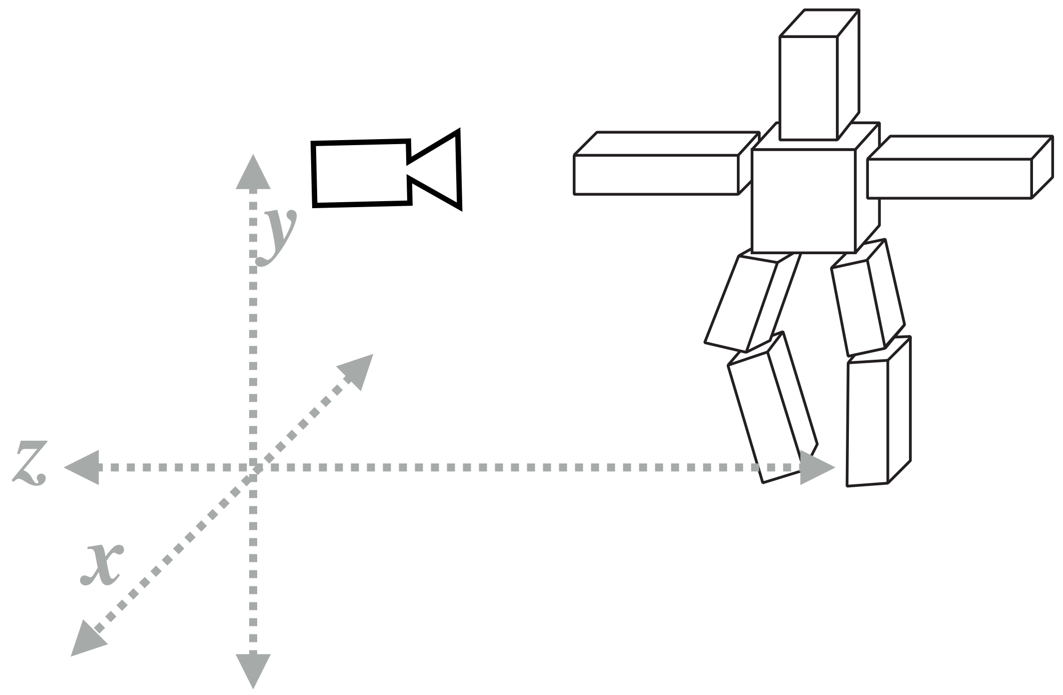
Lecture 6:

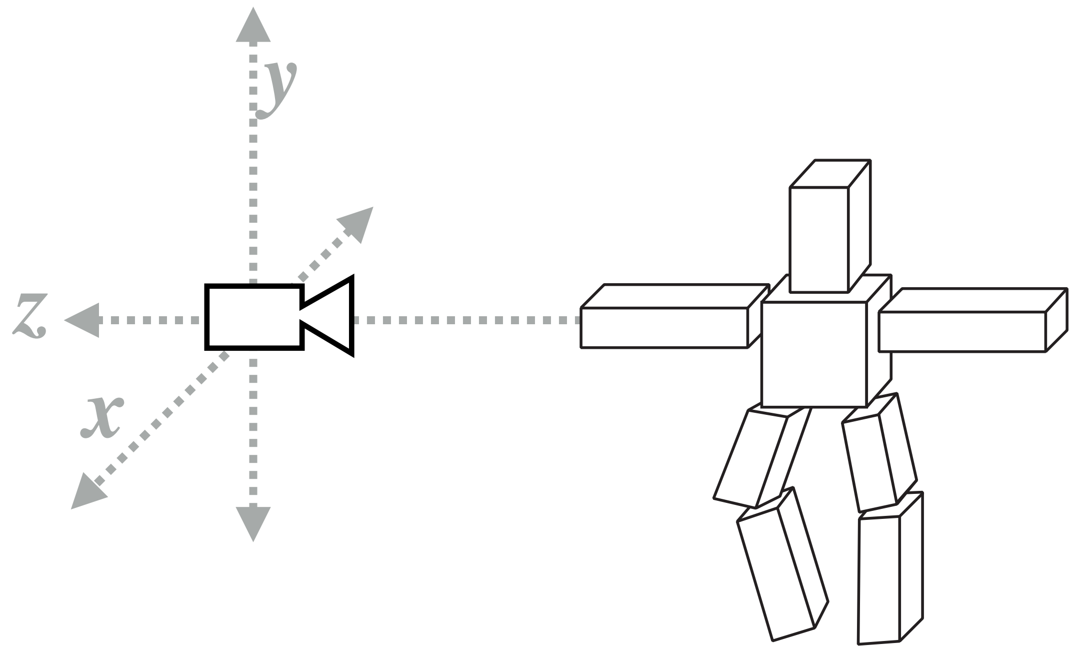
The Rasterization Pipeline

Computer Graphics and Imaging
UC Berkeley CS184/284A

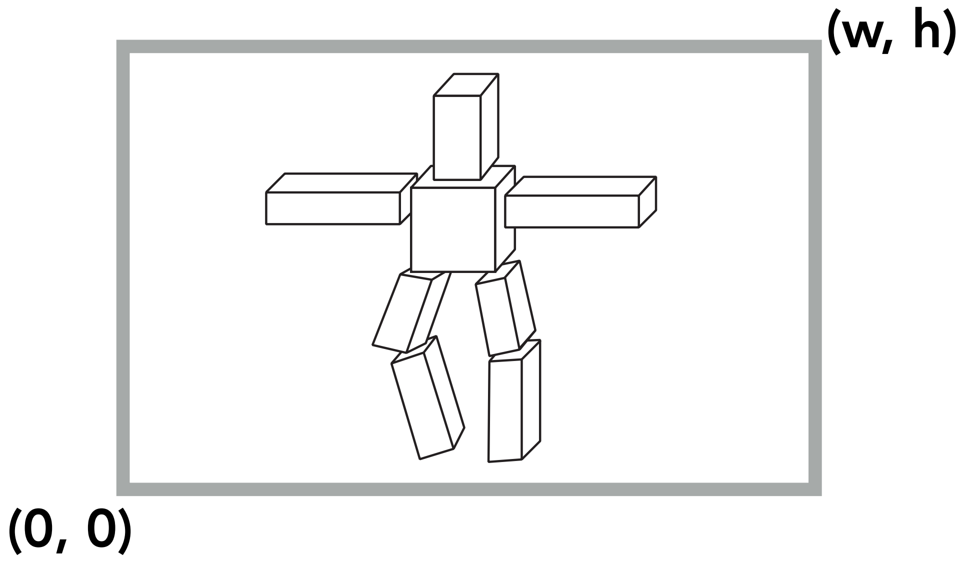
What We’ve Covered So Far



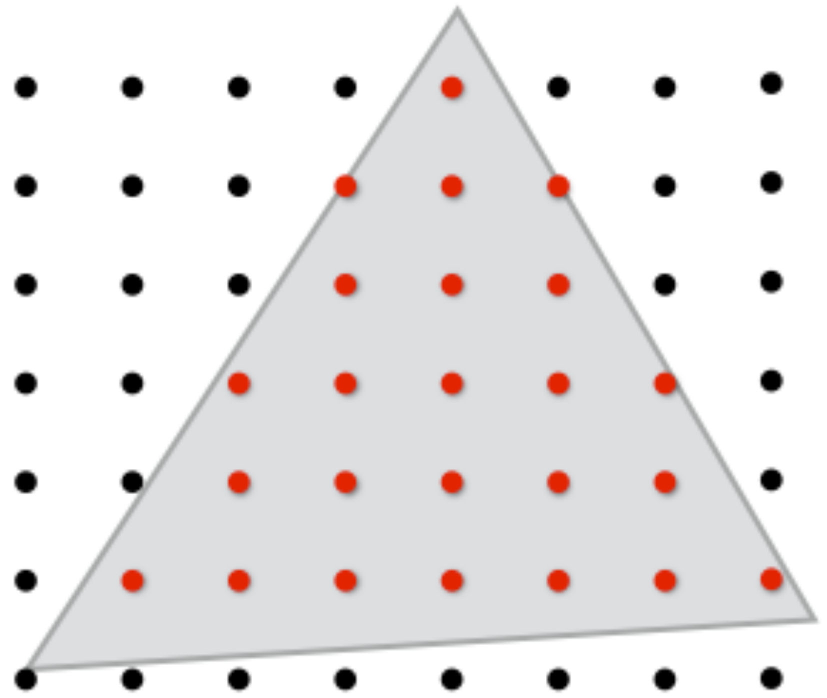
Position objects and the camera in the world



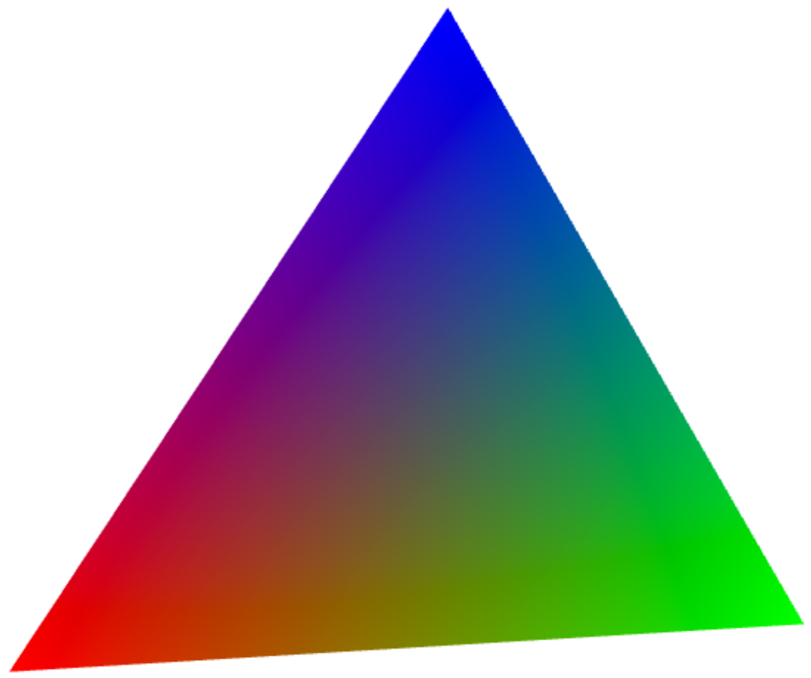
Compute position of objects relative to the camera



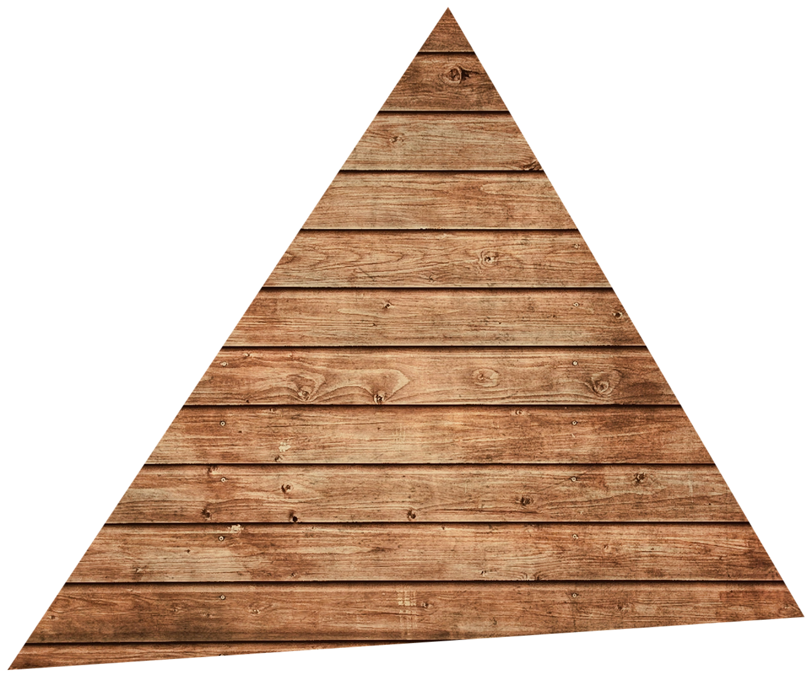
Project objects onto the screen



Sample triangle coverage

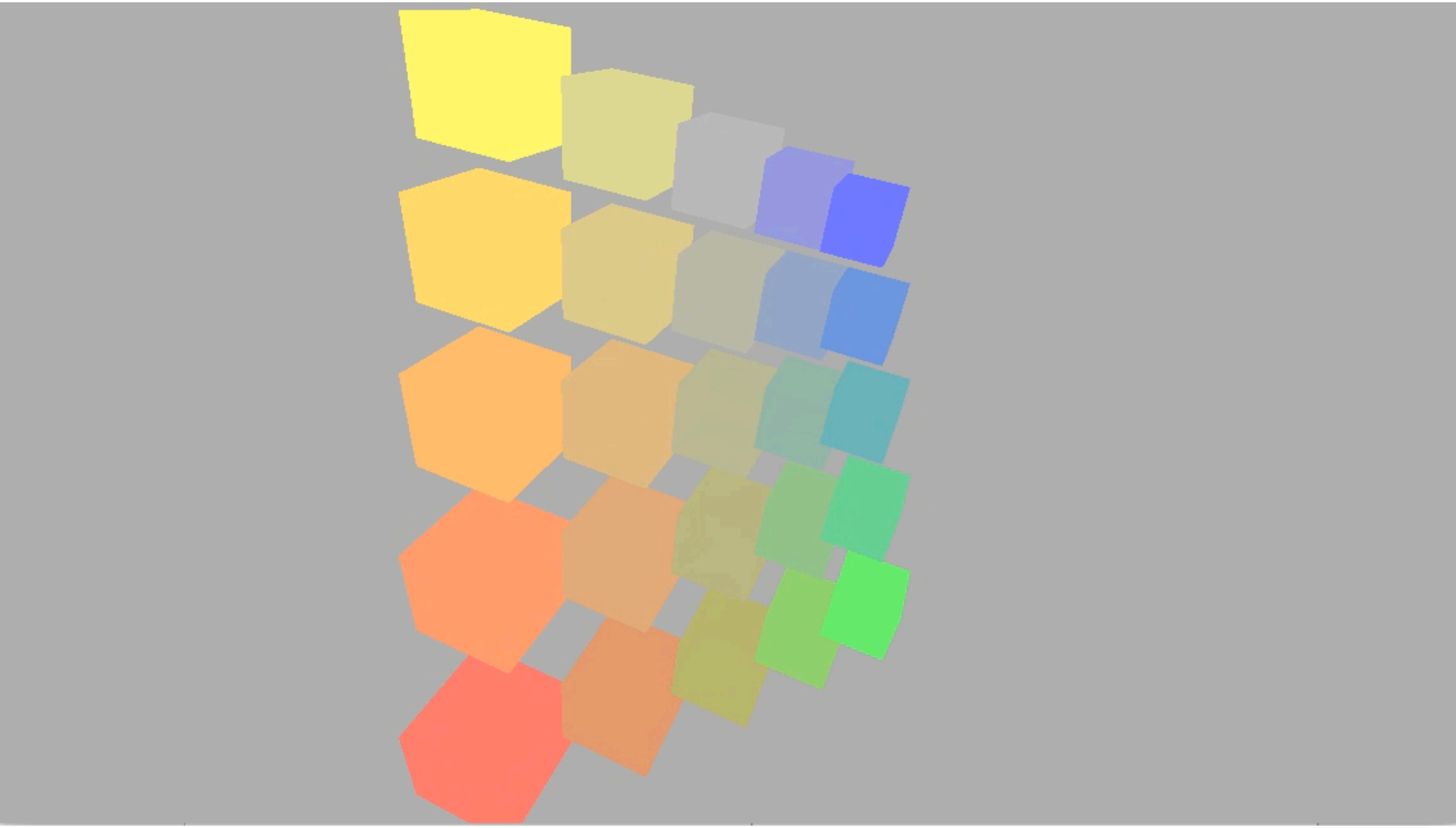


Interpolate triangle attributes

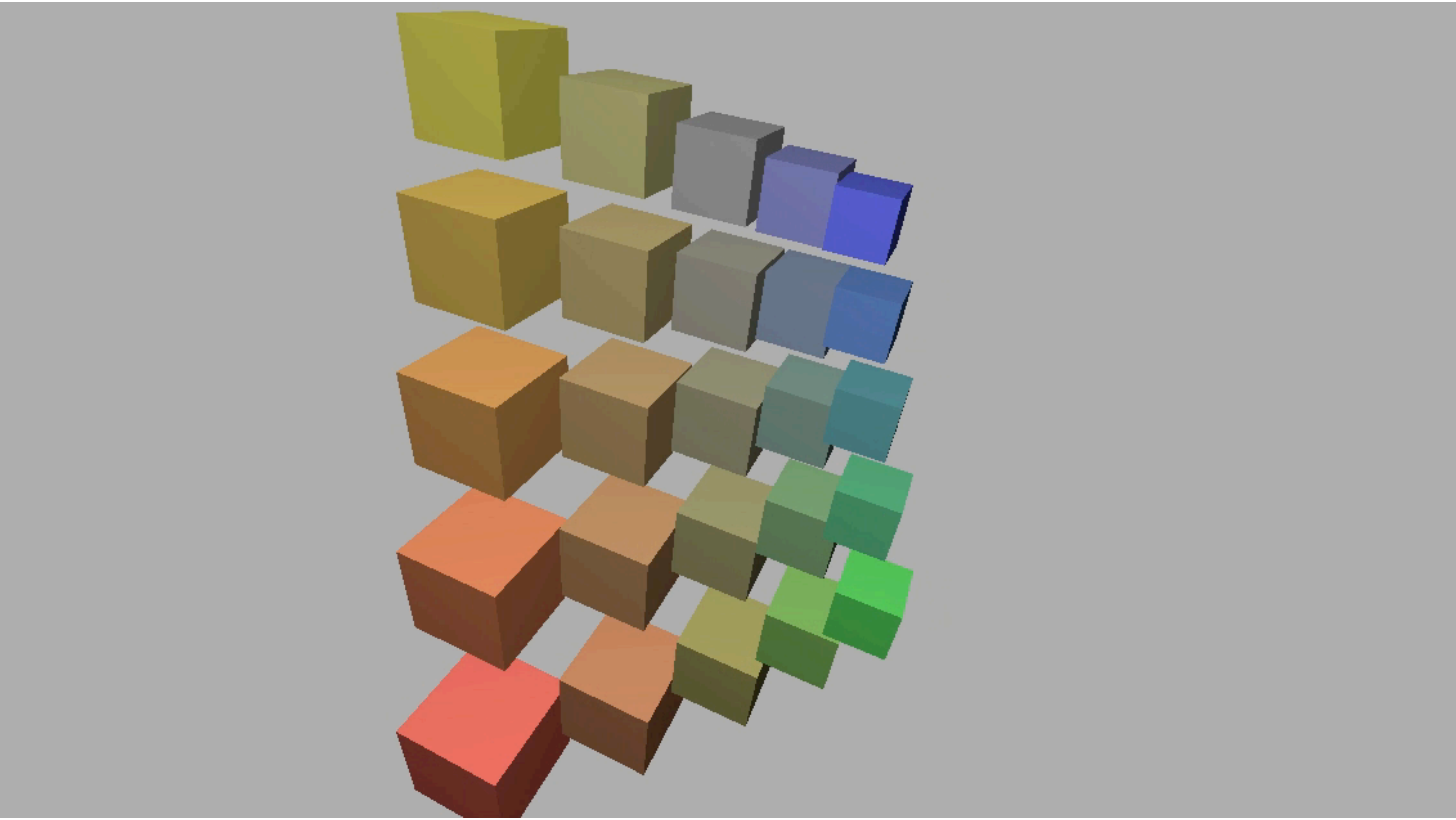


Sample texture maps

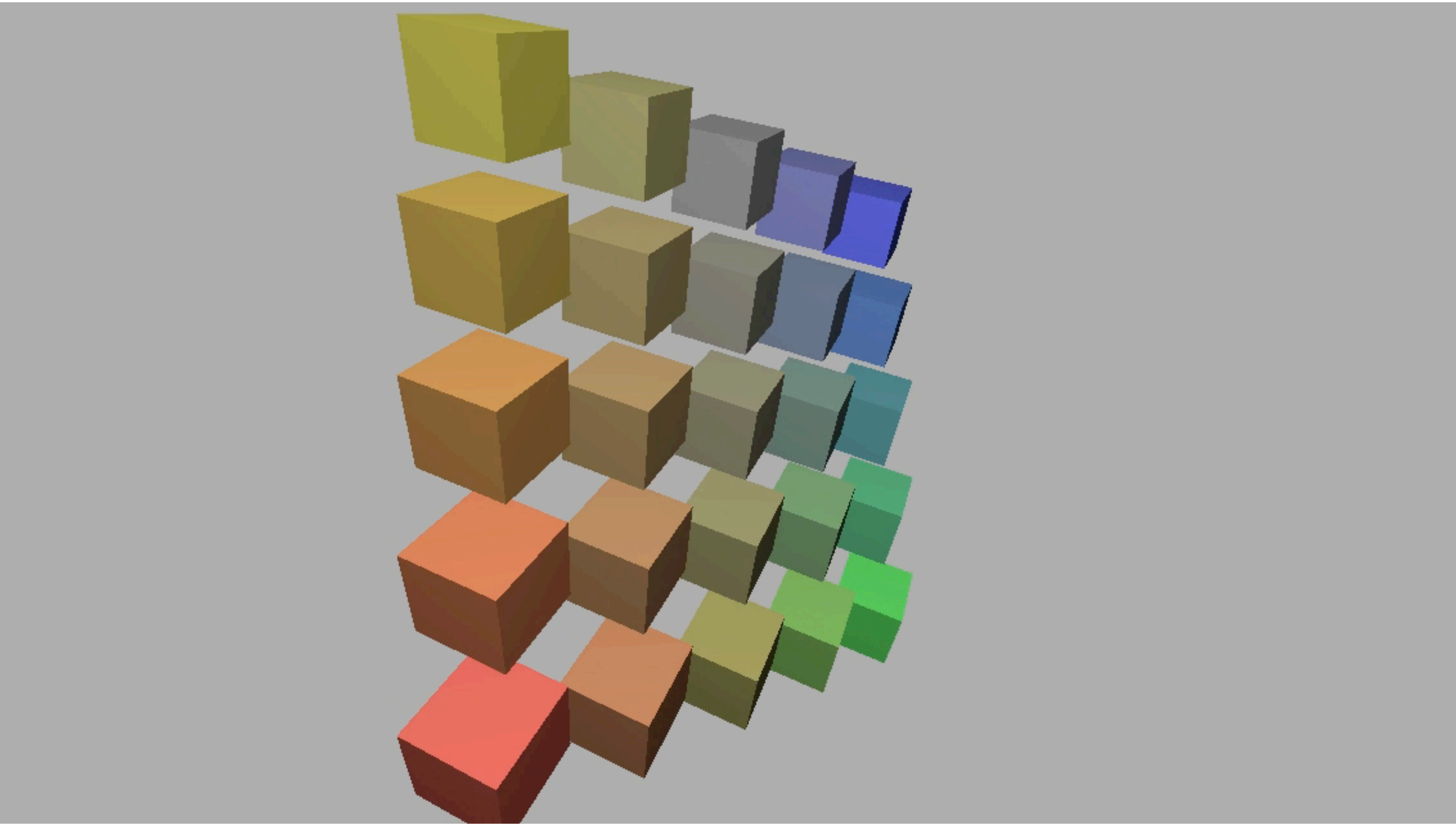
Rotating Cubes in Perspective



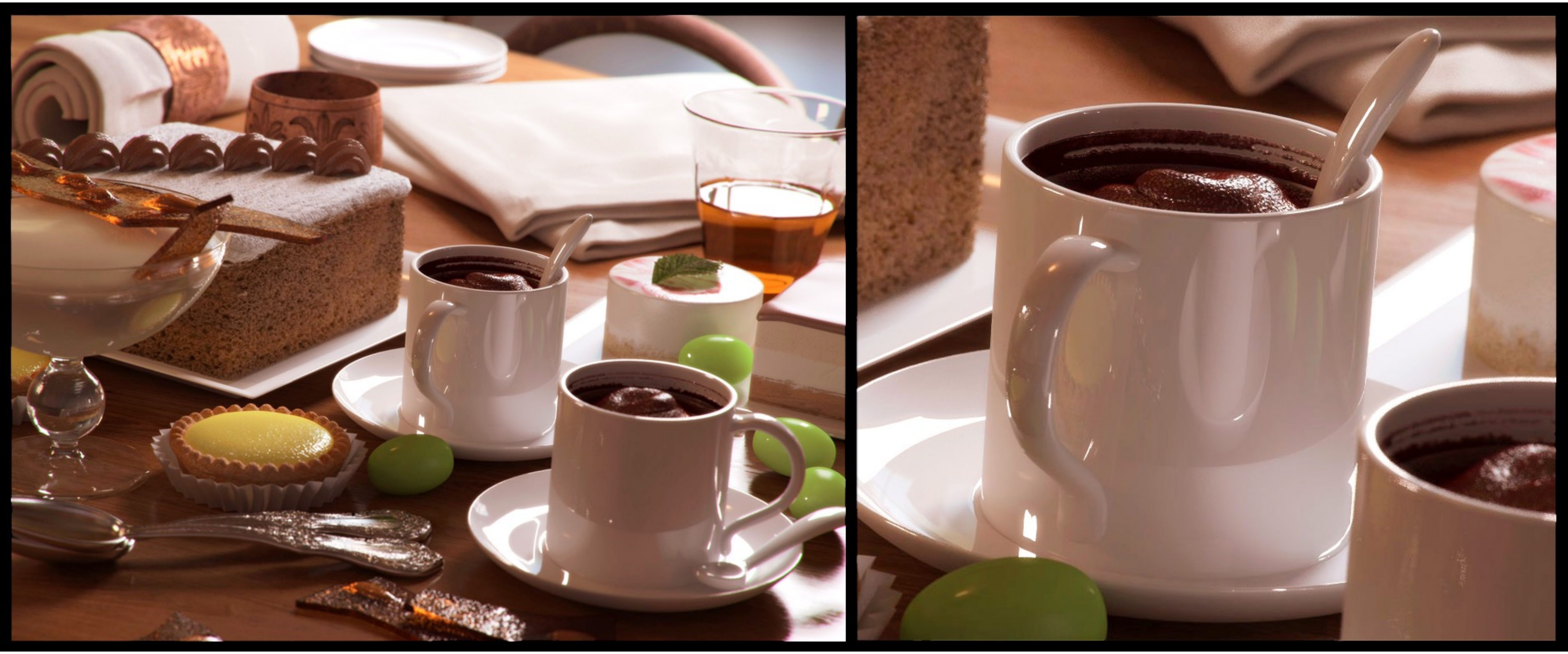
Rotating Cubes in Perspective



Rotating Cubes in Perspective



What Else Are We Missing?



