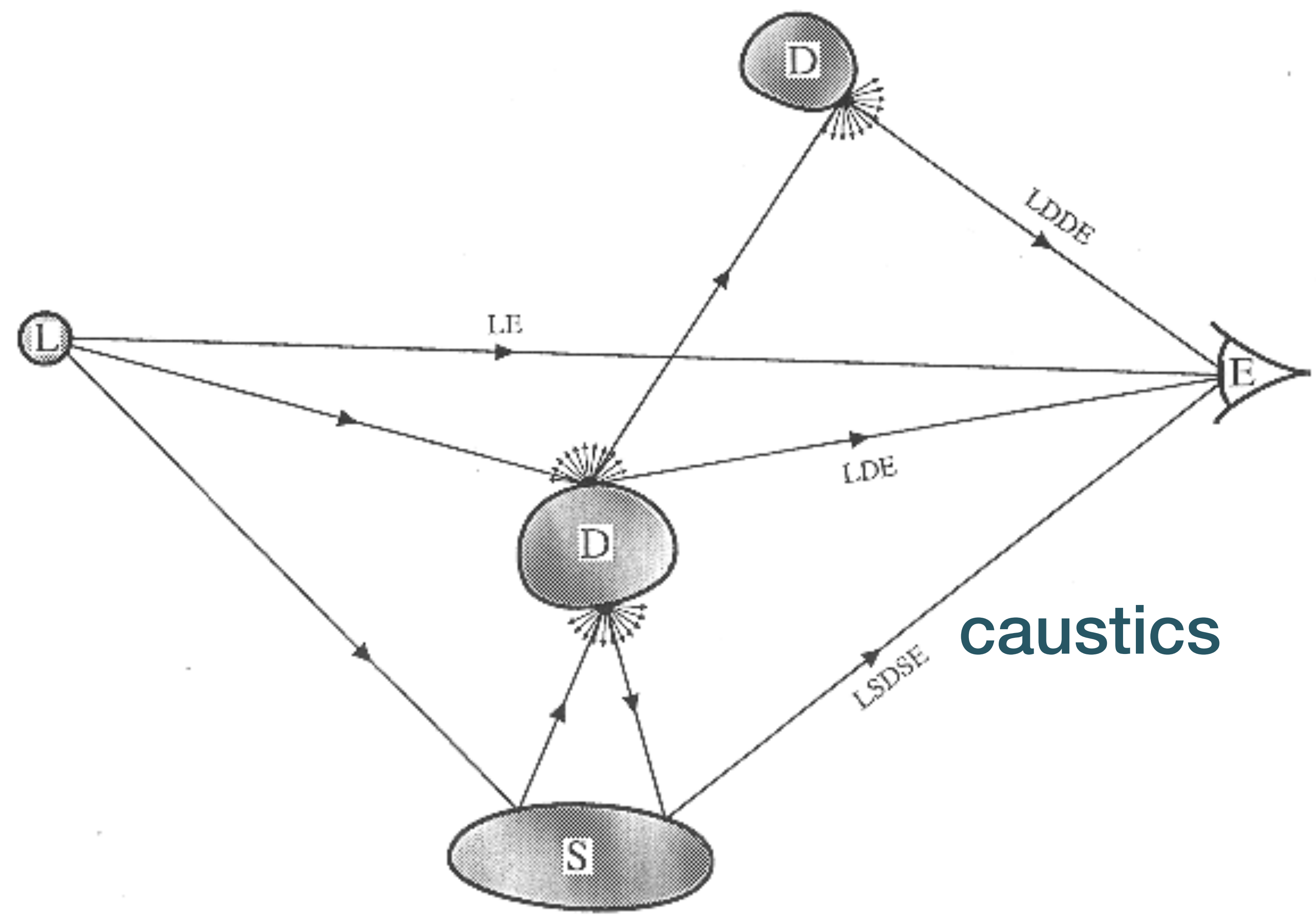
Caustics!



[from scratchapixel.com]

