# Image-based Lighting (Part 2)

T2

Computational Photography

Derek Hoiem, University of Illinois

Many slides from Debevec, some from Efros, Kevin Karsch

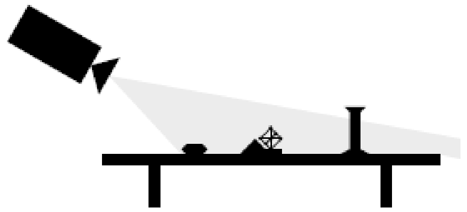
## Today

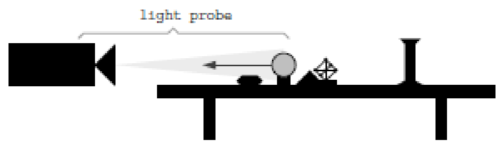
- Brief review of last class
- Show how to get an HDR image from several LDR images, and how to display HDR
- Show how to insert fake objects into real scenes using environment maps

# How to render an object inserted into an image?

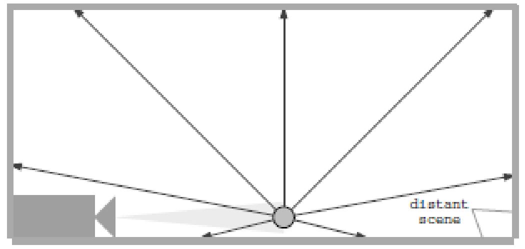
## Image-based lighting

- Capture incoming light with a "light probe"
- Model local scene
- Ray trace, but replace distant scene with info from light probe

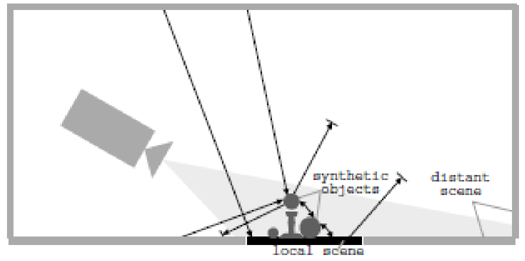

(a) Acquiring the background photograph



(b) Using the light probe



(c) Constructing the light-based model

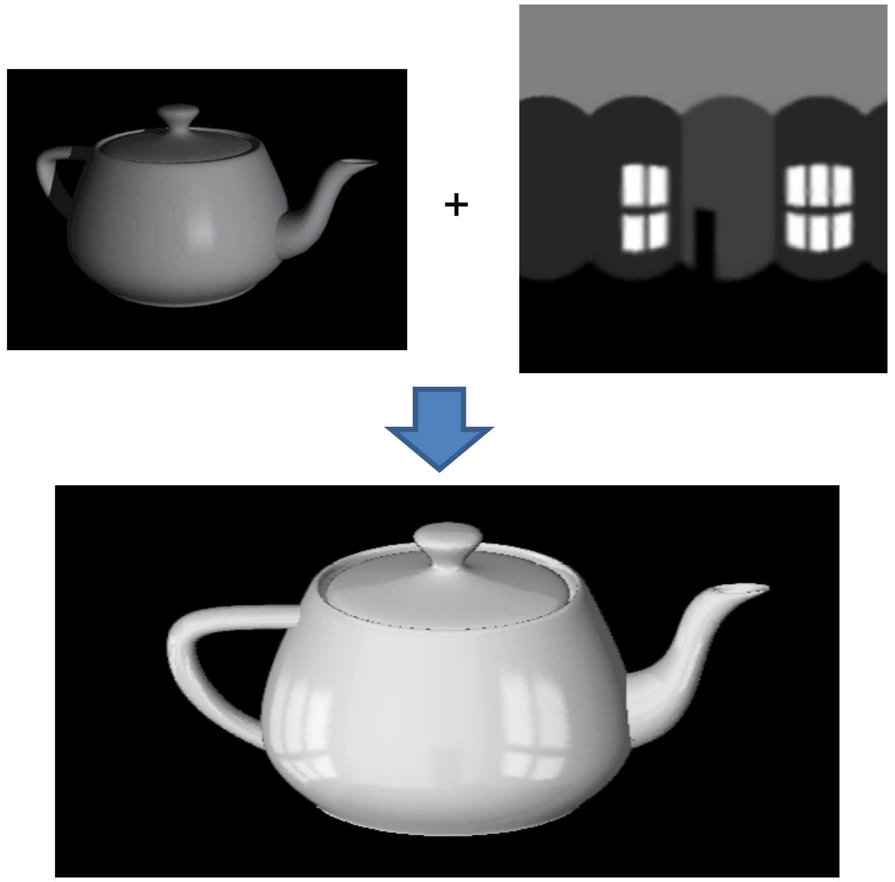


(d) Computing the global illumination solution

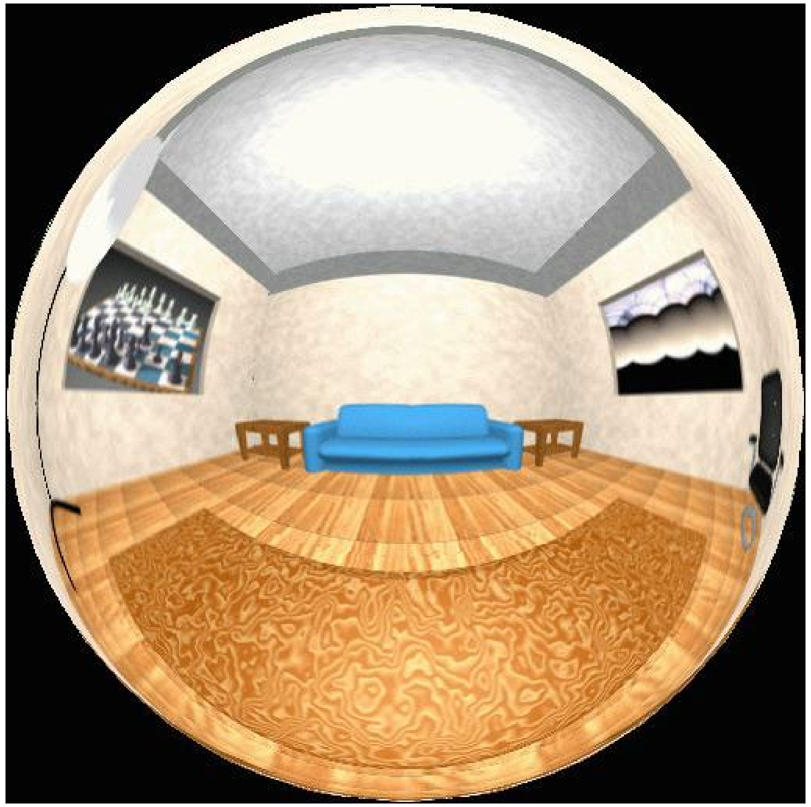
Debevec SIGGRAPH 1998

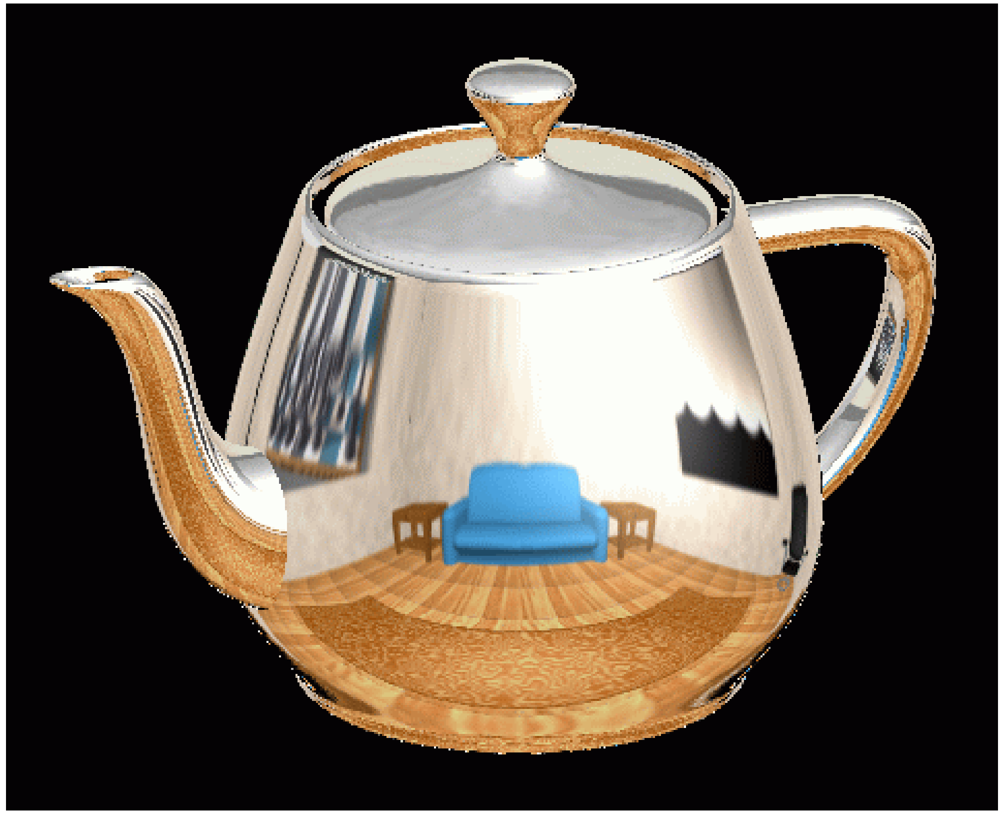
## Key ideas for Image-based Lighting

- Environment maps: tell what light is entering at each angle within some shell



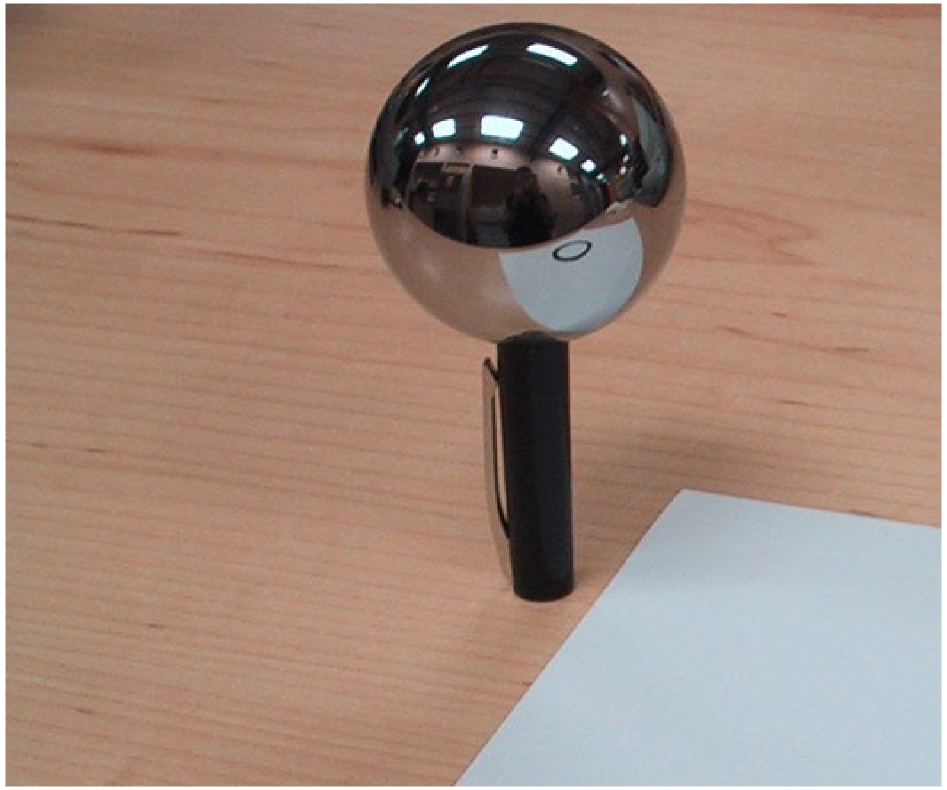
# Spherical Map Example



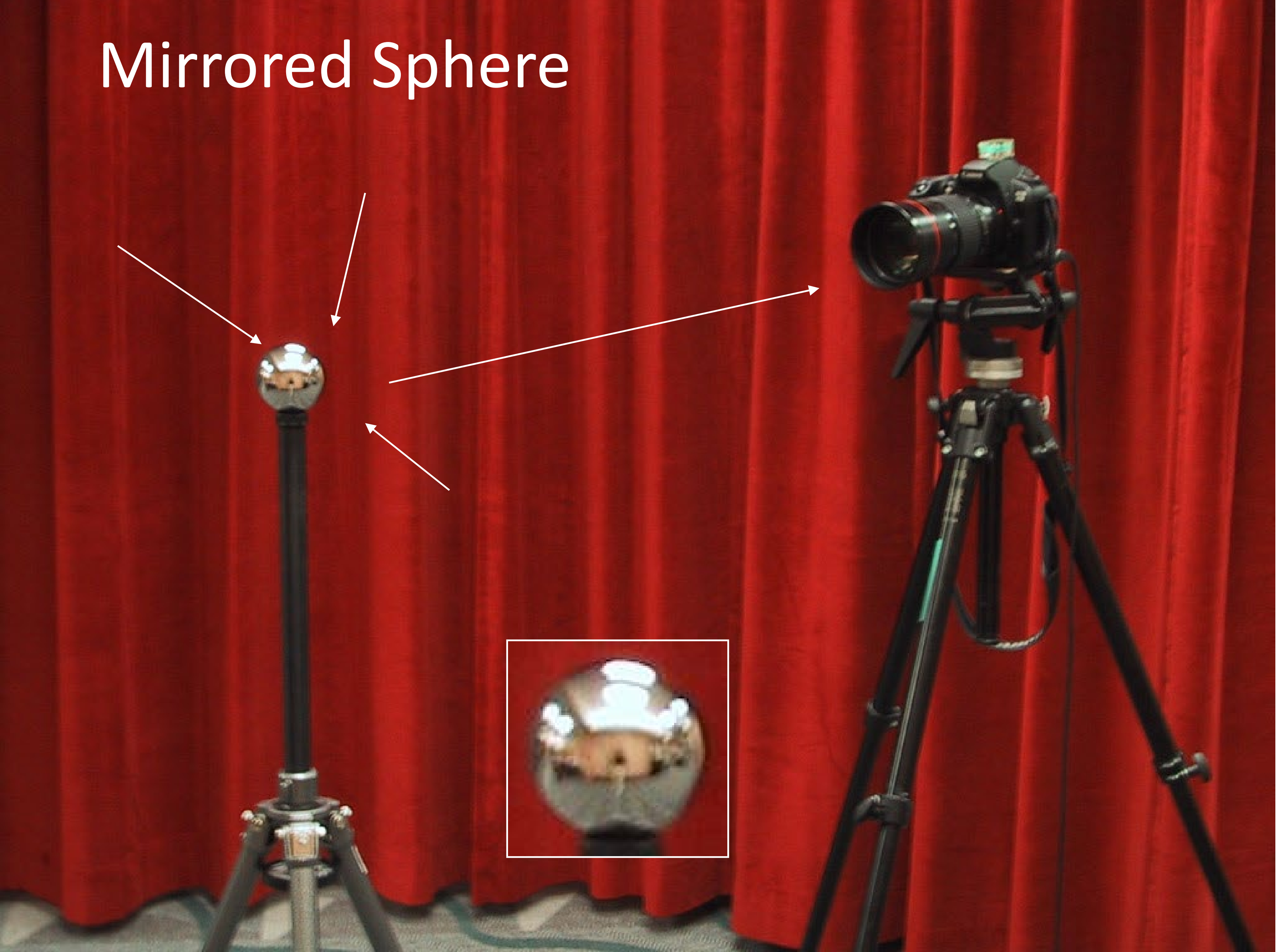


# Key ideas for Image-based Lighting

- Light probes: a way of capturing environment maps in real scenes

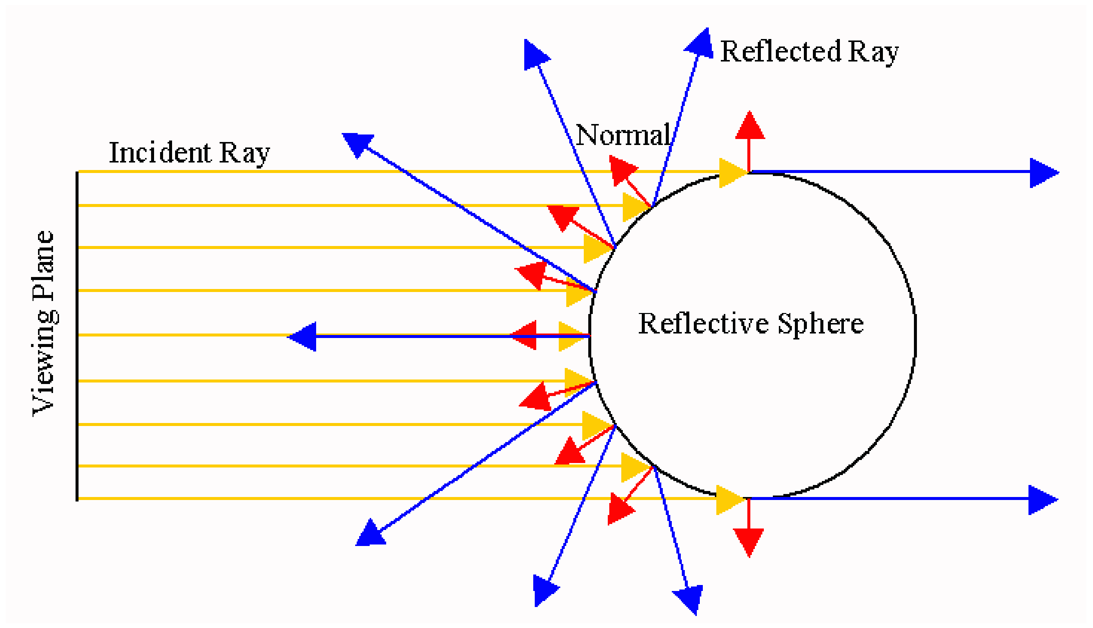


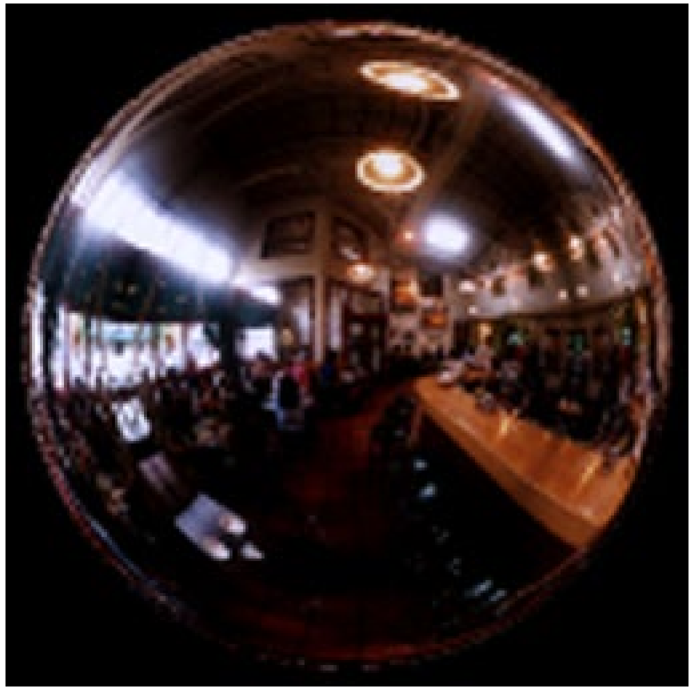
Mirrored Sphere



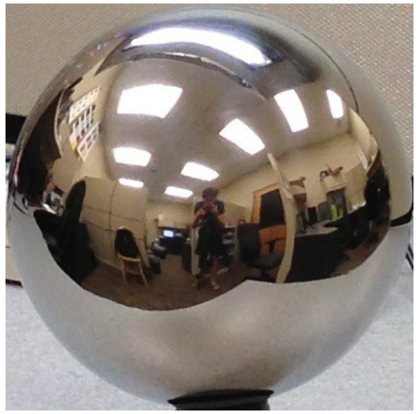
## One picture of a mirrored ball received light coming into the ball from nearly all angles (including behind)

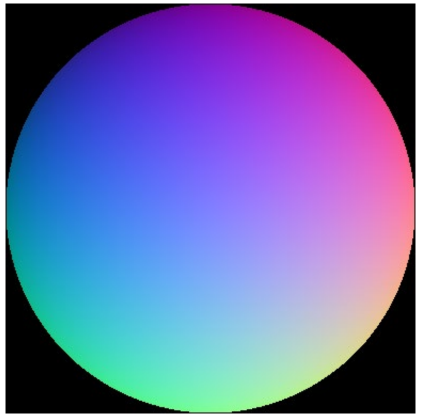
Assume camera is roughly same height as light probe and is sufficiently distant, so all viewing rays that hit light probe are roughly in direction of z-axis