Credit: Bertrand Benoit. “Sweet Feast,” 2009. [Blender /VRay]

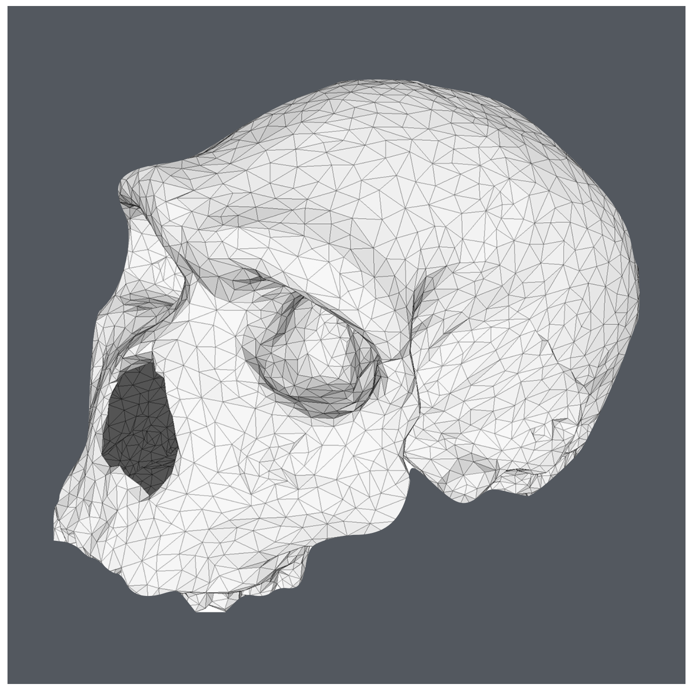
What Else Are We Missing?

Credit: Giuseppe Albergo. "Colibri" [Blender]

What Else Are We Missing?

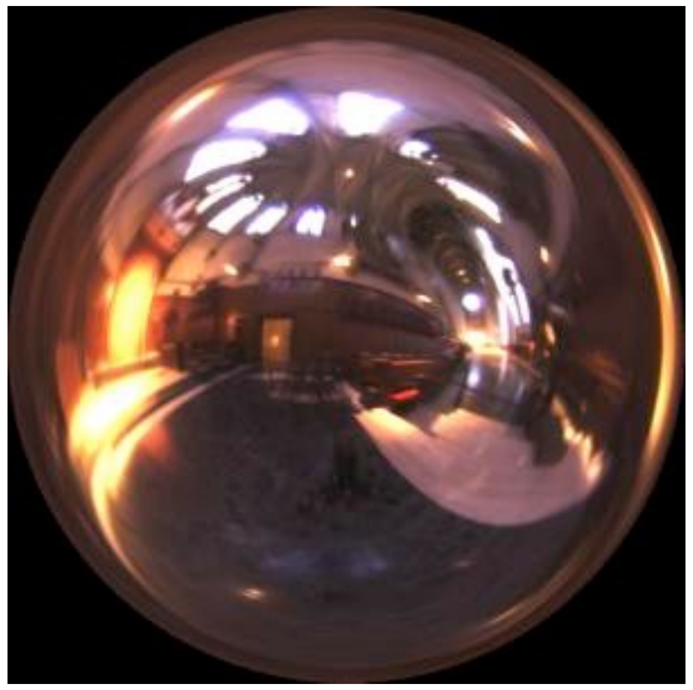
Surface representations

- Objects in the real world exhibit highly complex geometric details



Lighting and materials

- Appearance is a result of how light sources reflect off complex materials



Camera models

- Real lenses create images with focusing and other optical effects

Course Roadmap

Rasterization Pipeline

Core Concepts

- Sampling
- Antialiasing
- Transforms

Intro

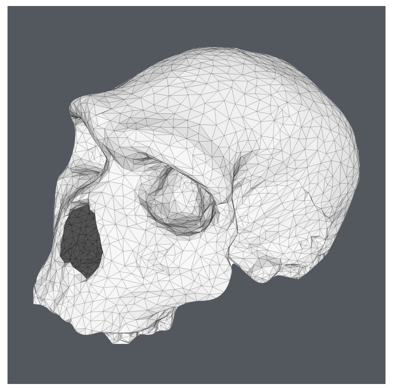
Rasterization

Transforms & Projection

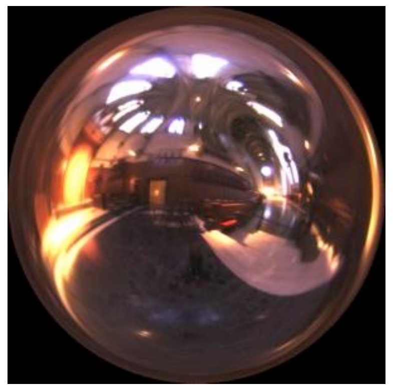
Texture Mapping

Today: Visibility, Shading, Overall Pipeline

Geometric Modeling



Lighting & Materials



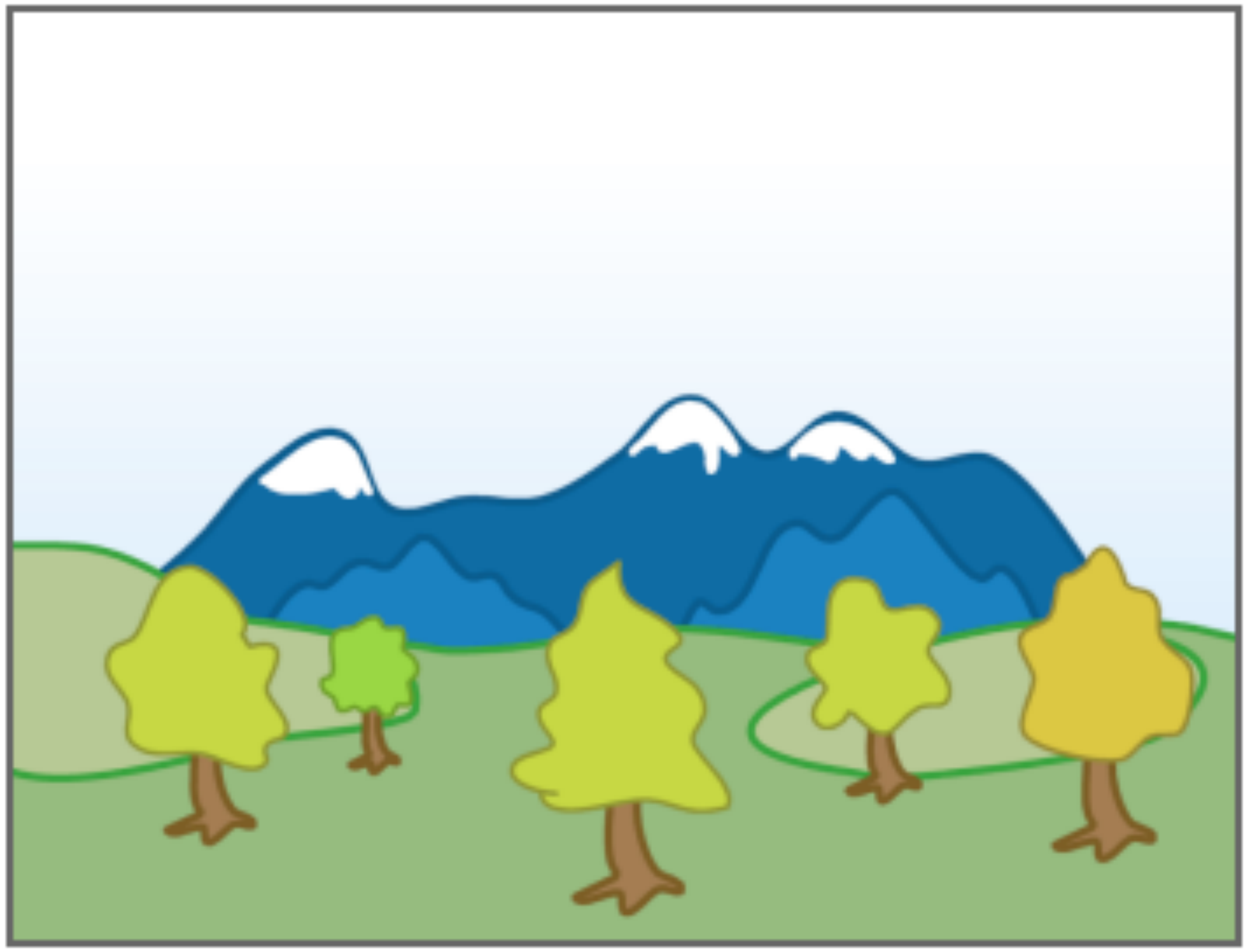
Cameras & Imaging

Visibility

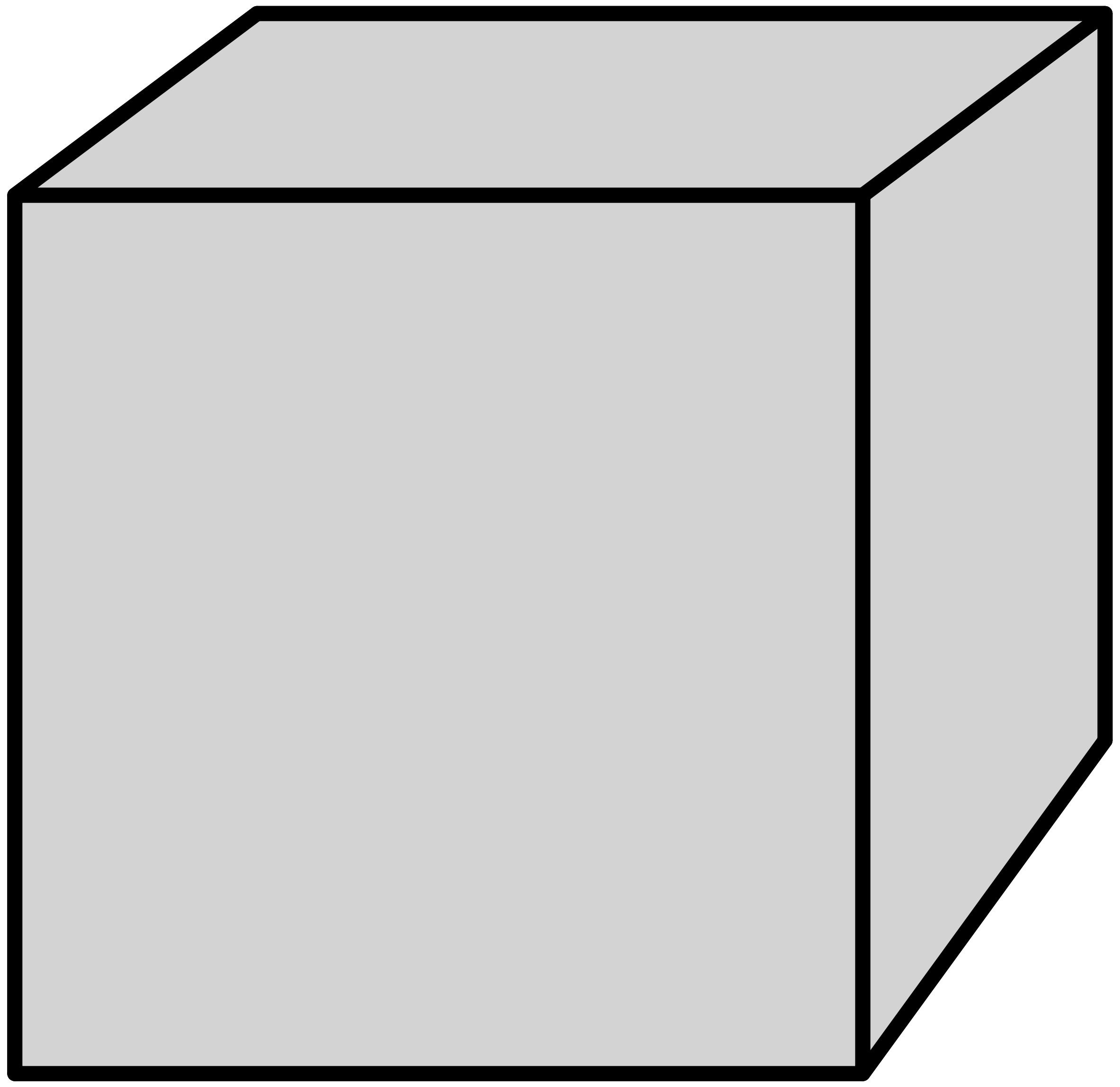
Painter's Algorithm

Inspired by how painters paint

Paint from back to front, overwrite in the framebuffer



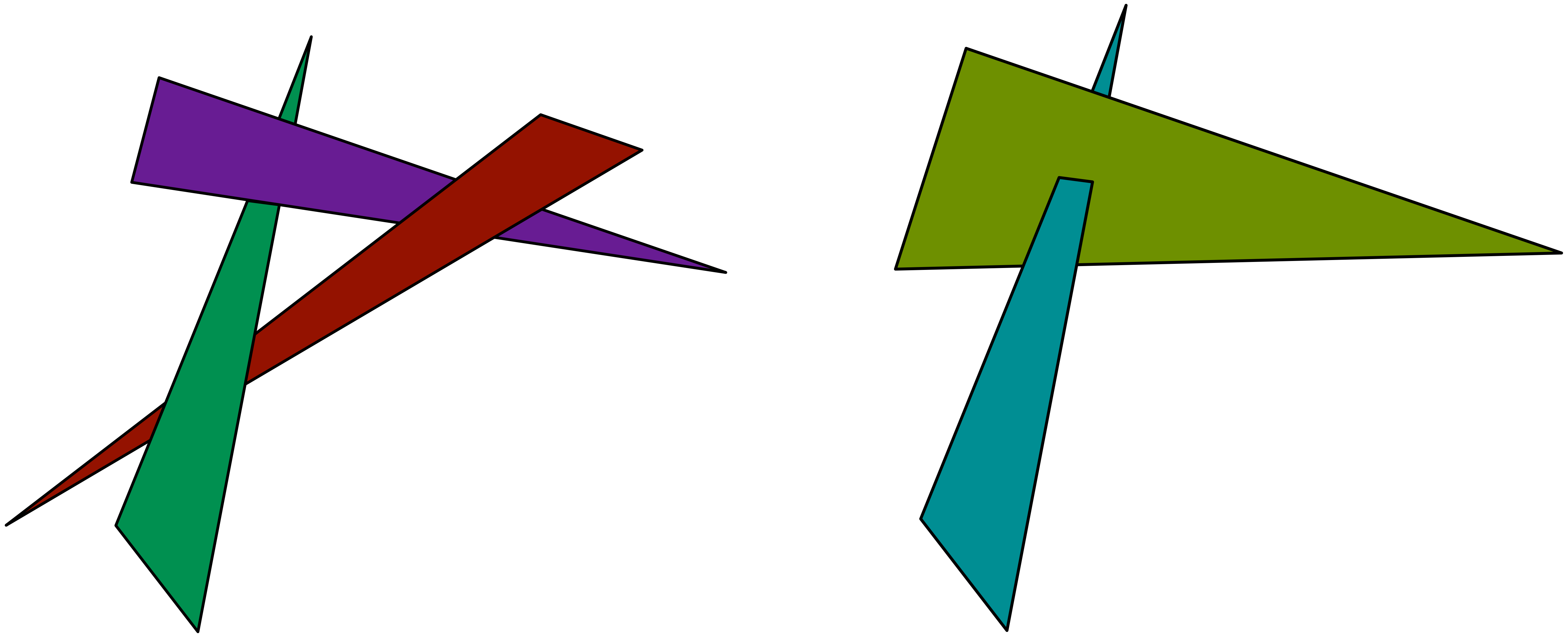
[Wikipedia]



Painter's Algorithm

Requires sorting in depth (O(n log n) for n triangles)

Can have unresolvable depth order



(BSP Trees will provide a way of dealing with this problem.)

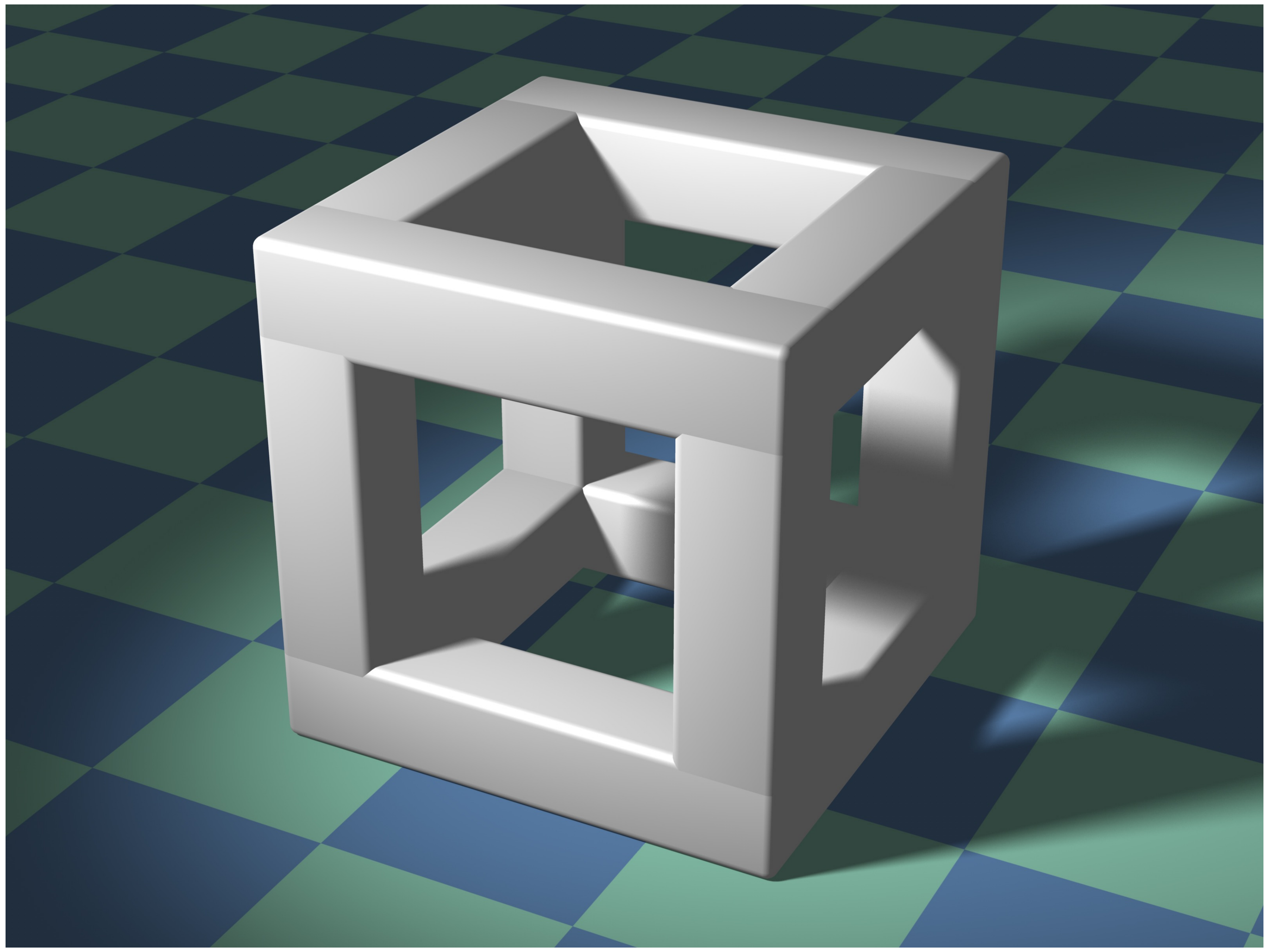
Z-Buffer

This is the hidden-surface-removal algorithm that eventually won.

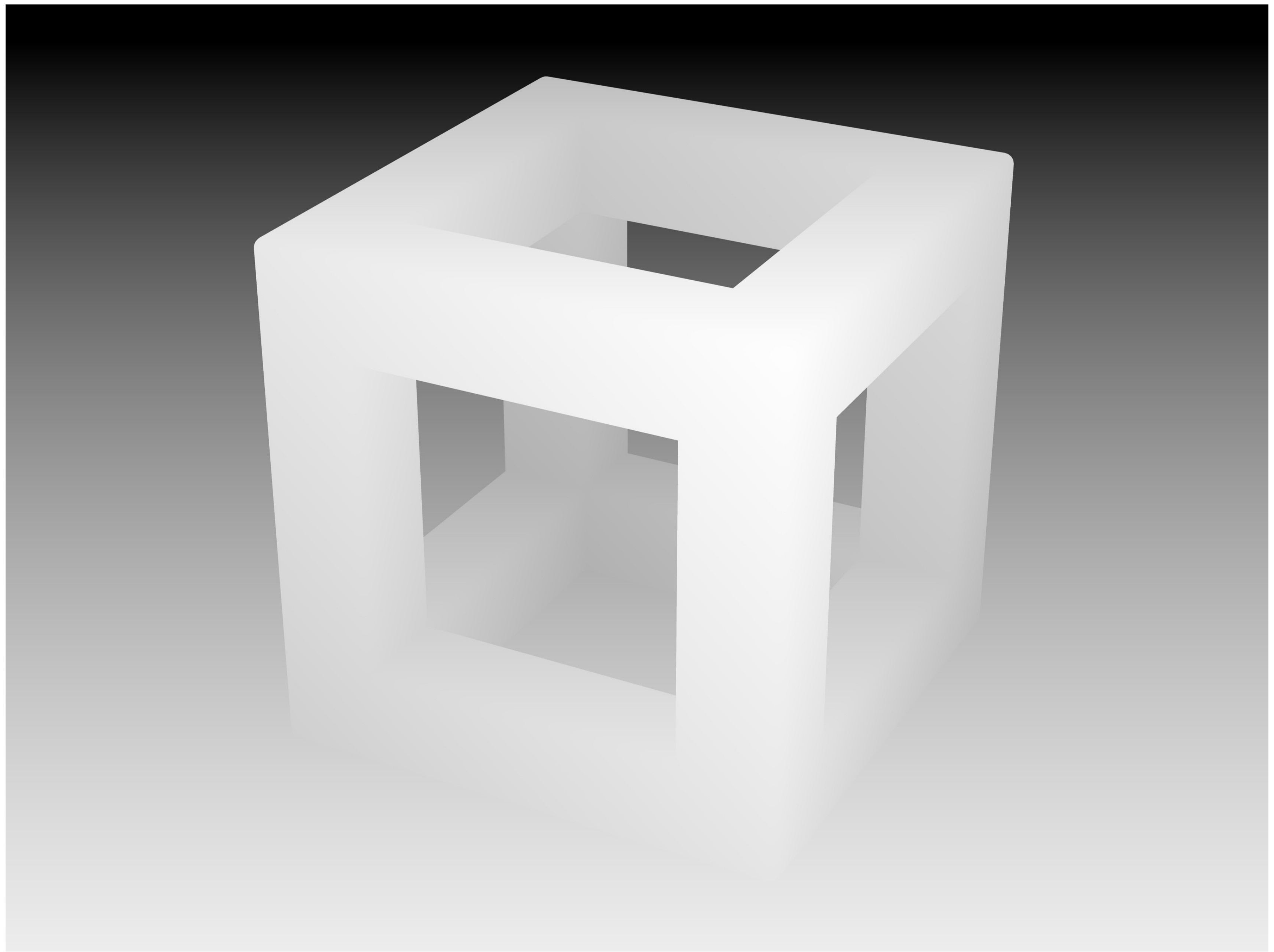
Idea:

- Store current min. z-value for <u>each</u> sample position
- Needs an additional buffer for depth values
  - framebuffer stores RBG color values
  - depth buffer (z-buffer) stores depth (16 to 32 bits)

Z-Buffer Example



Rendering



Depth buffer

Image credit: Dominic Alves, flickr.