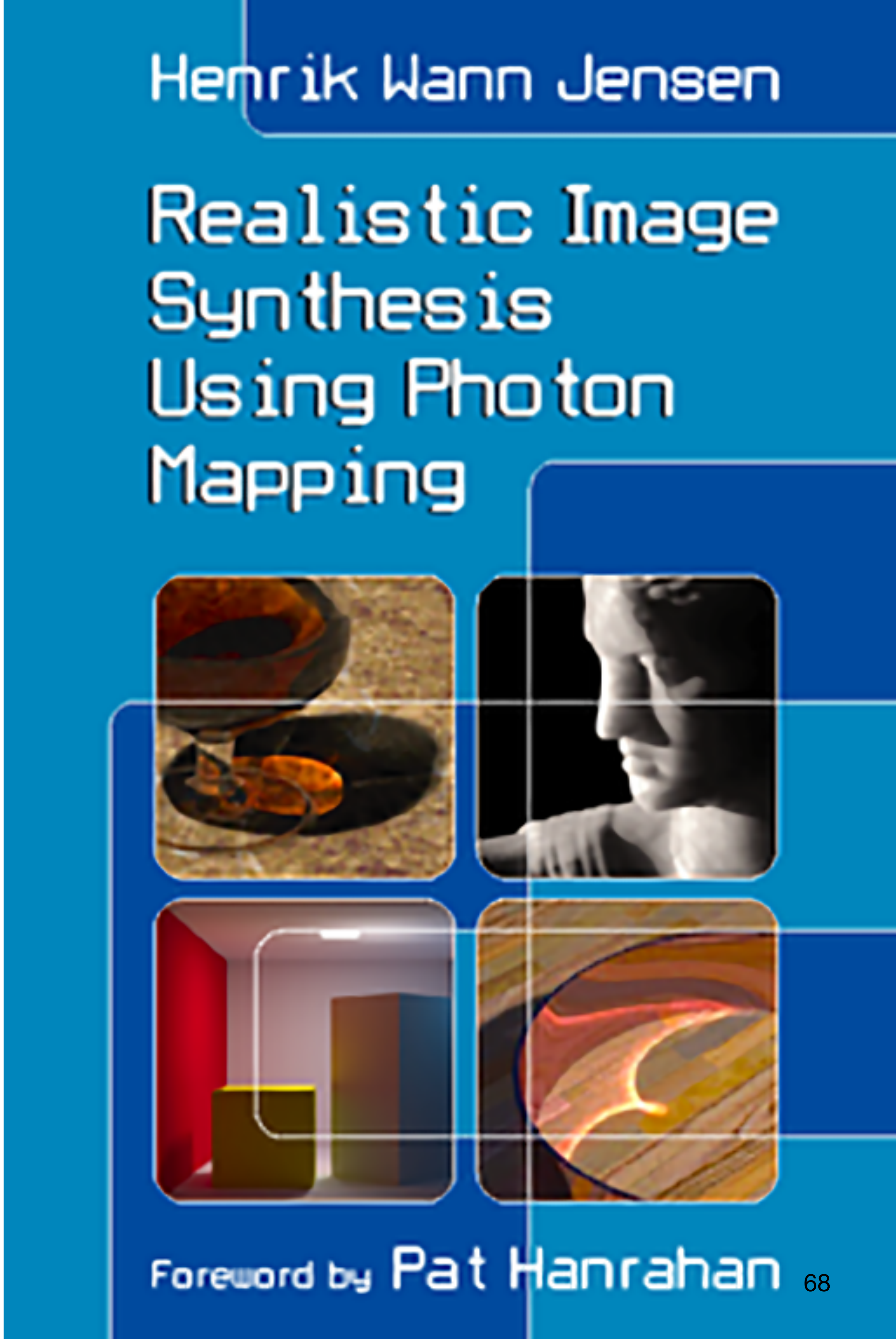


How might we improve this?