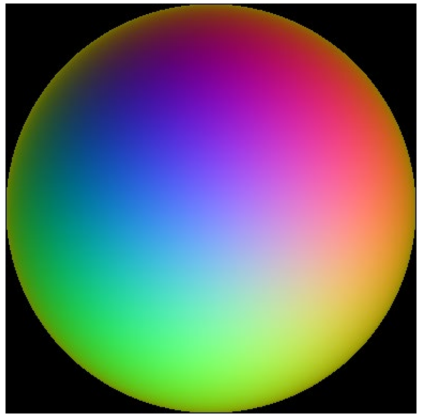


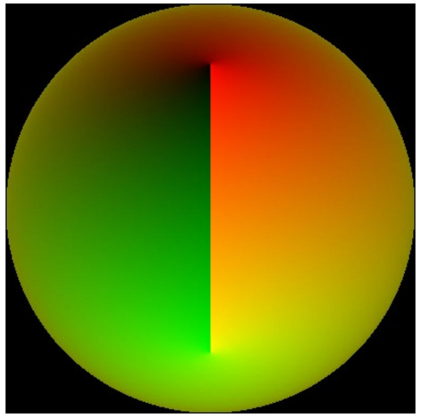


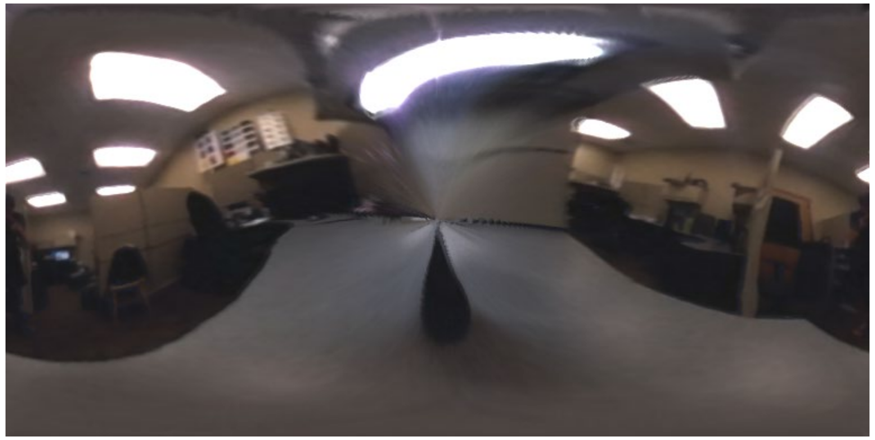
# Mirror ball -> equirectangular

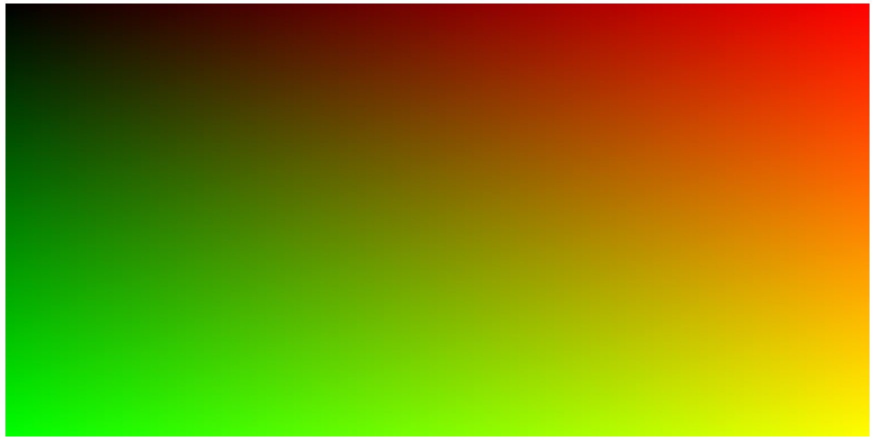

Mirror ball


Normals


Reflection vectors

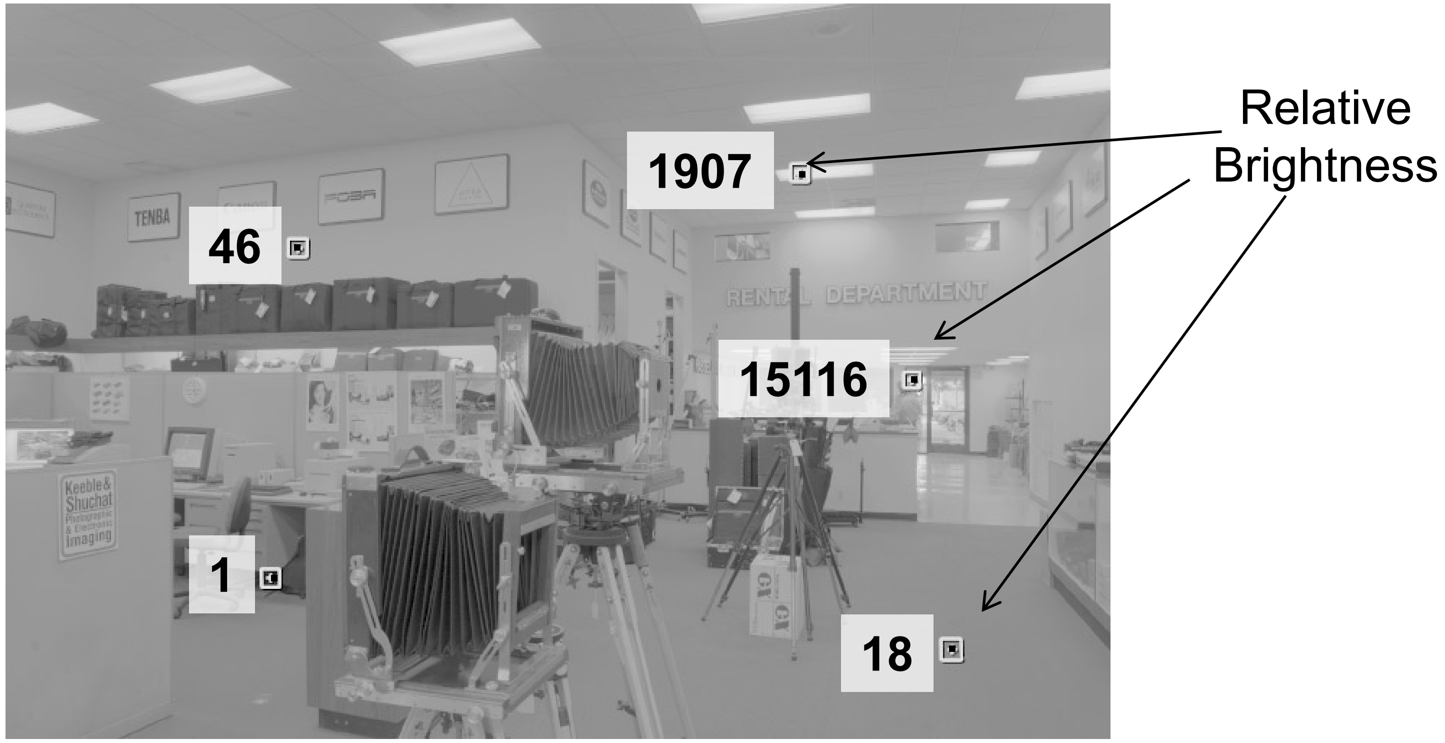

Phi/theta of reflection vecs


Equirectangular


Phi/theta equirectangular domain

## One small snag

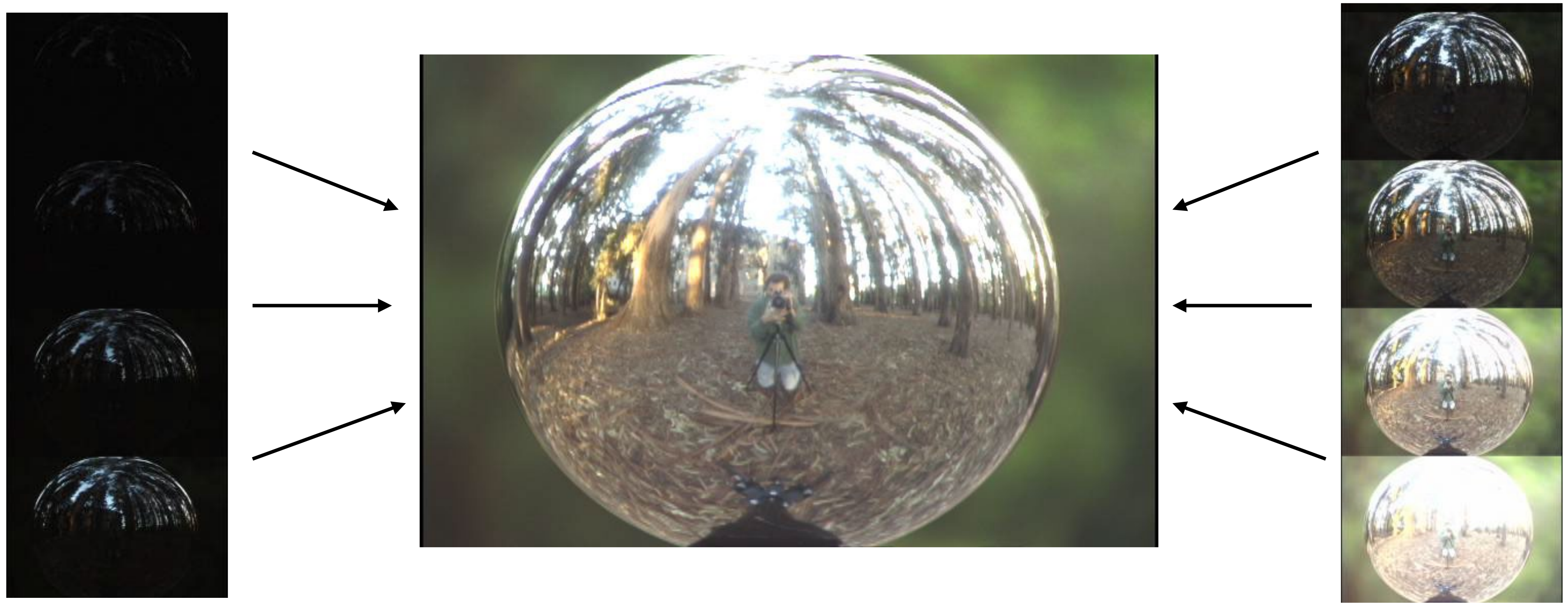
- How do we deal with light sources? Sun, lights, etc?
  - They are much, much brighter than the rest of the environment



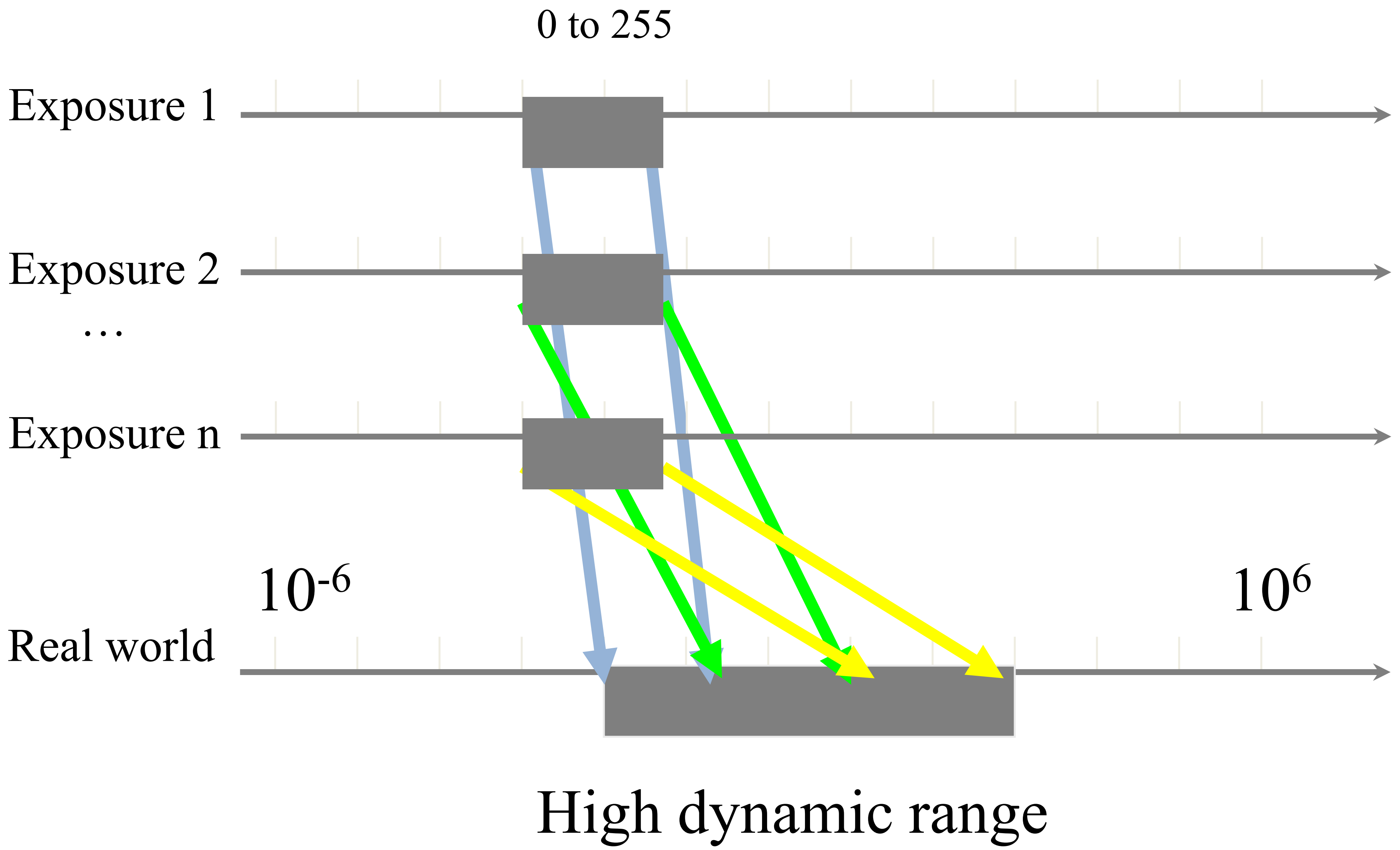
- Use High Dynamic Range photography!

## Key ideas for Image-based Lighting

- Capturing HDR images: needed so that light probes capture full range of radiance



# LDR->HDR by merging exposures

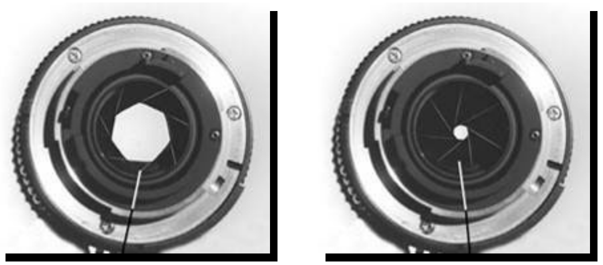


# Ways to vary exposure

Shutter Speed

F/stop (aperture, iris)

Neutral Density (ND) Filters



# Recovering High Dynamic Range Radiance Maps from Photographs

Paul E. Debevec Jitendra Malik

University of California at Berkeley[1]

SIGGRAPH 1997

## The Approach

- Get pixel values $Z_{ij}$ for image with shutter time $\Delta t_j$ ($i^{th}$ pixel location, $j^{th}$ image)
- Exposure is irradiance integrated over time:

$$E_{ij} = R_i \cdot \Delta t_j$$

- Pixel values are non-linearly mapped $E_{ij}$'s:

$$Z_{ij} = f(E_{ij}) = f(R_i \cdot \Delta t_j)$$

- Rewrite to form a (not so obvious) linear system:

$$\ln f^{-1}(Z_{ij}) = \ln E_{ij}$$

$$\ln f^{-1}(Z_{ij}) = \ln(R_i) + \ln(\Delta t_j)$$

$$g(Z_{ij}) = \ln(R_i) + \ln(\Delta t_j)$$

# The objective

Solve for irradiance $R$ and mapping $g$ for each of 256 pixel values to minimize:

$$\sum_{i=1}^{N}\sum_{j=1}^{P} w(Z_{ij})\left[\ln R_i + \ln \Delta t_j - g(Z_{ij})\right]^2 + \lambda \sum_{z=Z_{min}}^{Z_{max}} w(z) g''(z)^2$$

give pixels near 0 or 255 less weight

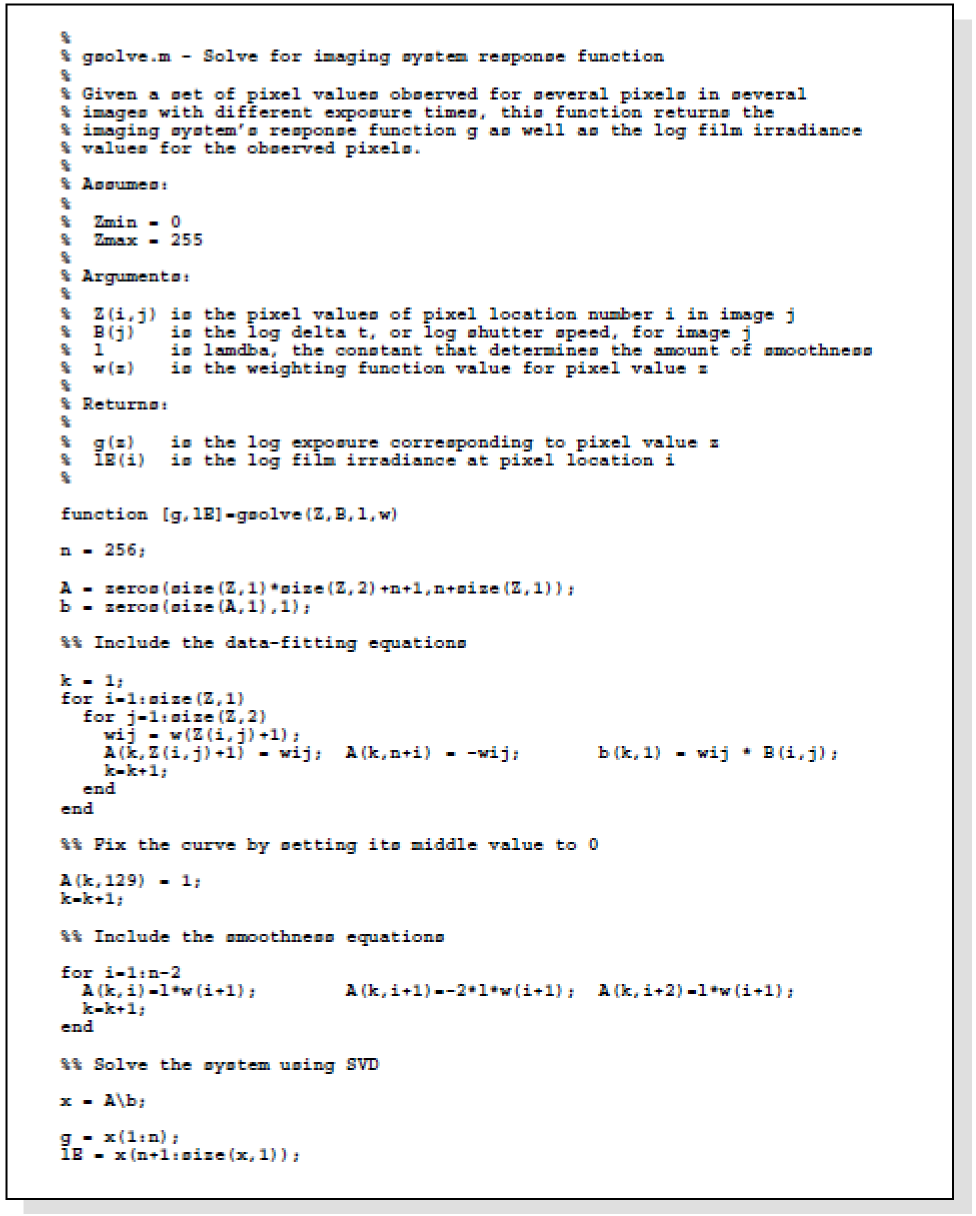
known shutter time for image j

exposure should smoothly increase as pixel intensity increases

irradiance at particular pixel site is the same for each image

log exposure, as a function of pixel value

# Matlab Code



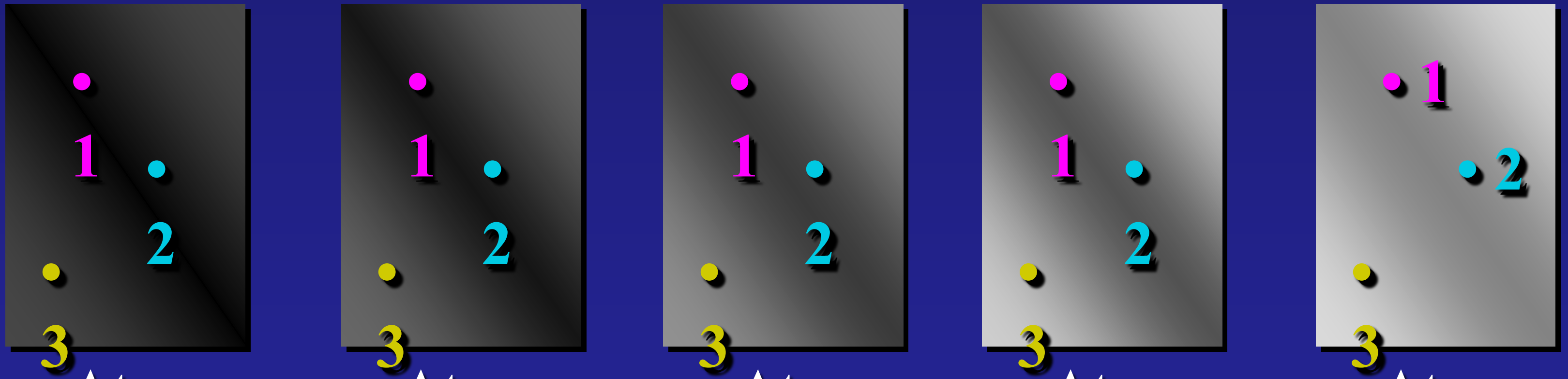
```
%
% gsolve.m - Solve for imaging system response function
%
% Given a set of pixel values observed for several pixels in several
% images with different exposure times, this function returns the
% imaging system's response function g as well as the log film irradiance
% values for the observed pixels.
%
% Assumes:
%
%  Zmin = 0
%  Zmax = 255
%
% Arguments:
%
%  Z(i,j) is the pixel values of pixel location number i in image j
%  B(j)   is the log delta t, or log shutter speed, for image j
%  l      is lamdba, the constant that determines the amount of smoothness
%  w(z)   is the weighting function value for pixel value z
%
% Returns:
%
%  g(z)   is the log exposure corresponding to pixel value z
%  lE(i)  is the log film irradiance at pixel location i
%

function [g,lE]=gsolve(Z,B,l,w)

n = 256;

A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

%% Include the data-fitting equations

k = 1;
for i=1:size(Z,1)
  for j=1:size(Z,2)
    wij = w(Z(i,j)+1);
    A(k,Z(i,j)+1) = wij;  A(k,n+i) = -wij;       b(k,1) = wij * B(i,j);
    k=k+1;
  end
end

%% Fix the curve by setting its middle value to 0

A(k,129) = 1;
k=k+1;

%% Include the smoothness equations

for i=1:n-2
  A(k,i)=l*w(i+1);        A(k,i+1)=-2*l*w(i+1);  A(k,i+2)=l*w(i+1);
  k=k+1;
end

%% Solve the system using SVD

x = A\b;

g = x(1:n);
lE = x(n+1:size(x,1));
```