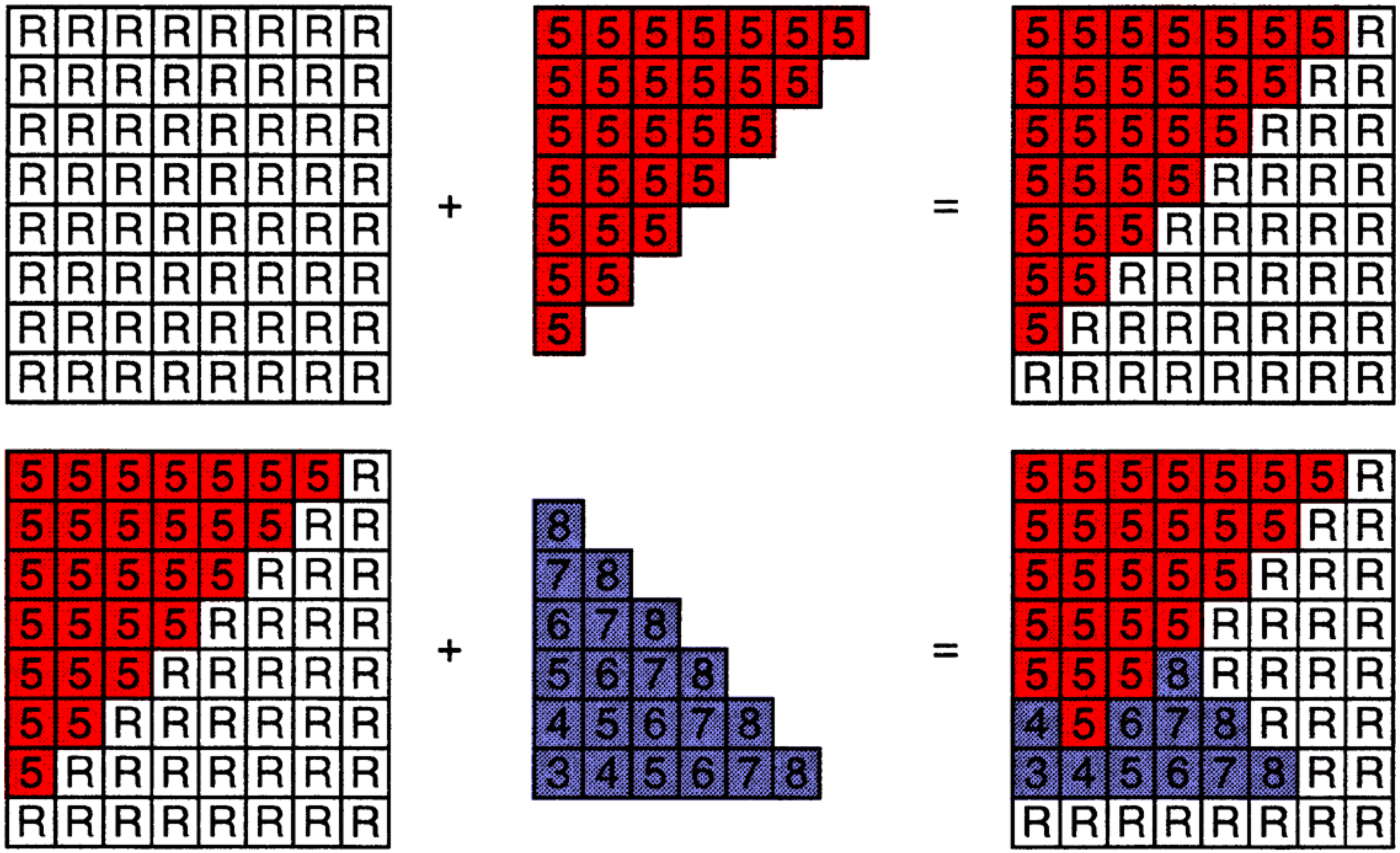
Z-Buffer Algorithm

Initialize depth buffer to ∞

During rasterization:

```
for (each triangle T)
  for (each sample (x,y,z) in T)
    if (z < zbuffer[x,y])        // closest sample so far
      framebuffer[x,y] = rgb;    // update color
      zbuffer[x,y]     = z;      // update z
    else
      ;    // do nothing, this sample is not closest
```

Z-Buffer Algorithm



R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R

+

5	5	5	5	5	5	5
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5	5	5	5	5	5	5	R
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5	5	5	5	R	R	R	R
5	5	5	R	R	R	R	R
5	5	R	R	R	R	R	R
5	R	R	R	R	R	R	R
R	R	R	R	R	R	R	R

5	5	5	5	5	5	5	R
5	5	5	5	5	5	R	R
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+

8					
7	8				
6	7	8			
5	6	7	8		
4	5	6	7	8	
3	4	5	6	7	8

=

5	5	5	5	5	5	5	R
5	5	5	5	5	5	R	R
5	5	5	5	5	R	R	R
5	5	5	5	R	R	R	R
5	5	5	8	R	R	R	R
4	5	6	7	8	R	R	R
3	4	5	6	7	8	R	R
R	R	R	R	R	R	R	R

(Pretend these numbers are negative, i.e. distance from near plane.)

Z-Buffer Complexity

Complexity

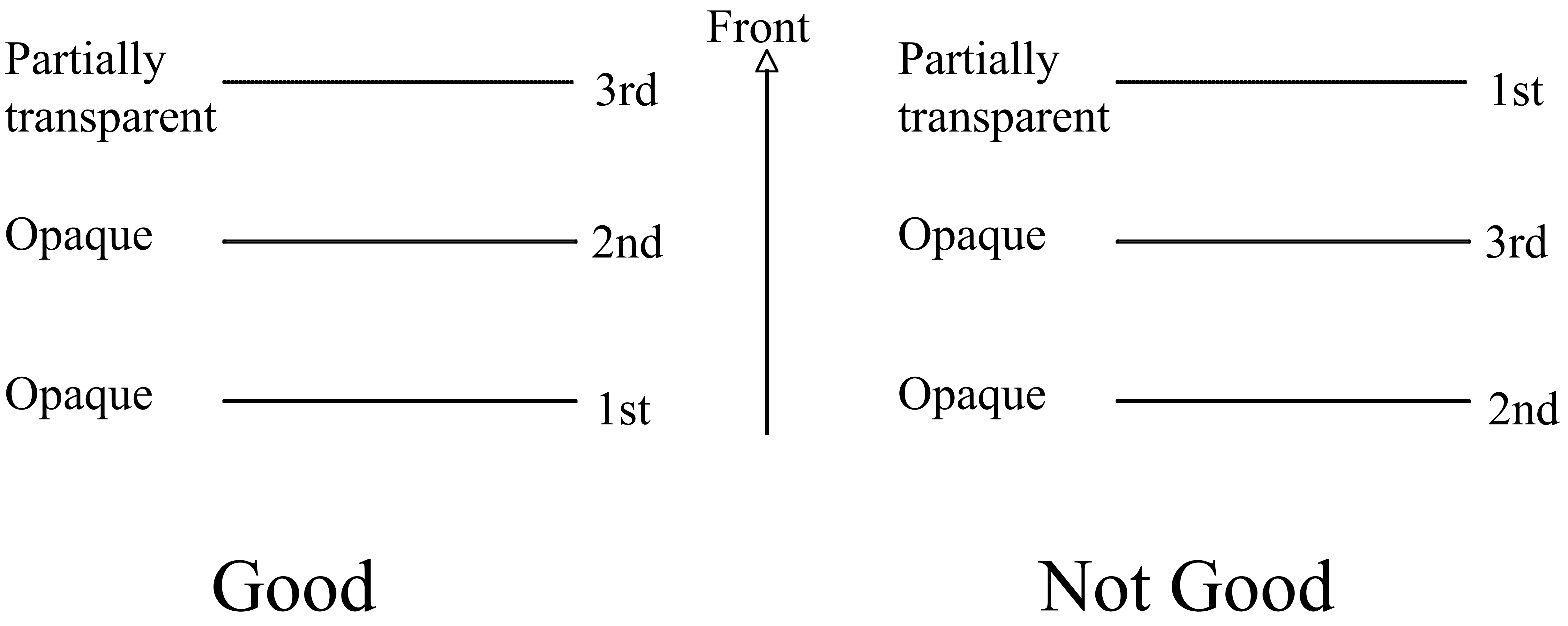
- O(*n*) for *n* triangles
- How can we sort *n* triangles in linear time?

Most important visibility algorithm

- Implemented in hardware for all GPUs
- Used by OpenGL

Z-Buffer and Transparency

Transparency requires partial sorting

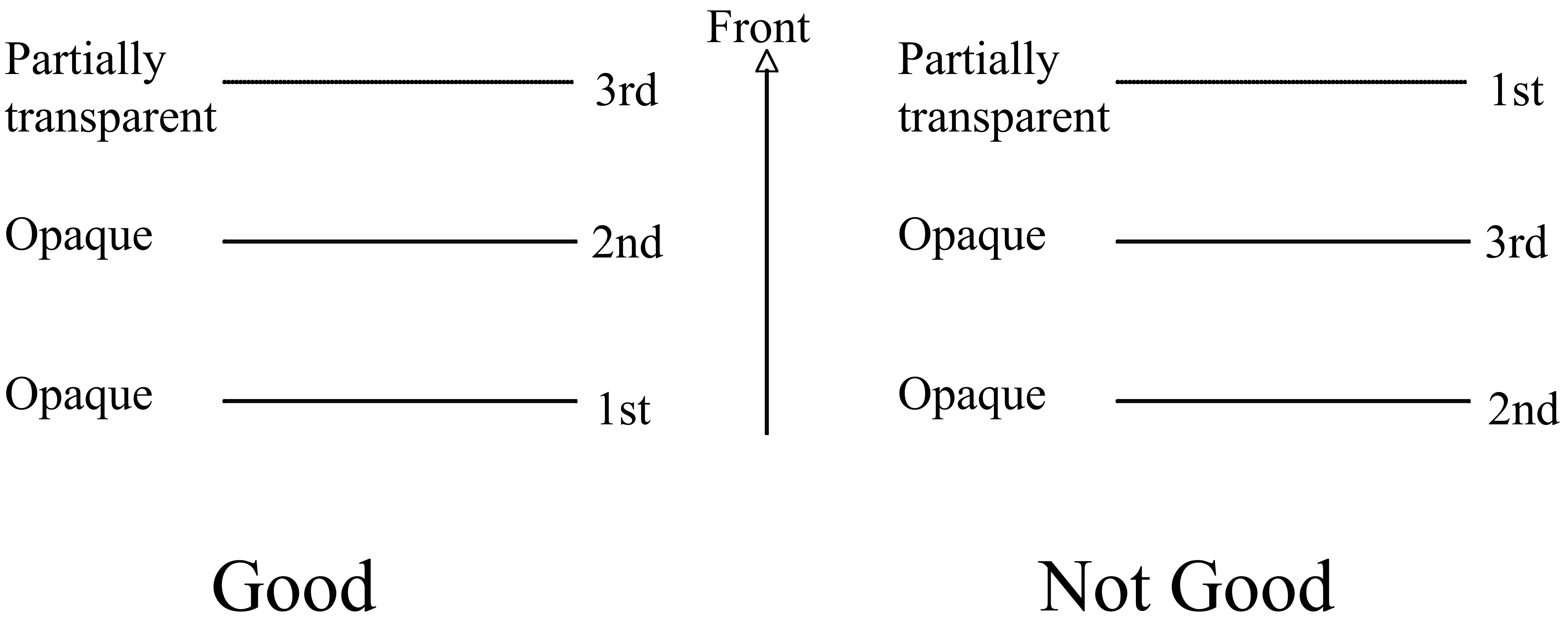


Common solution:

- Draw opaque polygons first
- Then draw transparent polygons (Ideally in sorted order)

Z-Buffer and Transparency

Transparency requires partial sorting



Another solution:

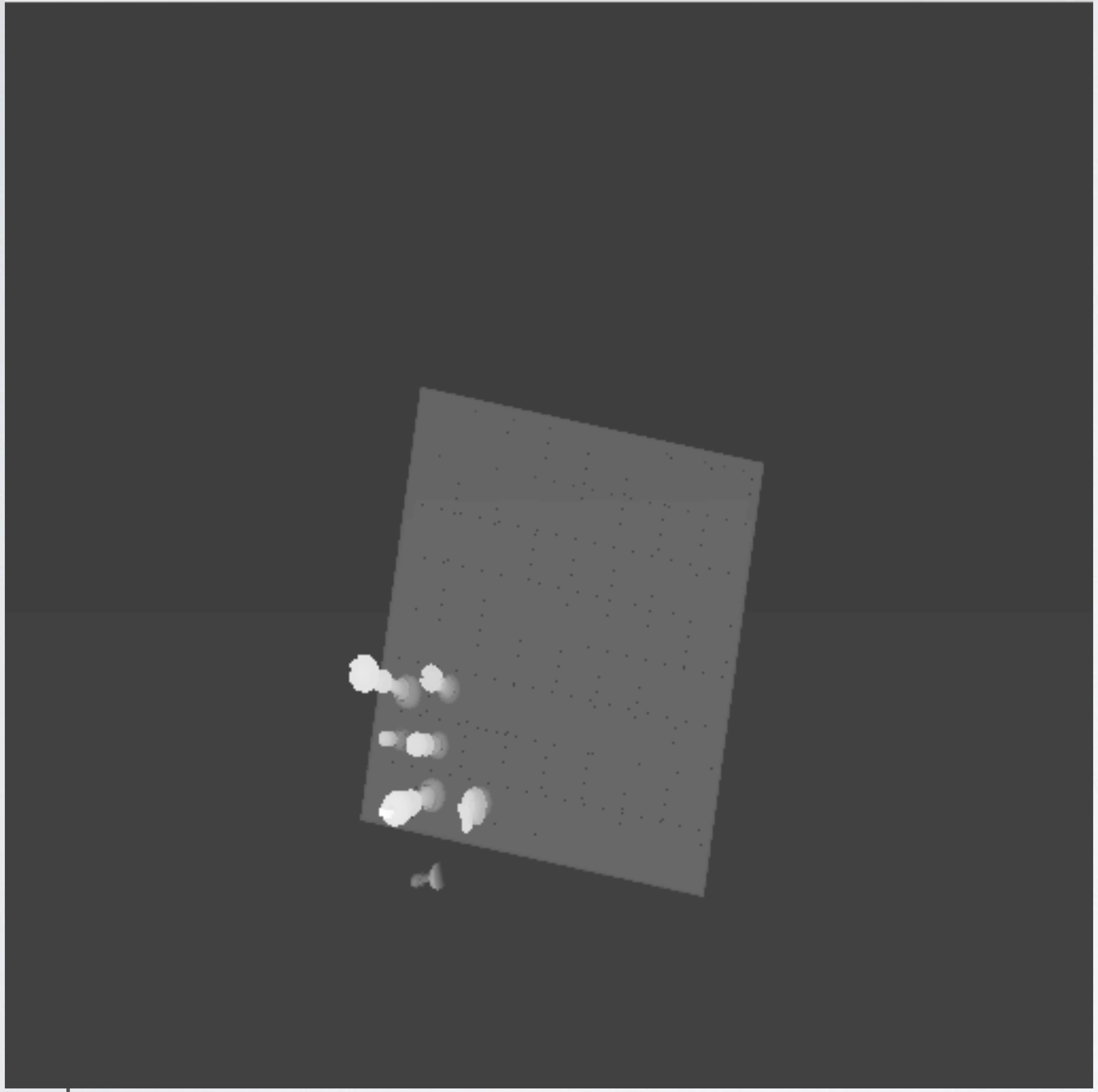
- Linked list of RGB-Z-α at each pixel (Alpha Buffer)

Shadow Maps

- Pre-render scene from perspective of light source
  - Only render Z-Buffer (the shadow buffer)
- Render scene from camera perspective
  - Compare with shadow buffer
  - If nearer light, if further shadow

Ren Ng, James O'Brien

Shadow Maps



Shadow Buffer

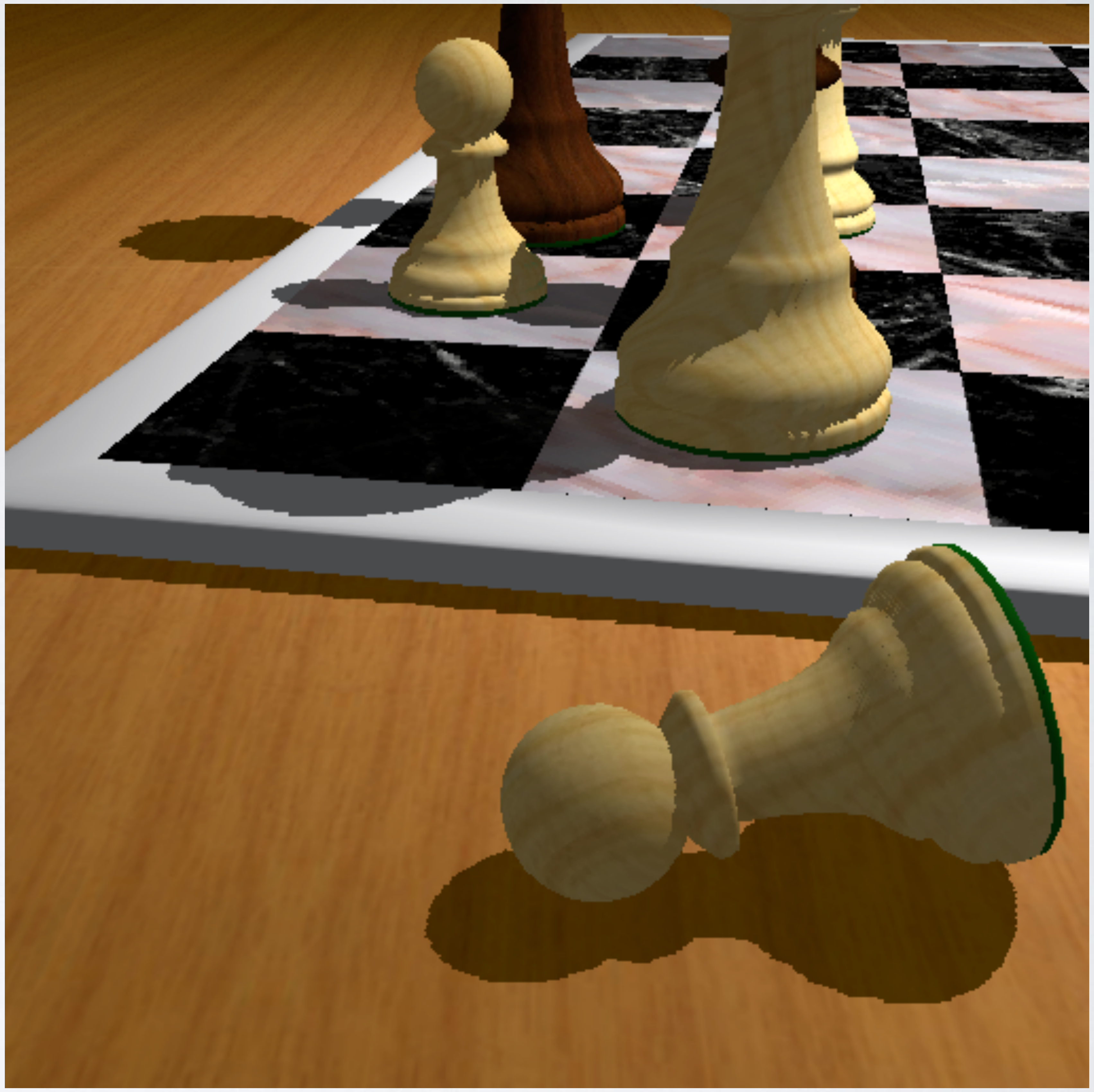


Image w/ Shadows

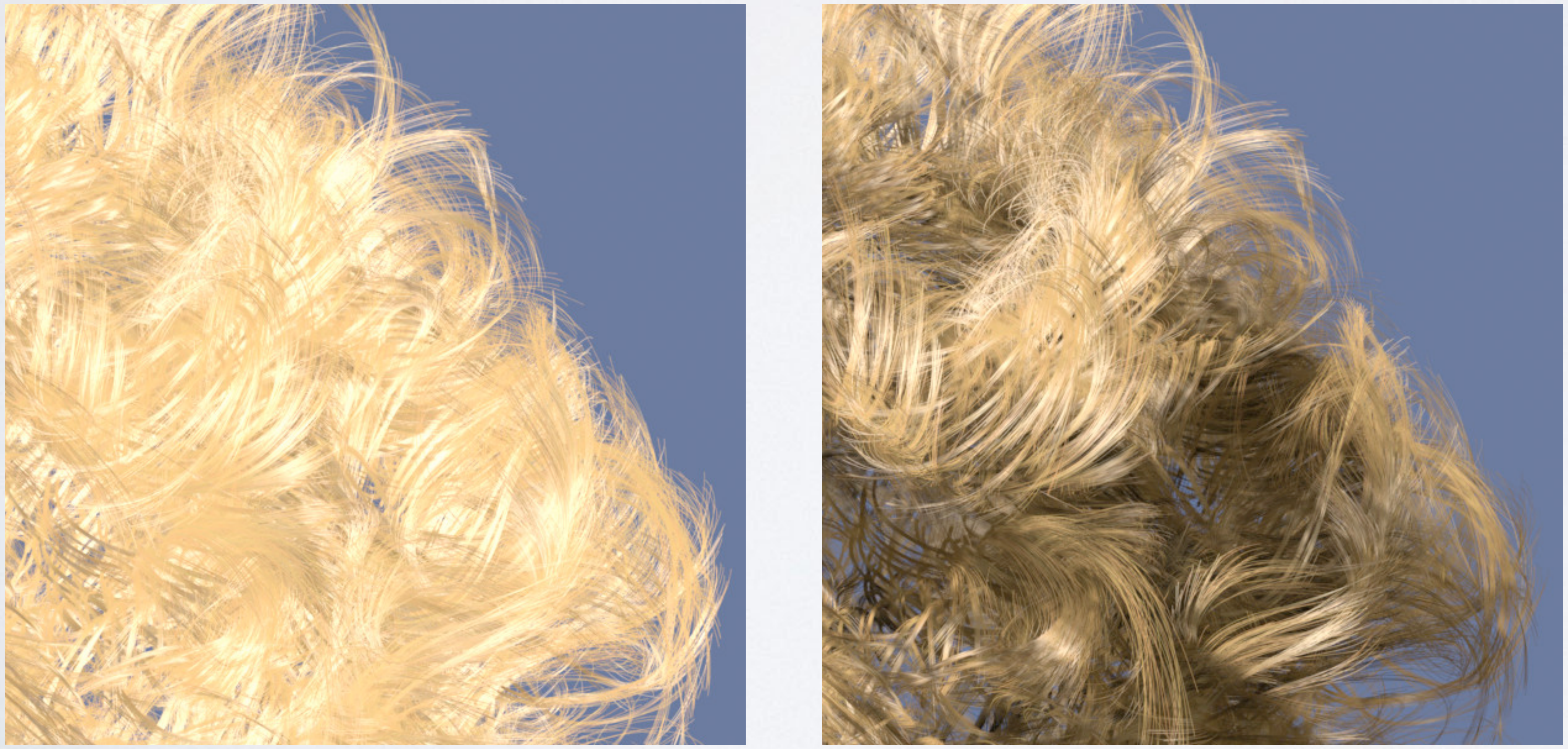
From Stamminger and Drettakis
SIGGRAPH 2002

Note: These images don't really go together, see the paper...

Ren Ng, James O'Brien

Deep Shadow Maps

- Some objects only partially occlude light
  - A single shadow value will not work
  - Similar to transparency in Z-Buffer



From
Lokovic and Veach
SIGGRAPH 2000

Ren Ng, James O’Brien

Simple Shading
(Blinn-Phong Reflection Model)

Simple Shading vs Realistic Lighting & Materials

What we will cover today

- A local shading model: simple, per-pixel, fast
- Based on perceptual observations, not physics

What we will cover later in the course

- Physics-based lighting and material representations
- Global light transport simulation

Perceptual Observations

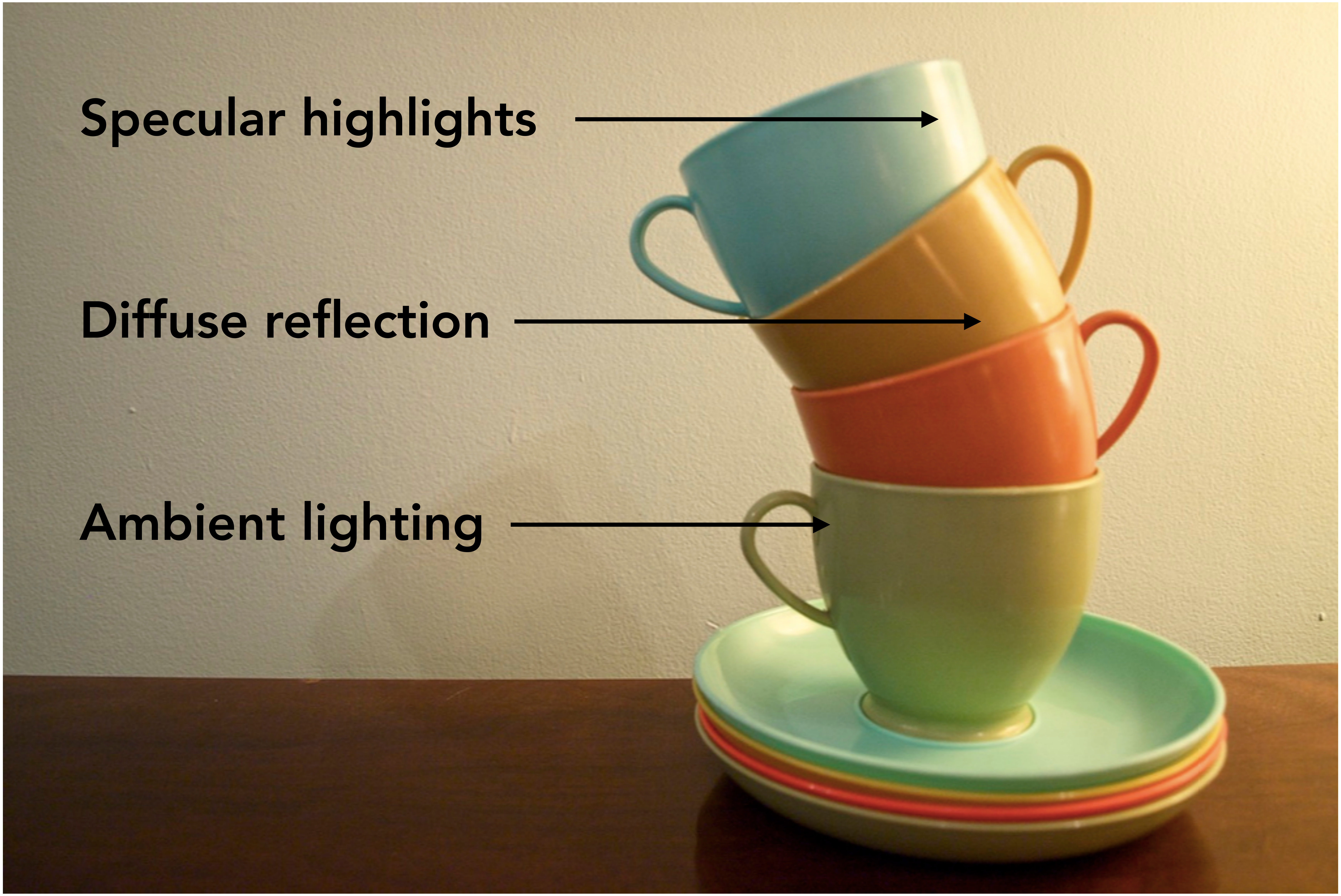


Photo credit: Jessica Andrews, flickr

Local Shading

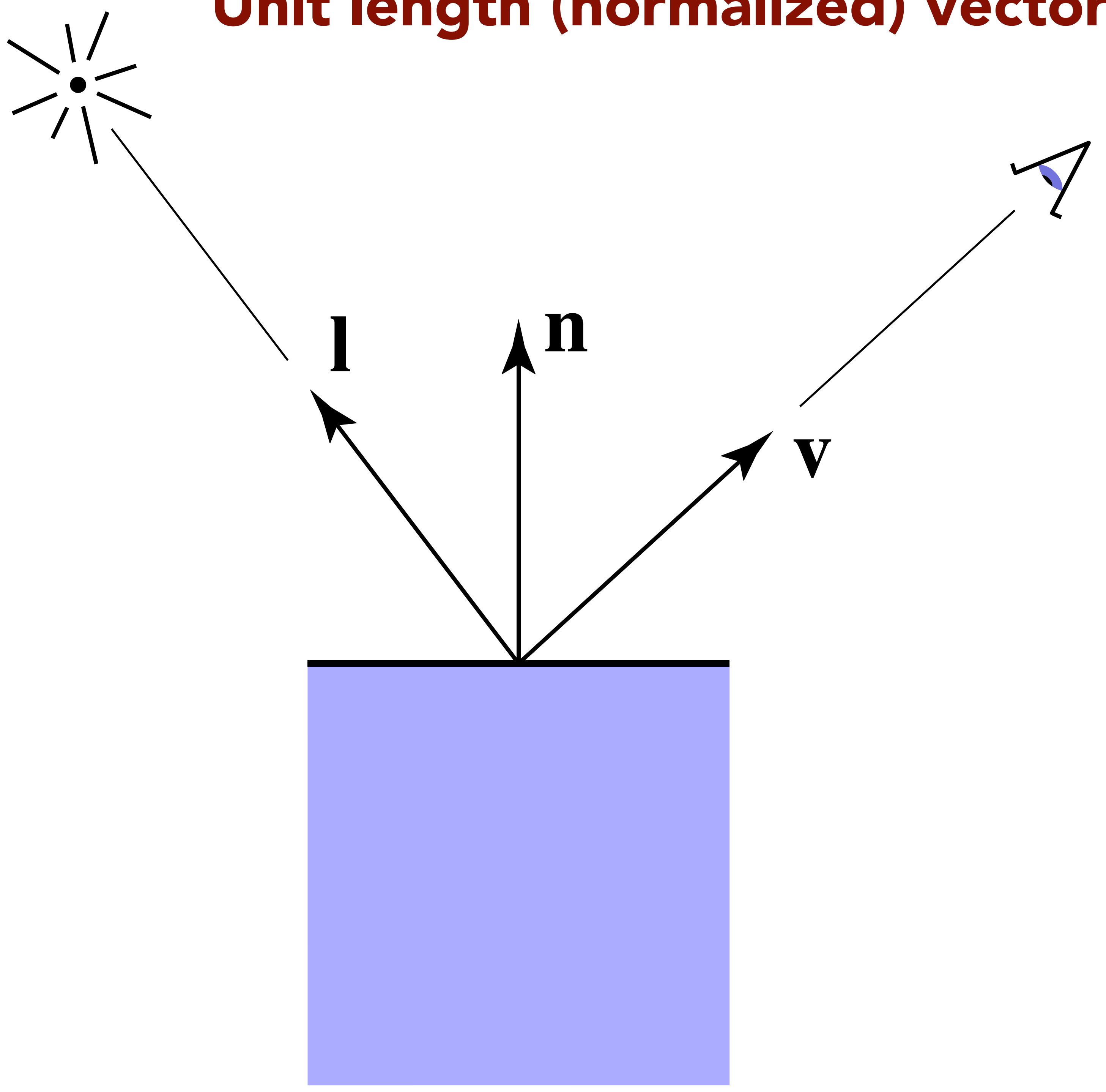
Compute light reflected toward camera

Inputs:

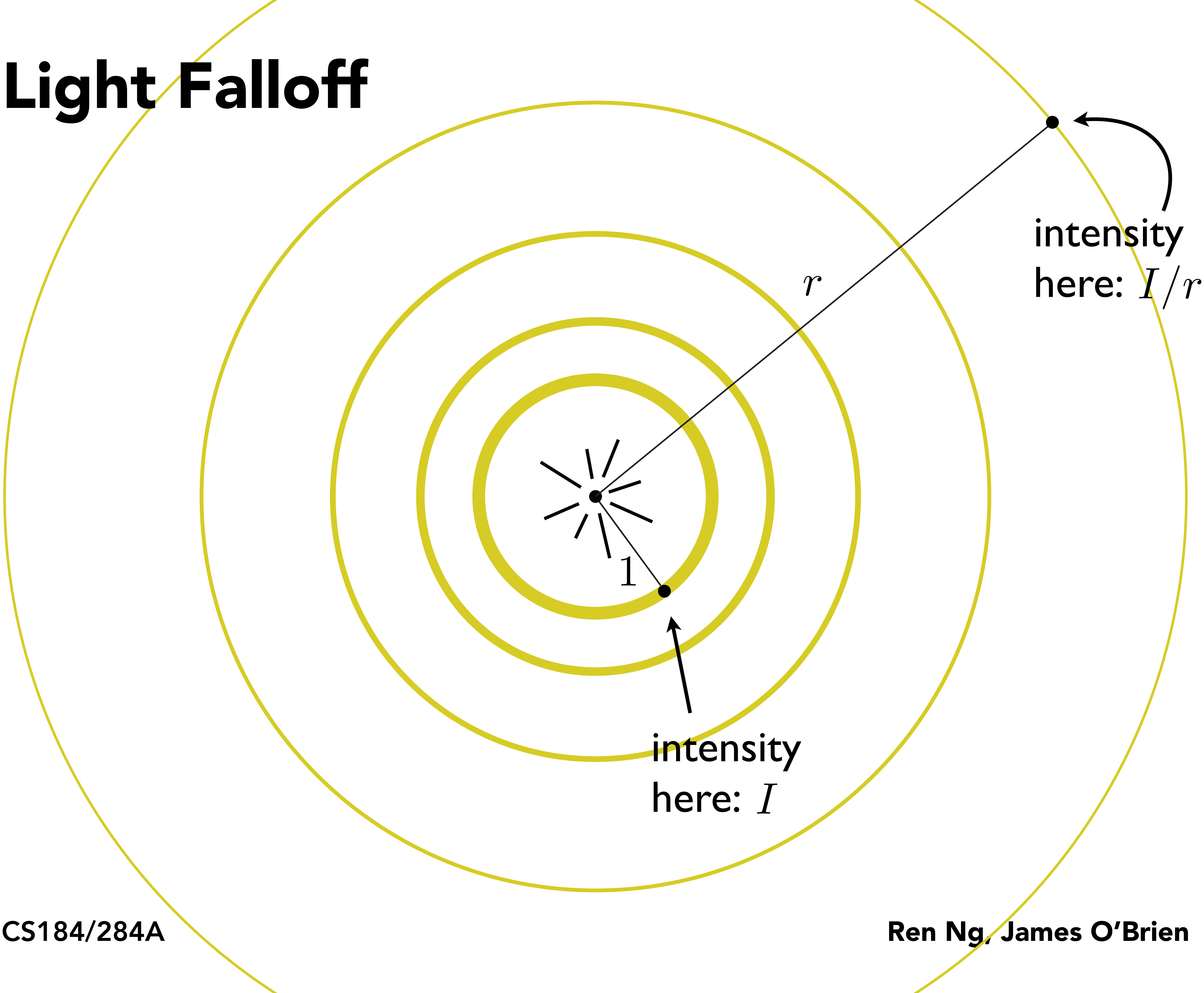
- Viewer direction, v
- Surface normal, n
- Light direction, l
  (for each of many lights)
- Surface parameters
  (color, shininess, …)

No “global” effects.

Unit length (normalized) vectors!!!



Light Falloff



intensity here: I/r^2

intensity here: I

Falloff

Physically correct: $1/r^2$ light intensify falloff

- Tends to look bad with local shading (why?)

Sometimes compromise of $1/r$ used.

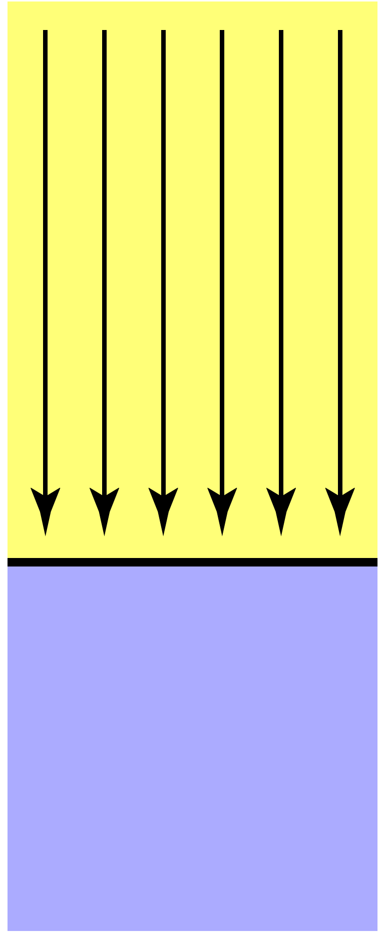
Very important to use $1/r^2$ for correct global illumination methods.

Diffuse Reflection

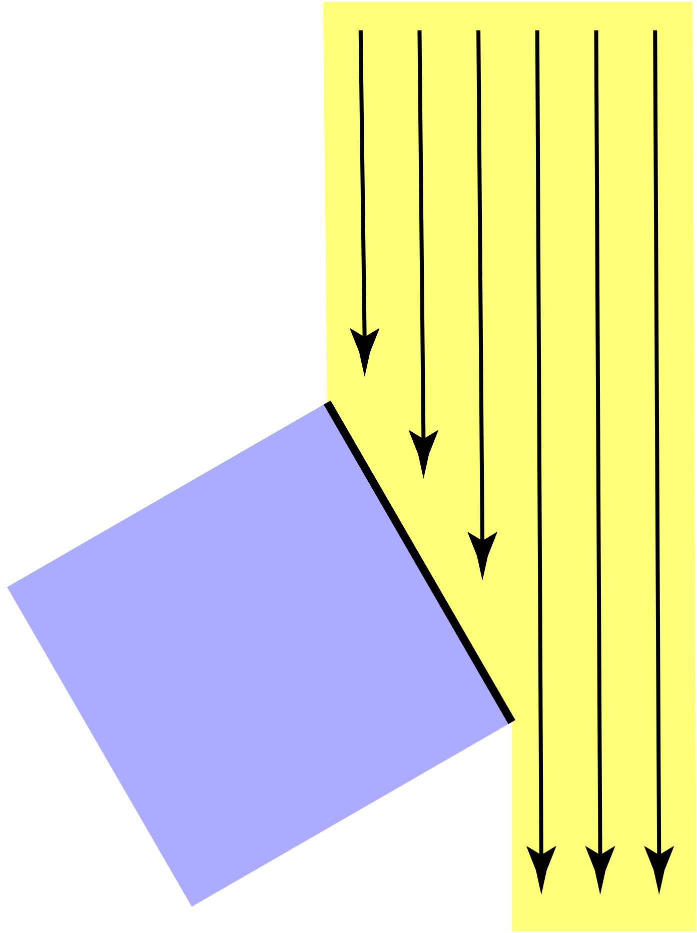
Light is scattered uniformly in all directions

- Surface color is the same for all viewing directions

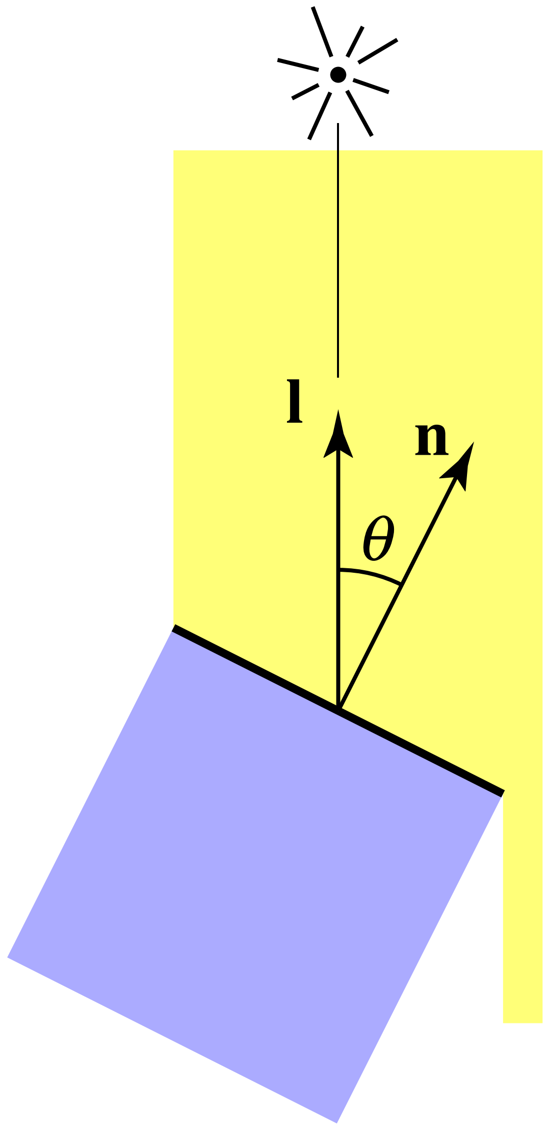
Lambert's cosine law



Top face of cube receives a certain amount of light



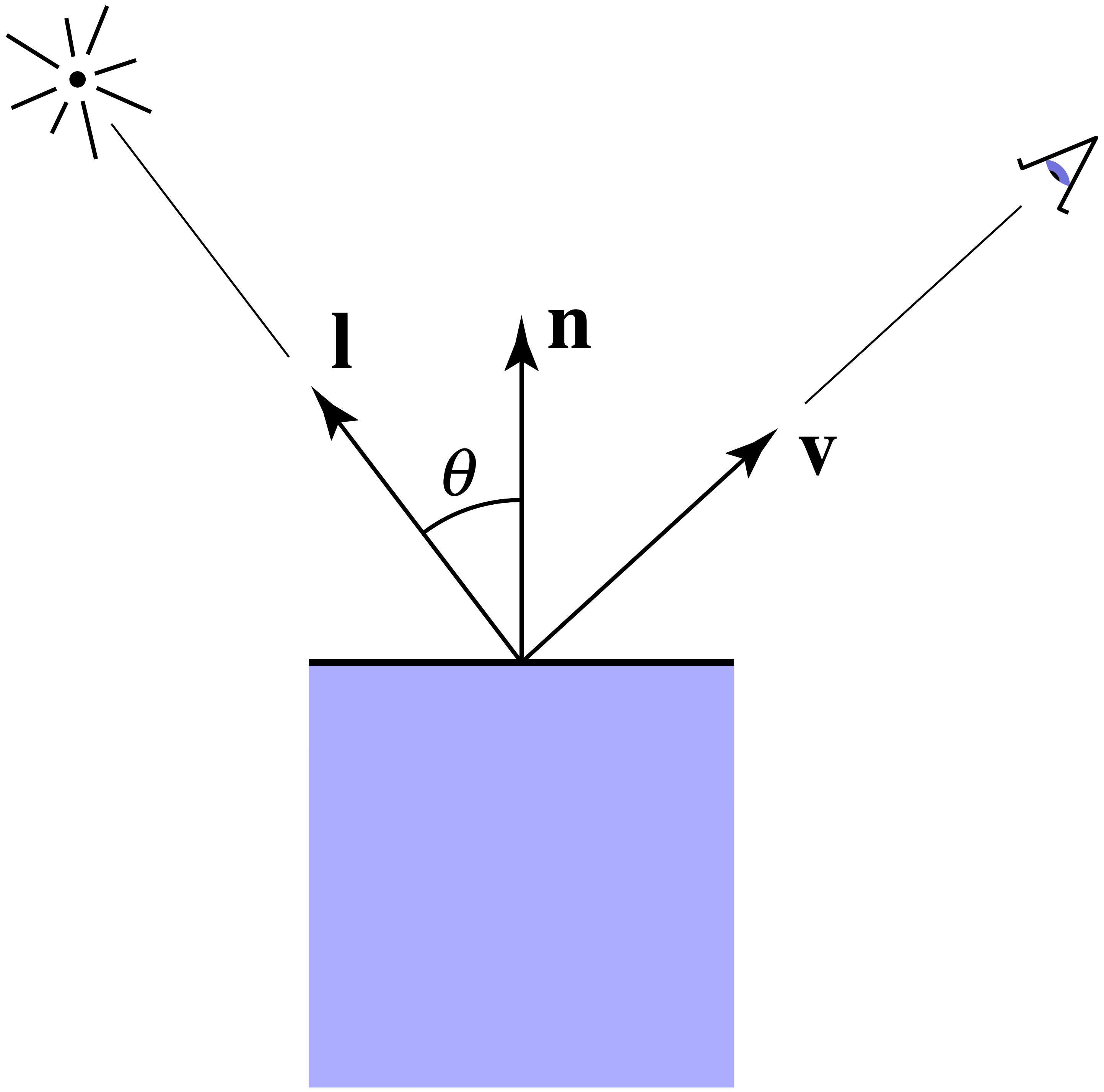
Top face of 60° rotated cube intercepts half the light



In general, light per unit area is proportional to cos θ = **l • n**

Lambertian (Diffuse) Shading

Shading independent of view direction



illumination
from source

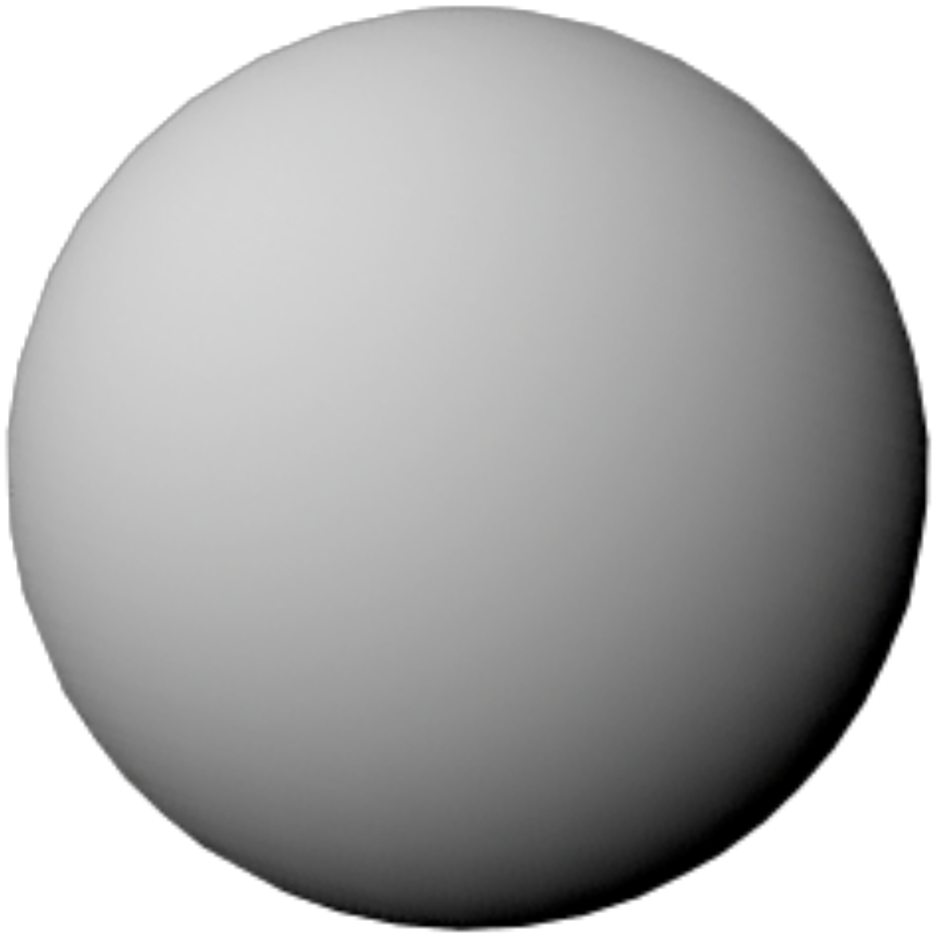
$$L_d = k_d\,(I/r^2)\,\max(0, \mathbf{n}\cdot\mathbf{l})$$

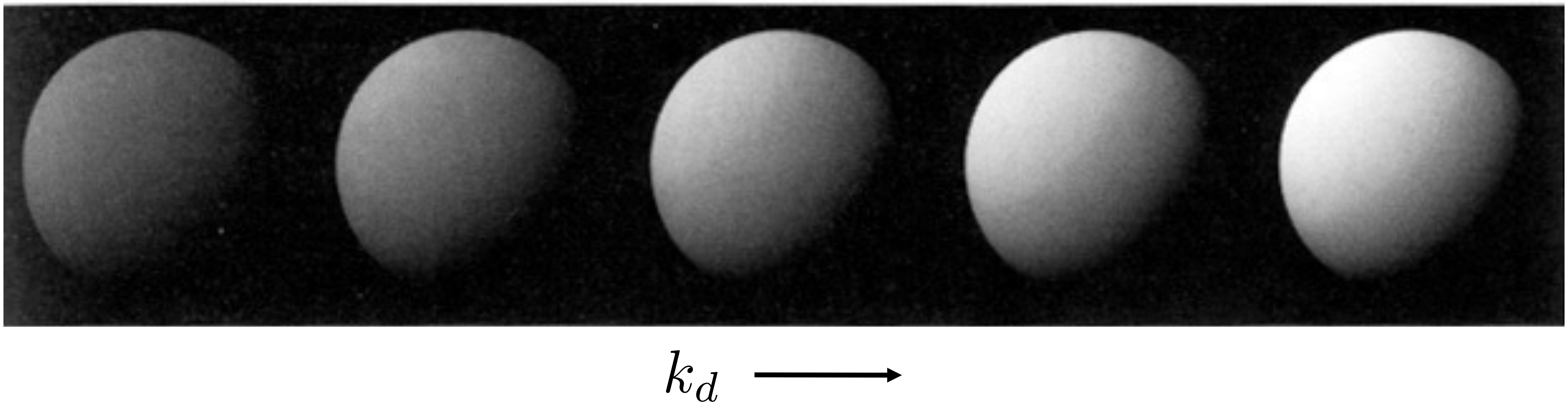
diffuse
coefficient

diffusely
reflected
light

Lambertian (Diffuse) Shading

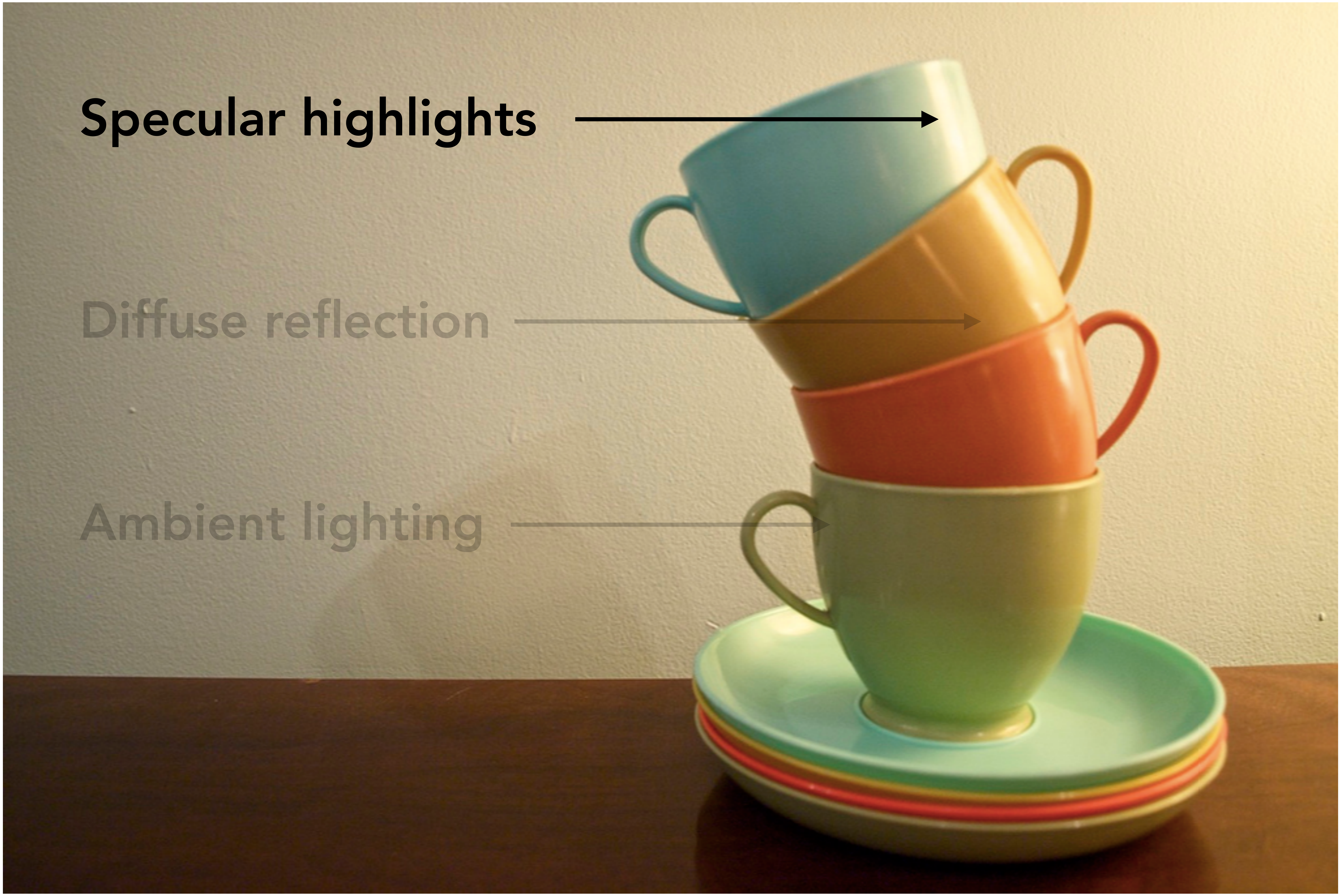
Produces matte appearance





[Foley et al.]