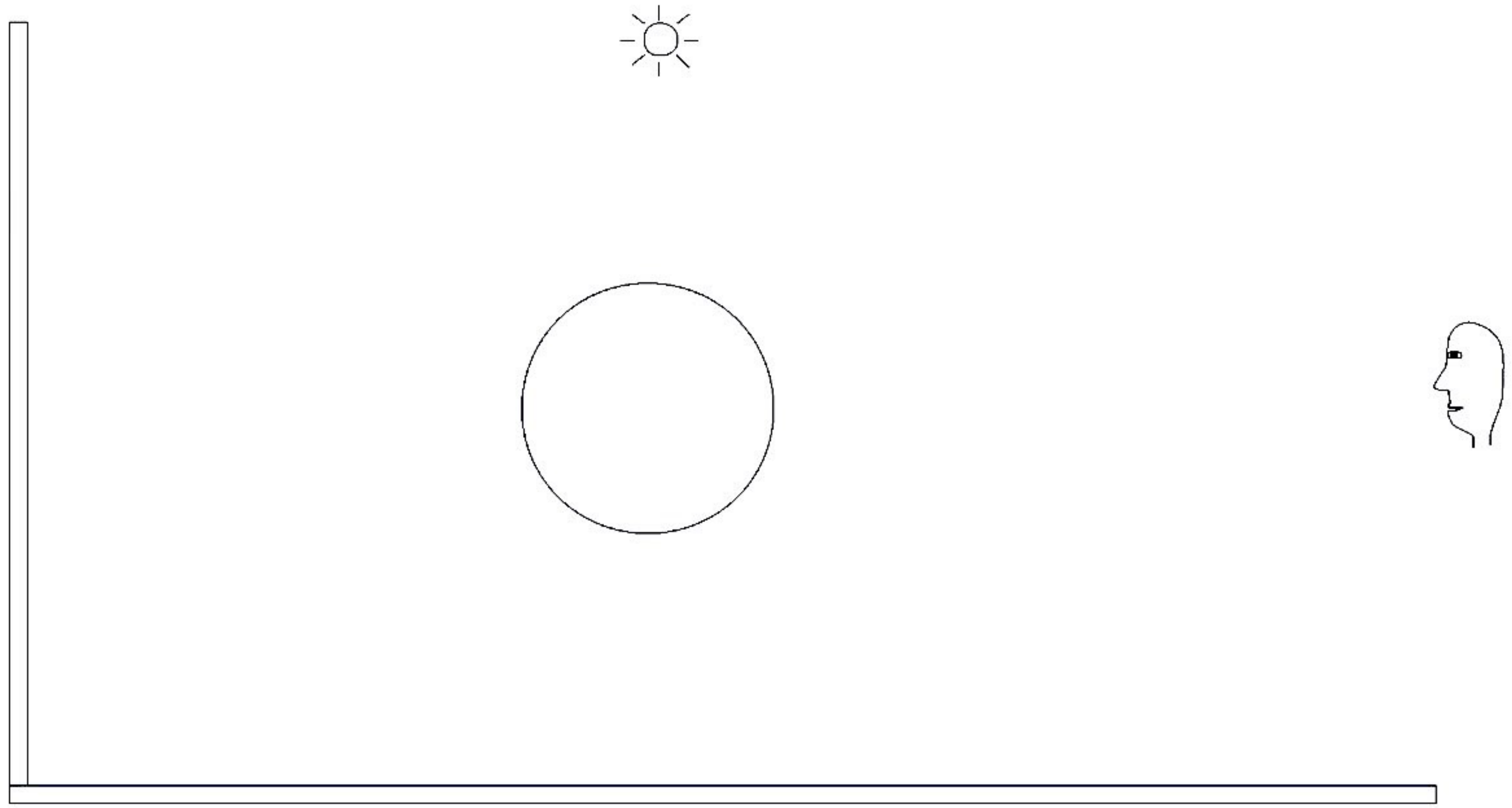
Photon Mapping

Henrik Wann Jensen

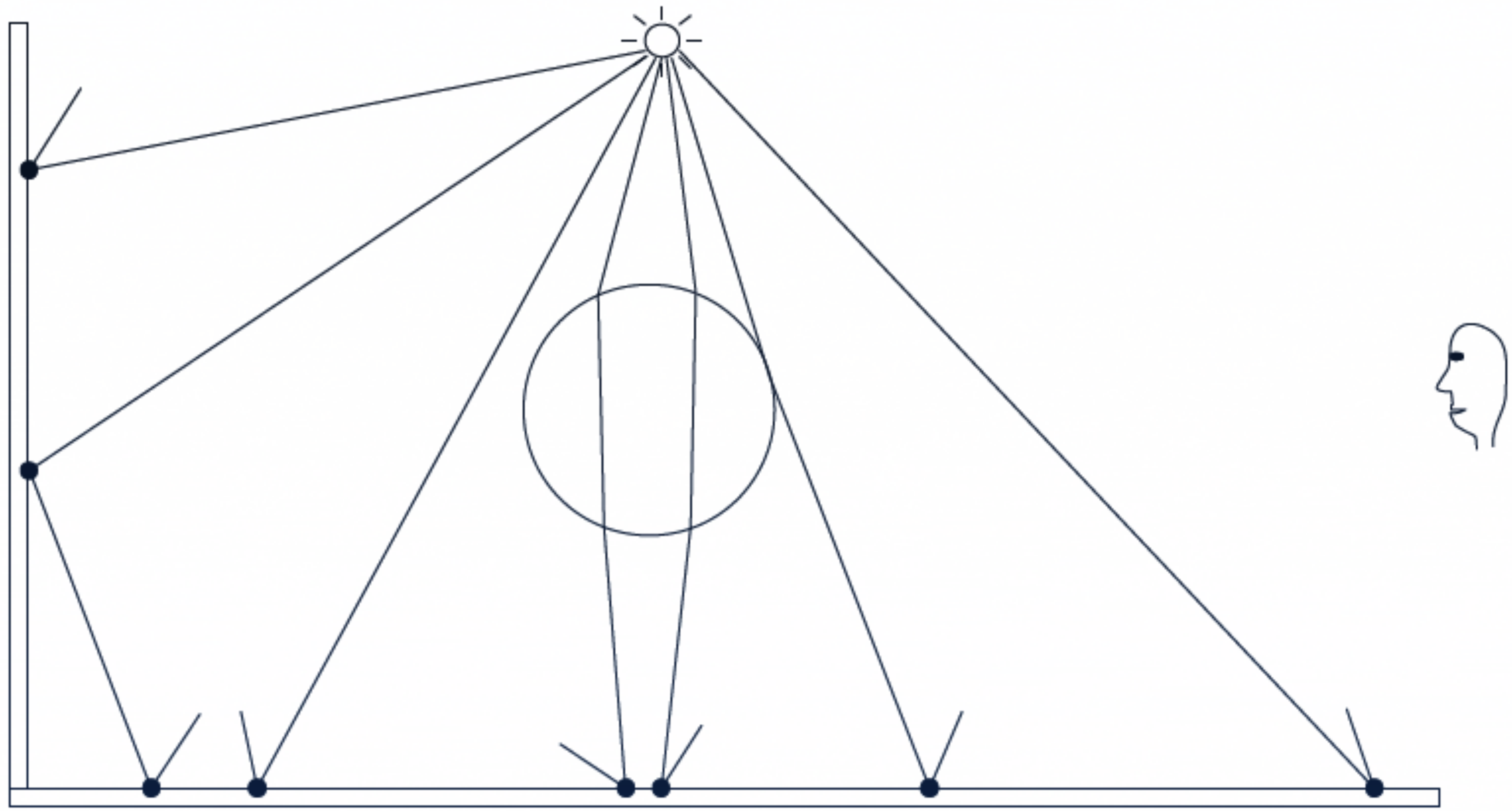


Photon Mapping

- Trace rays emanating from the light sources: **“photons”**



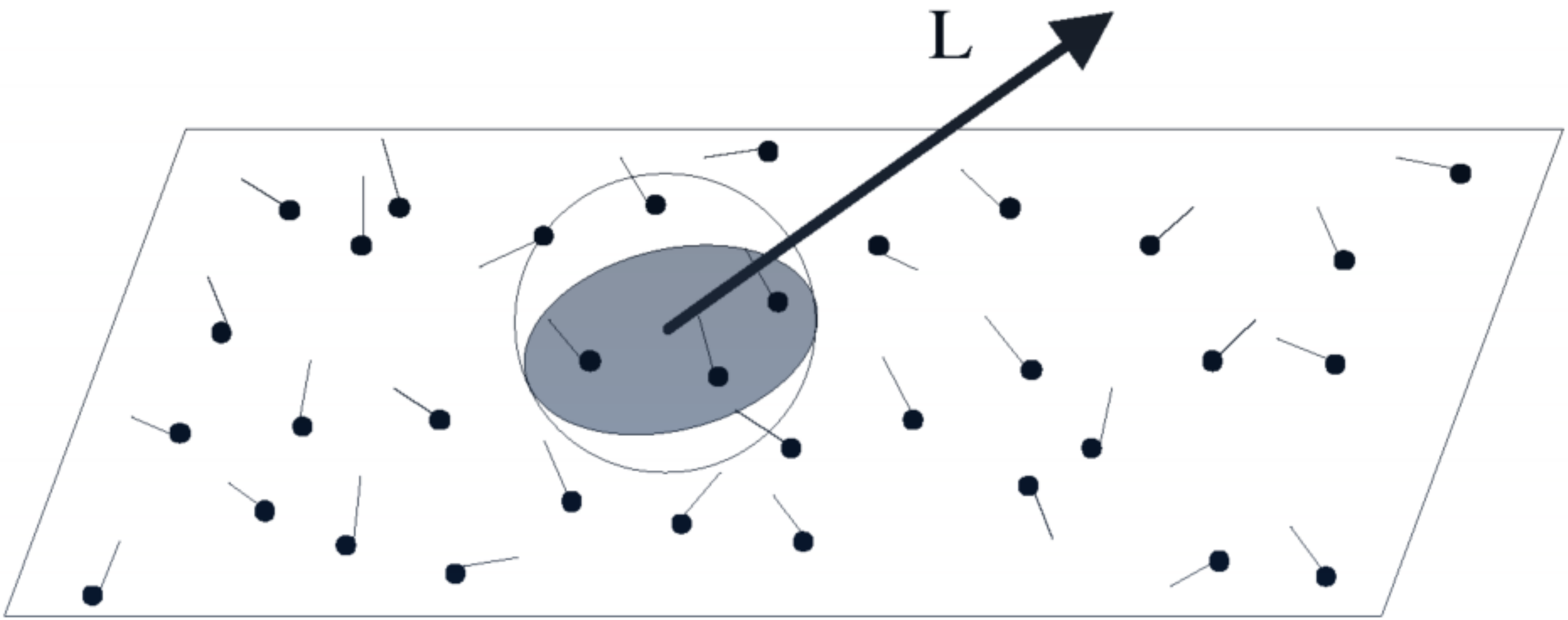
[courtesy of P. Hanrahan, Stanford University]