# Matlab Code

```
function [g,lE]=gsolve(Z,B,l,w)

n = 256;
A = zeros(size(Z,1)*size(Z,2)+n+1,n+size(Z,1));
b = zeros(size(A,1),1);

k = 1;                  %% Include the data-fitting equations
for i=1:size(Z,1)
  for j=1:size(Z,2)
    wij = w(Z(i,j)+1);
    A(k,Z(i,j)+1) = wij; A(k,n+i) = -wij; b(k,1) = wij * B(j);
    k=k+1;
  end
end

for i=1:n-2             %% Include the smoothness equations
  A(k,i)=l*w(i+1); A(k,i+1)=-2*l*w(i+1); A(k,i+2)=l*w(i+1);
  k=k+1;
end

A(k,129) = 1;           %% Fix the curve by setting its middle value to 0

x = A\b;                %% Solve the system using pseudoinverse

g = x(1:n);
lE = x(n+1:size(x,1));
```

# Illustration

Image series



$\Delta t =$ **1/64 sec** | $\Delta t =$ **1/16 sec** | $\Delta t =$ **1/4 sec** | $\Delta t =$ **1 sec** | $\Delta t =$ **4 sec**

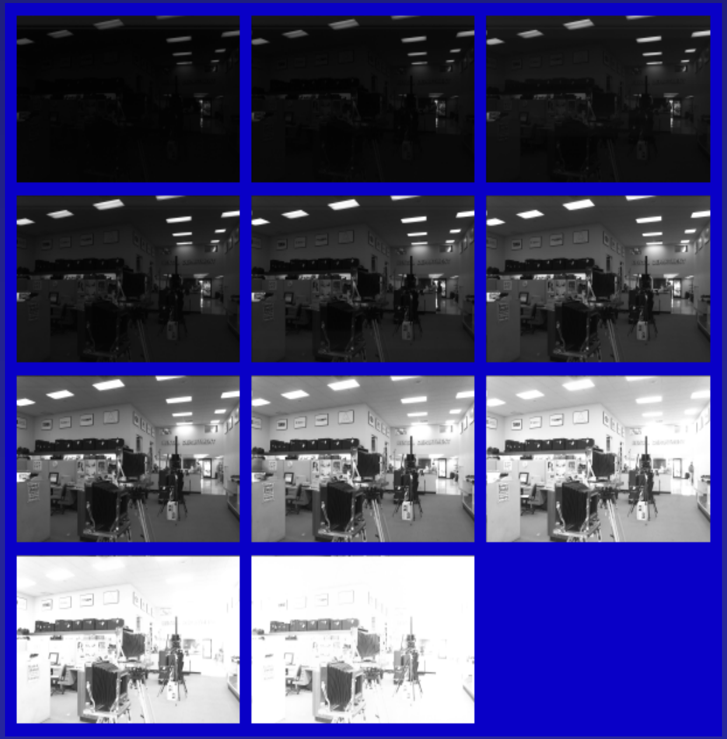
Pixel Value Z = f(Exposure)

Exposure = Radiance * $\Delta t$

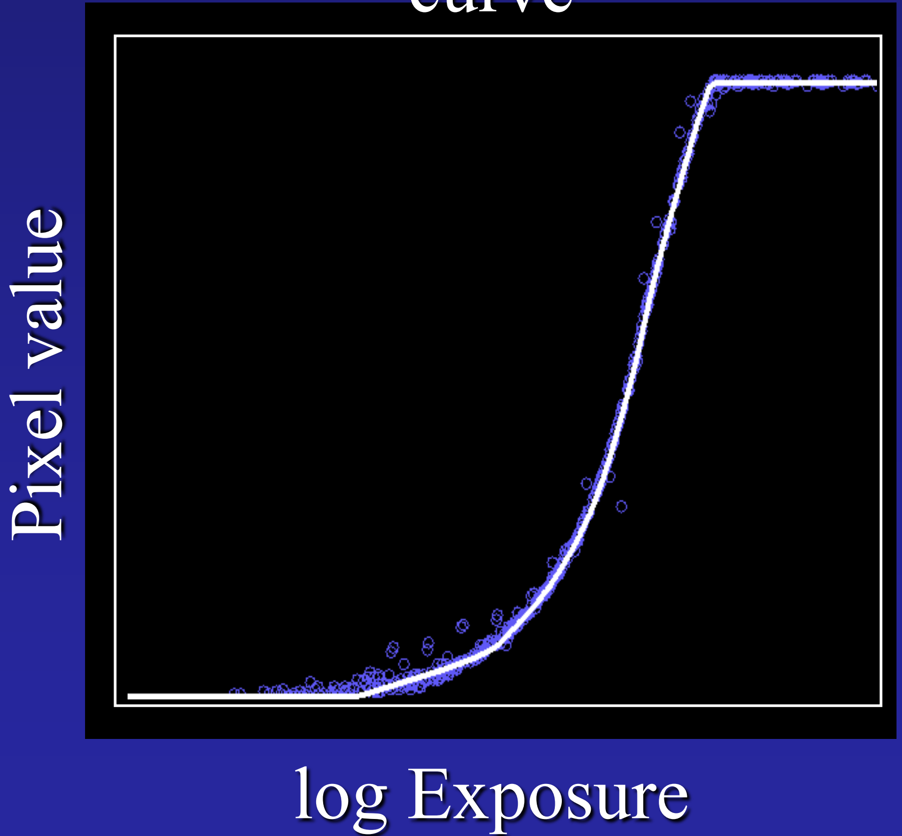
log Exposure = log Radiance + log $\Delta t$