Perceptual Observations



Specular highlights

Diffuse reflection

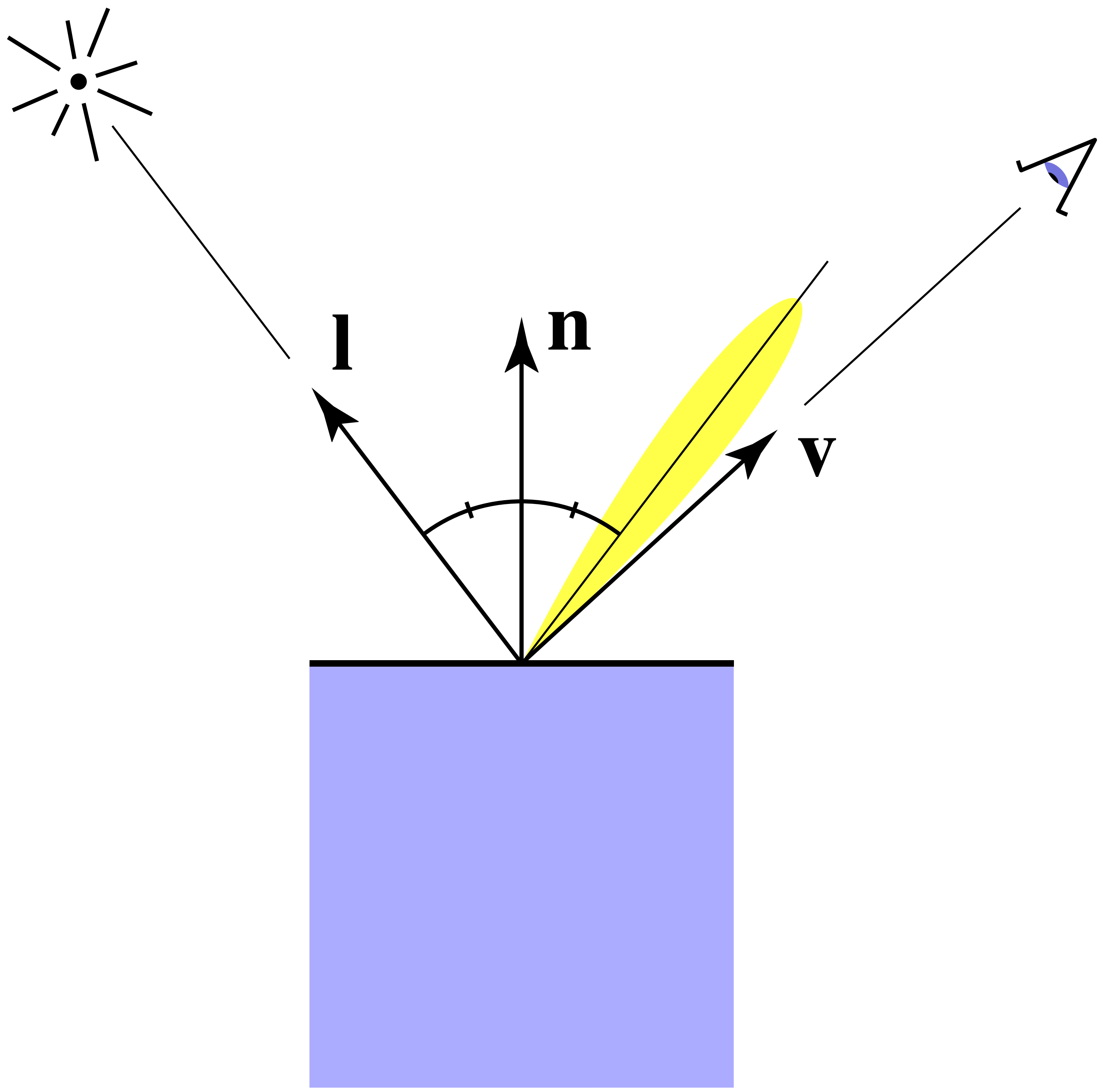
Ambient lighting

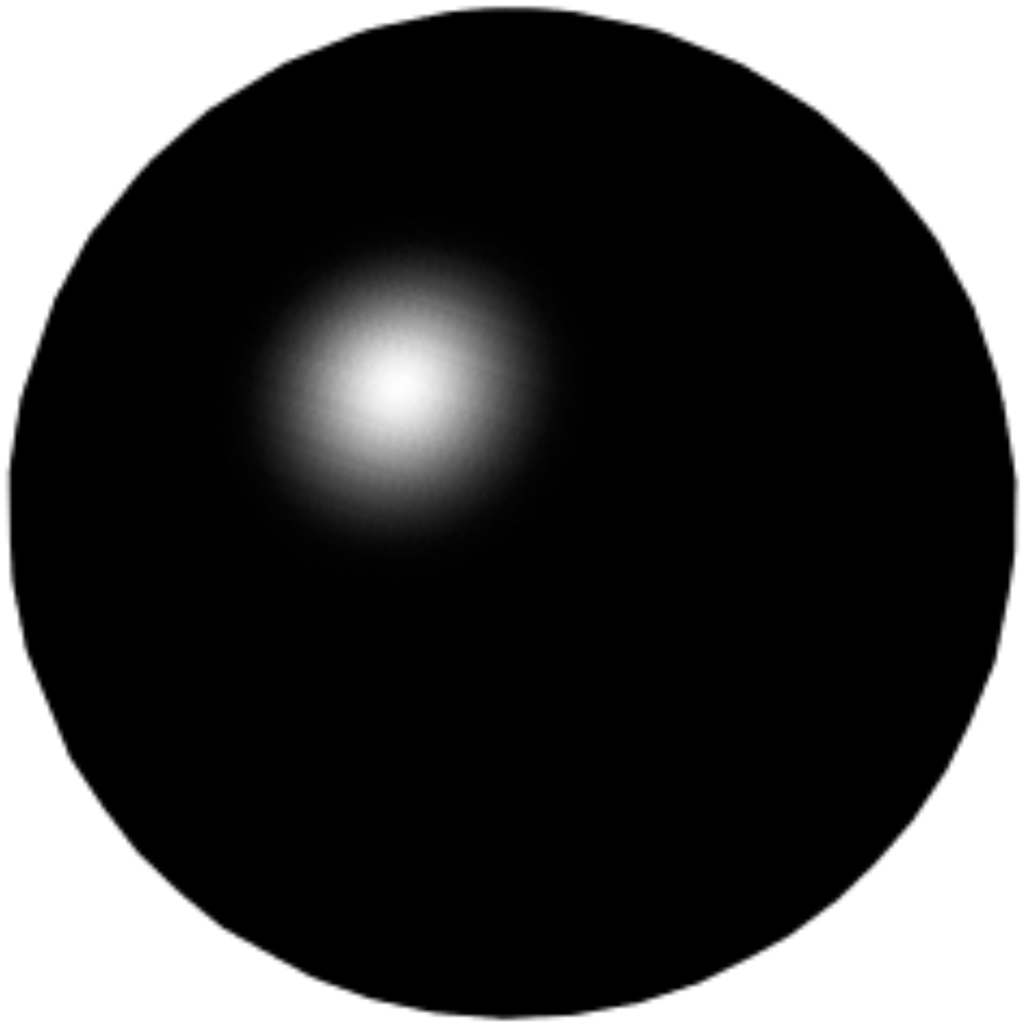
Photo credit: Jessica Andrews, flickr

Specular Shading (Blinn-Phong)

Intensity depends on view direction

- Bright near mirror reflection direction

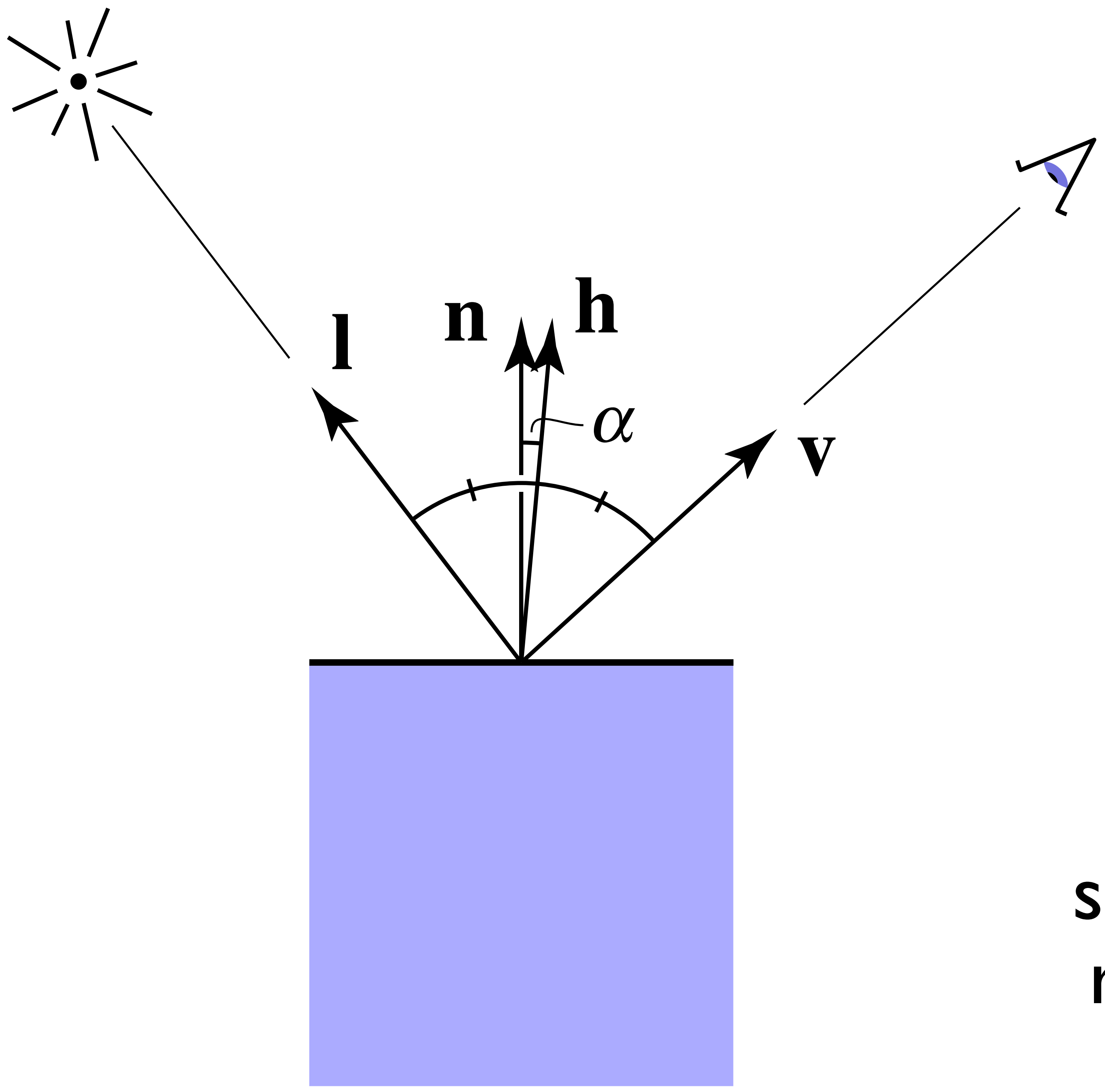




Specular Shading (Blinn-Phong)

Close to mirror direction ⇔ half vector near normal

- Measure "near" by dot product of unit vectors



$$\begin{aligned}\mathbf{h} &= \operatorname{bisector}(\mathbf{v}, \mathbf{l}) \\ &= \frac{\mathbf{v}+\mathbf{l}}{\|\mathbf{v}+\mathbf{l}\|}\end{aligned}$$

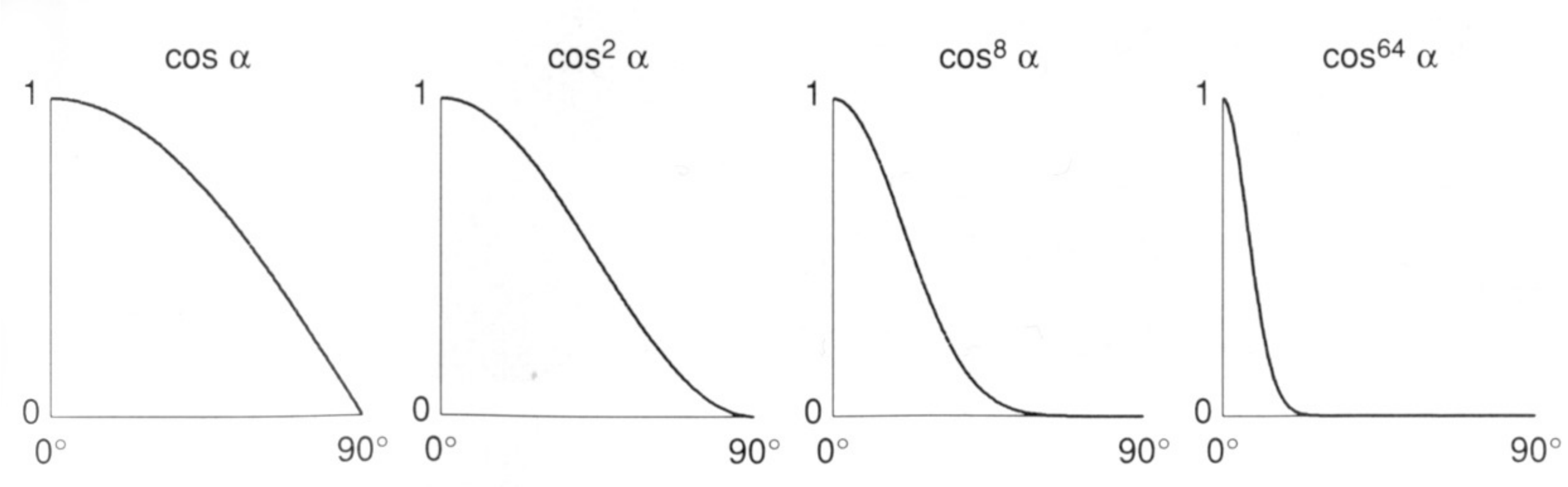
$$\begin{aligned}L_s &= k_s\,(I/r^2)\max(0, \cos\alpha)^p \\ &= k_s\,(I/r^2)\max(0, \mathbf{n}\cdot\mathbf{h})^p\end{aligned}$$

specularly reflected light

specular coefficient

Cosine Power Plots

Increasing p narrows the reflection lobe

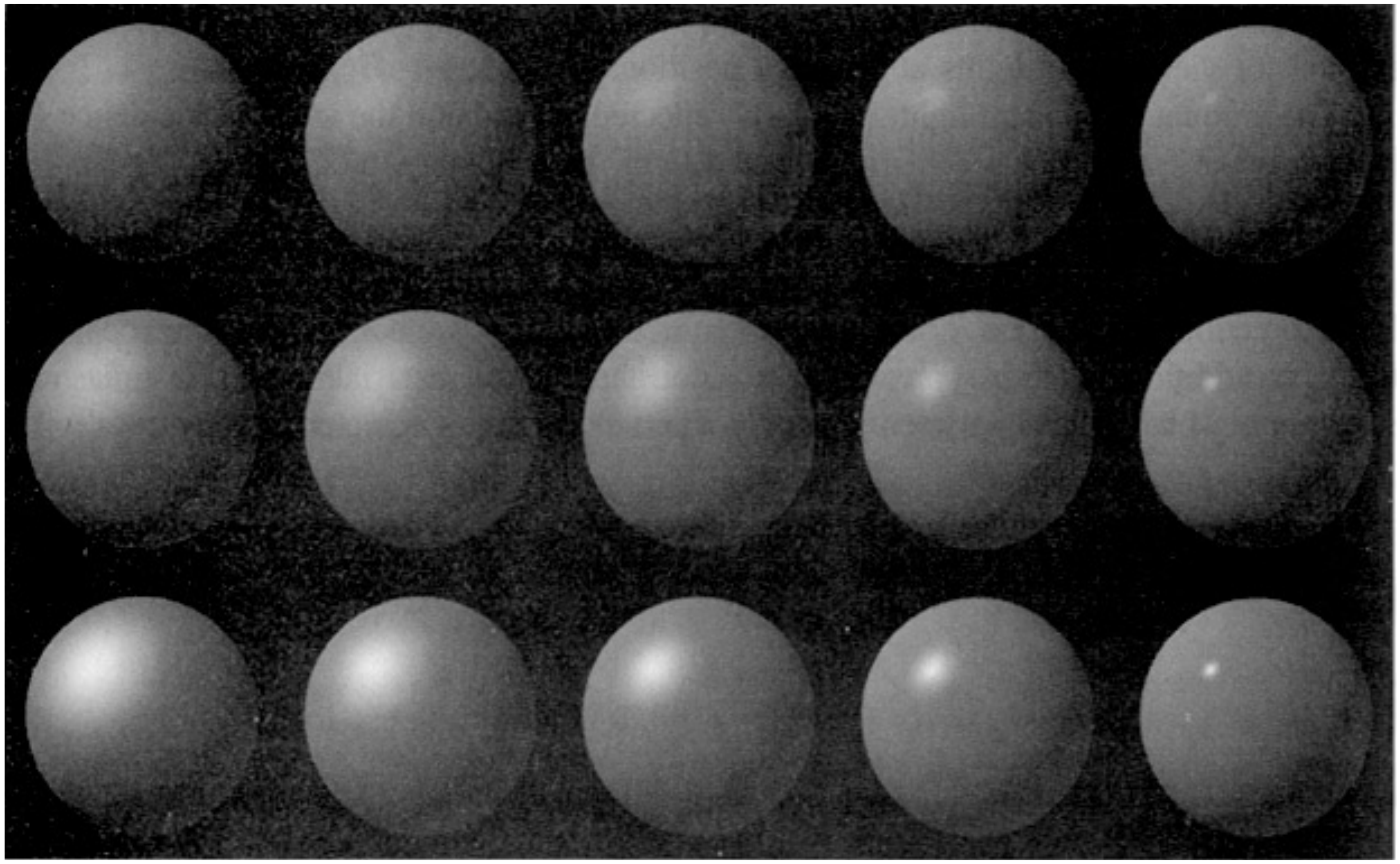


[Foley et al.]

Specular Shading (Blinn-Phong)

$$L_s = k_s\,(I/r^2)\max(0, \mathbf{n}\cdot\mathbf{h})^p$$

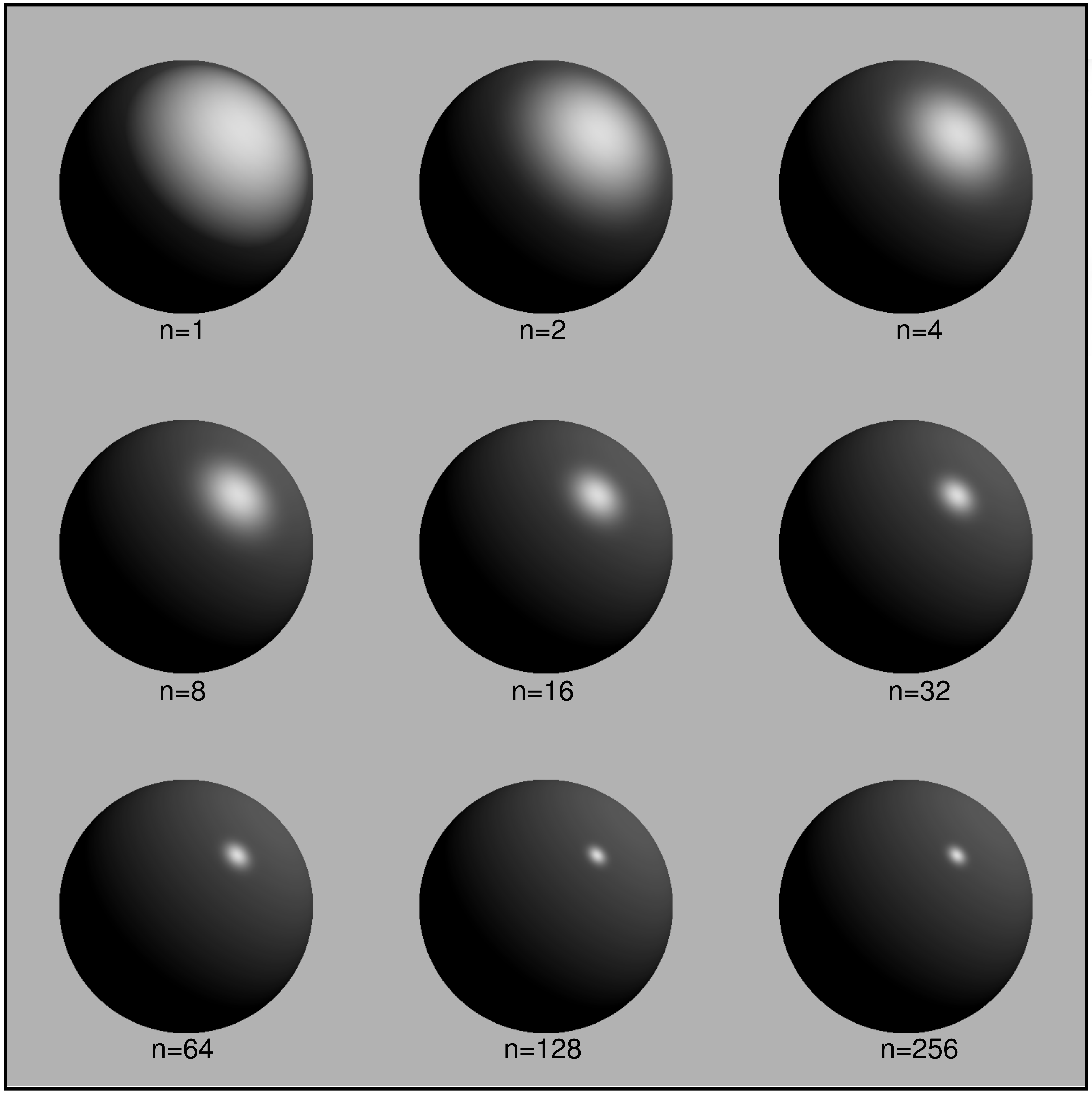
k_s ↓

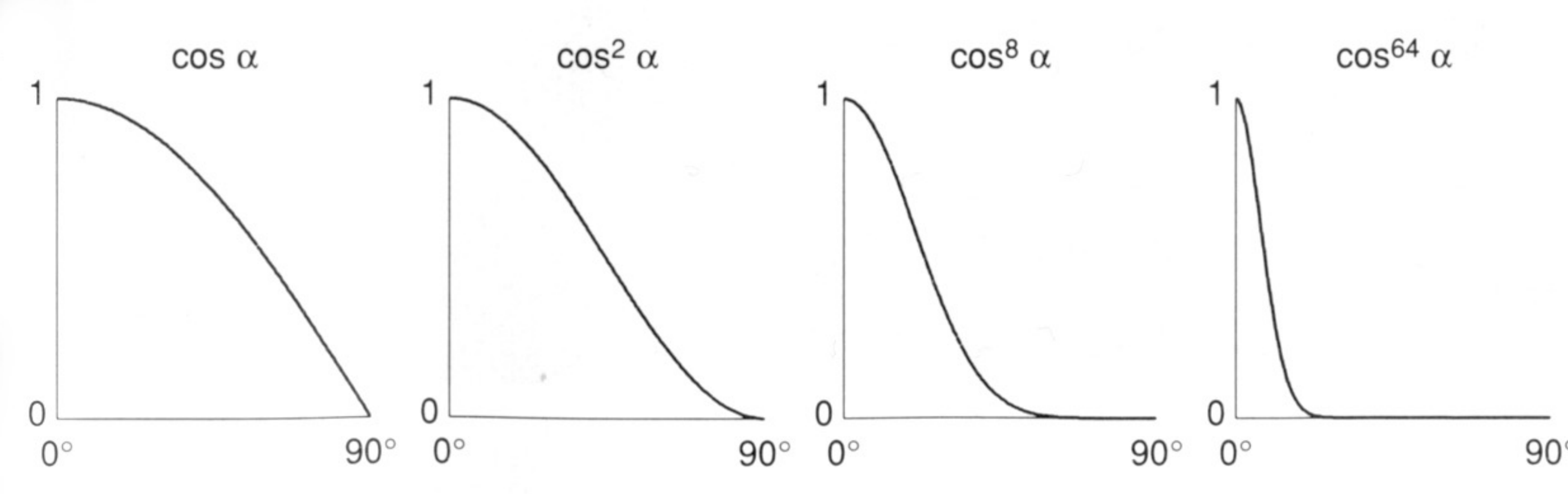


p →

[Foley et al.]

Specular Shading (Blinn-Phong)



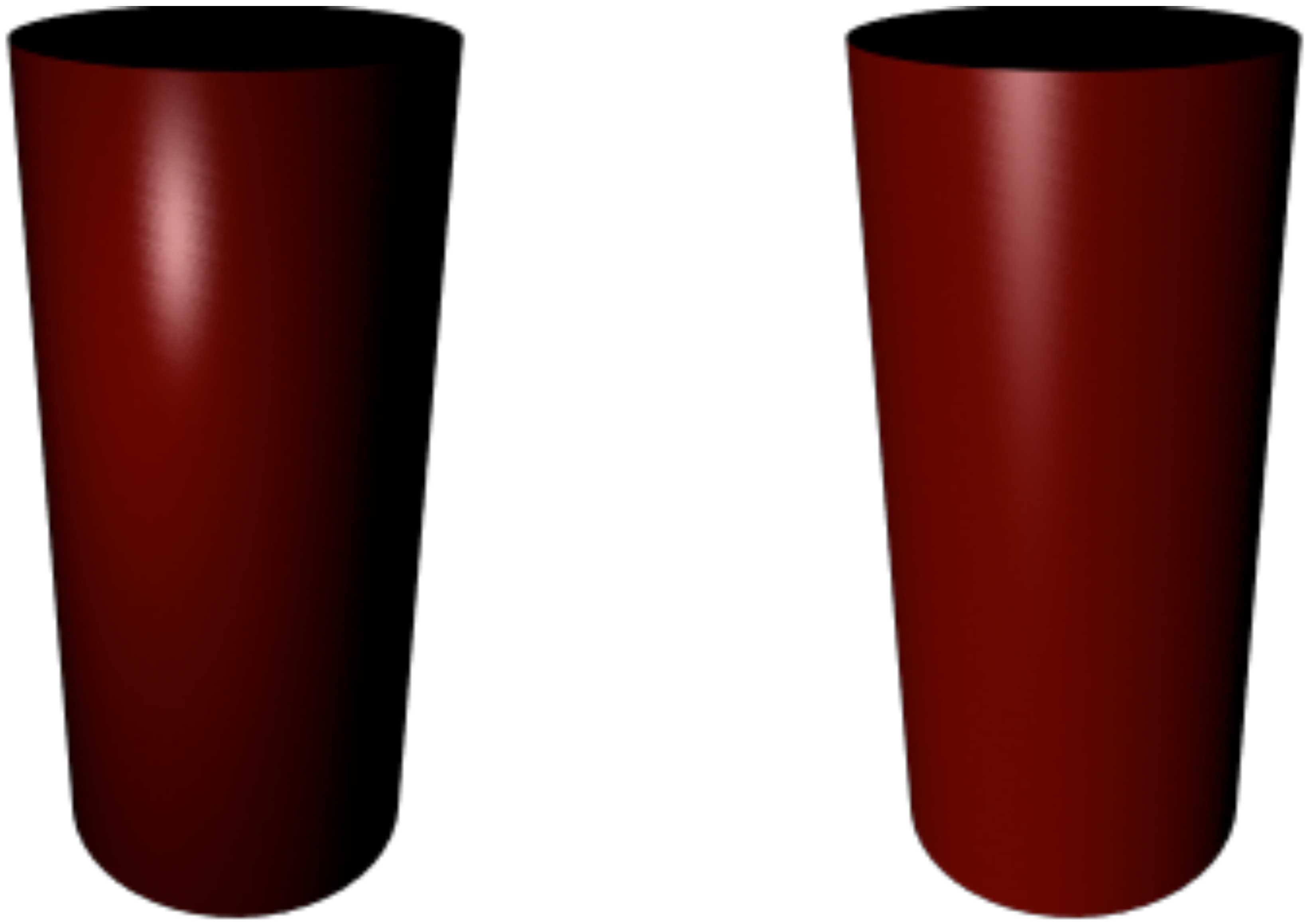


Direction -vs- Point Lights

For a point light, the light direction changes over the surface.