Photons will stick or “bounce” with some probability proportional to surface reflectance

[courtesy of P. Hanrahan, Stanford University]

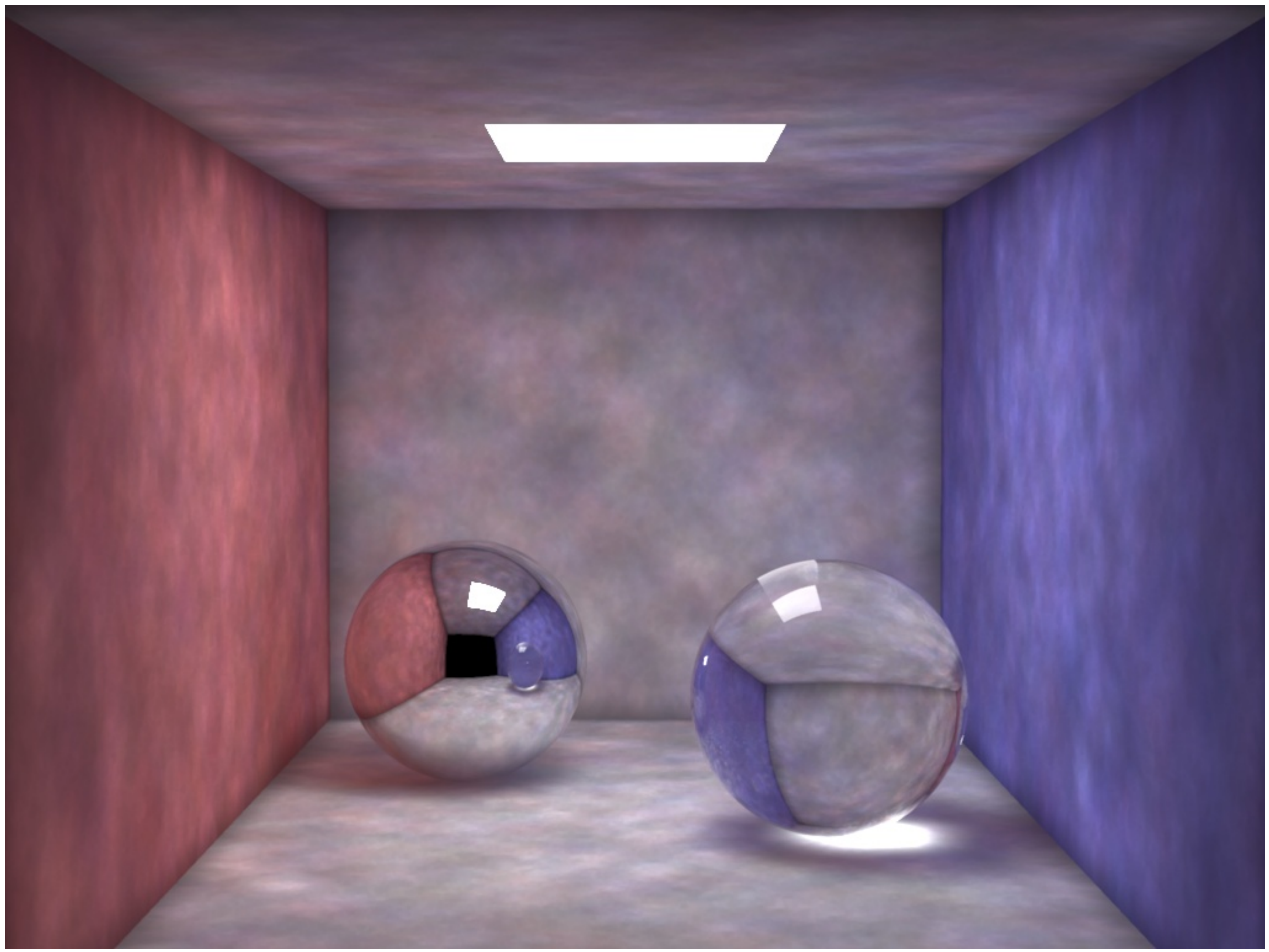
Irradiance Gather



$$L_r(x,\omega_r) = \int_{\mathcal{H}^2} f_r(x,\omega_i \to \omega_r) L_i(x,\omega_i) \cos\theta_i \; d\omega_i$$

[courtesy of P. Hanrahan, Stanford University]