## Results: Digital Camera

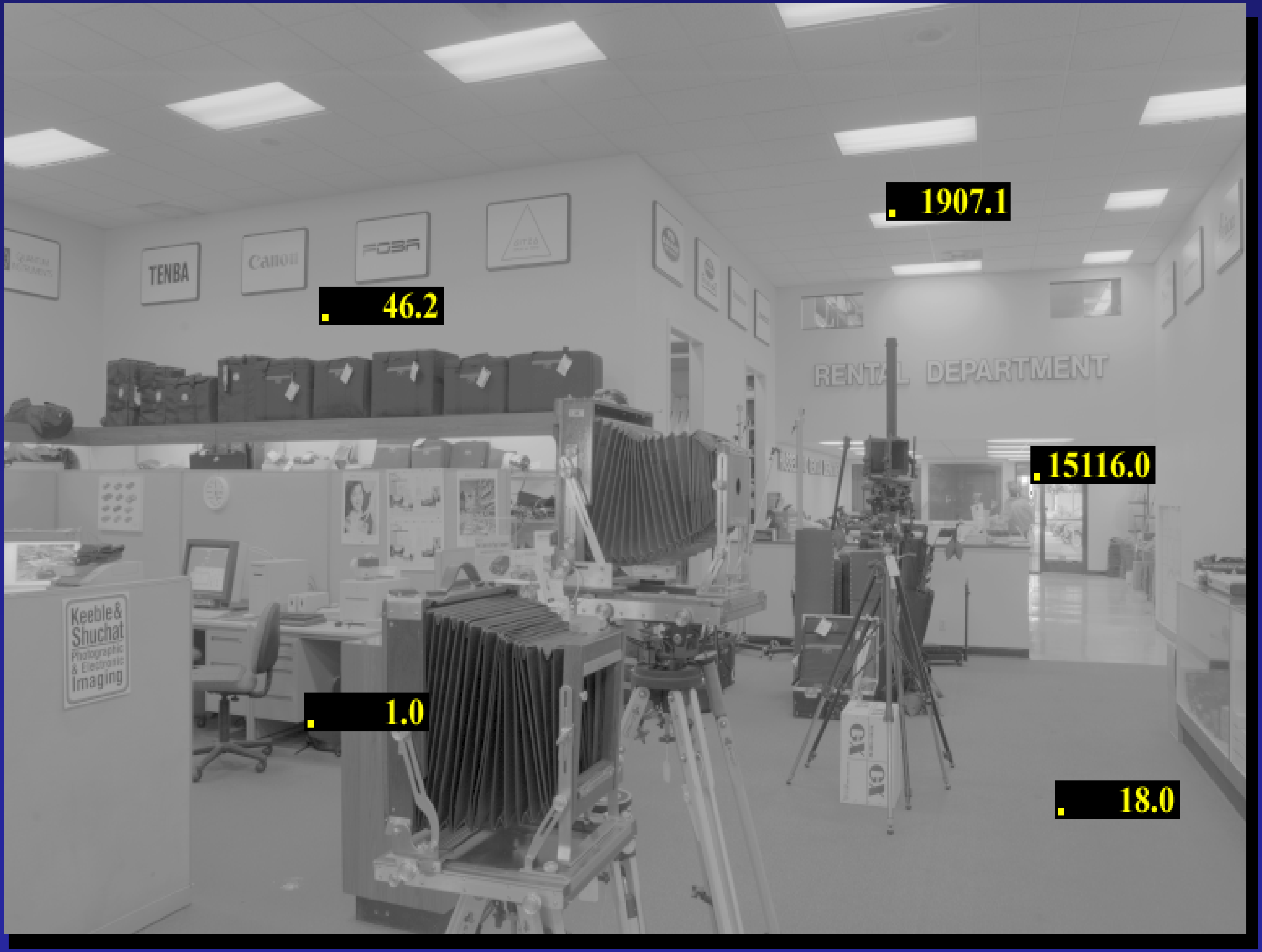
Kodak DCS460
1/30 to 30 sec



Recovered response curve

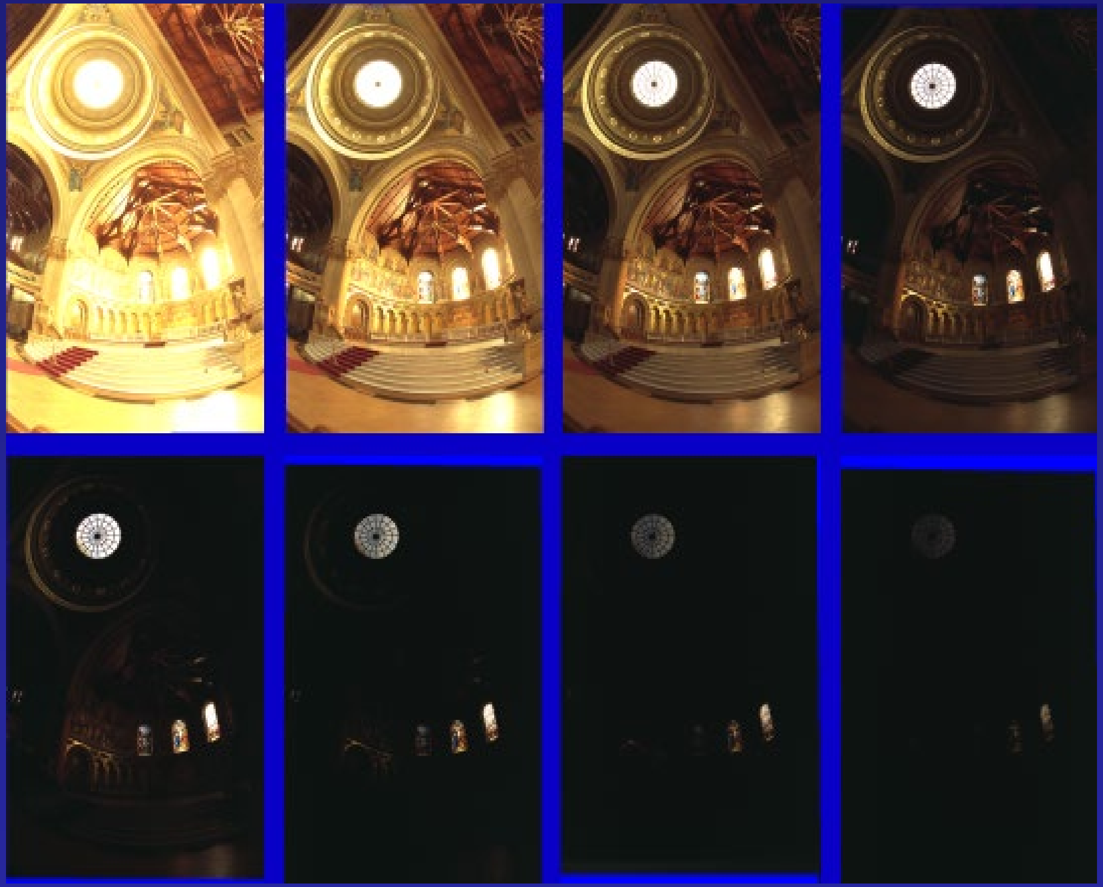


## Reconstructed radiance map

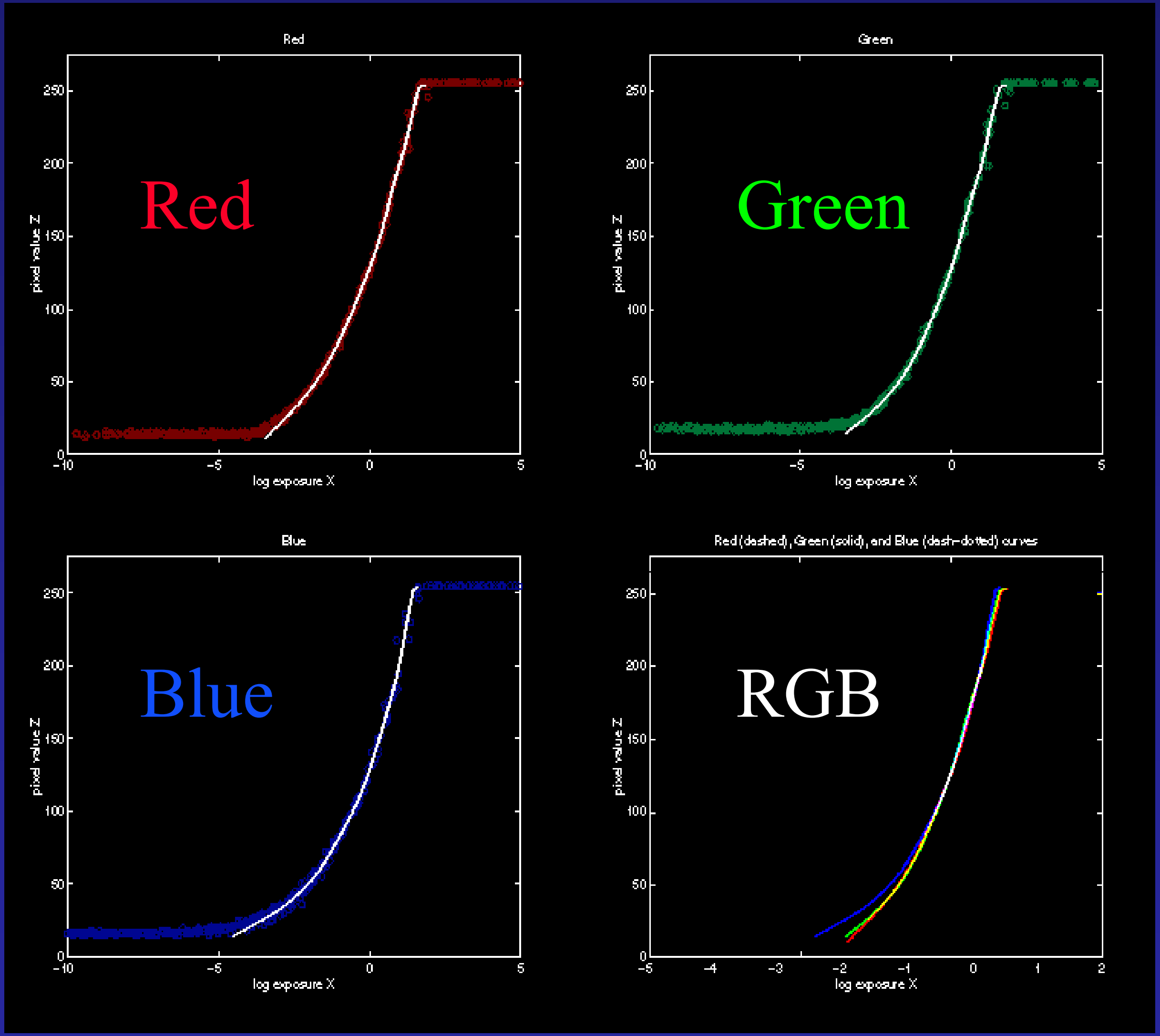


## Results: Color Film

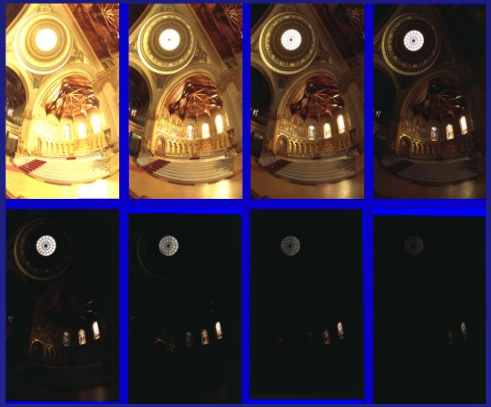
- Kodak Gold ASA 100, PhotoCD

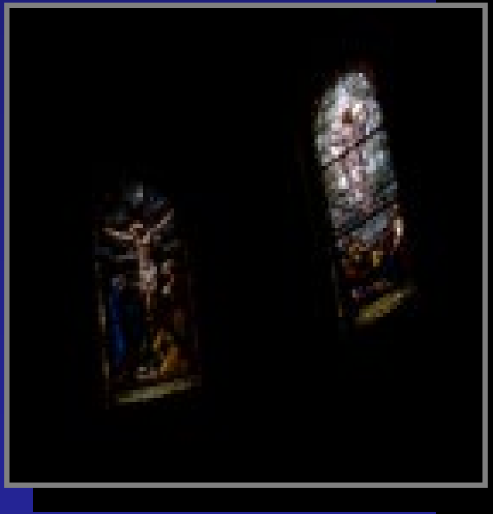


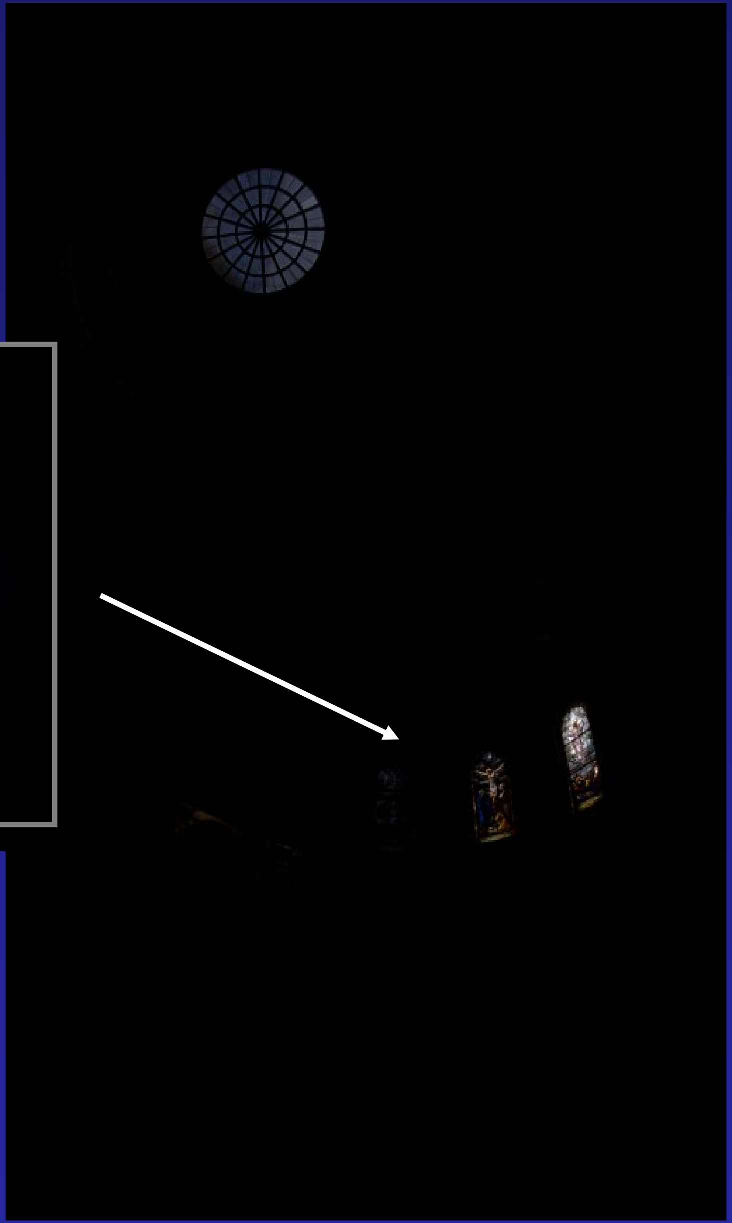
# Recovered Response Curves



# How to display HDR?



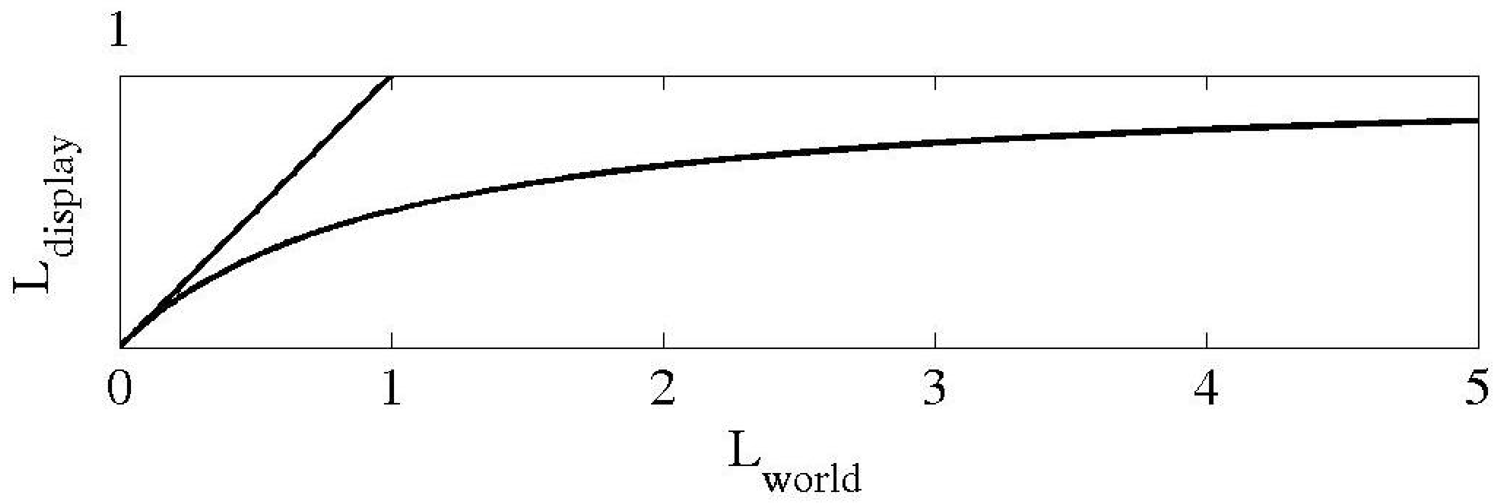




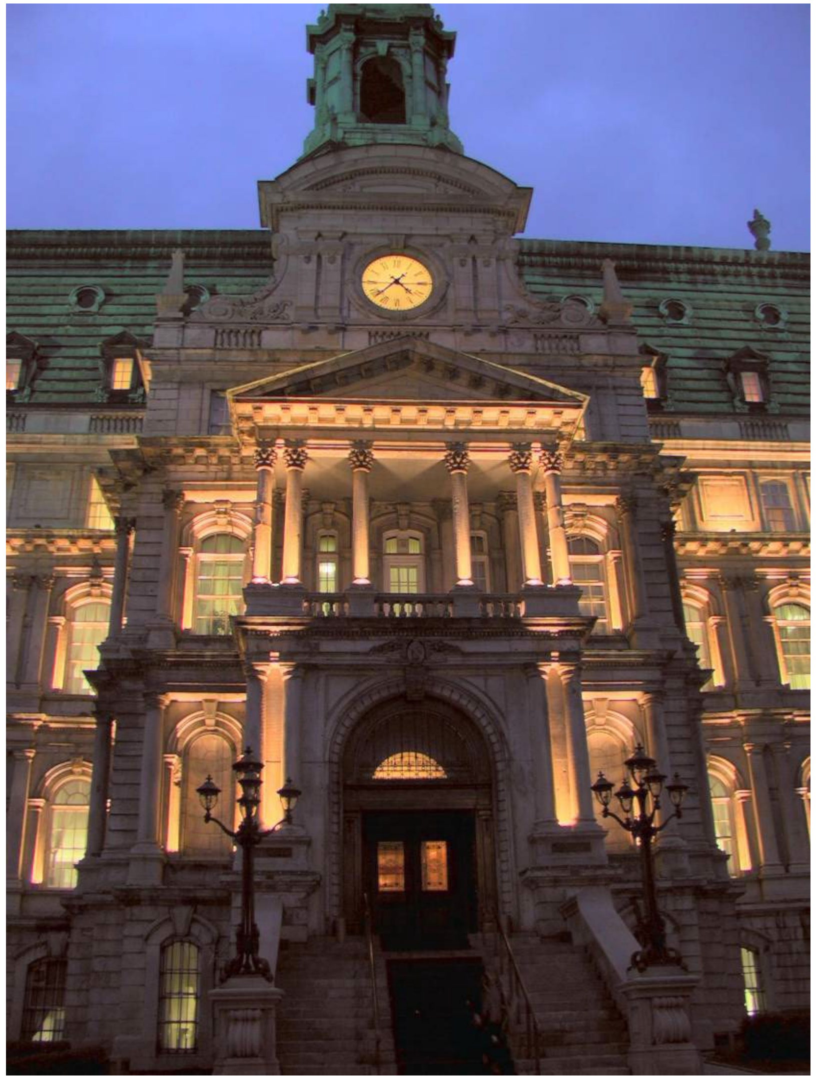
Linearly scaled to display device

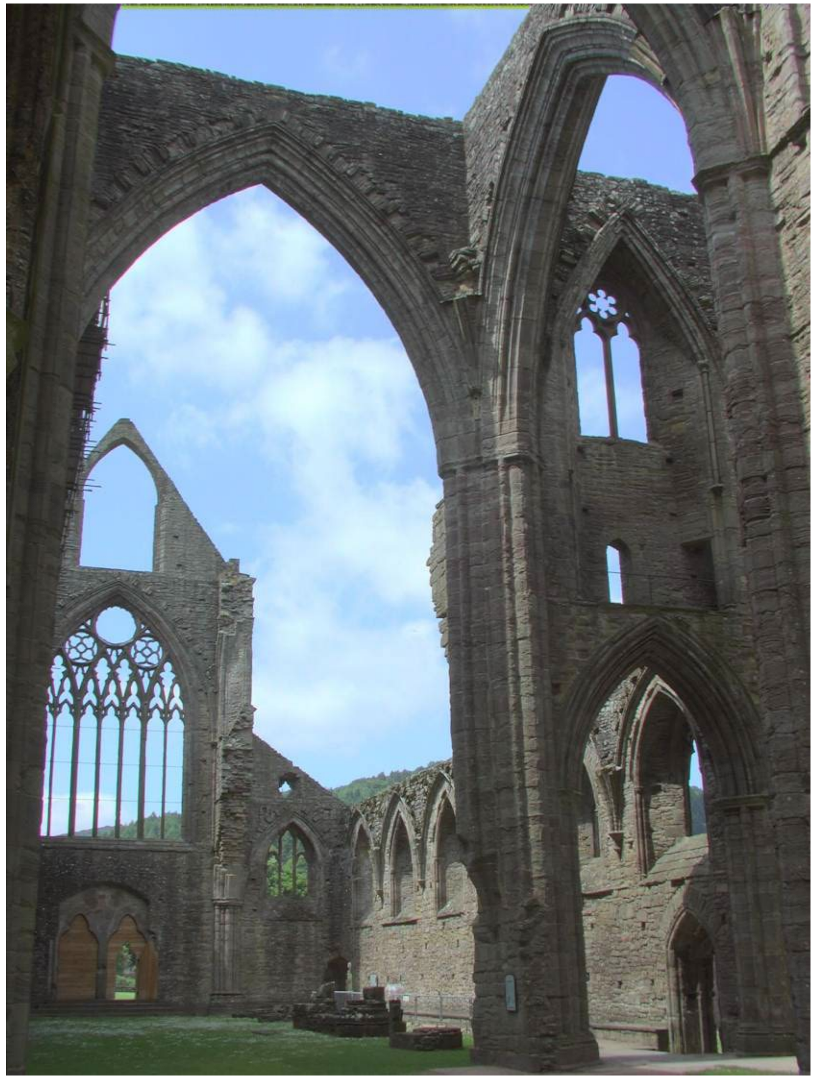
## Global Operator (Reinhart et al)

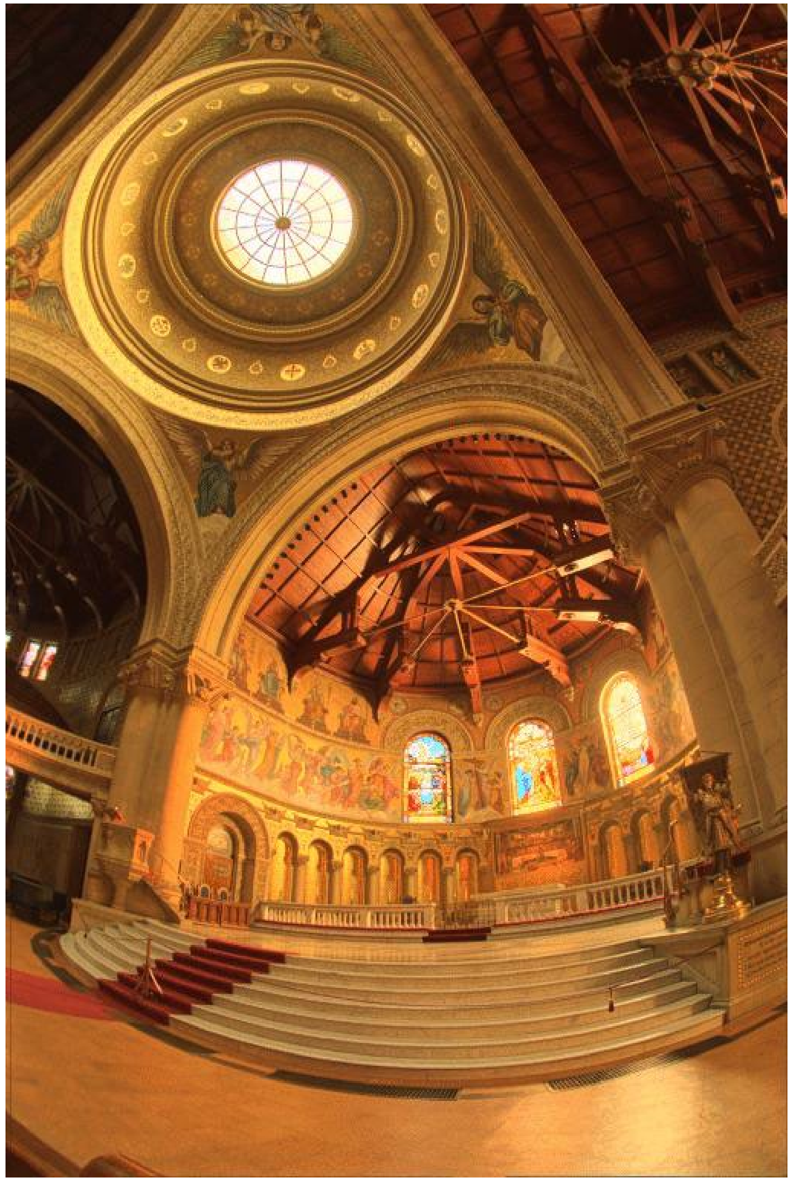
$$L_{display} = \frac{L_{world}}{1 + L_{world}}$$

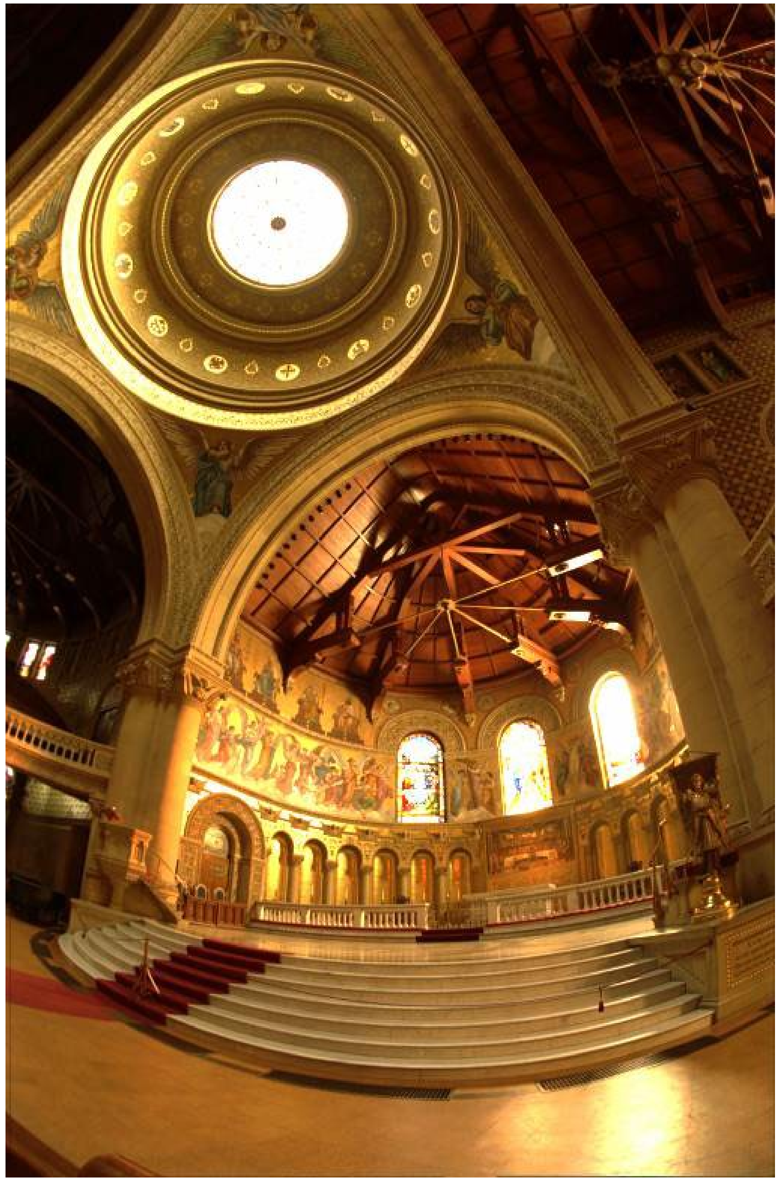


## Global Operator Results



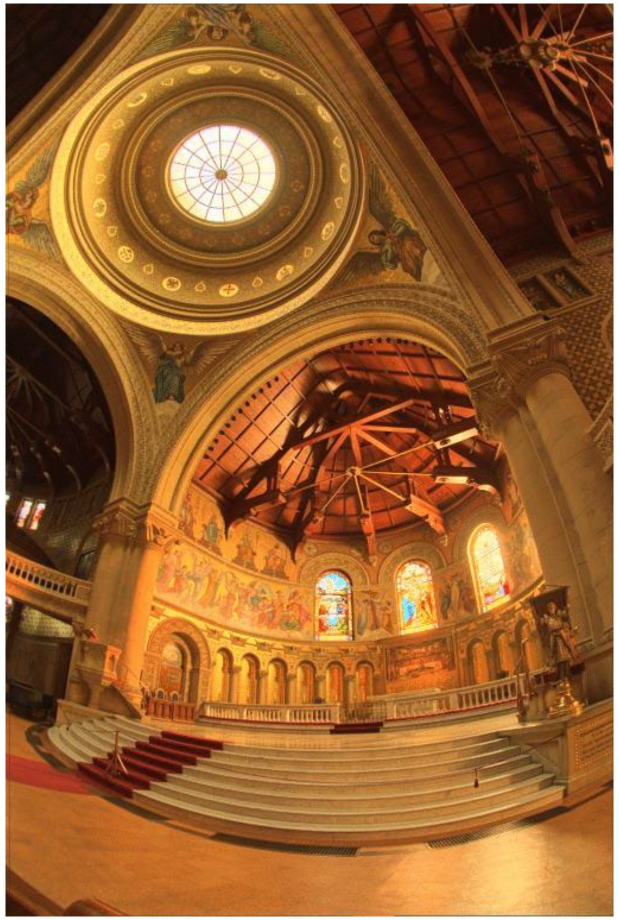


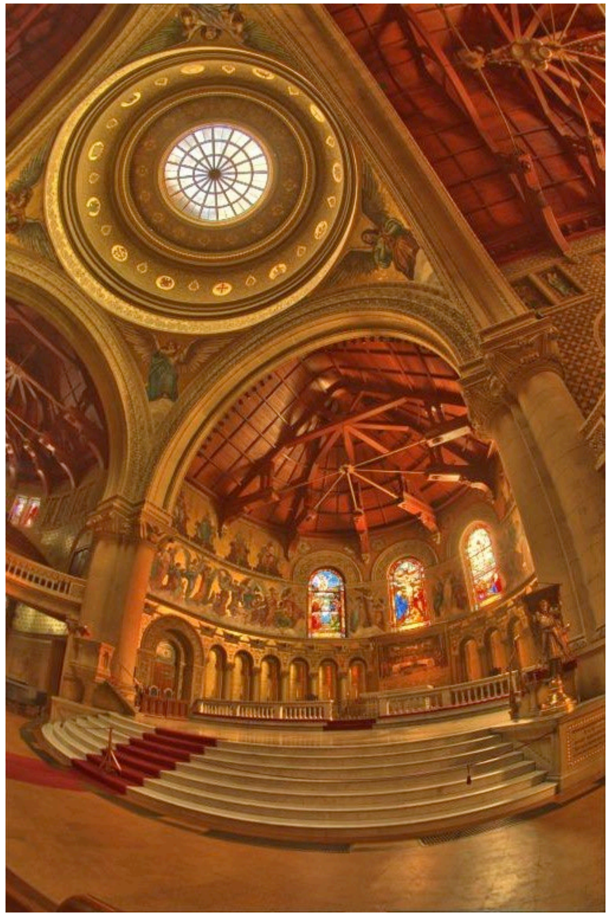

Reinhart Operator


Darkest 0.1% scaled linearly

## Local operator

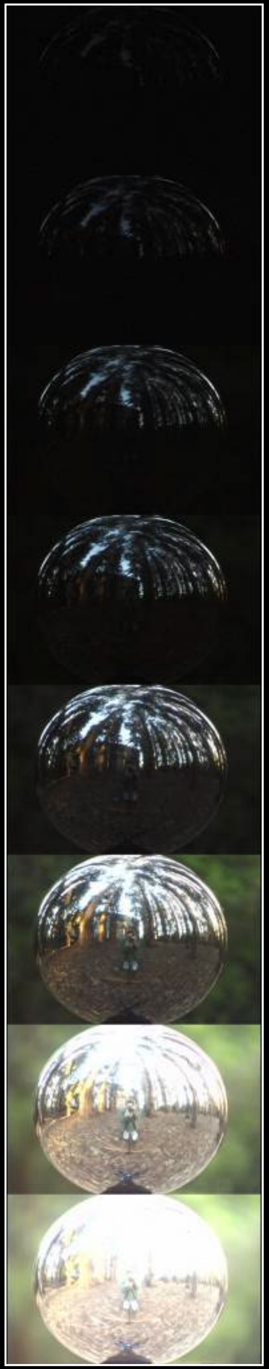
1. Use bilateral filter to smooth image and separate into “base” and “detail”
2. Compress “base” range and keep “detail”

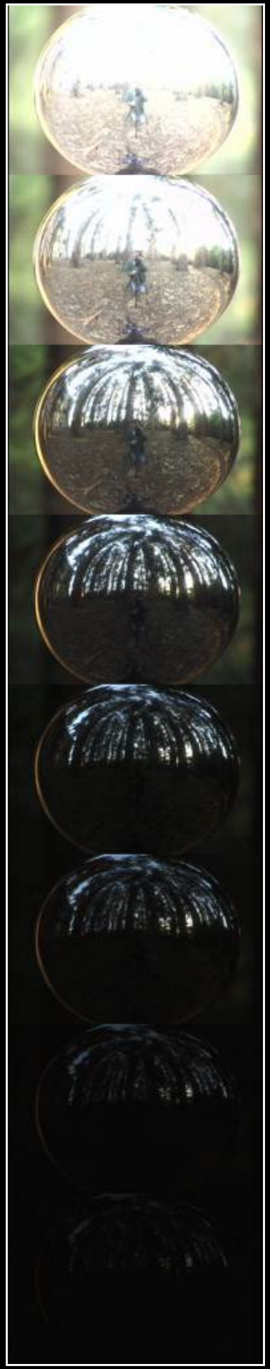




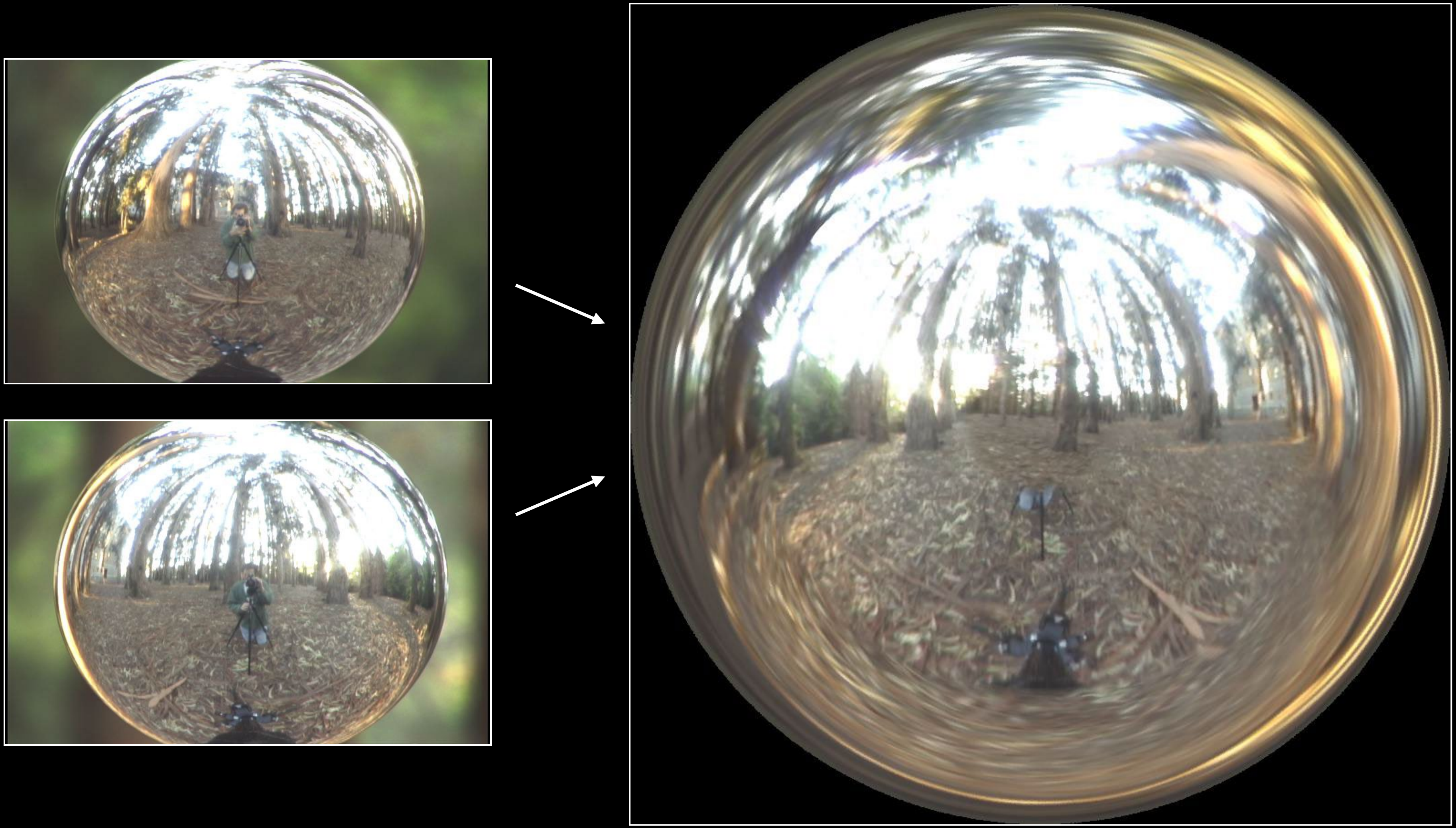
http://people.csail.mit.edu/fredo/PUBLI/Siggraph2002/DurandBilateral.pdf