For “distant” light, the direction is constant

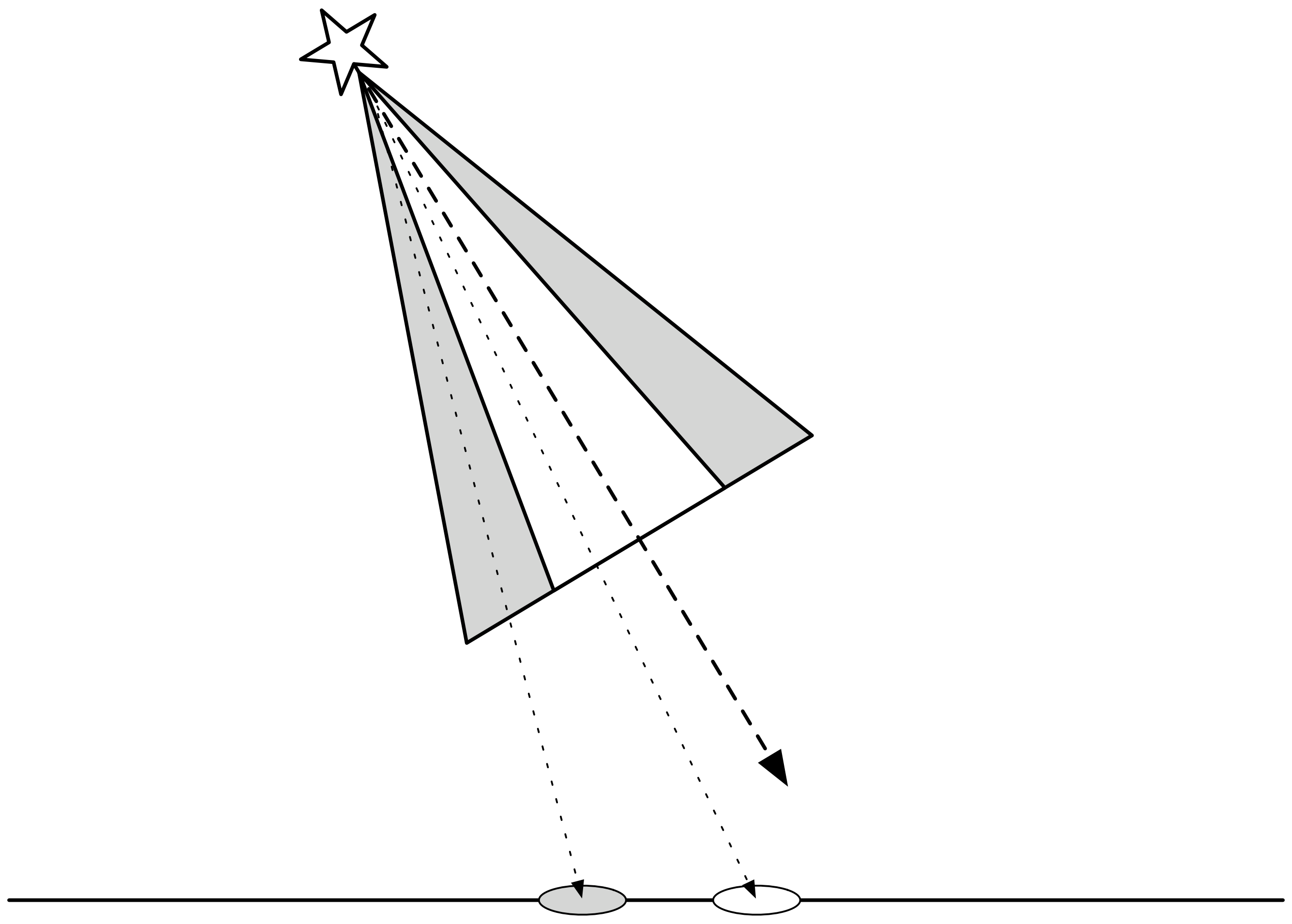
Similar for orthographic/perspective viewer

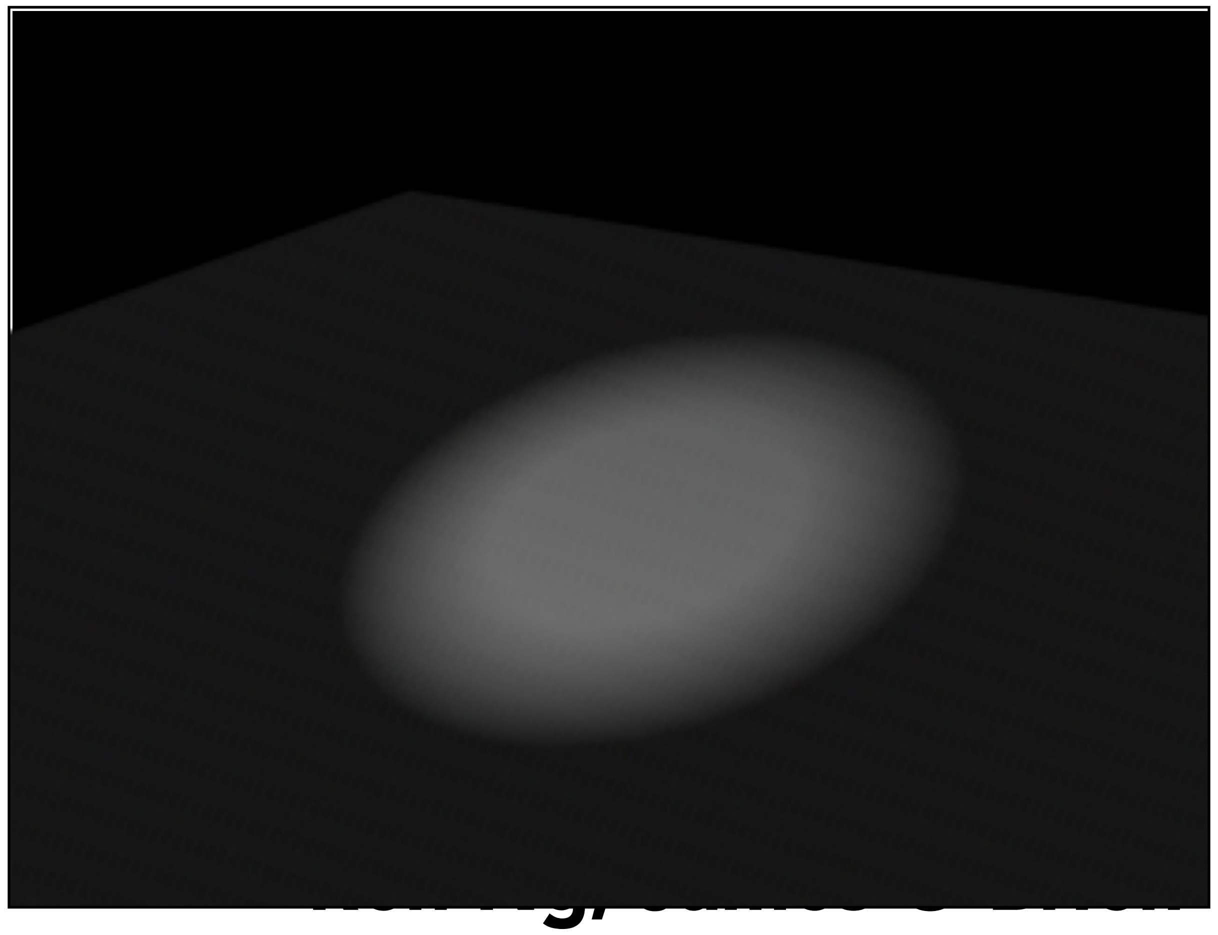


Spot and Other Lights

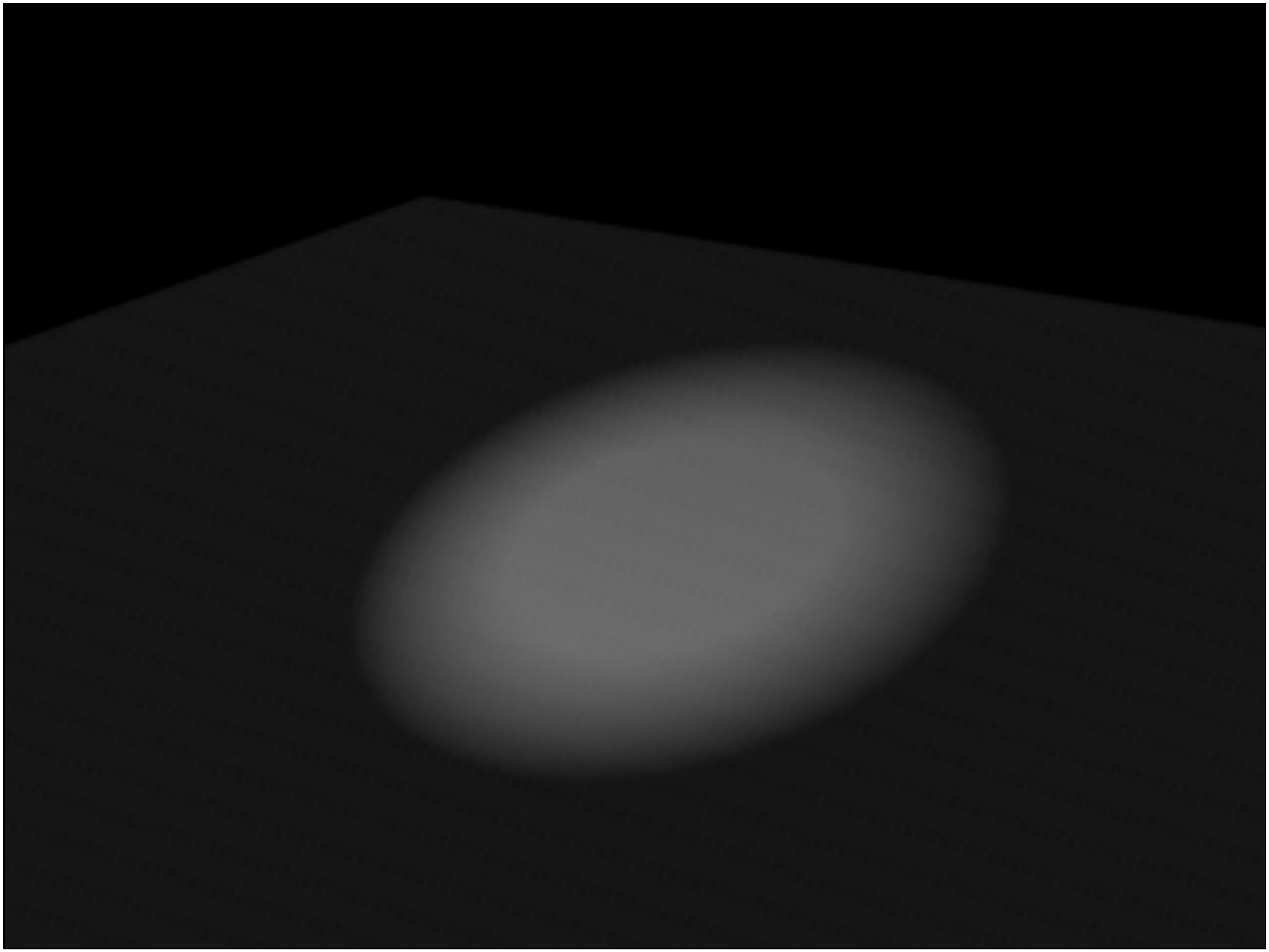
Other calculations for useful effects

- Spot light
- Only light certain objects
- Negative lights
- *etc.*

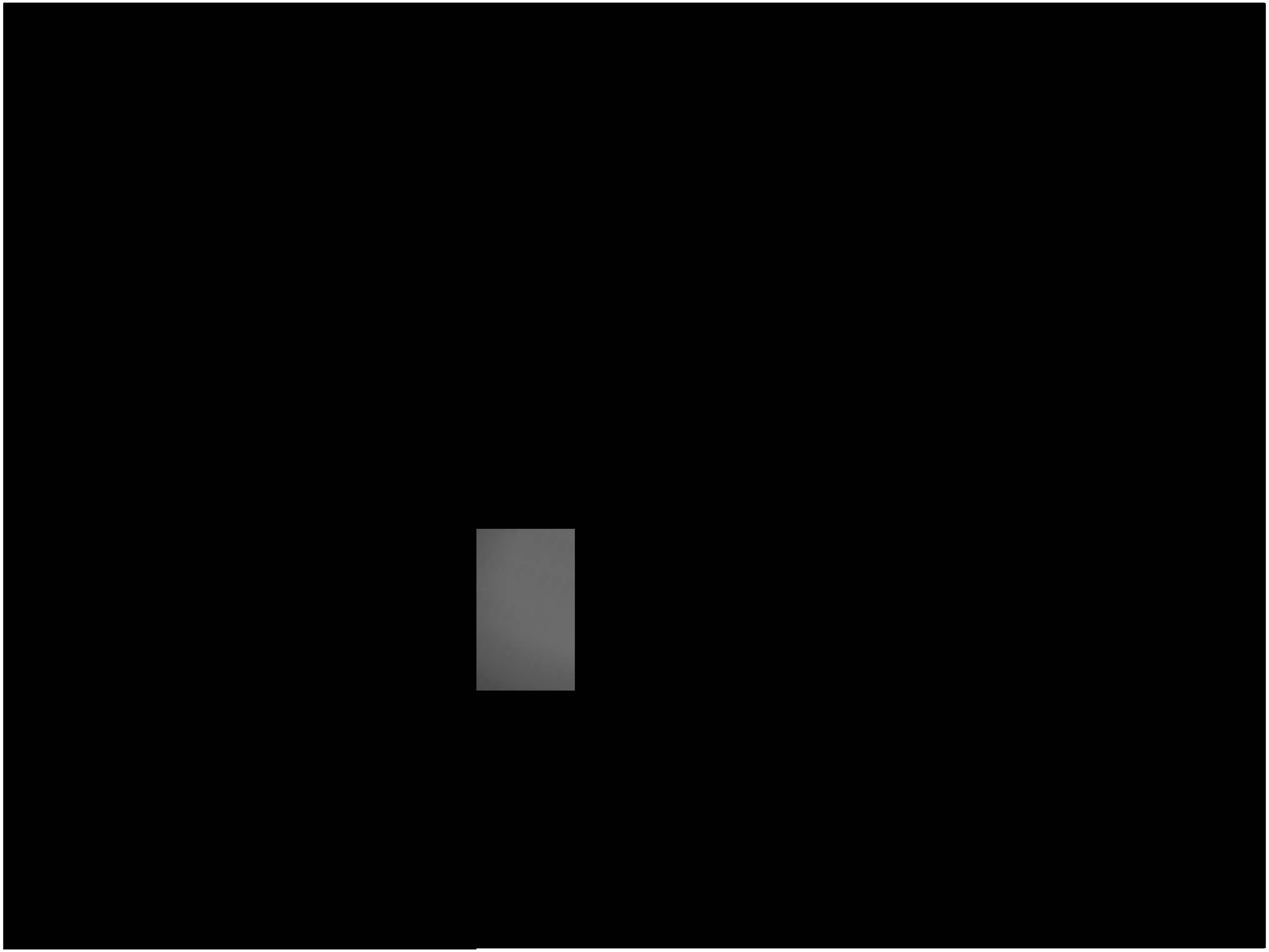




Ugly....



Ugly....



Perceptual Observations

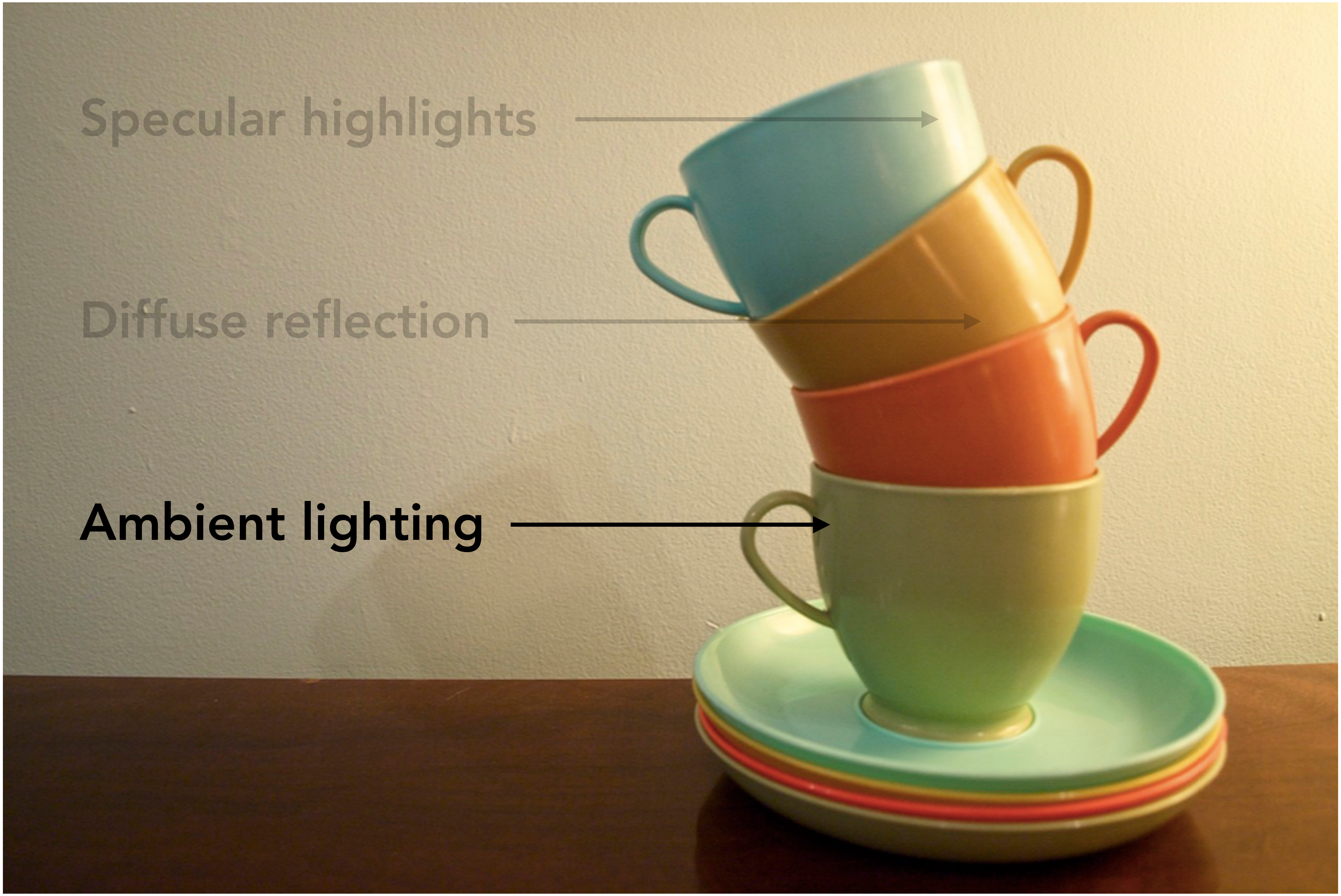
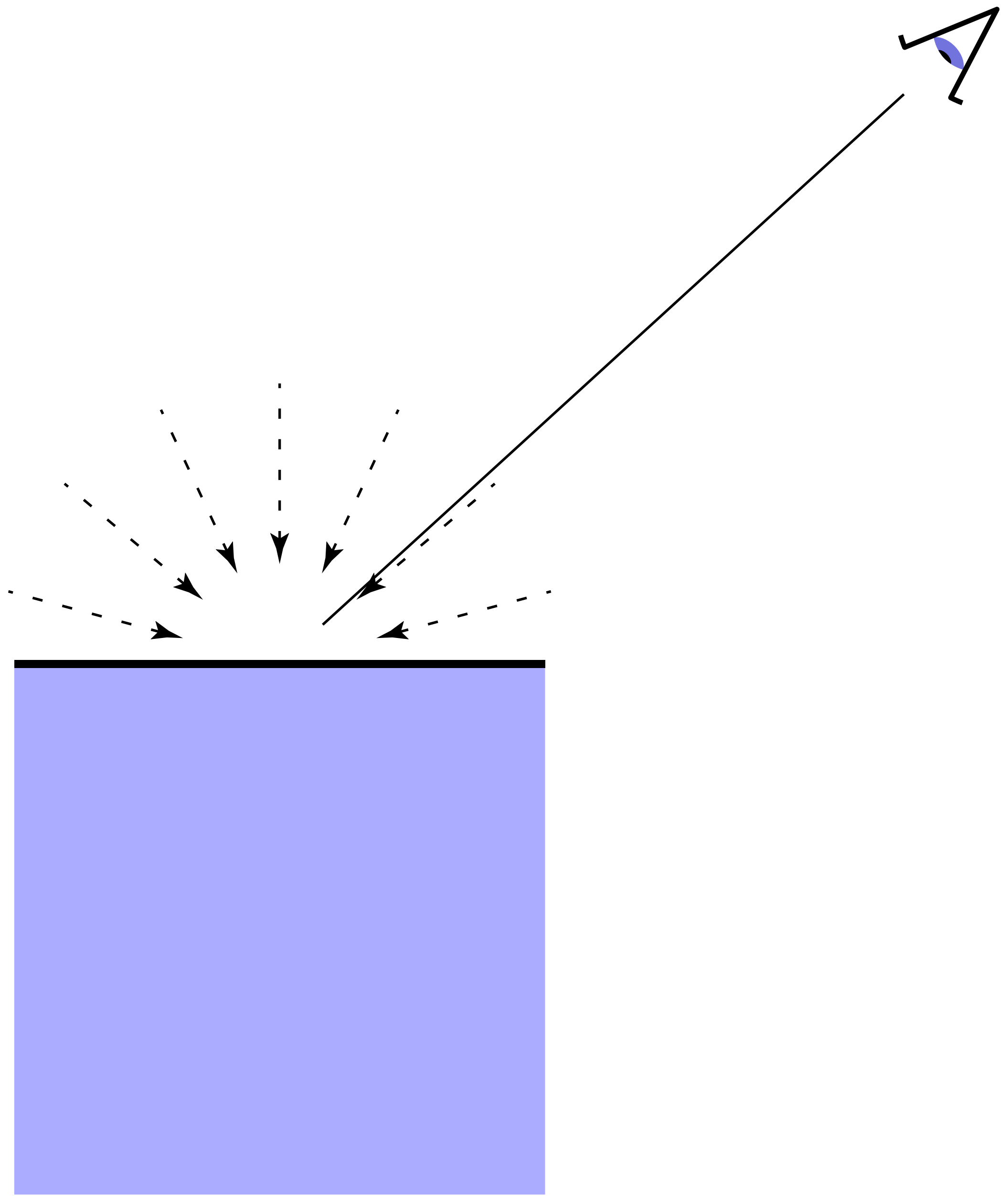


Photo credit: Jessica Andrews, flickr

Ambient Shading

Shading that does not depend on anything

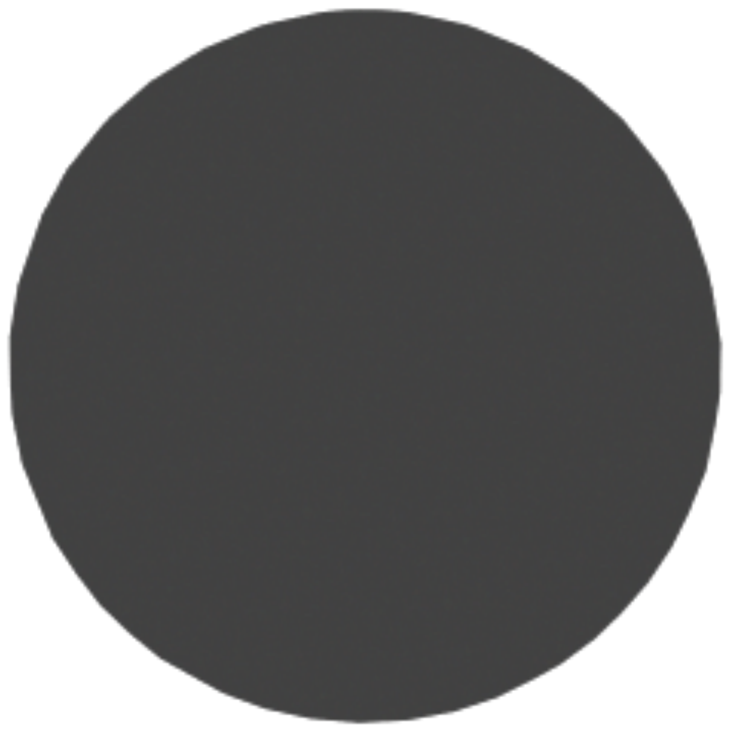
- Add constant color to account for disregarded illumination and fill in black shadows