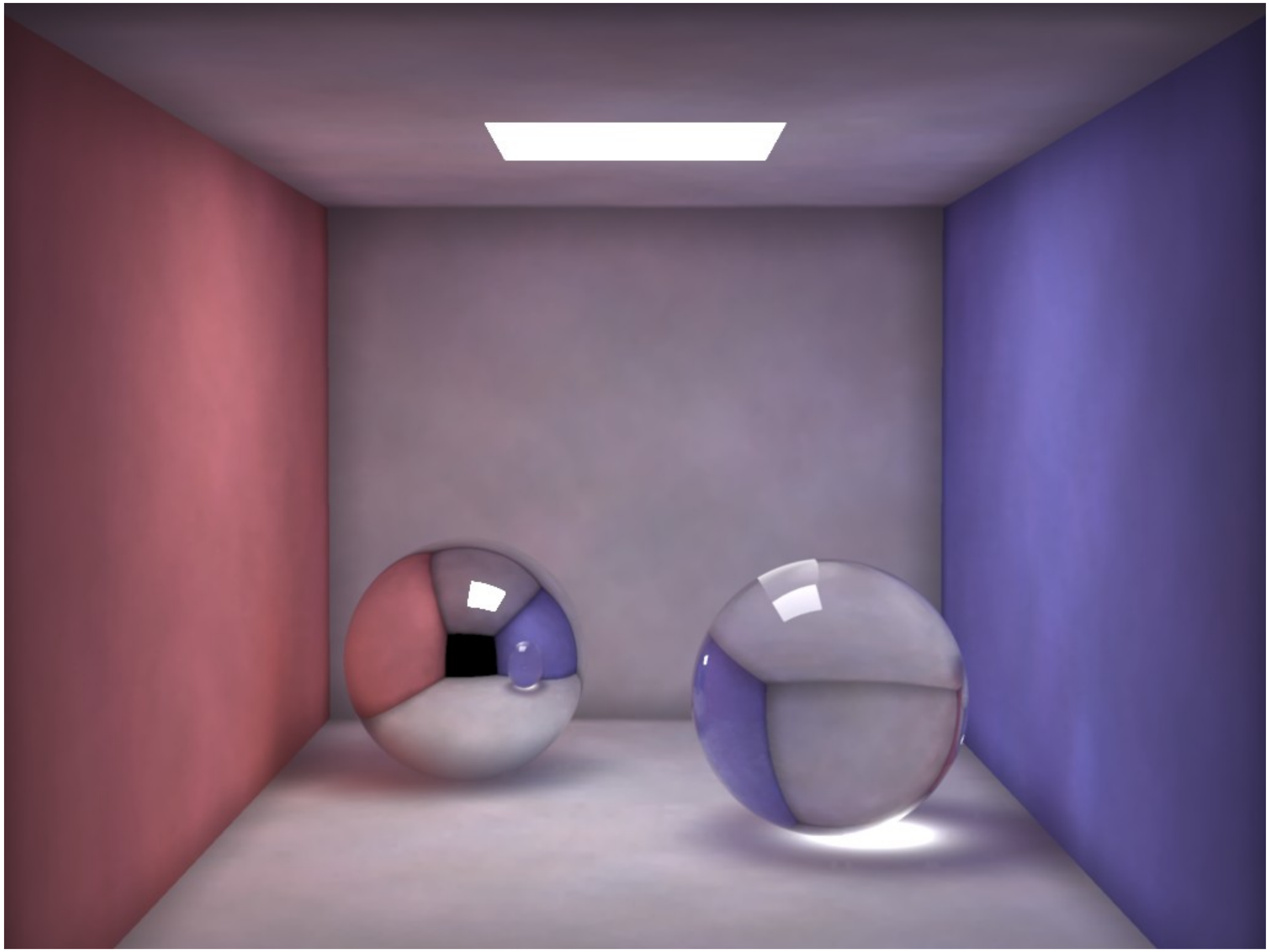
Photon Mapping



100 000 photons, gather 50 for radiance estimate

[image by Henrik Wann Jensen, UCSD]

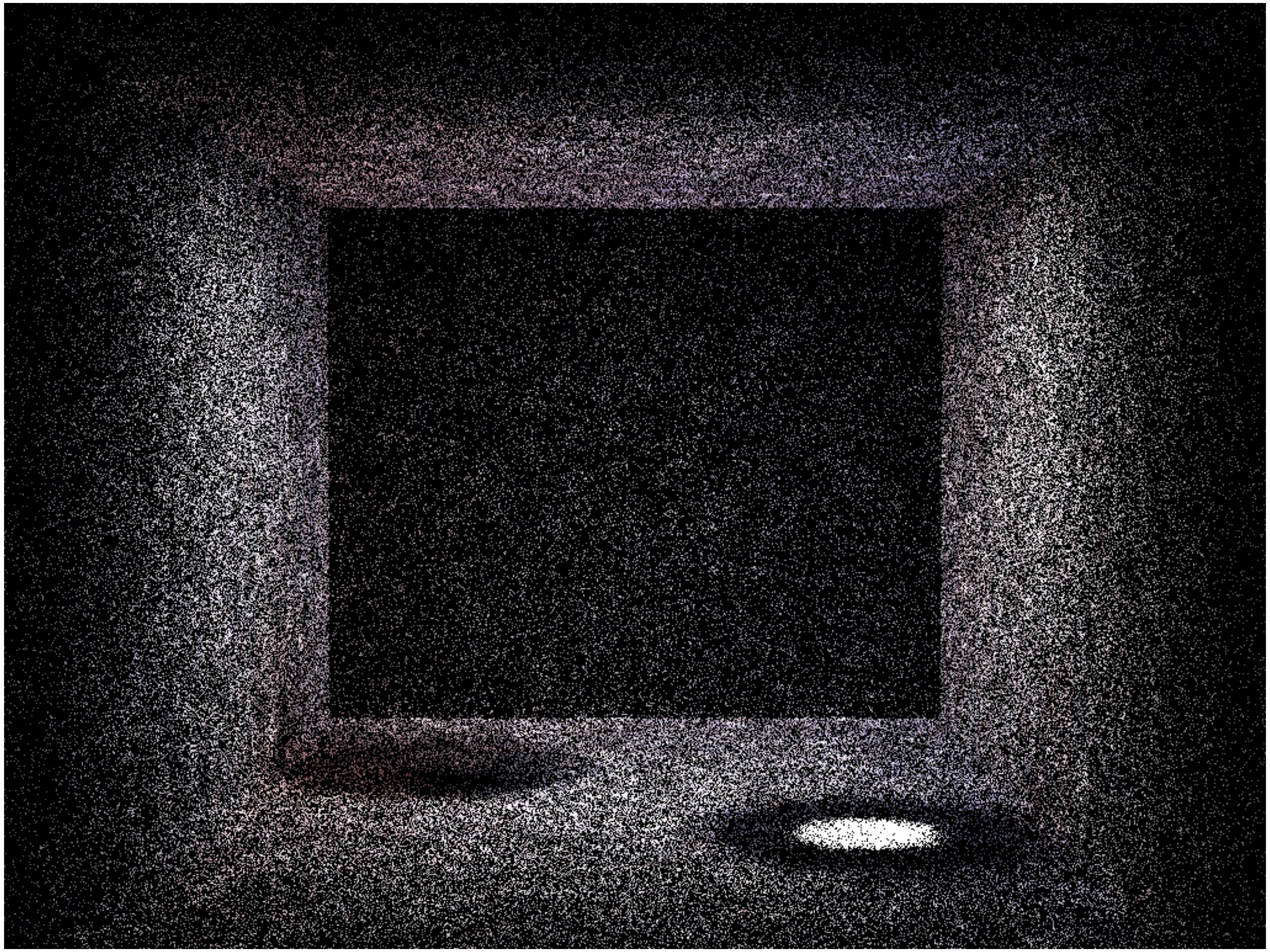
Photon Mapping



500 000 photons, gather 500 for radiance estimate

[image by Henrik Wann Jensen, UCSD]