# Acquiring the Light Probe





# Assembling the Light Probe



Funston Beach

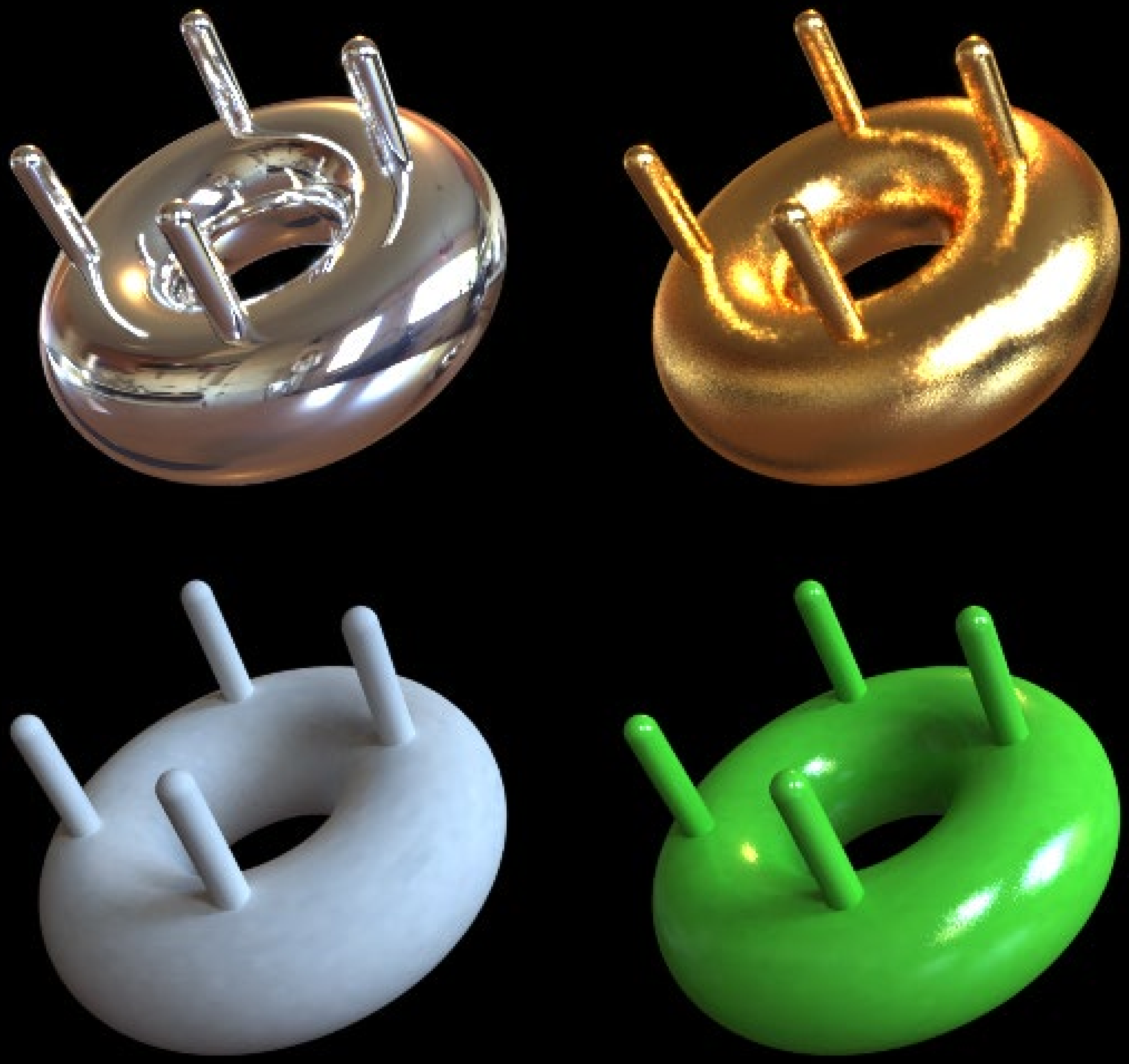
Eucalyptus Grove

Uffizi Gallery

Grace Cathedral

Lighting Environments from the Light Probe Image Gallery:
http://www.debevec.org/Probes/

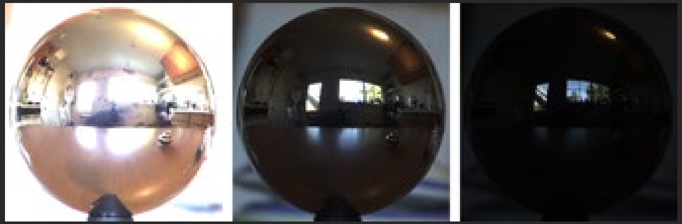
# Illumination Results

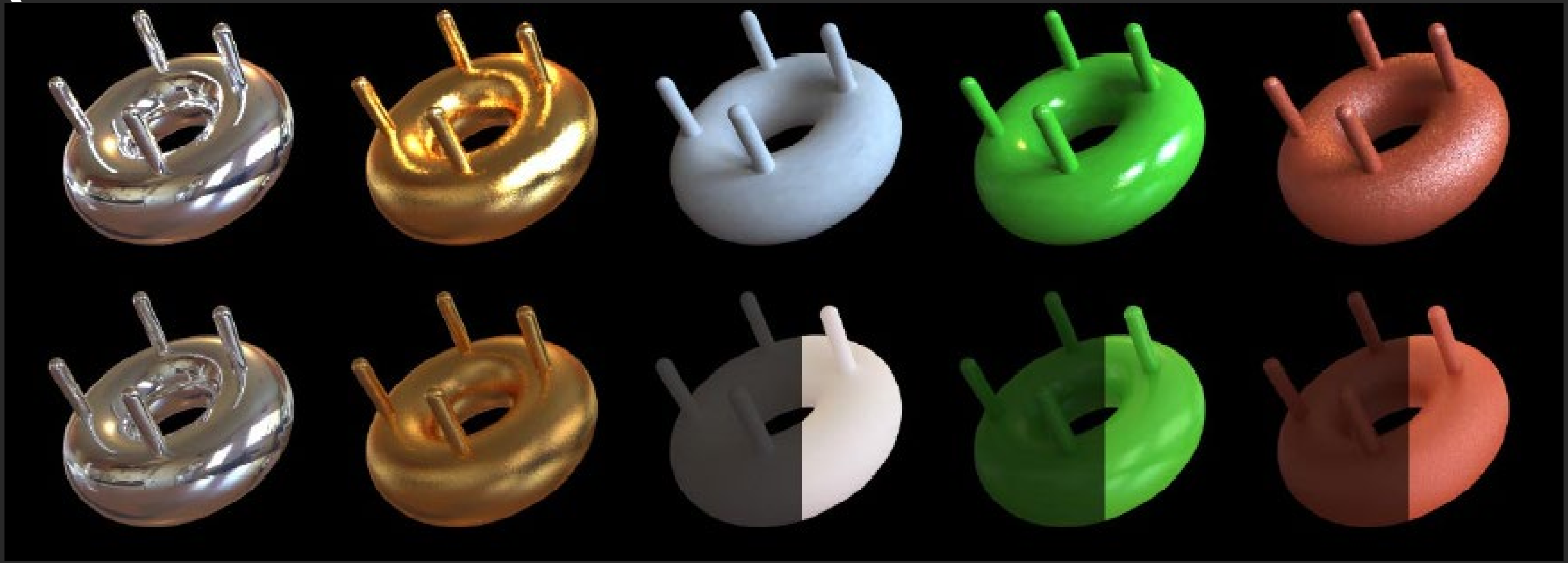


Rendered with Greg Larson's RADIANCE synthetic imaging system

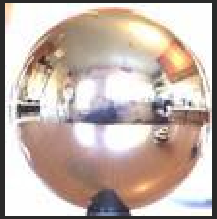
## Comparison: Radiance map versus single image

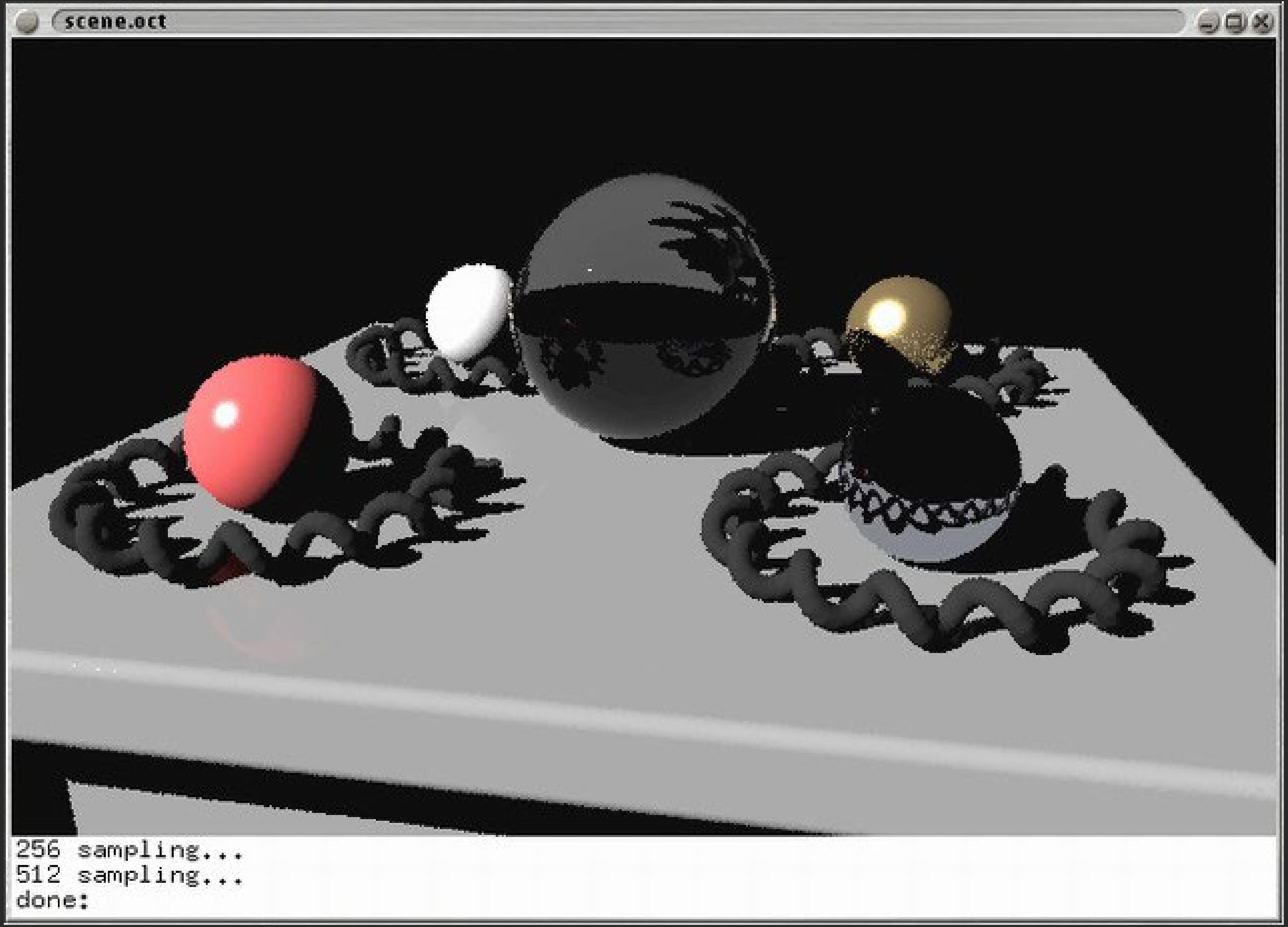
HDR





LDR

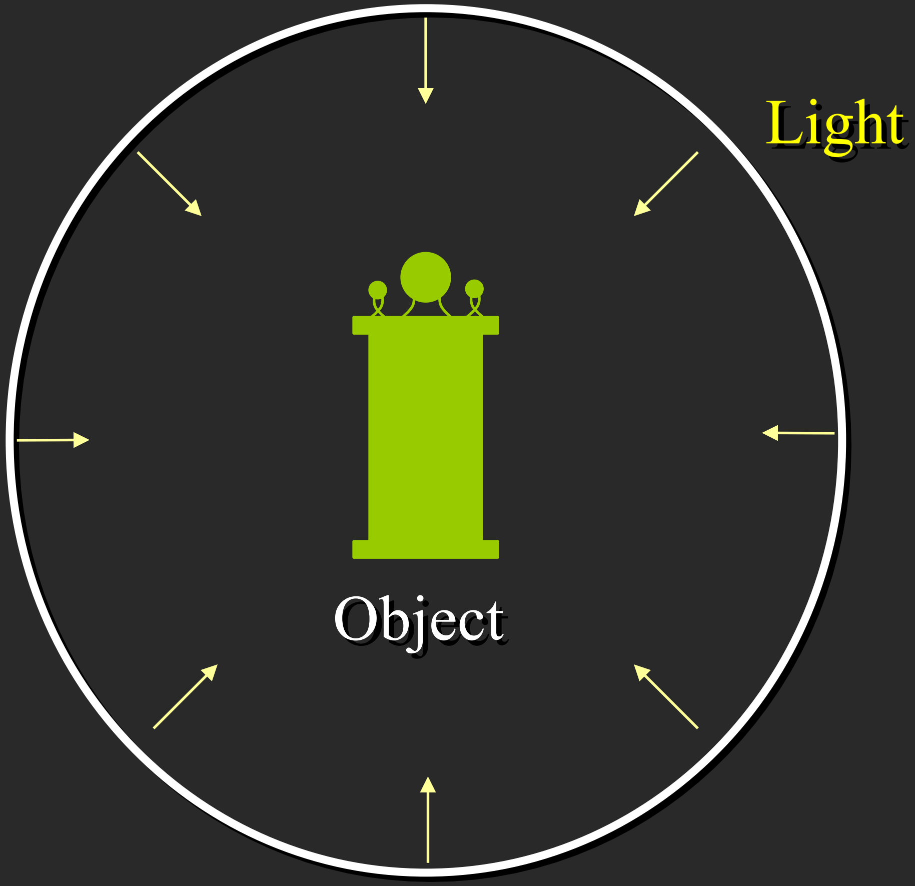




```
256 sampling...
512 sampling...
done:
```

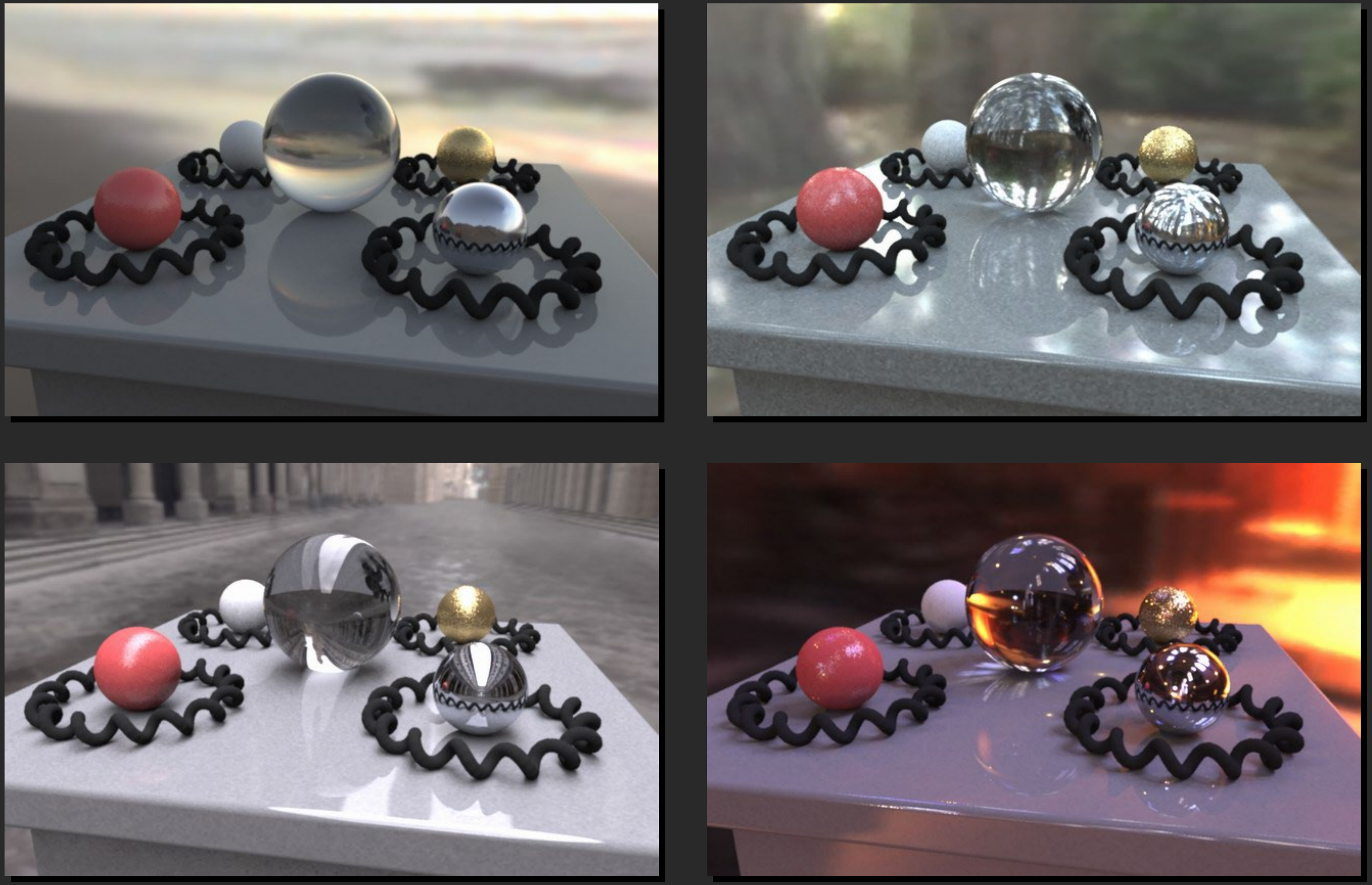
CG Objects Illuminated by a Traditional CG Light Source

# Illuminating Objects using Measurements of Real Light



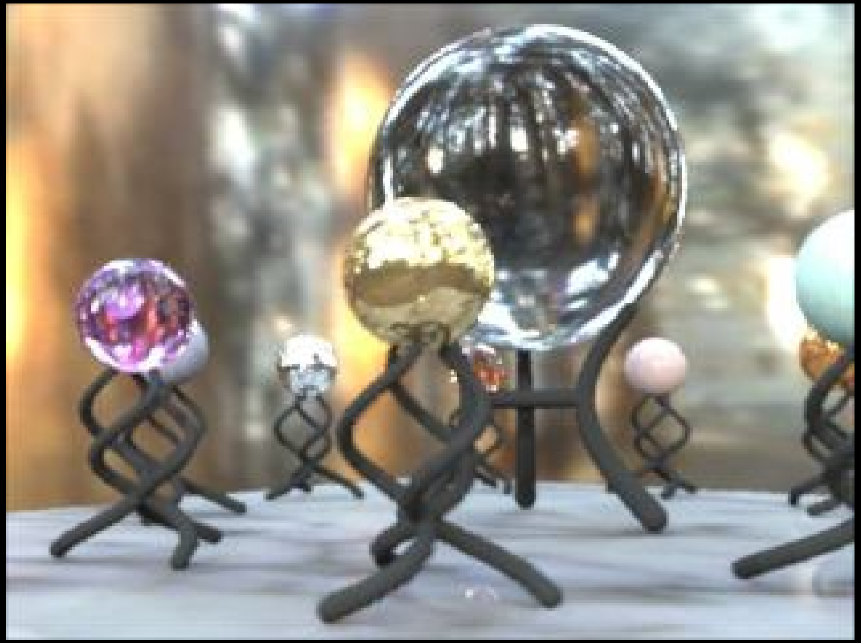
Environment assigned "glow" material property in Greg Ward's RADIANCE system.

http://radsite.lbl.gov/radiance/



Paul Debevec. A Tutorial on Image-Based Lighting. IEEE Computer Graphics and Applications, Jan/Feb 2002.