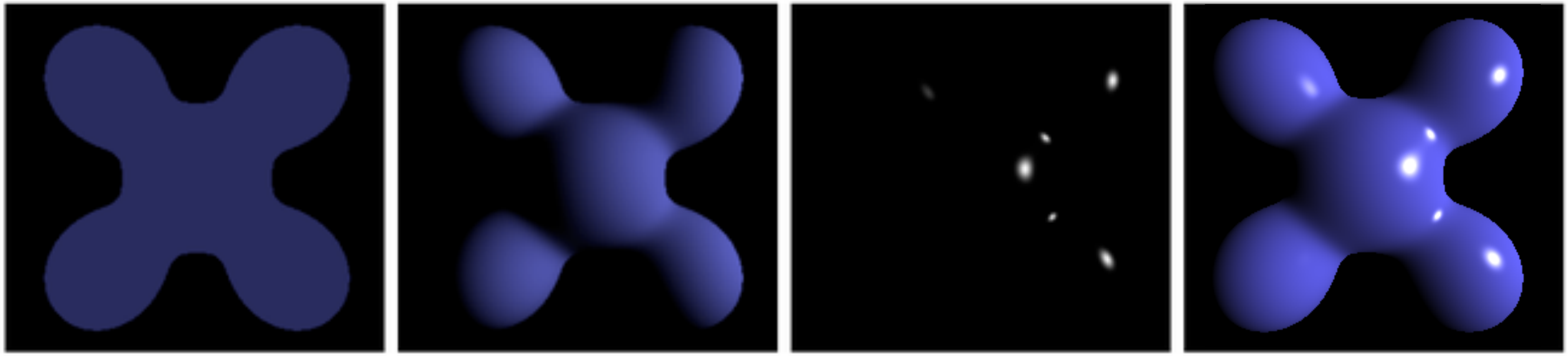
$$L_a = k_a \, I_a$$

ambient coefficient

reflected ambient light



Blinn-Phong Reflection Model



Ambient + Diffuse + Specular = Phong Reflection

$$
\begin{aligned}
L &= L_a + L_d + L_s \\
&= k_a\, I_a + k_d\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l}) + k_s\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p
\end{aligned}
$$

Blinn-Phong Reflection Model

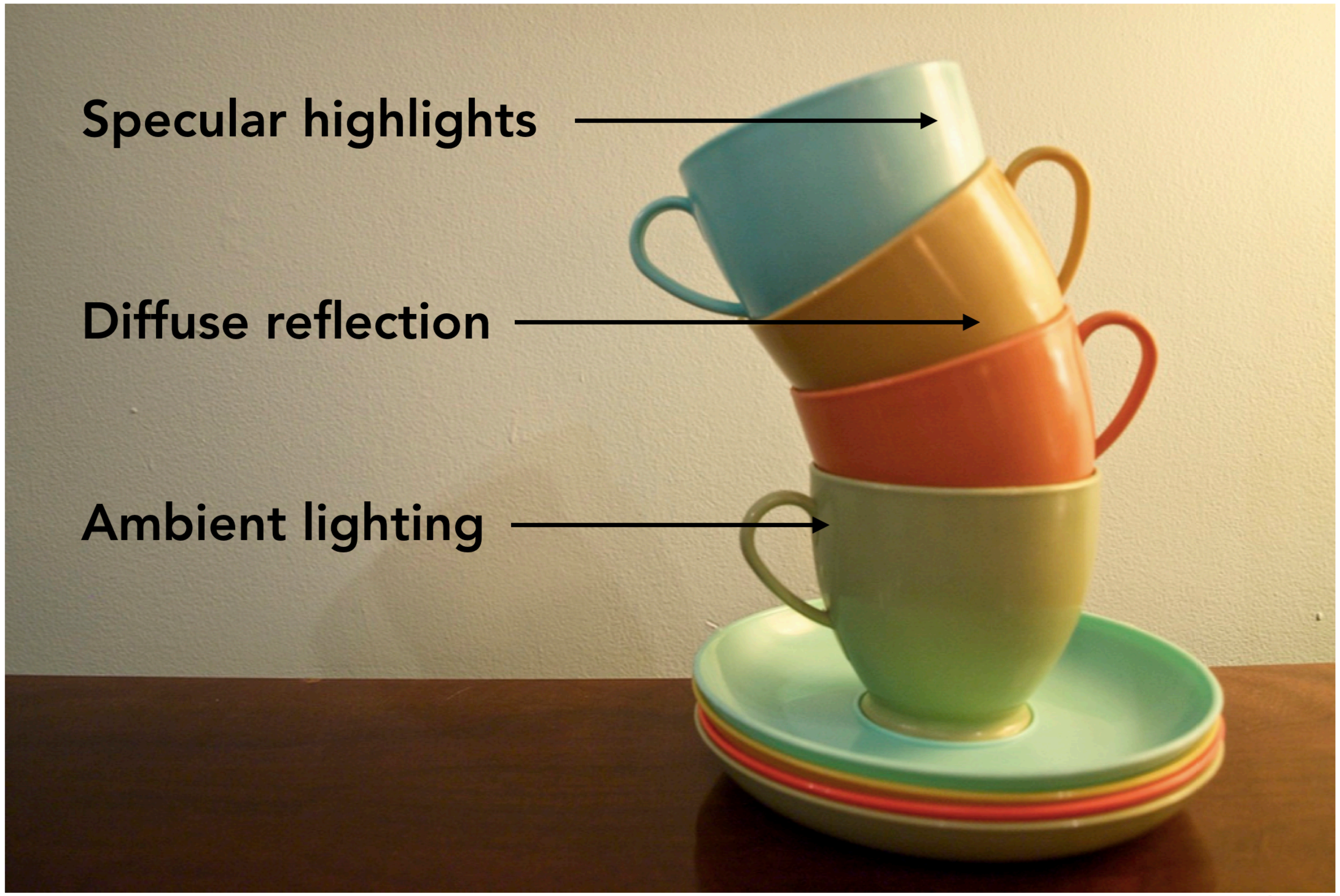


Photo credit: Jessica Andrews, flickr

$$
\begin{aligned}
L &= L_a + L_d + L_s \\
&= k_a\, I_a + k_d\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l}) + k_s\, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p
\end{aligned}
$$

Ashikhmin-Shirley BRDF

- More realistic specular term (for some materials)
- Anisotropic specularities
- Fresnel behavior (grazing angle highlights)
- Energy preserving diffuse term
- Sum of diffuse and specular terms (as before)

$$\rho(\hat{\mathbf{l}}, \hat{\mathbf{v}}) = \rho_d(\hat{\mathbf{l}}, \hat{\mathbf{v}}) + \rho_s(\hat{\mathbf{l}}, \hat{\mathbf{v}})$$

Michael Ashikhmin and Peter Shirley. 2000. An anisotropic phong BRDF model. J. Graph. Tools 5, 2 (February 2000), 25-32.
https://www.cs.utah.edu/~shirley/papers/jgtbrdf.pdf

Ashikhmin-Shirley BRDF

$$\rho_s(\hat{\mathbf{l}},\hat{\mathbf{e}}) = \frac{\sqrt{(p_u+1)(p_v+1)}}{8\pi}\,\frac{(\hat{\mathbf{n}}\cdot\hat{\mathbf{h}})^{p_u\cos^2\phi+p_v\sin^2\phi}}{(\hat{\mathbf{h}}\cdot\hat{\mathbf{e}})\max\Big((\hat{\mathbf{n}}\cdot\hat{\mathbf{e}}),(\hat{\mathbf{n}}\cdot\hat{\mathbf{l}})\Big)}F(\hat{\mathbf{h}}\cdot\hat{\mathbf{e}})$$

$$F(\hat{\mathbf{h}}\cdot\hat{\mathbf{e}}) = K_s + (1-K_s)(1-(\hat{\mathbf{h}}\cdot\hat{\mathbf{e}}))^5$$

$\hat{\mathbf{l}}$	Light direction
$\hat{\mathbf{e}}$	Viewer (eye) direction
p_u, p_v	Specular powers
$\hat{\mathbf{n}}$	Normal
$\hat{\mathbf{h}}$	Half angle
K_s	Specular coefficient (color)
$\hat{\mathbf{u}}, \hat{\mathbf{v}}$	Parametric directions

Ashikhmin-Shirley BRDF

$$\rho_s(\hat{\mathbf{l}}, \hat{\mathbf{e}}) = \frac{\sqrt{(p_u + 1)(p_v + 1)}}{8\pi} \frac{(\hat{\mathbf{n}} \cdot \hat{\mathbf{h}})^{\frac{p_u (\hat{\mathbf{h}} \cdot \hat{\mathbf{u}})^2 + p_u (\hat{\mathbf{h}} \cdot \hat{\mathbf{v}})^2}{1 - (\hat{\mathbf{h}} \cdot \hat{\mathbf{n}})^2}}}{(\hat{\mathbf{h}} \cdot \hat{\mathbf{e}}) \max\Big((\hat{\mathbf{n}} \cdot \hat{\mathbf{e}}), (\hat{\mathbf{n}} \cdot \hat{\mathbf{l}})\Big)} F(\hat{\mathbf{h}} \cdot \hat{\mathbf{e}})$$

$$F(\hat{\mathbf{h}} \cdot \hat{\mathbf{e}}) = K_s + (1 - K_s)(1 - (\hat{\mathbf{h}} \cdot \hat{\mathbf{e}}))^5$$

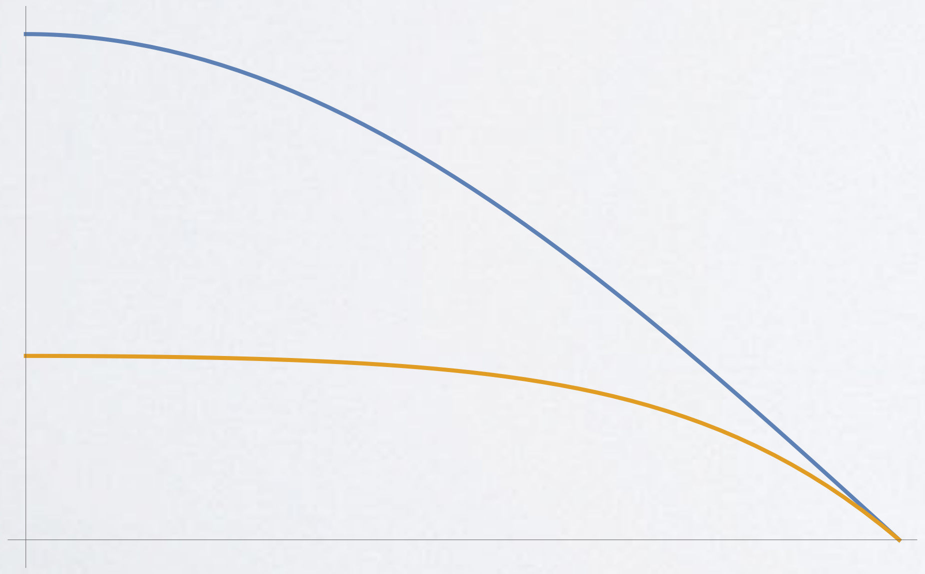
Approximate Fresnel function

$\hat{\mathbf{l}}$	Light direction
$\hat{\mathbf{e}}$	Viewer (eye) direction
p_u, p_v	Specular powers
$\hat{\mathbf{n}}$	Normal
$\hat{\mathbf{h}}$	Half angle
K_s	Specular coefficient (color)
$\hat{\mathbf{u}}, \hat{\mathbf{v}}$	Parametric directions

Ashikhmin-Shirley BRDF

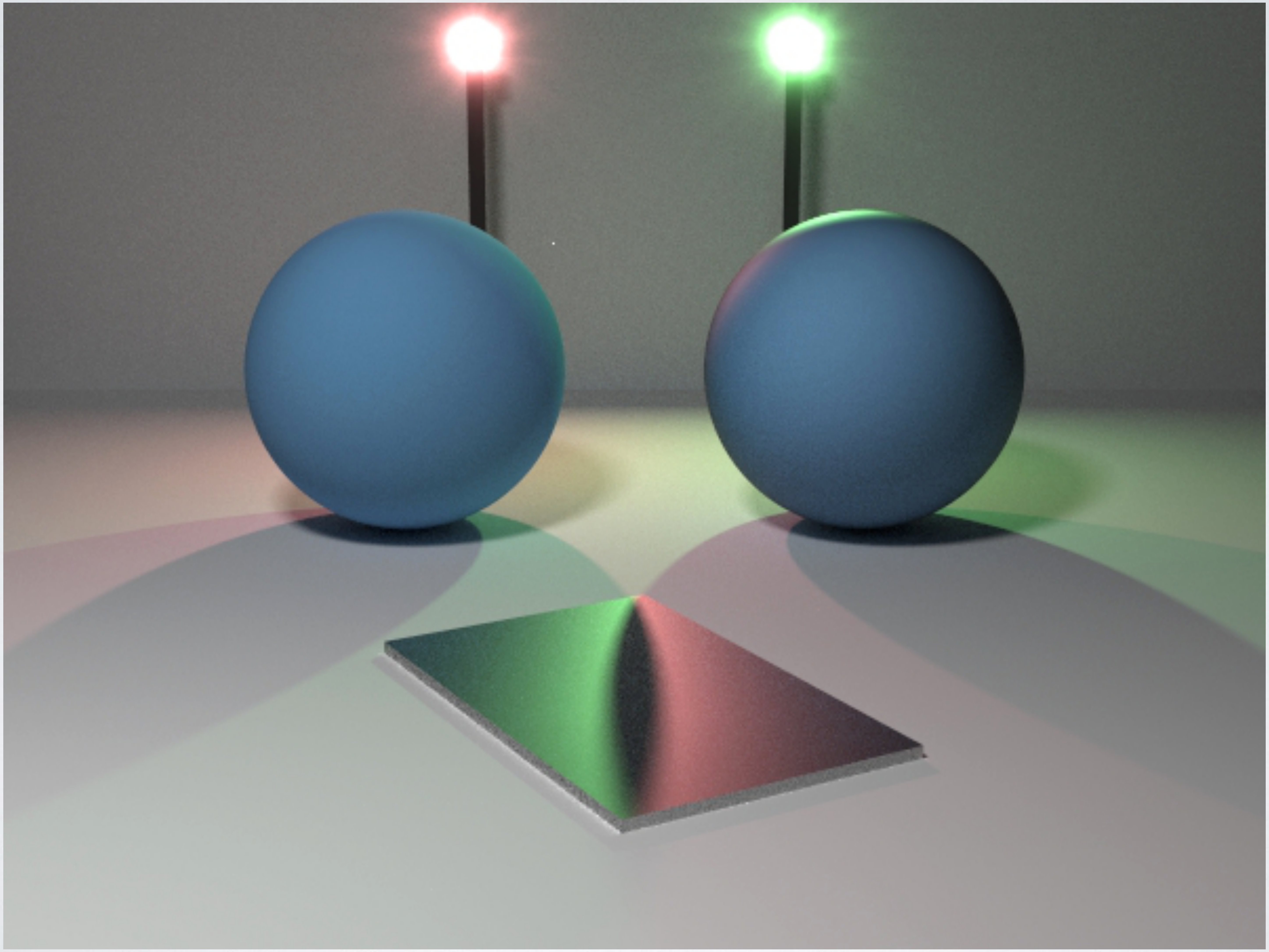
$$\rho_d(\hat{\mathbf{l}}, \hat{\mathbf{e}}) = \frac{28K_d}{23\pi}(1 - K_s)\left(1 - \left(1 - \frac{\hat{\mathbf{n}} \cdot \hat{\mathbf{e}}}{2}\right)^5\right)\left(1 - \left(1 - \frac{\hat{\mathbf{n}} \cdot \hat{\mathbf{l}}}{2}\right)^5\right)$$

Note: The Phong diffuse term (Lambertian) is independent of view. But this term accounts for unavailable light due to specular/Fresnel reflection.

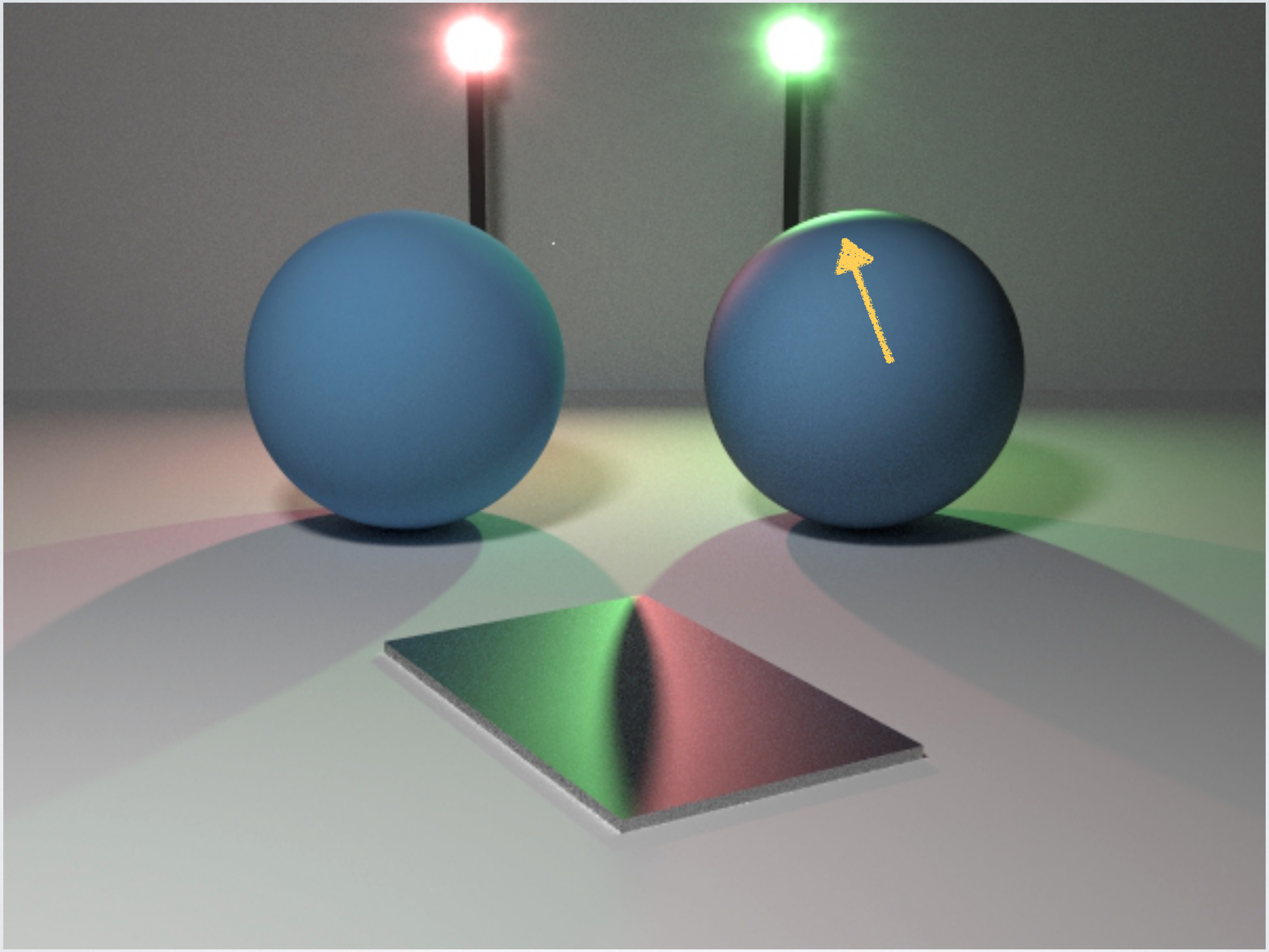


$\hat{\mathbf{l}}$	Light direction
$\hat{\mathbf{e}}$	Viewer (eye) direction
p_u, p_v	Specular powers
$\hat{\mathbf{n}}$	Normal
$\hat{\mathbf{h}}$	Half angle
K_s	Specular coefficient (color)
$\hat{\mathbf{u}}, \hat{\mathbf{v}}$	Parametric directions