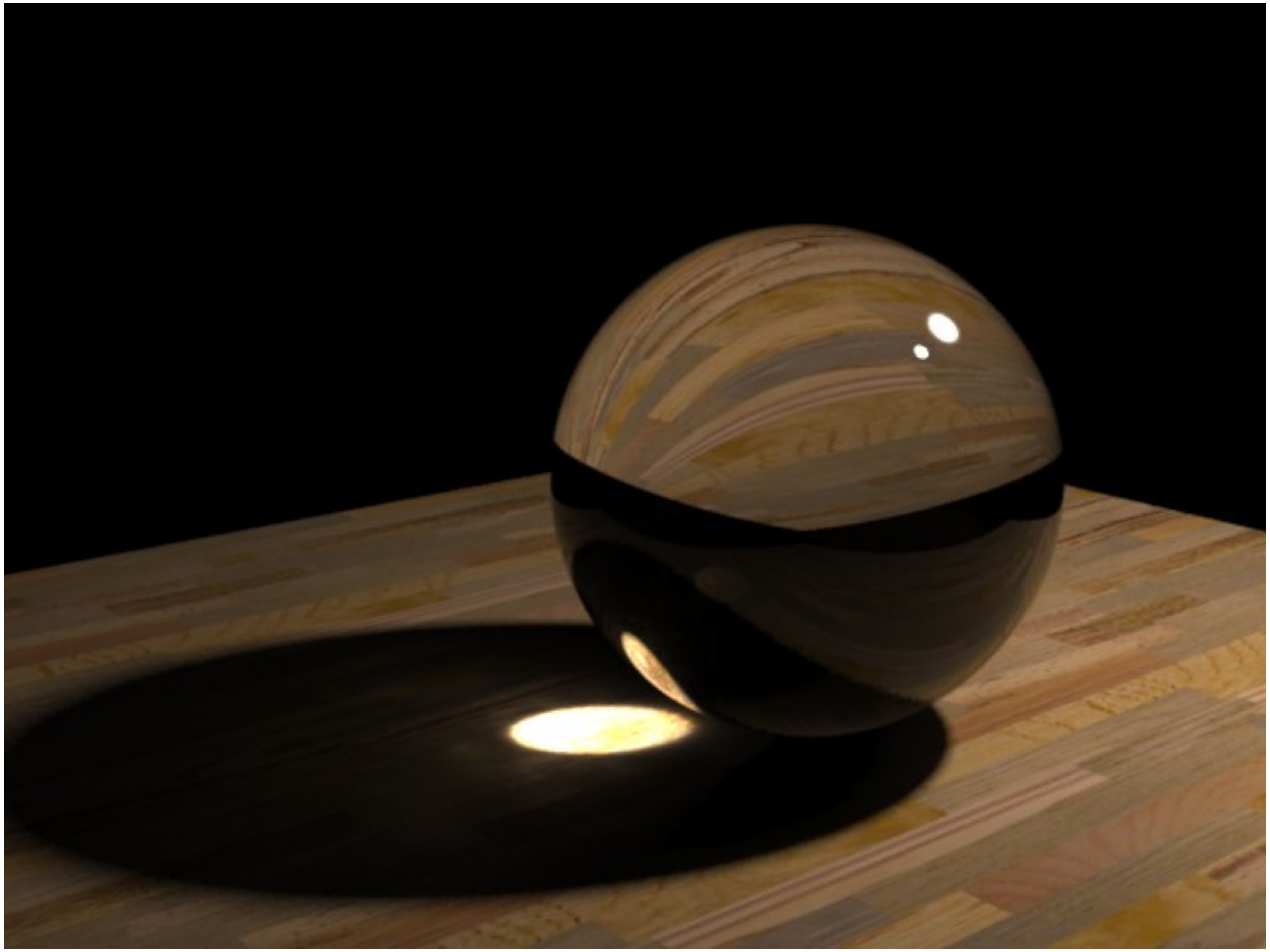
Photon Mapping



positions of 200 000 photons

[image by Henrik Wann Jensen, UCSD]