## *Rendering with Natural Light*



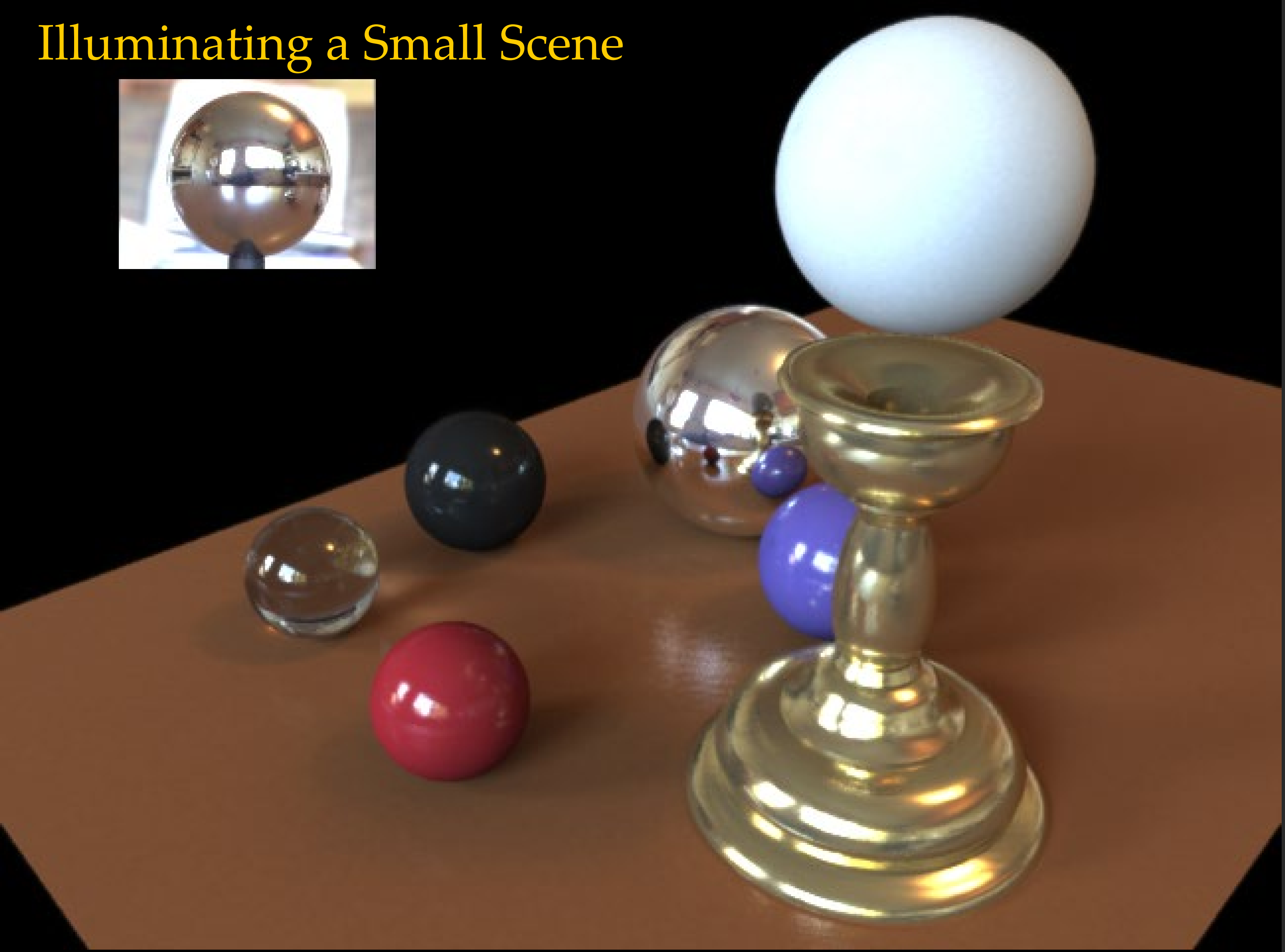
SIGGRAPH 98 Electronic Theater

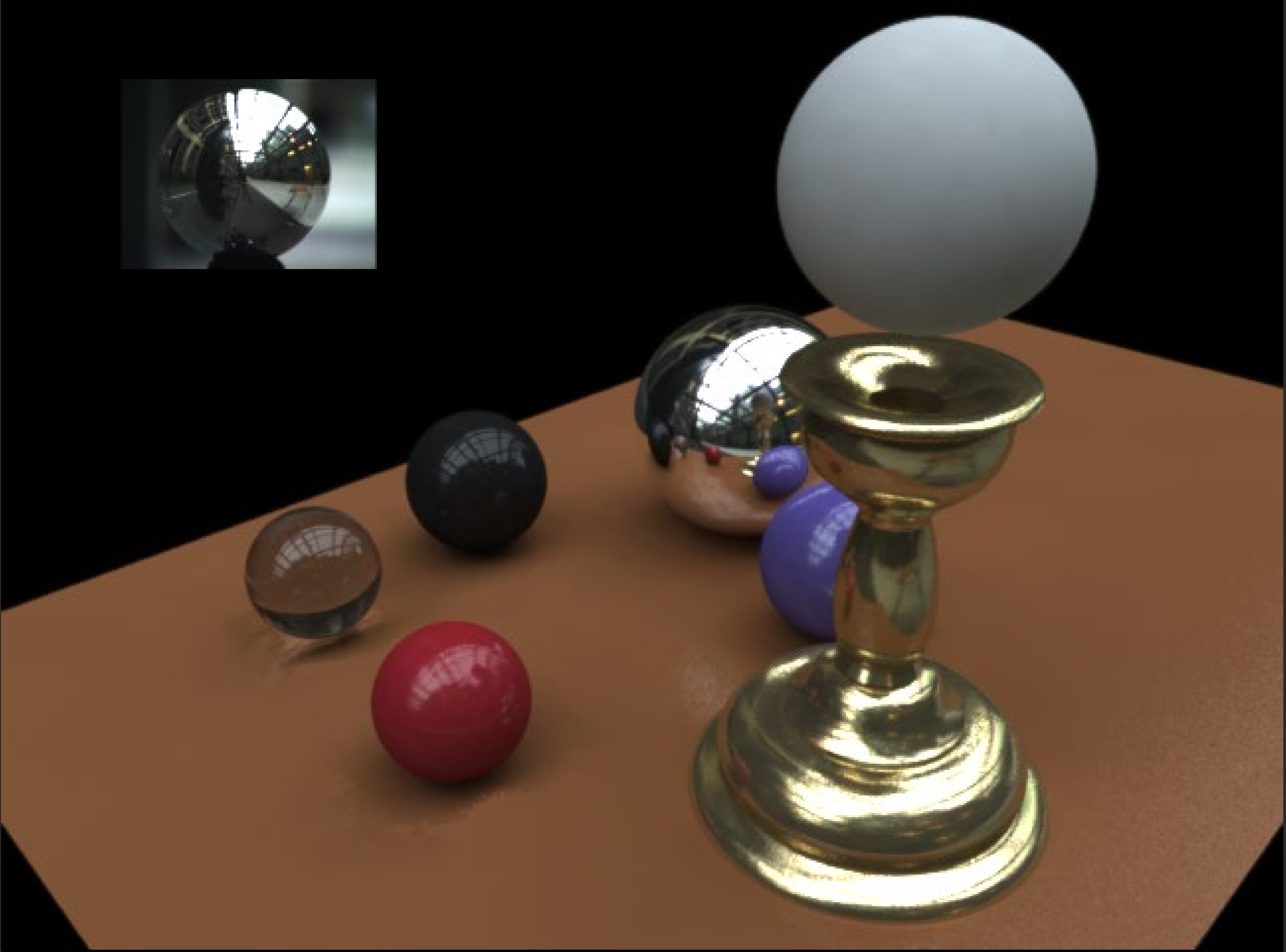
## Movie

- http://www.youtube.com/watch?v=EHBgkeXH9lU

(stretch break during movie)

## Illuminating a Small Scene





We can now illuminate
**synthetic objects** with **real light**.

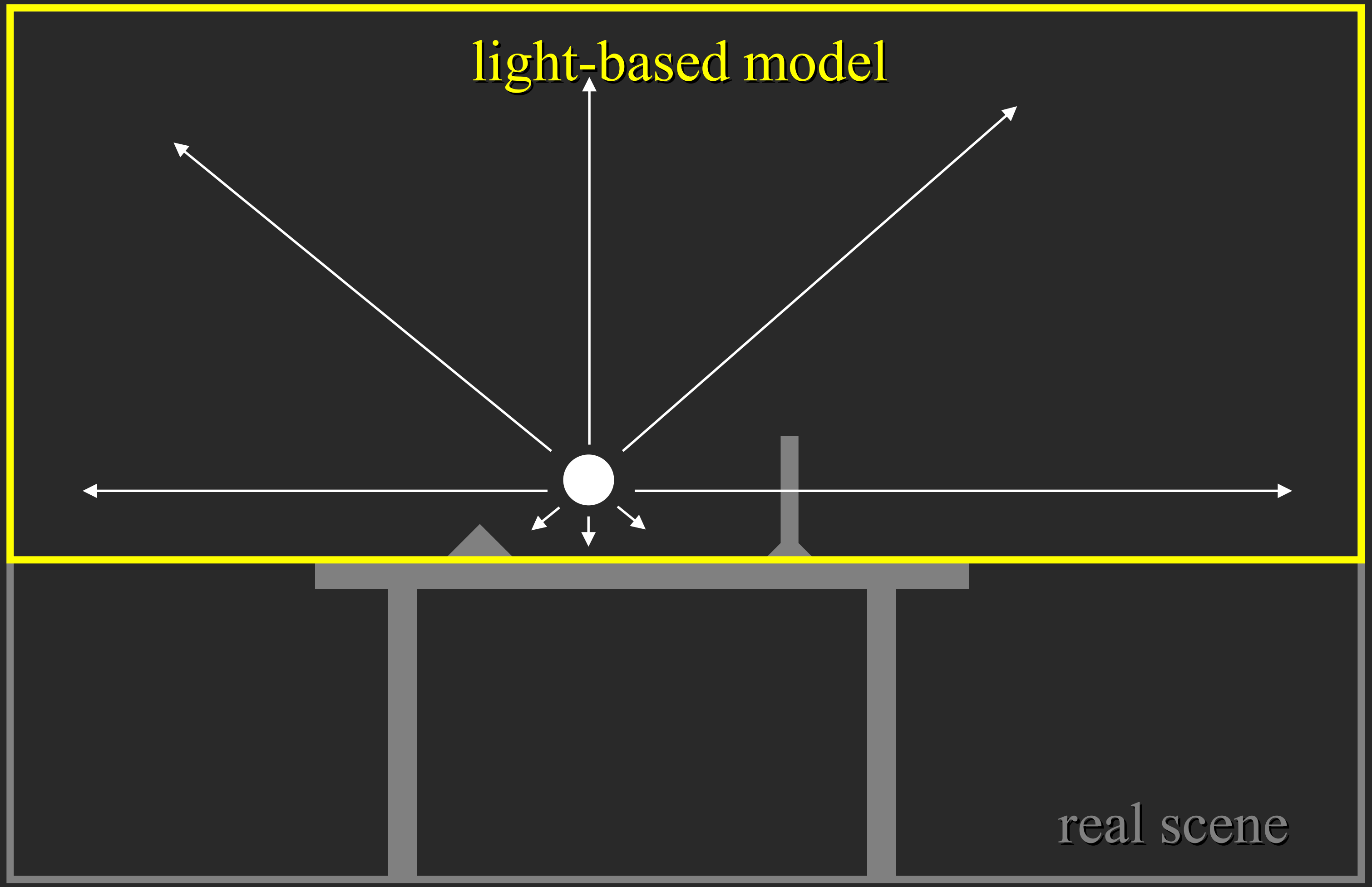
- Environment map
- Light probe
- HDR
- Ray tracing

How do we add synthetic objects to a **real scene**?

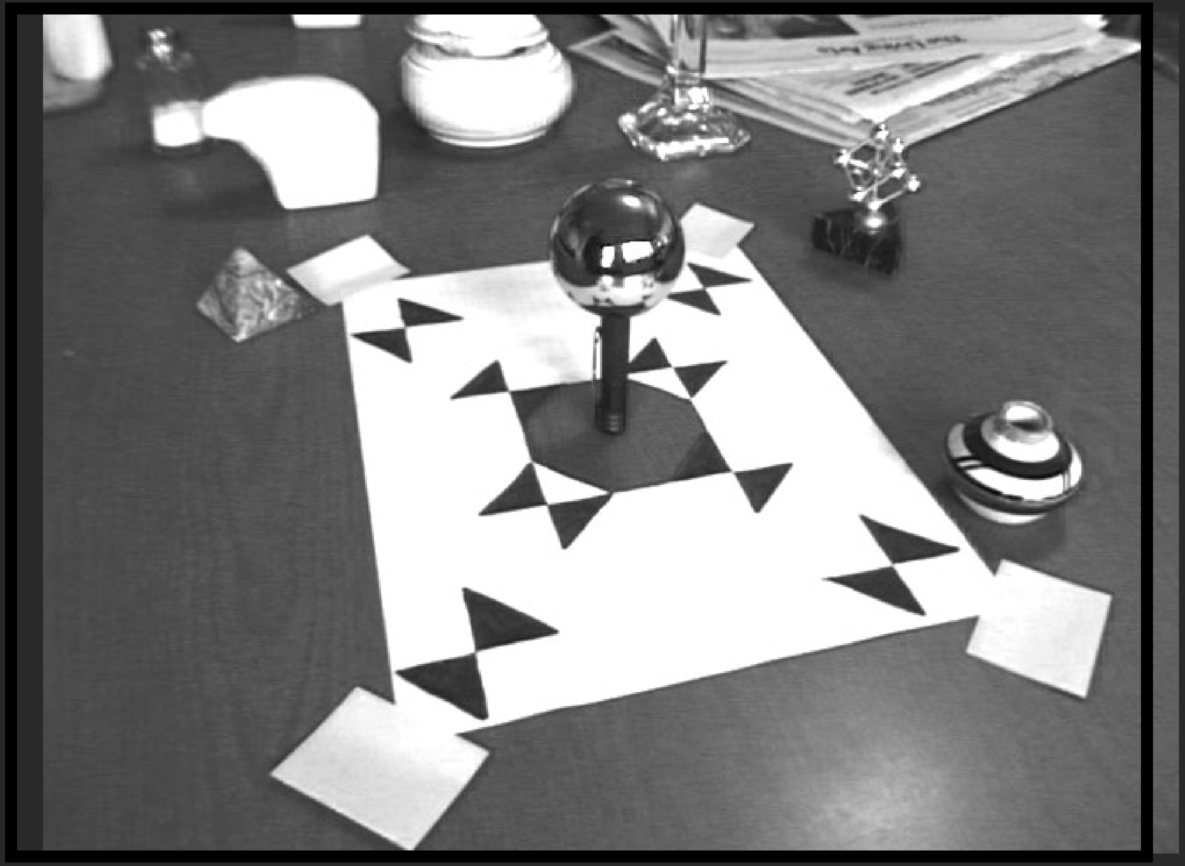
## Real Scene Example

Goal: place synthetic objects on table

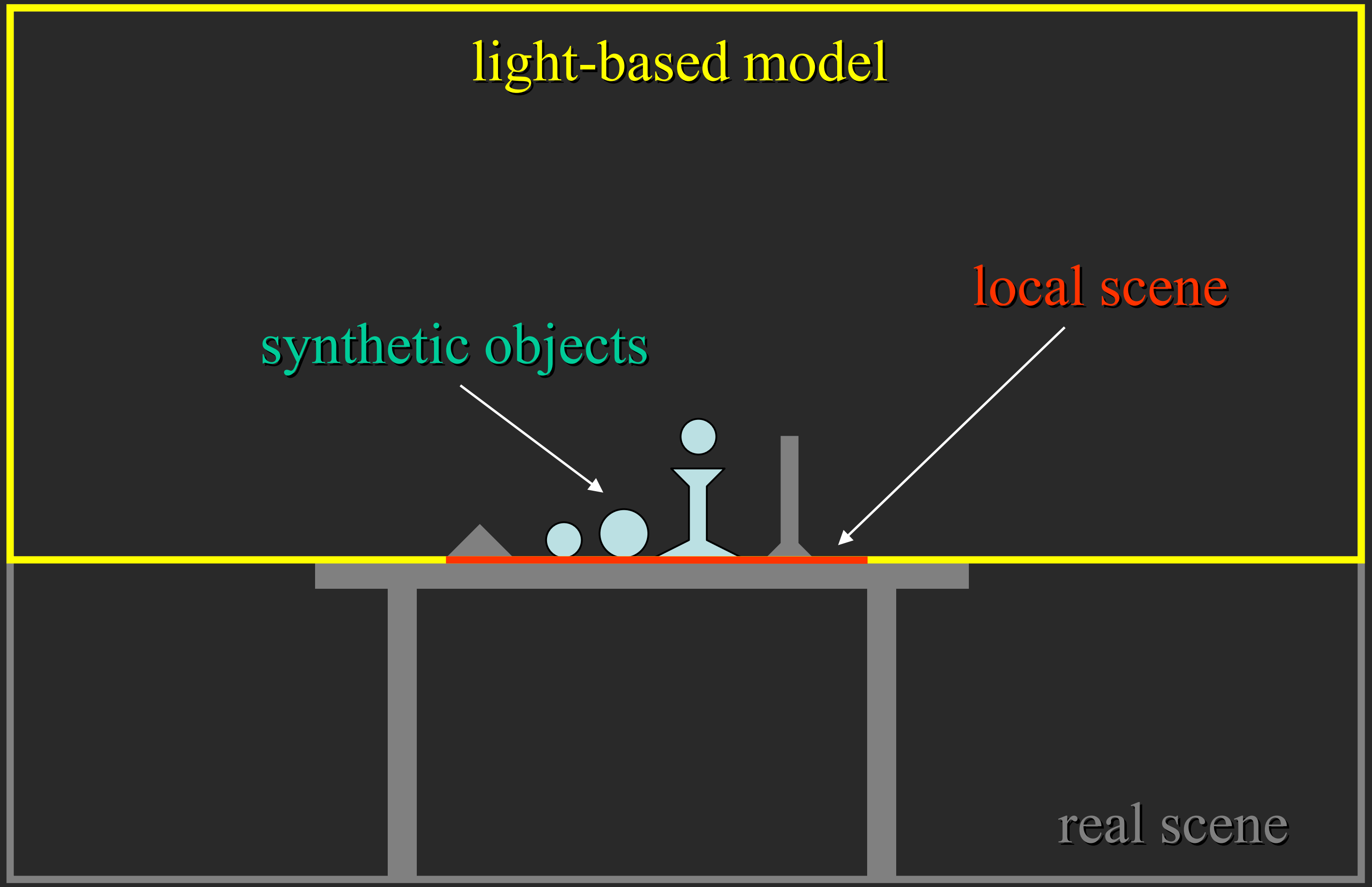
## Modeling the Scene



## Light Probe / Calibration Grid



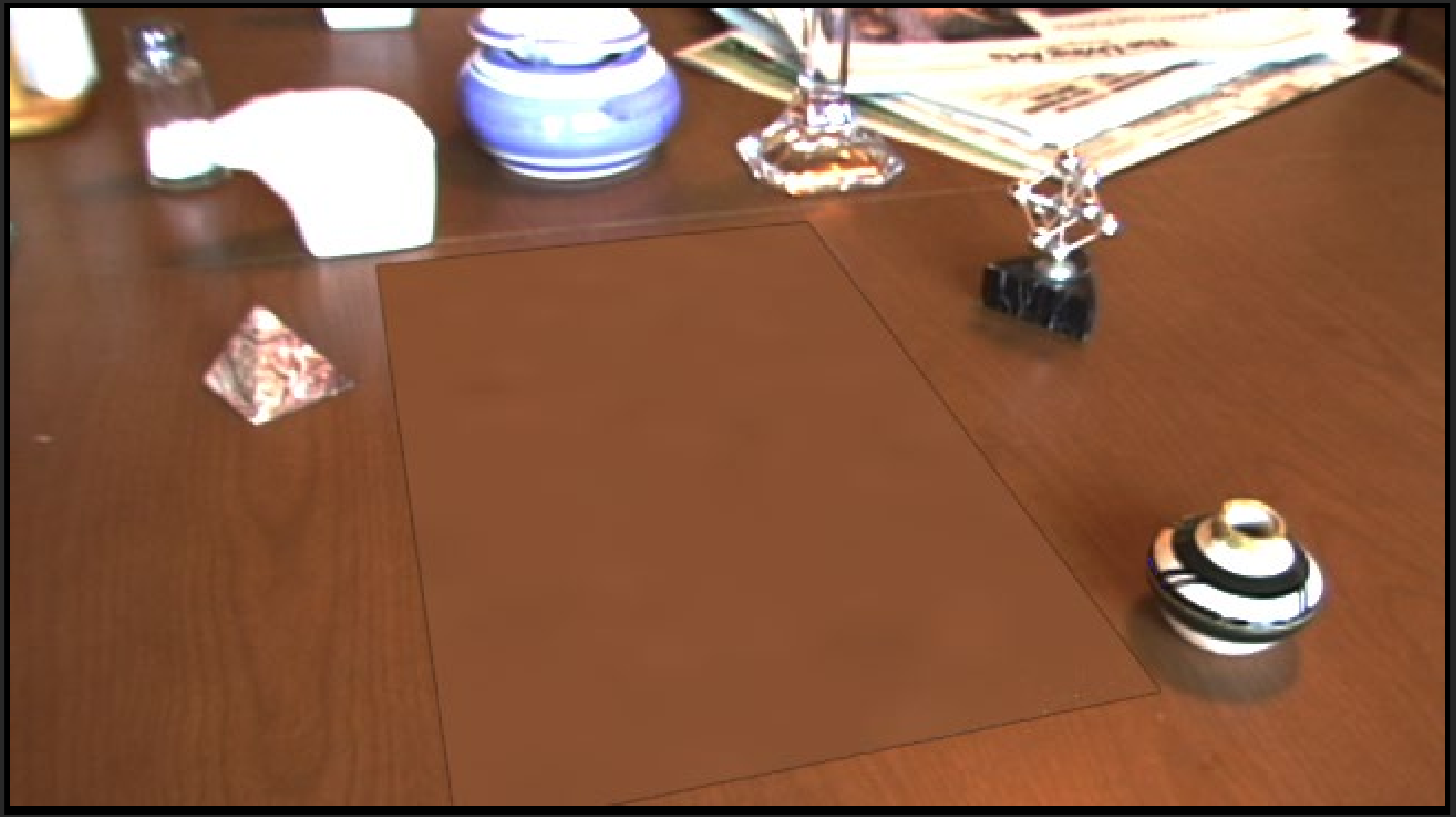
# Modeling the Scene



## Rendering into the Scene

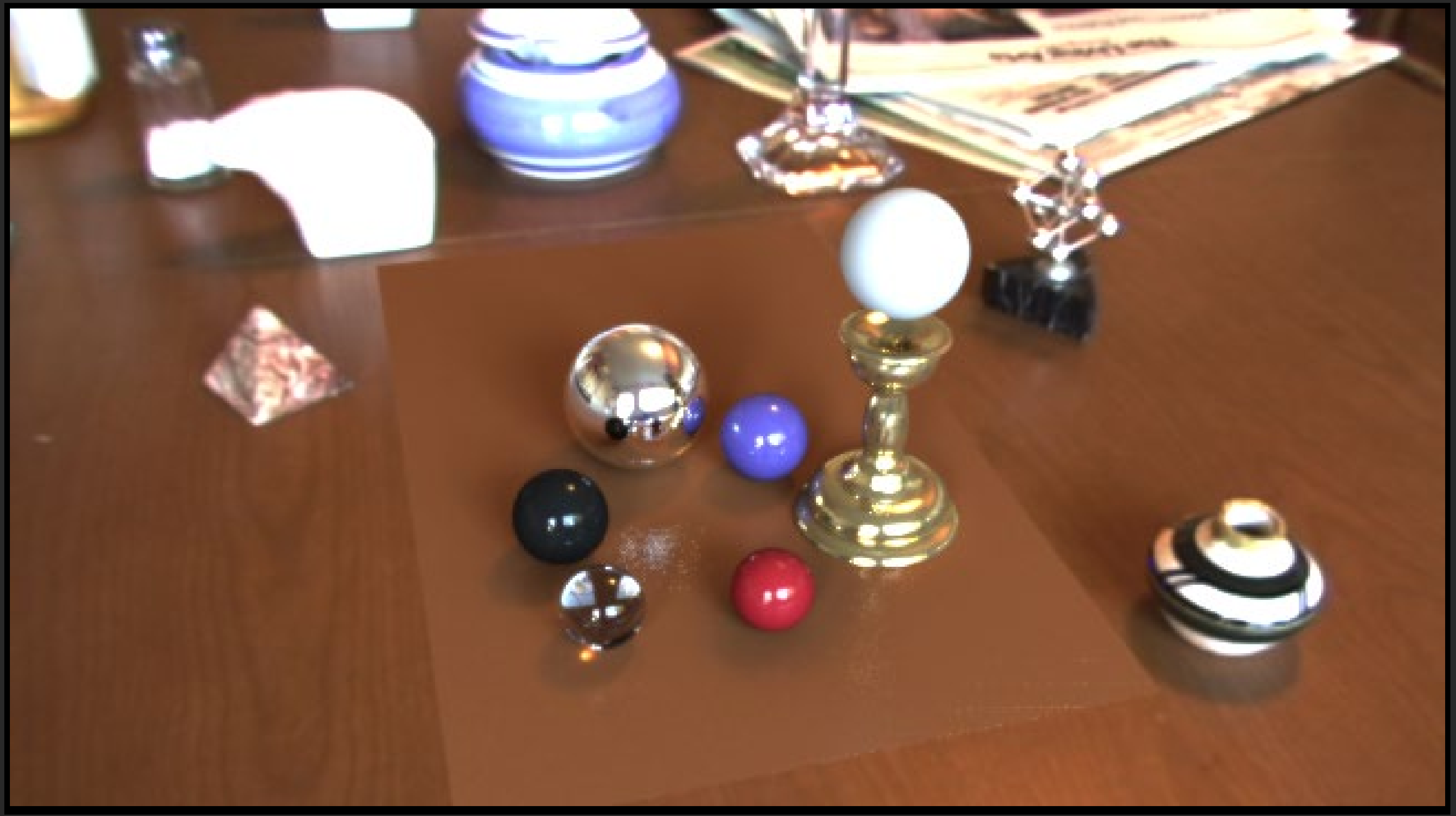
Background Image

## Differential Rendering



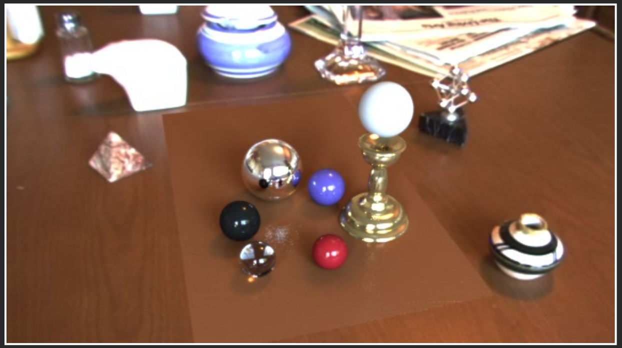
Local scene w/o objects, illuminated by model