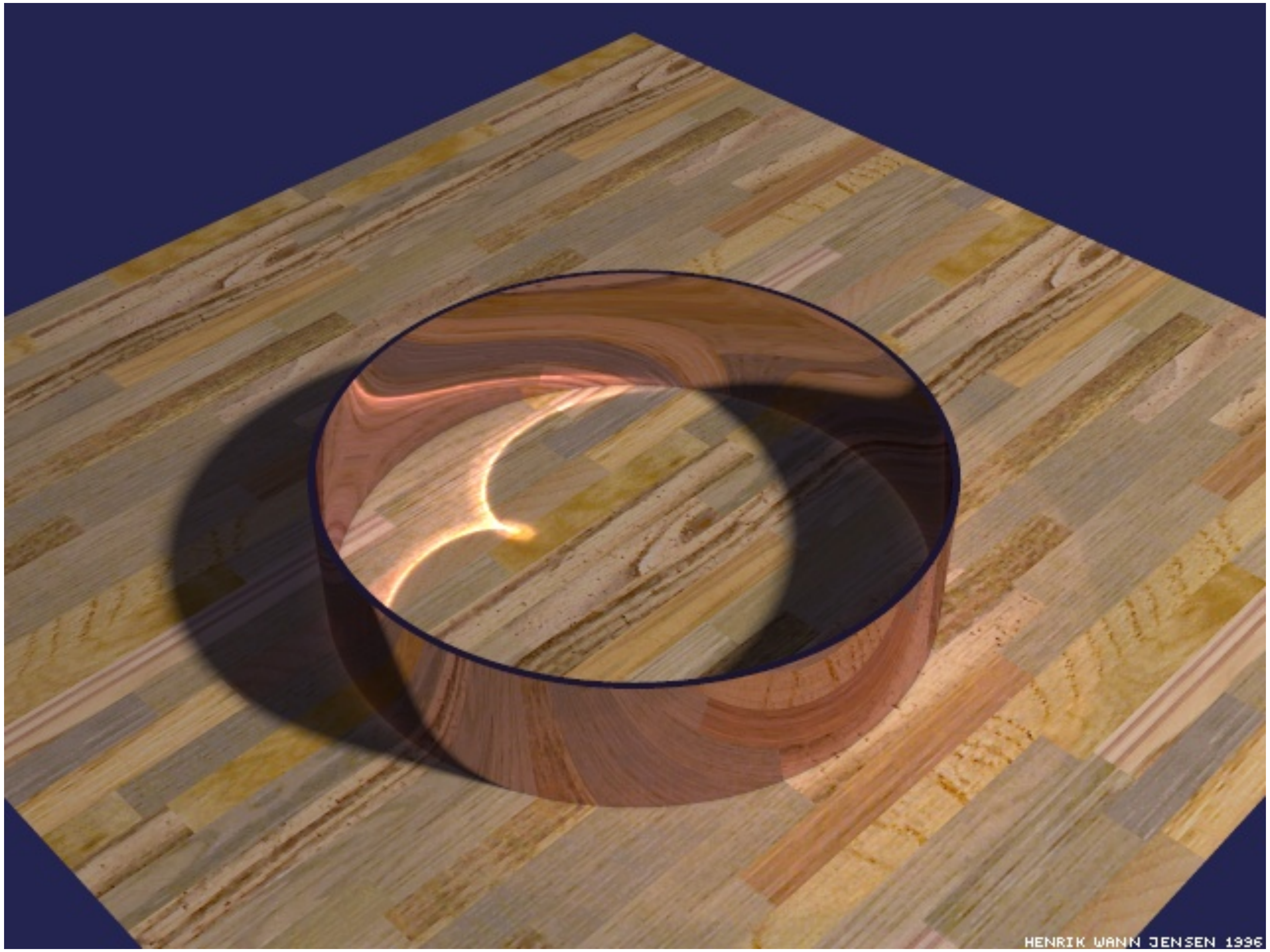
Photon Mapping: Caustics



10 000 photons, gather 50 for radiance estimate

[image by Henrik Wann Jensen, UCSD]

Photon Mapping: Caustics



50 000 photons, gather 50 for radiance estimate

[image by Henrik Wann Jensen, UCSD]

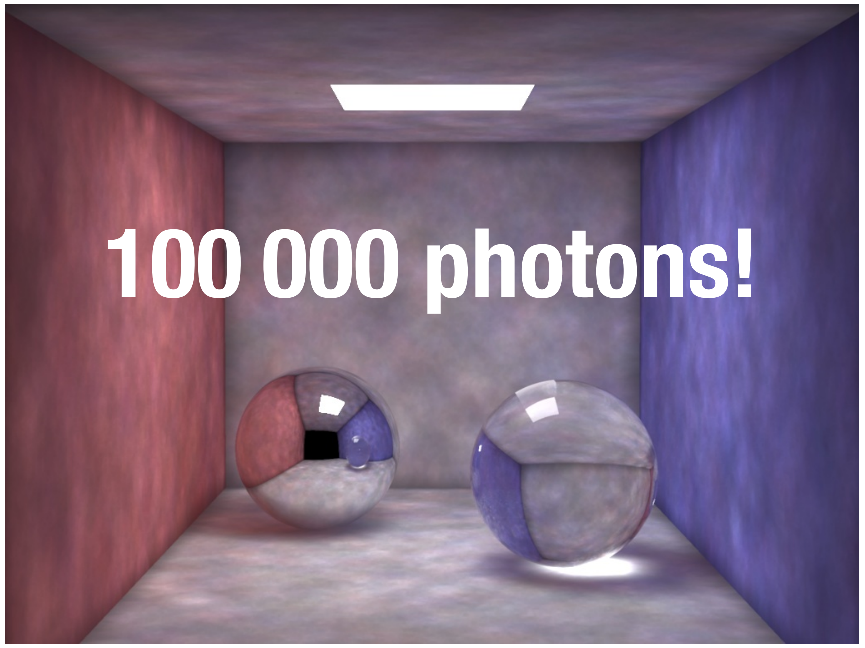
Photon Mapping: Caustics

Henrik likes cognac

[image by Henrik Wann Jensen, UCSD]

What are the main

challenges or limitations?



Real or Synthetic?

[image by Henrik Wann Jensen, UCSD]

Real or Synthetic?

[from wsj.com]

Real or Synthetic?

[from wsj.com]

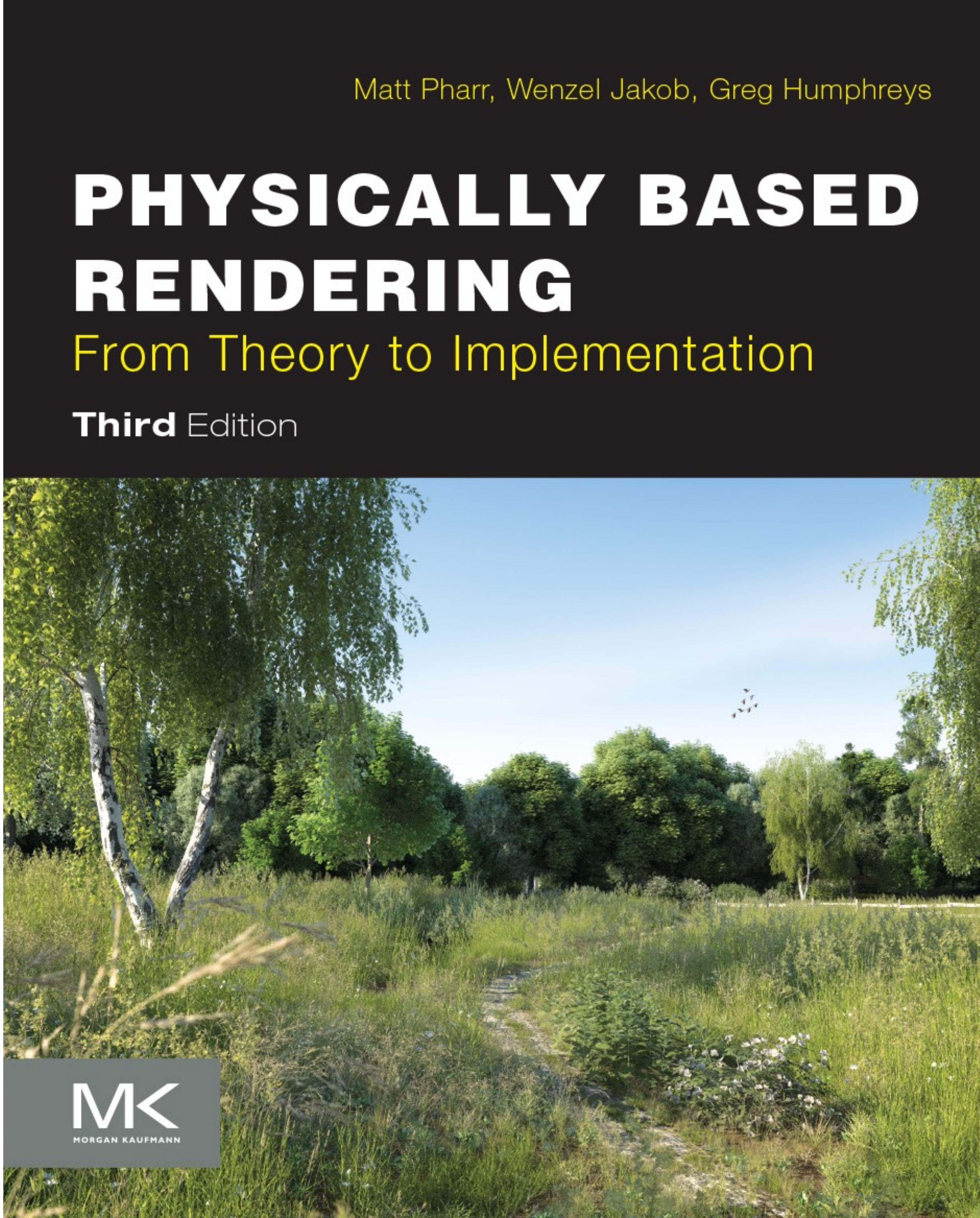
Real or Synthetic?

[from wsj.com]

I still haven't talked about how to do this…


[from blendernation.com]

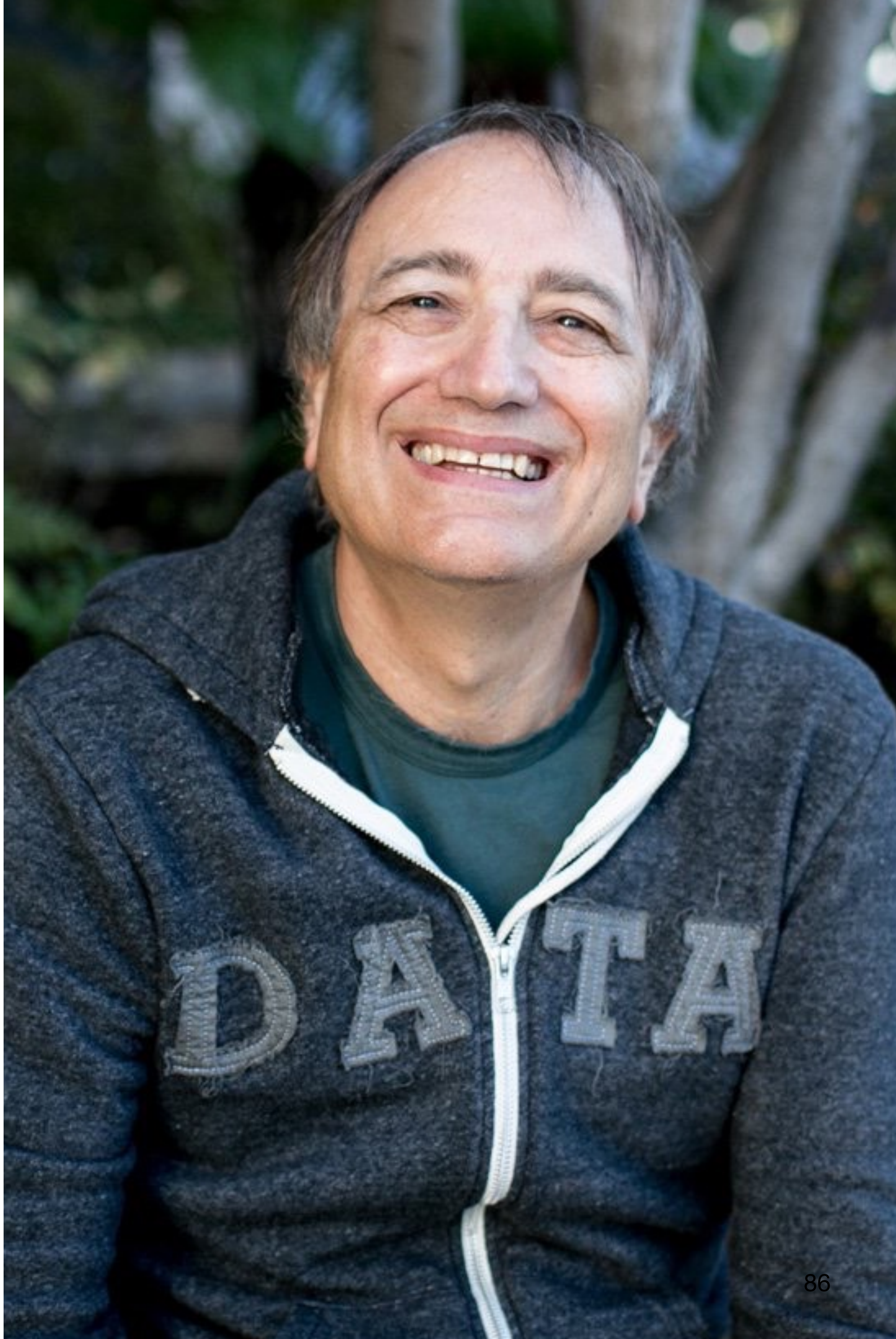
The Reference



Who is Pat Hanrahan?

[accolades too numerous to list]

Most of today's lecture content was adapted, borrowed, or downright pilfered from the works of Dr. Hanrahan. Thanks Pat!



Things to Remember

- Heuristic lighting techniques we learned in this course cannot reproduce global illumination effects
  - caustics, radiosity, and shadows are neglected
- Physically-based rendering equations allow for accurate simulation of light transport
  - but we get integral equations that are wicked hard to solve!
- Various Monte Carlo integration techniques can be used to synthesize realistic images in reasonable time