## Rendering into the Scene



Objects and Local Scene matched to Scene

# Differential Rendering
## Difference in local scene



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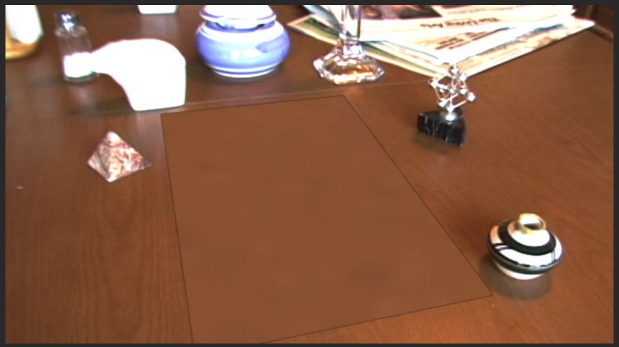

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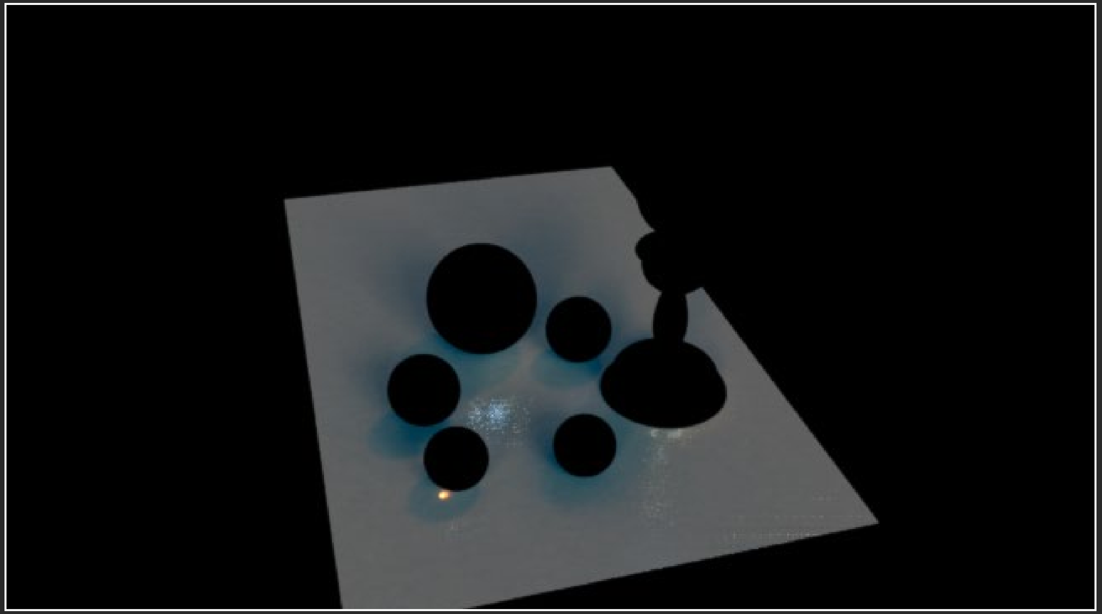


# Example rendering with Blender

(see video linked from web page)

Input Components:

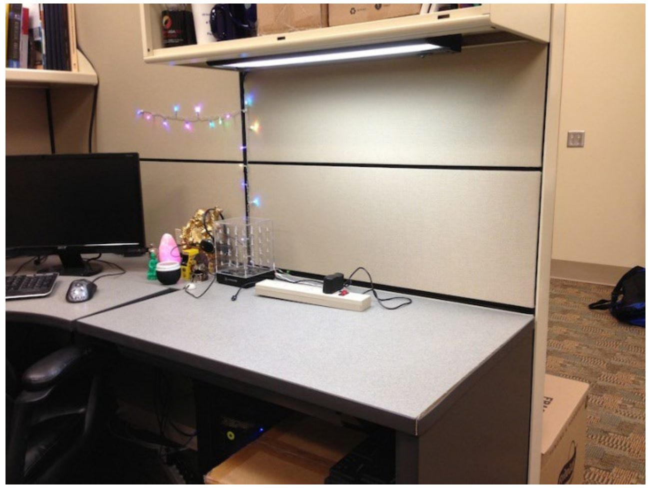
1. Background image
2. Equirectangular lighting environment map
3. 3D objects to insert, positioned in 3D scene
4. Local environment mesh/texture (e.g. supporting plane)

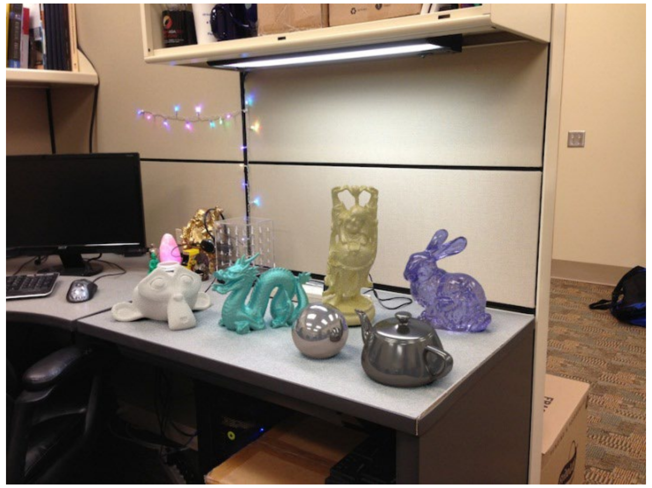
Process:

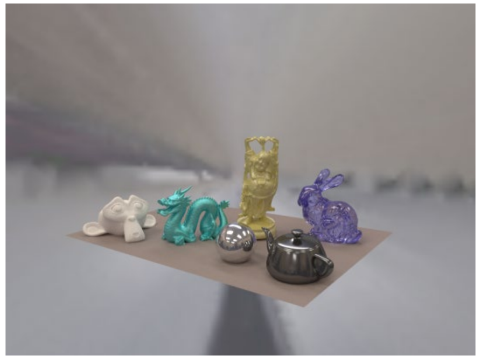
1. Render scene with objects
2. Render scene without objects
3. Render mask (objects only setting materials to emit light)
4. Compute composite image

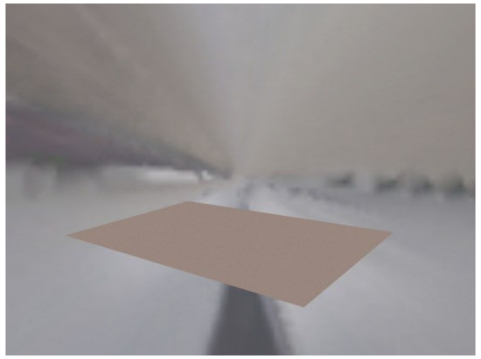
composite = M.*R + (1-M).*I + (1-M).*(R-E)*c

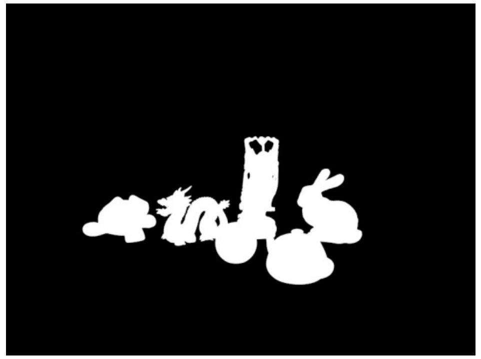
effect multiplier


I (background)


composite


R (rendered)


E (empty)


M (mask)

## IMAGE-BASED LIGHTING IN *FIAT LUX*

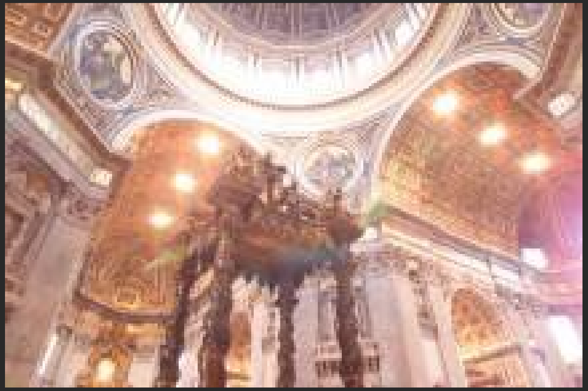
Paul Debevec, Tim Hawkins, Westley Sarokin, H. P. Duiker, Christine Cheng, Tal Garfinkel, Jenny Huang

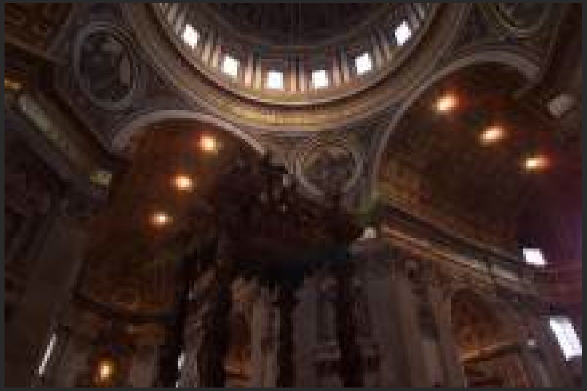
SIGGRAPH 99 Electronic Theater

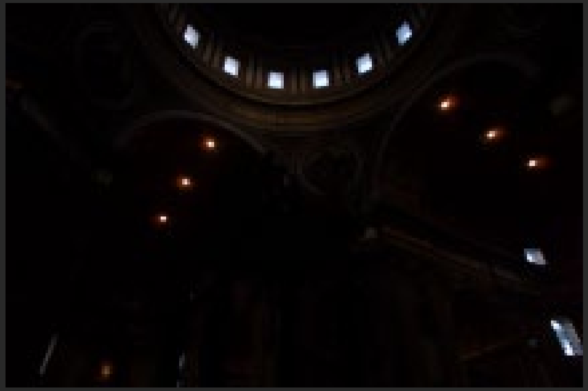
## Fiat Lux

- http://ict.debevec.org/~debevec/FiatLux/movie/
- http://ict.debevec.org/~debevec/FiatLux/technology/

# HDR Image Series


2 sec


1/4 sec

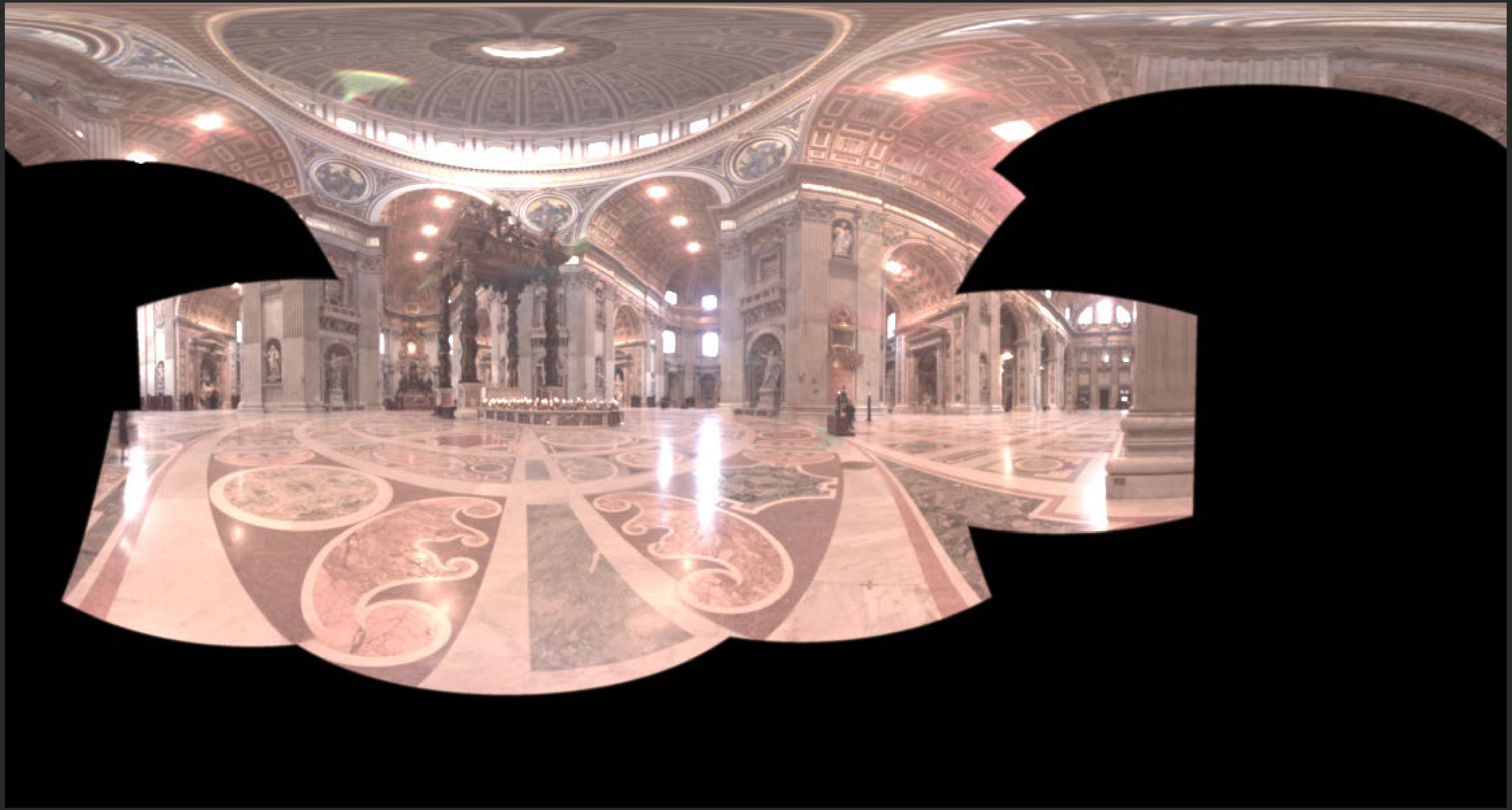

1/30 sec

1/250 sec

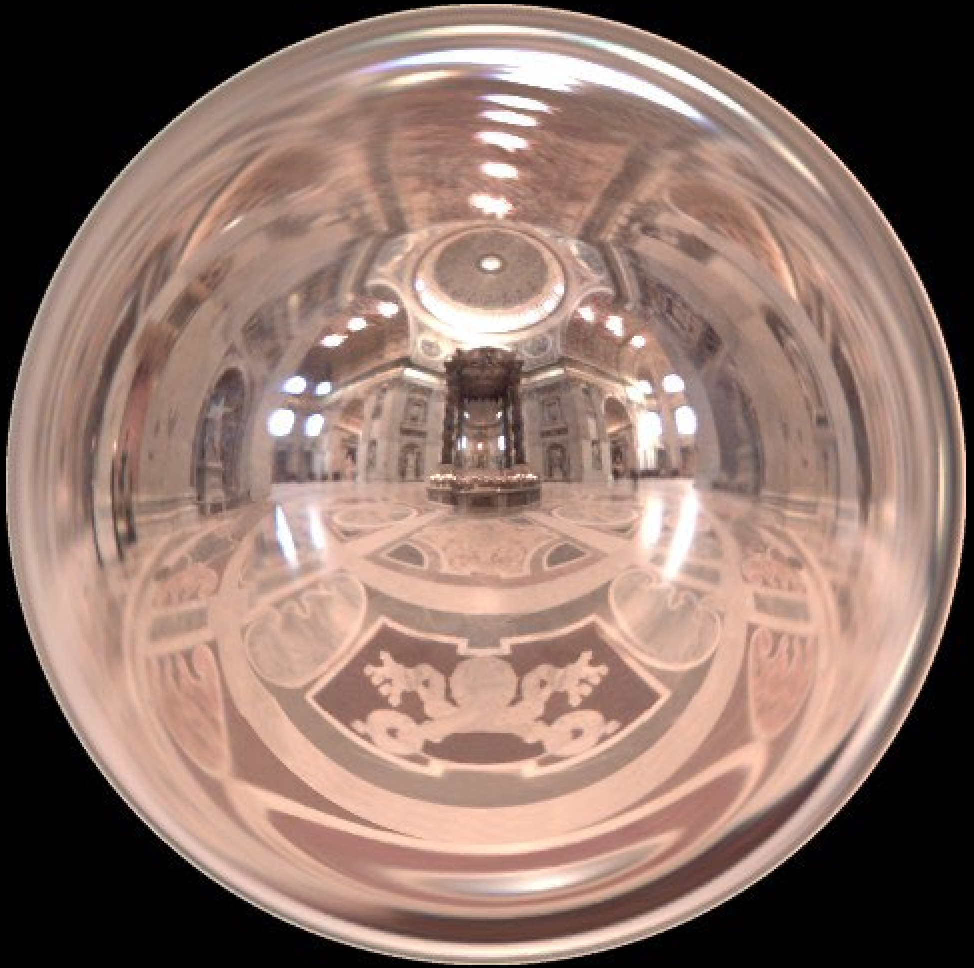
1/2000 sec

1/8000 sec

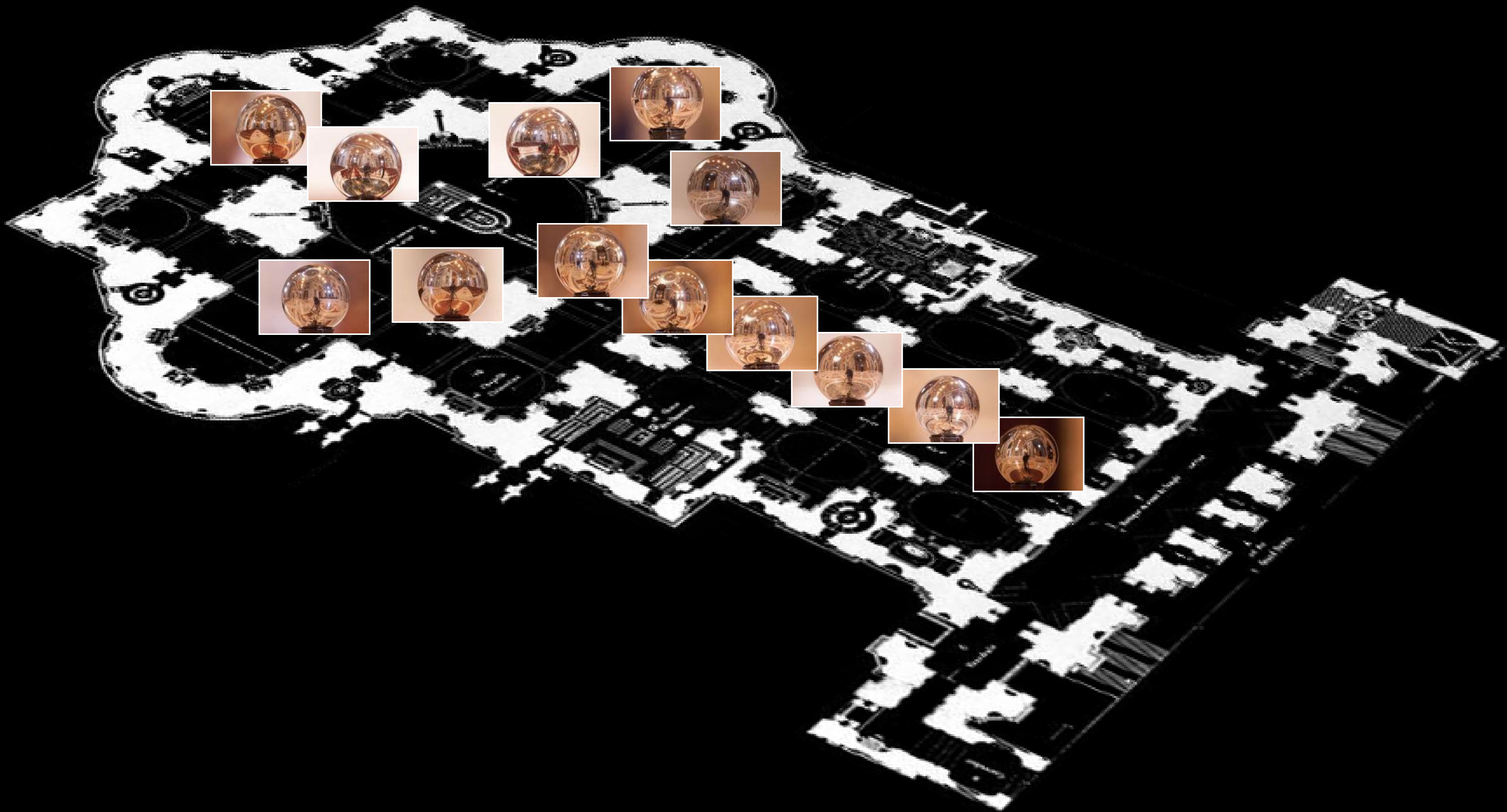
## Assembled Panorama



## Light Probe Images

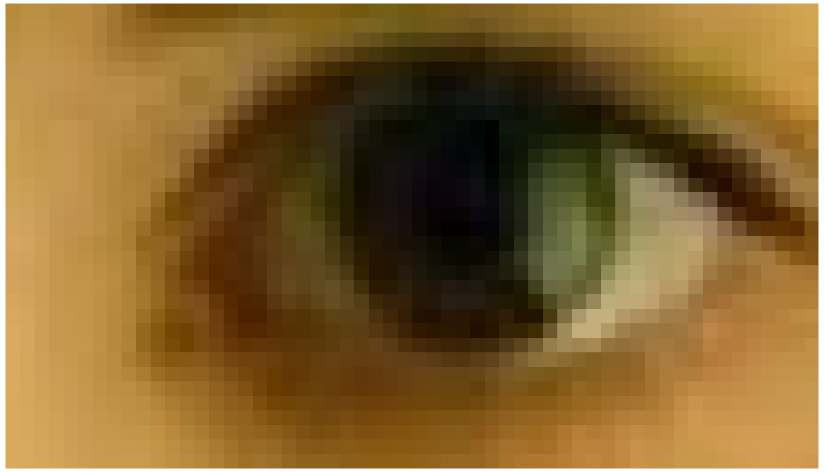


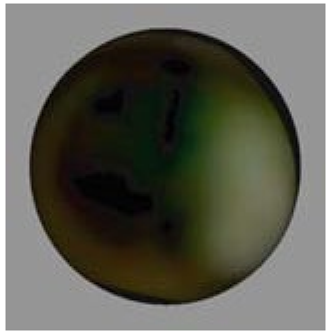
# Capturing a Spatially-Varying Lighting Environment



# What if we don’t have a light probe?

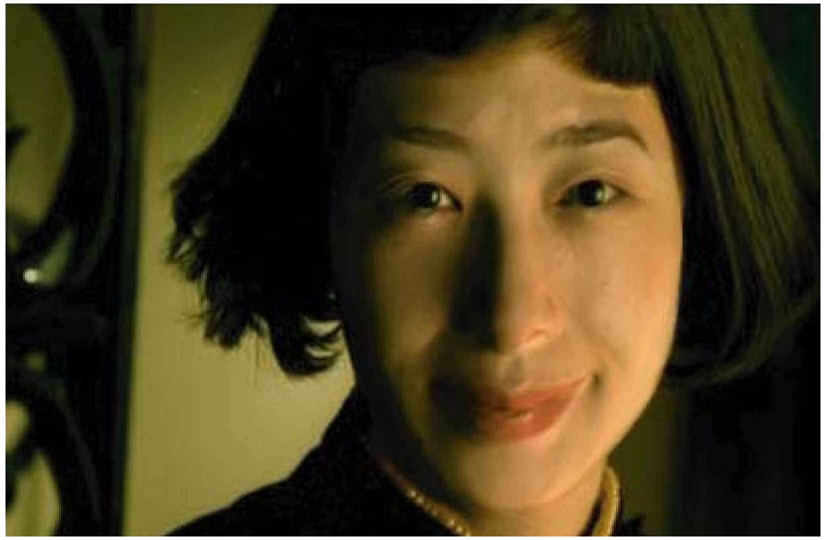
Zoom in on eye



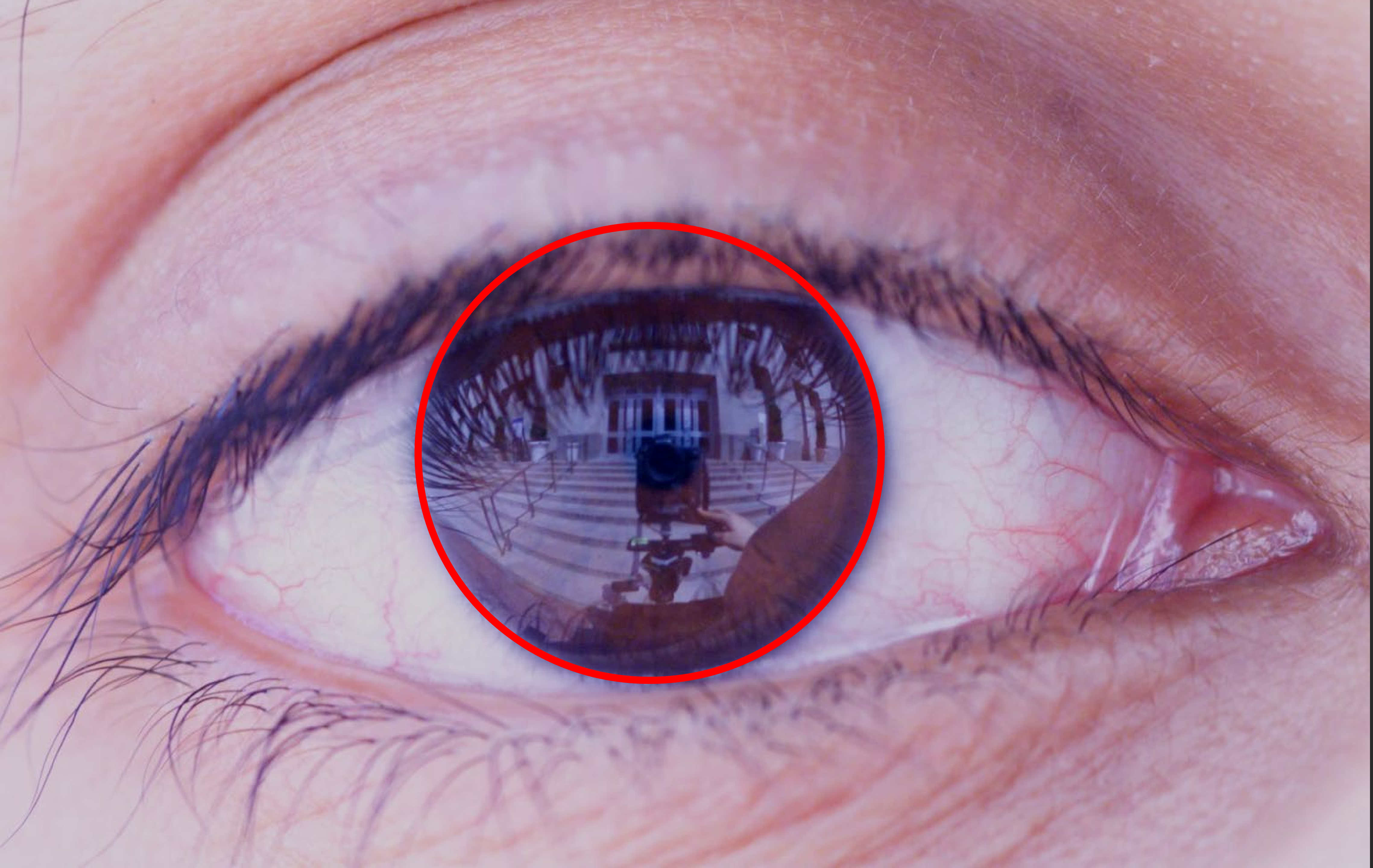


Environment map

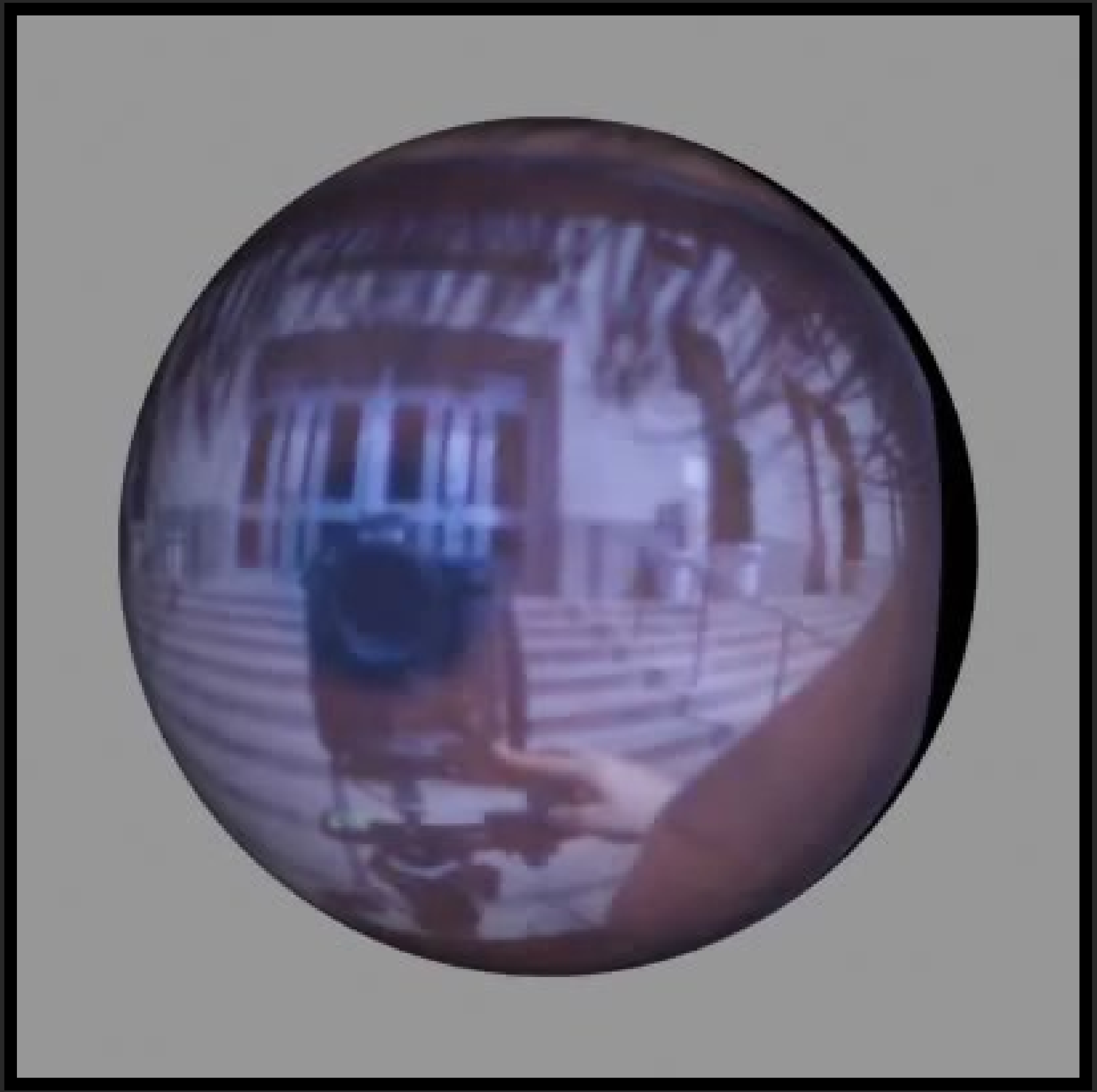
Insert Relit Face



http://www1.cs.columbia.edu/CAVE/projects/world_eye/ -- Nishino Nayar 2004

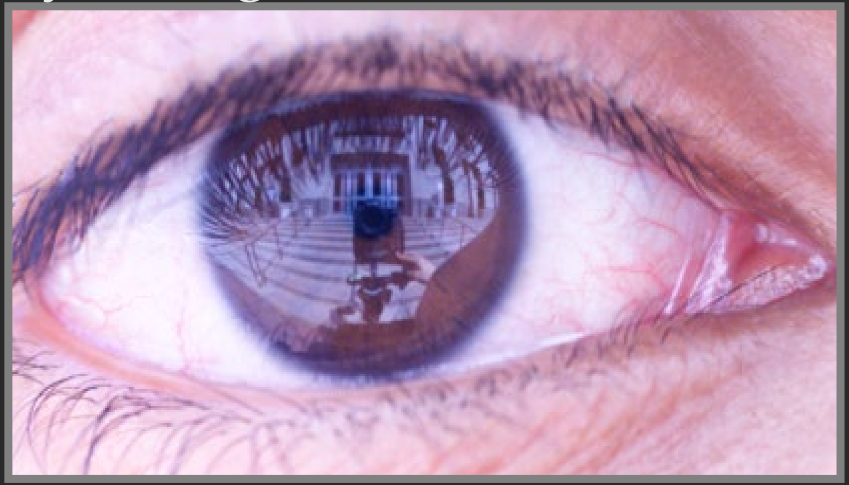


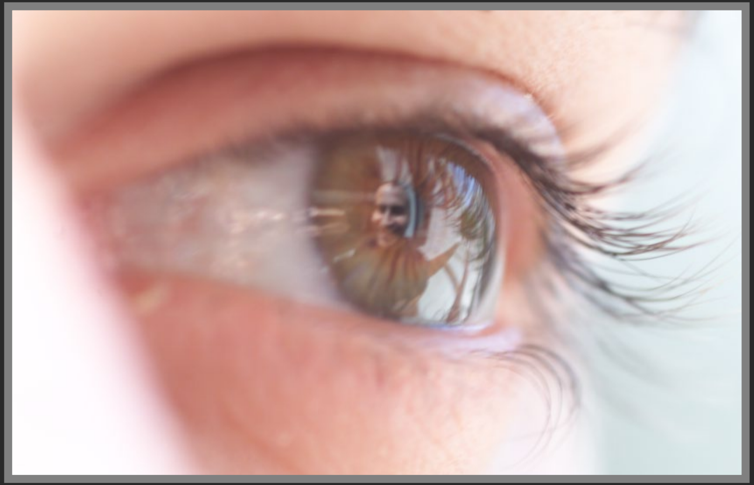
## Environment Map from an Eye



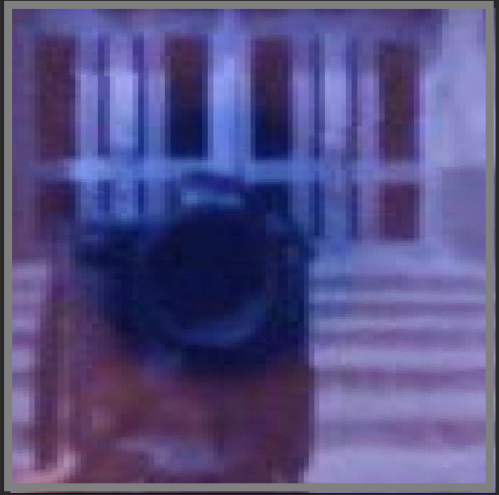
## Can Tell What You are Looking At

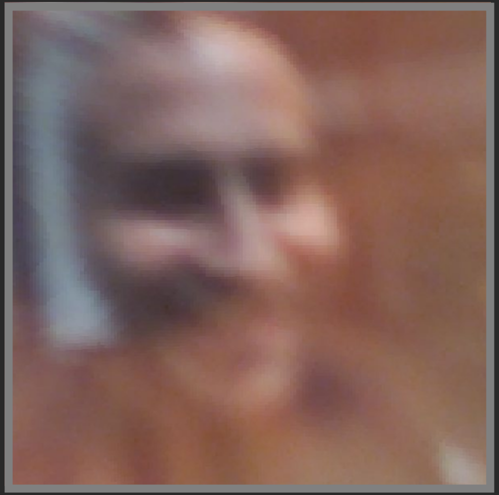
Eye Image:

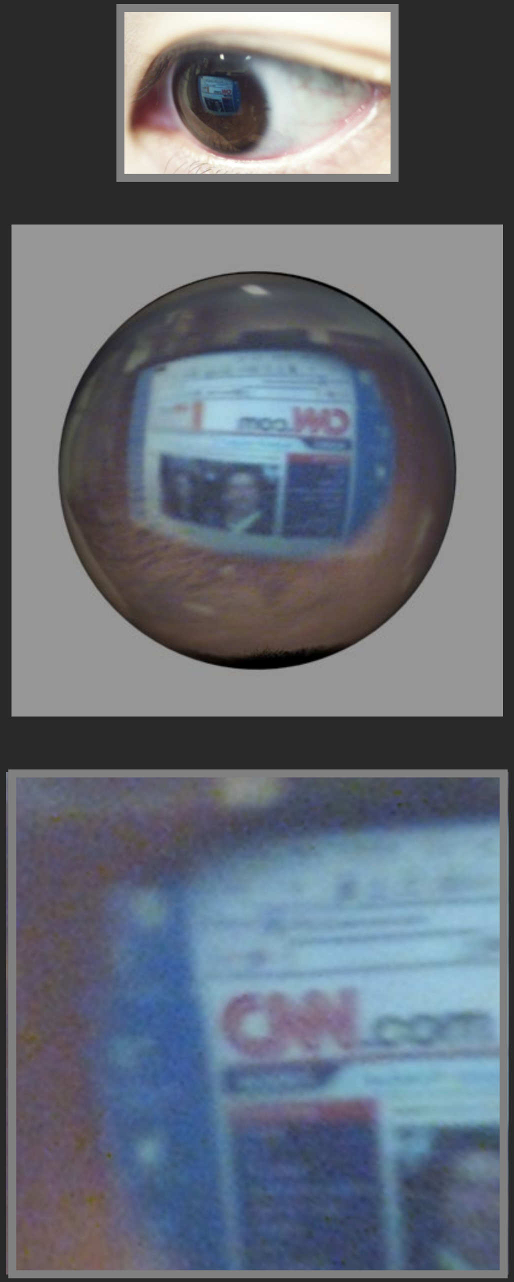
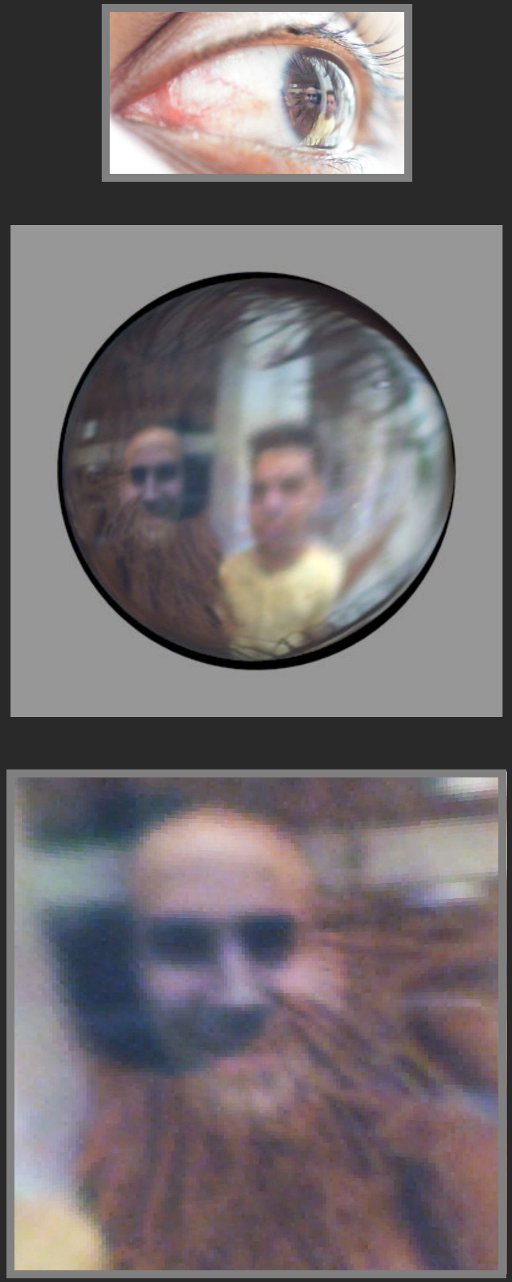
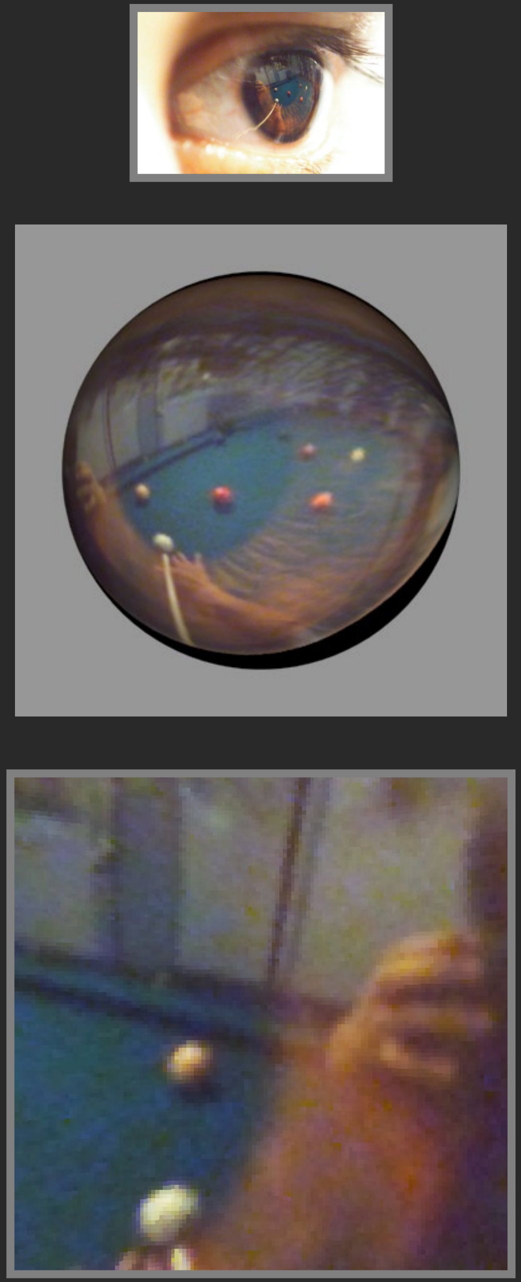




Computed Retinal Image:






CNN.com



## Video

## Summary

- Real scenes have complex geometries and materials that are difficult to model
- We can use an environment map, captured with a light probe, as a replacement for distance lighting
- We can get an HDR image by combining bracketed shots
- We can relight objects at that position using the environment map