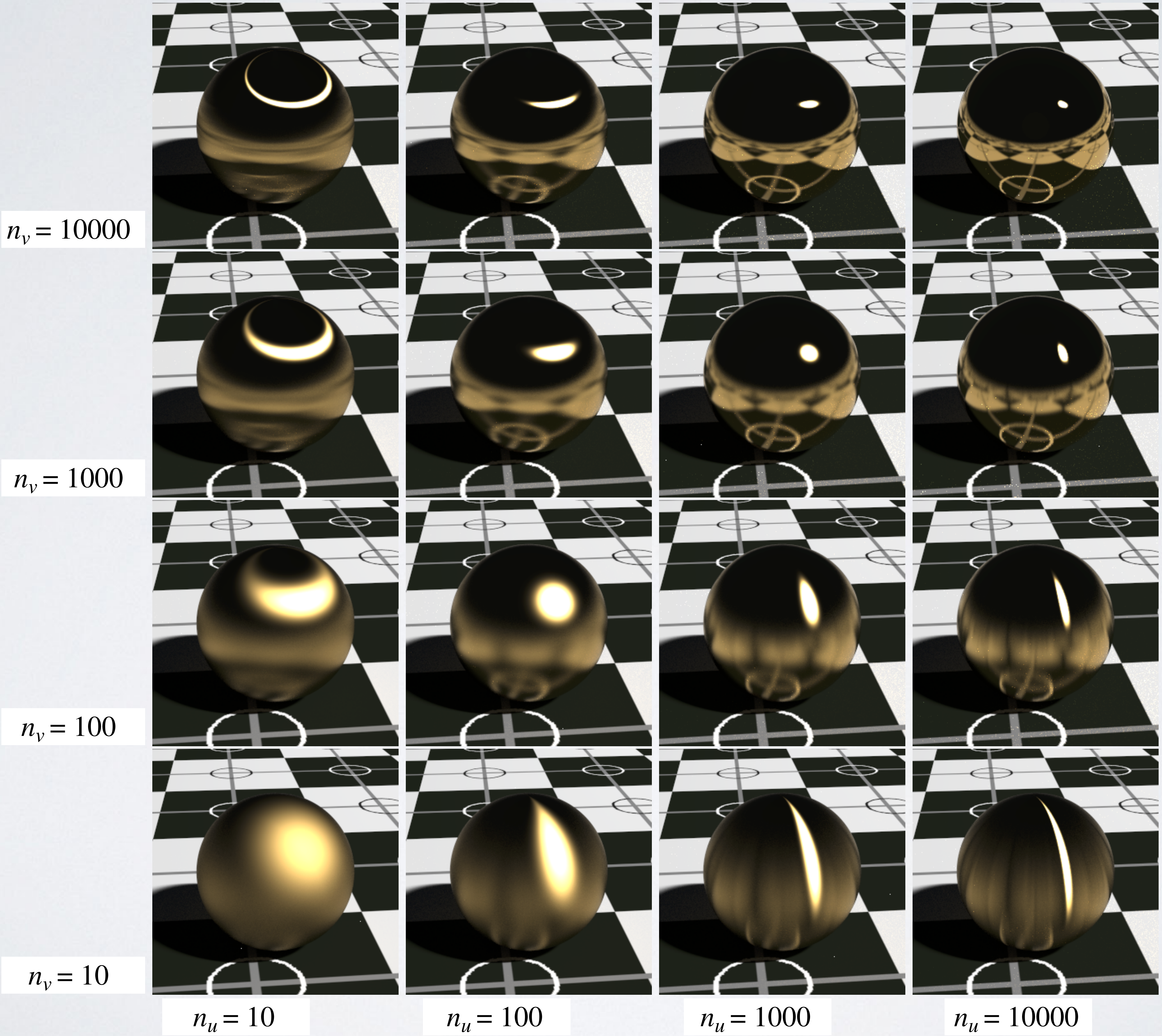
Ashikhmin-Shirley BRDF



Ashikhmin-Shirley BRDF



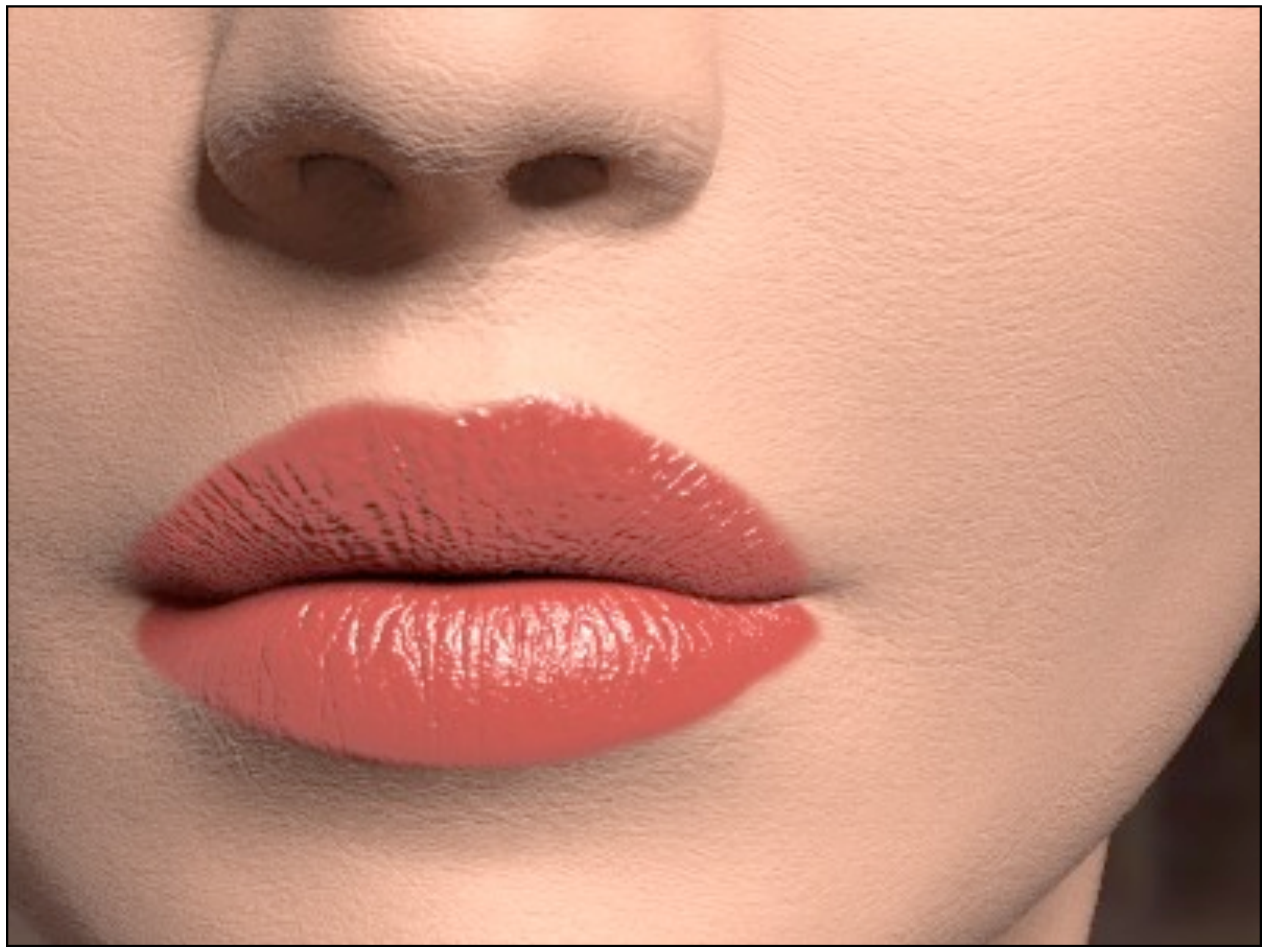
Ashikhmin-Shirley BRDF

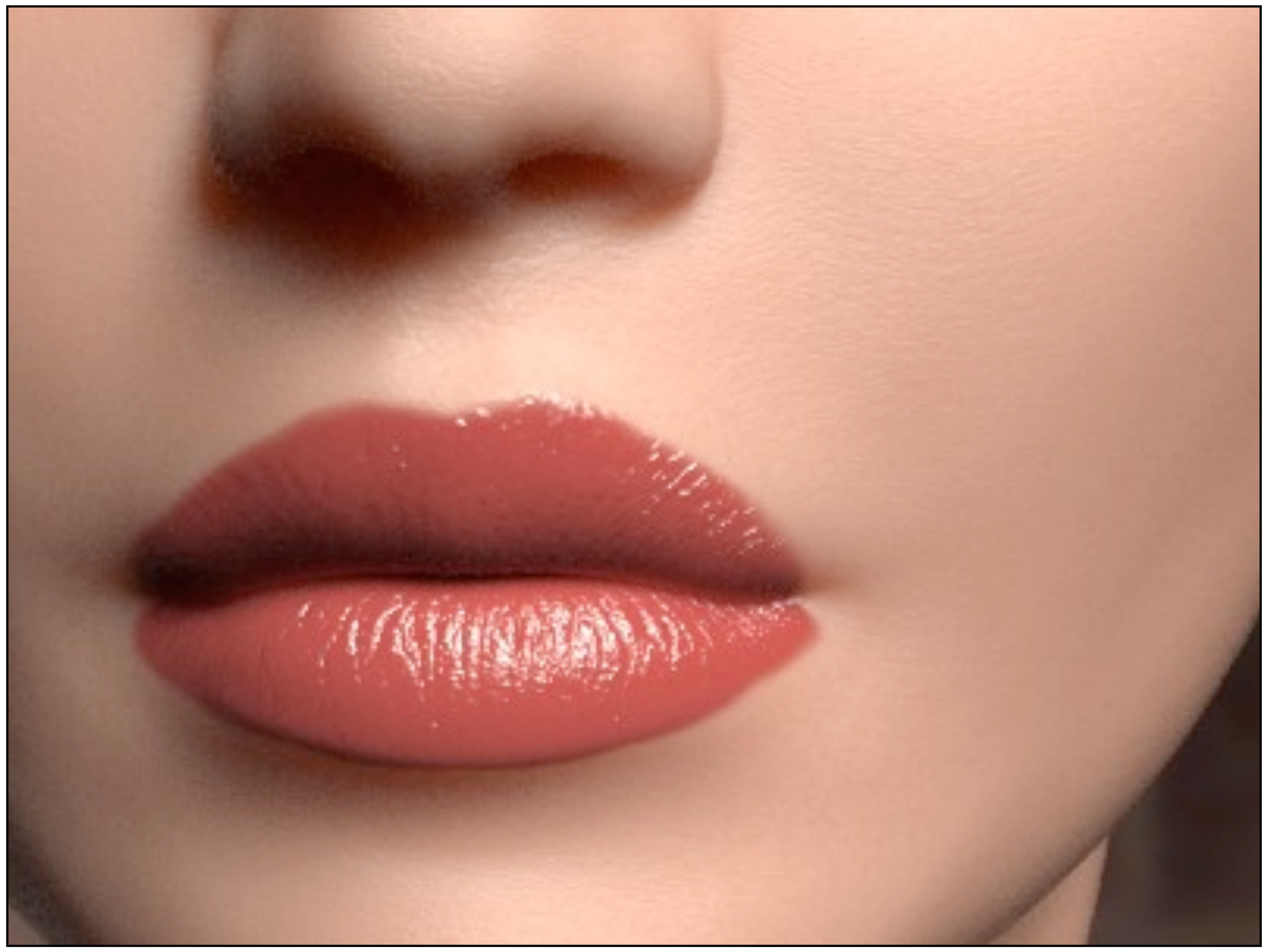


Beyond BRDFs

The BRDF model does not capture everything

- e.g. Subsurface scattering (BSSRDF)



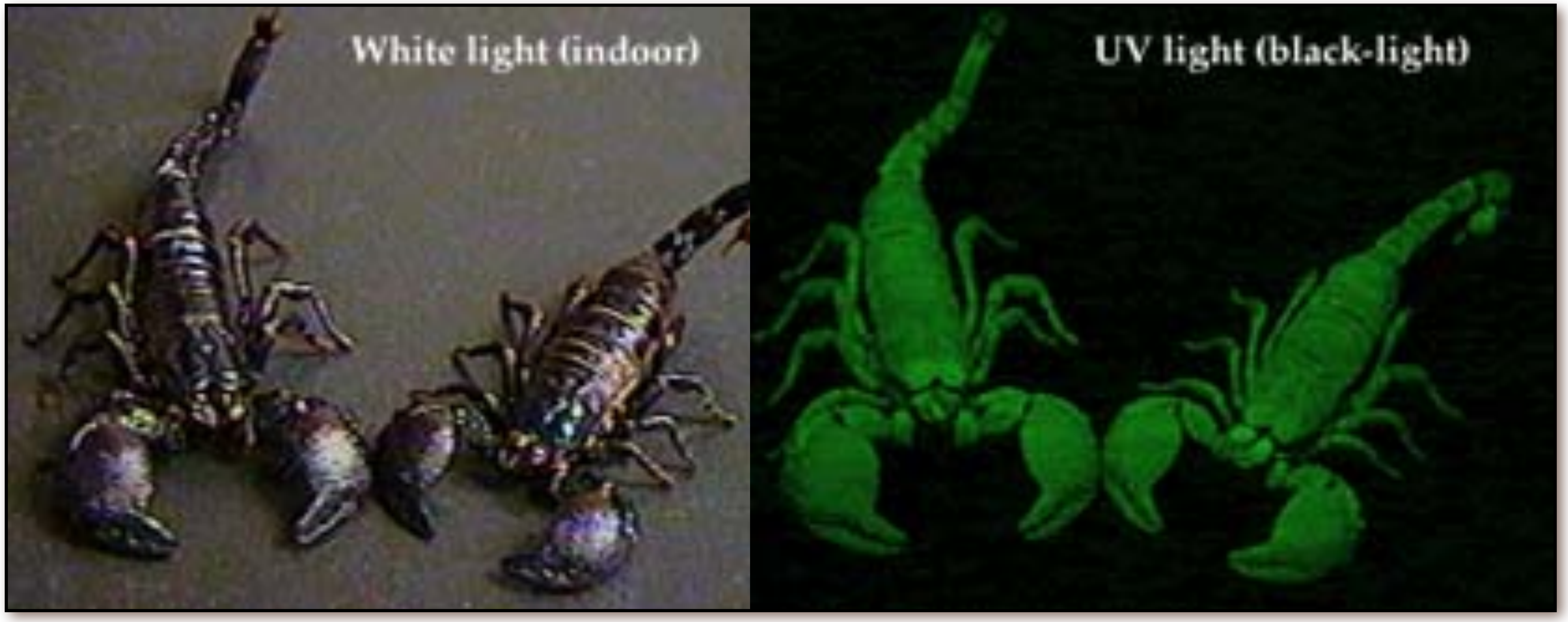


Images from Jensen *et. al, SIGGRAPH 2001*

Beyond BRDFs

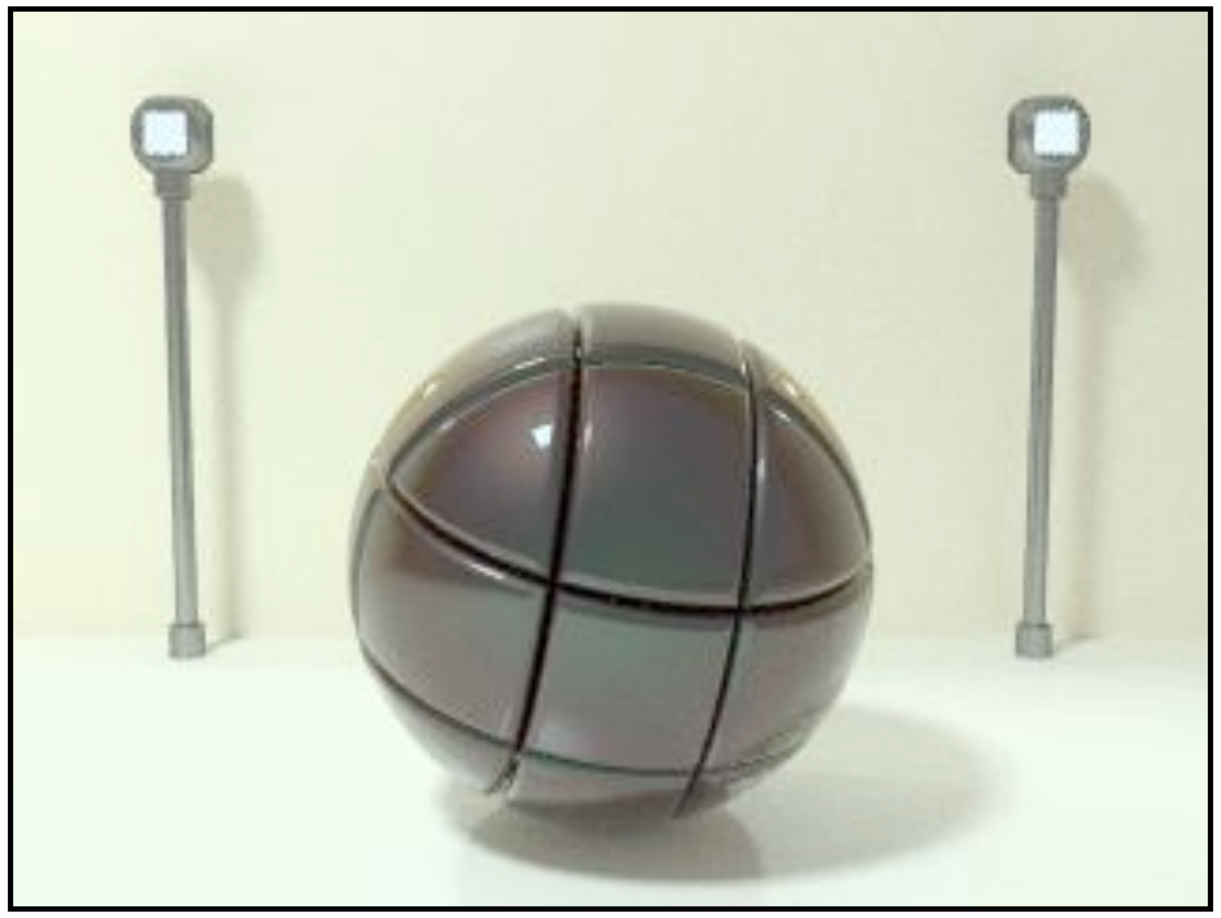
The BRDF model does not capture everything

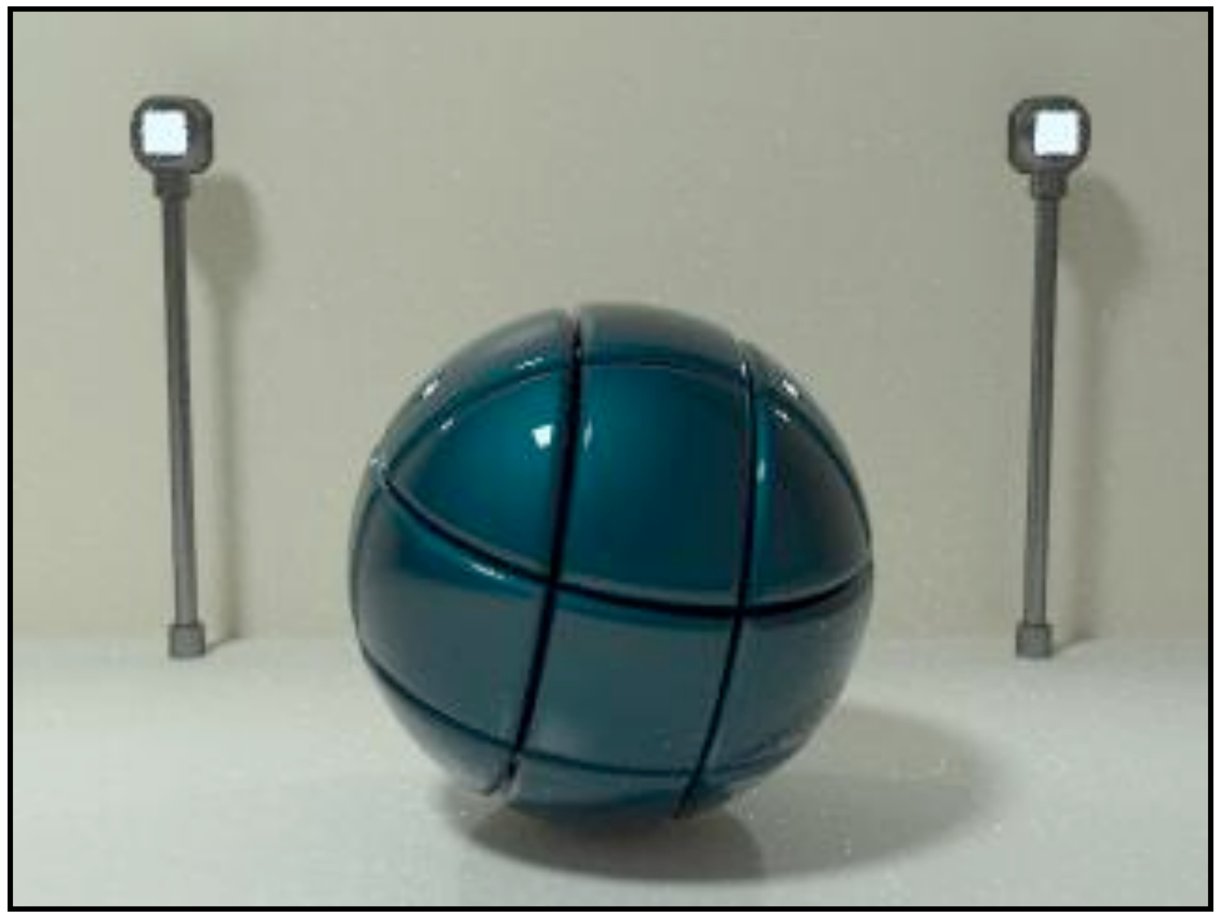
- e.g. Inter-frequency interactions



$\rho = \rho(\theta_V, \theta_L, \lambda_{\text{in}}, \lambda_{\text{out}})$ This version would work....

Measured BRDFs

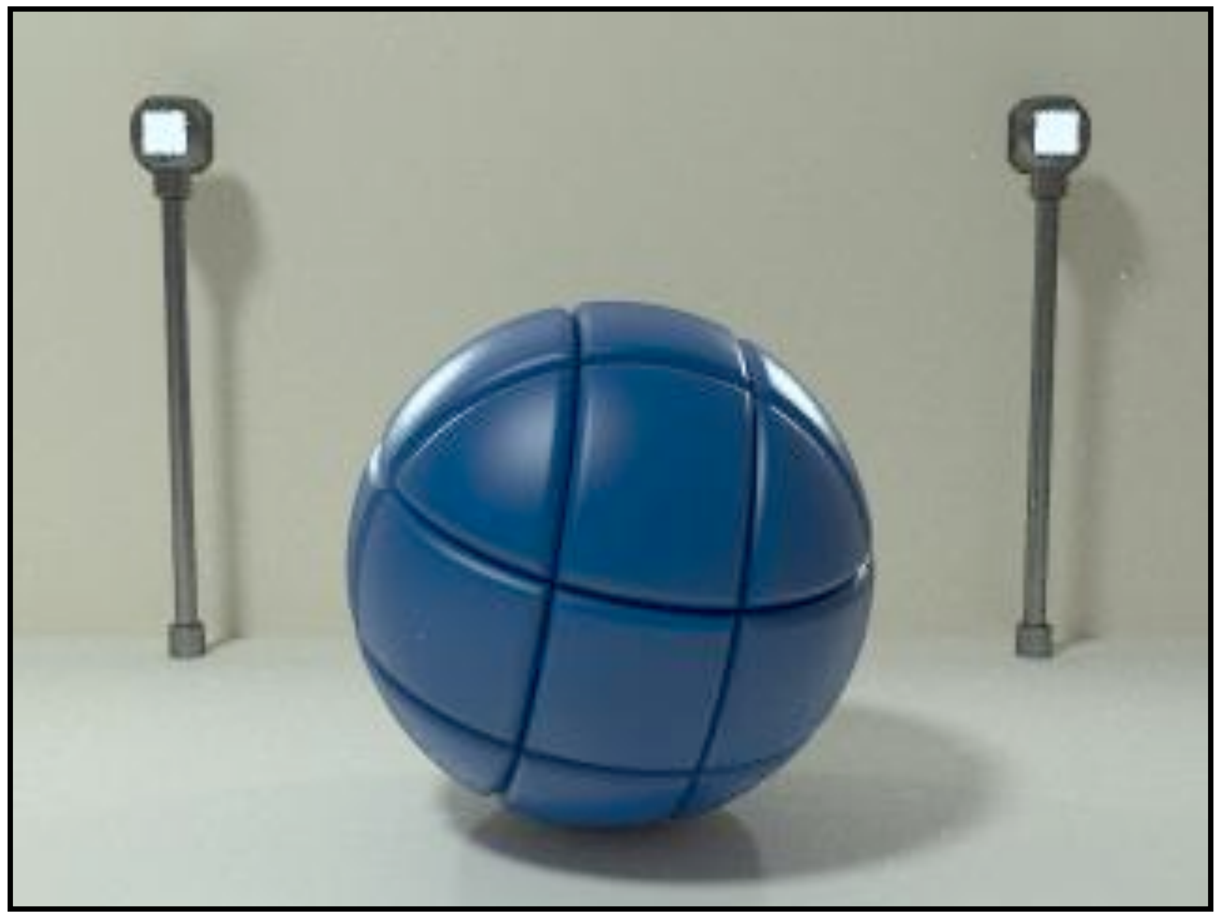




BRDFs for automotive paint

Images from Cornell University Program of Computer Graphics

Measured BRDFs



BRDFs for aerosol spray paint

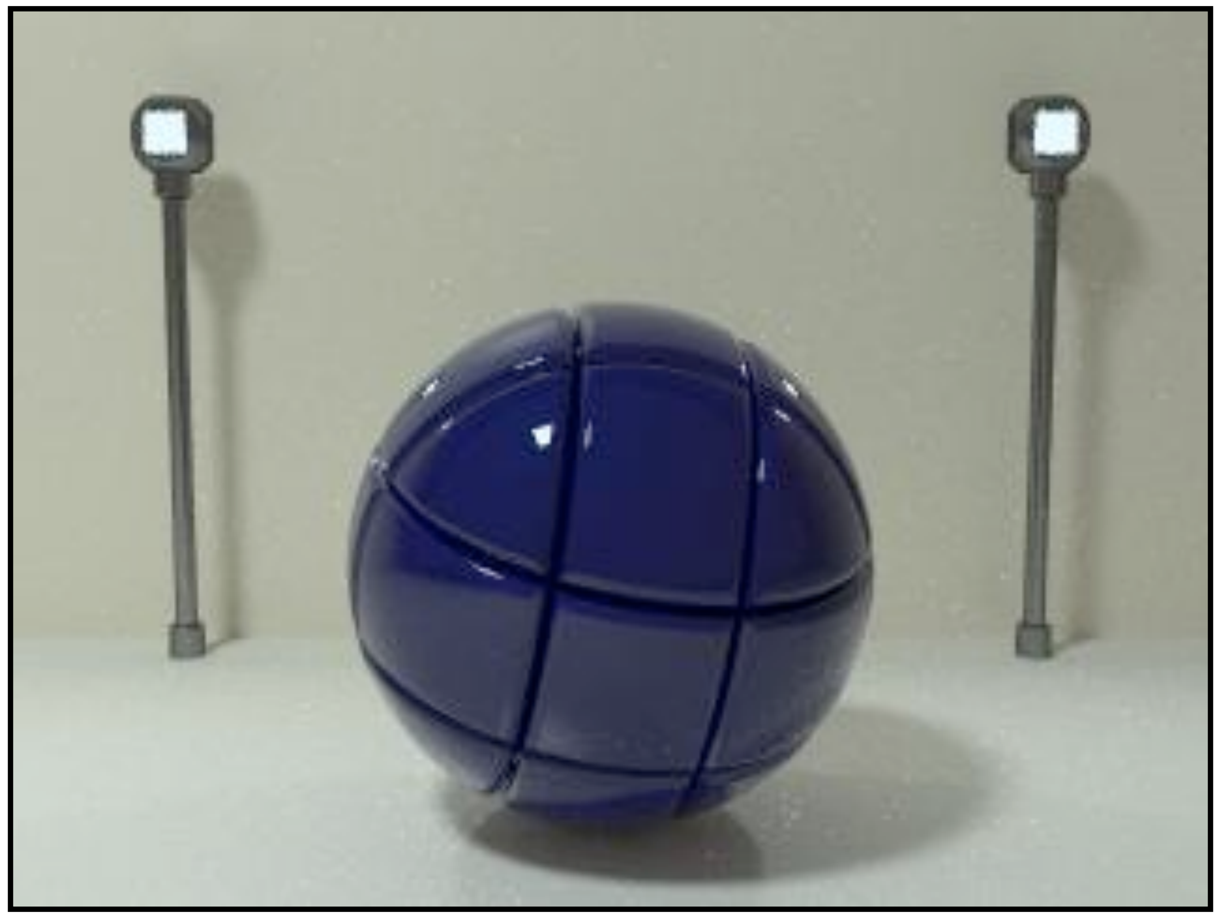
Images from Cornell University Program of Computer Graphics

Measured BRDFs

BRDFs for house paint

Images from Cornell University Program of Computer Graphics

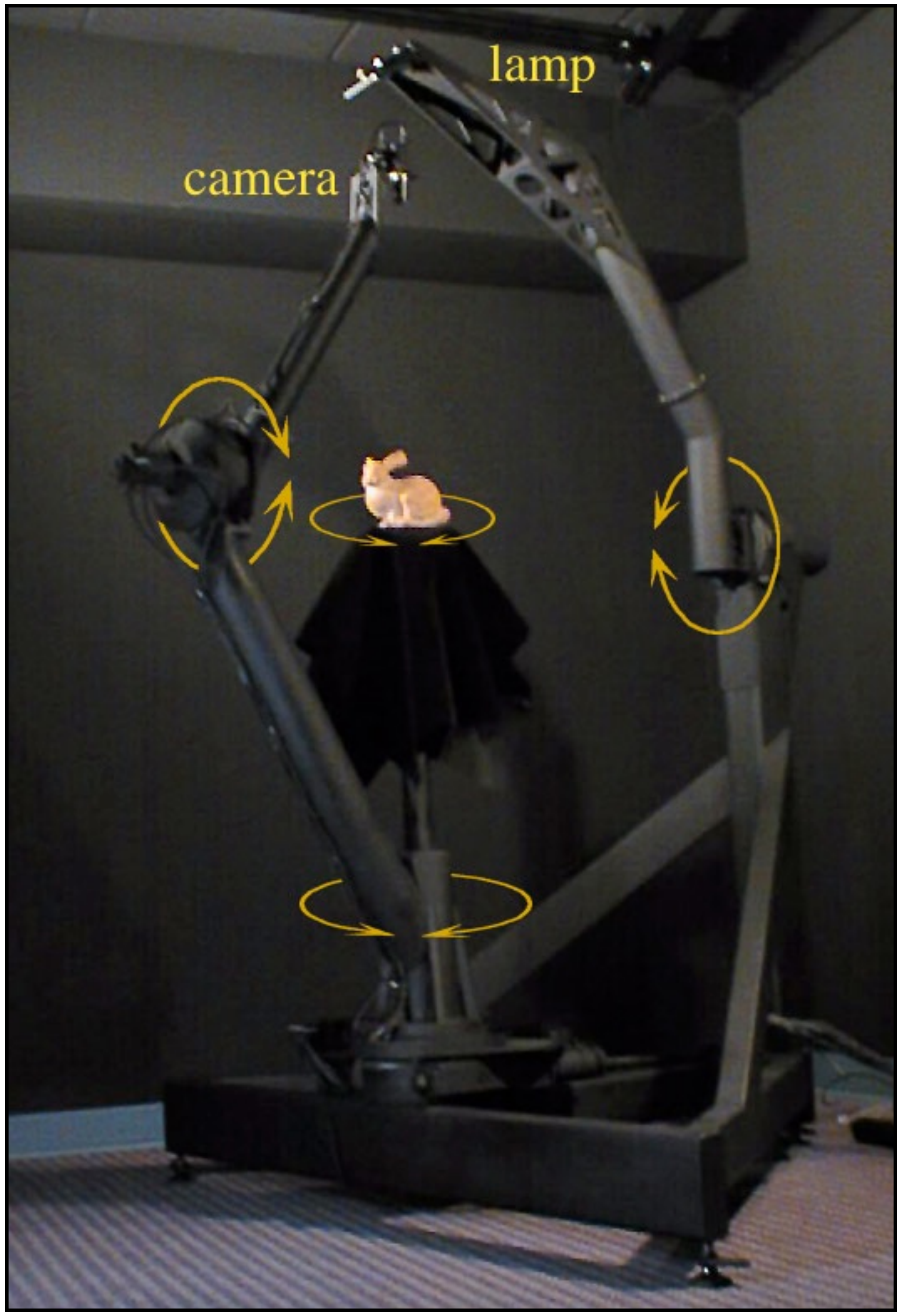
Measured BRDFs

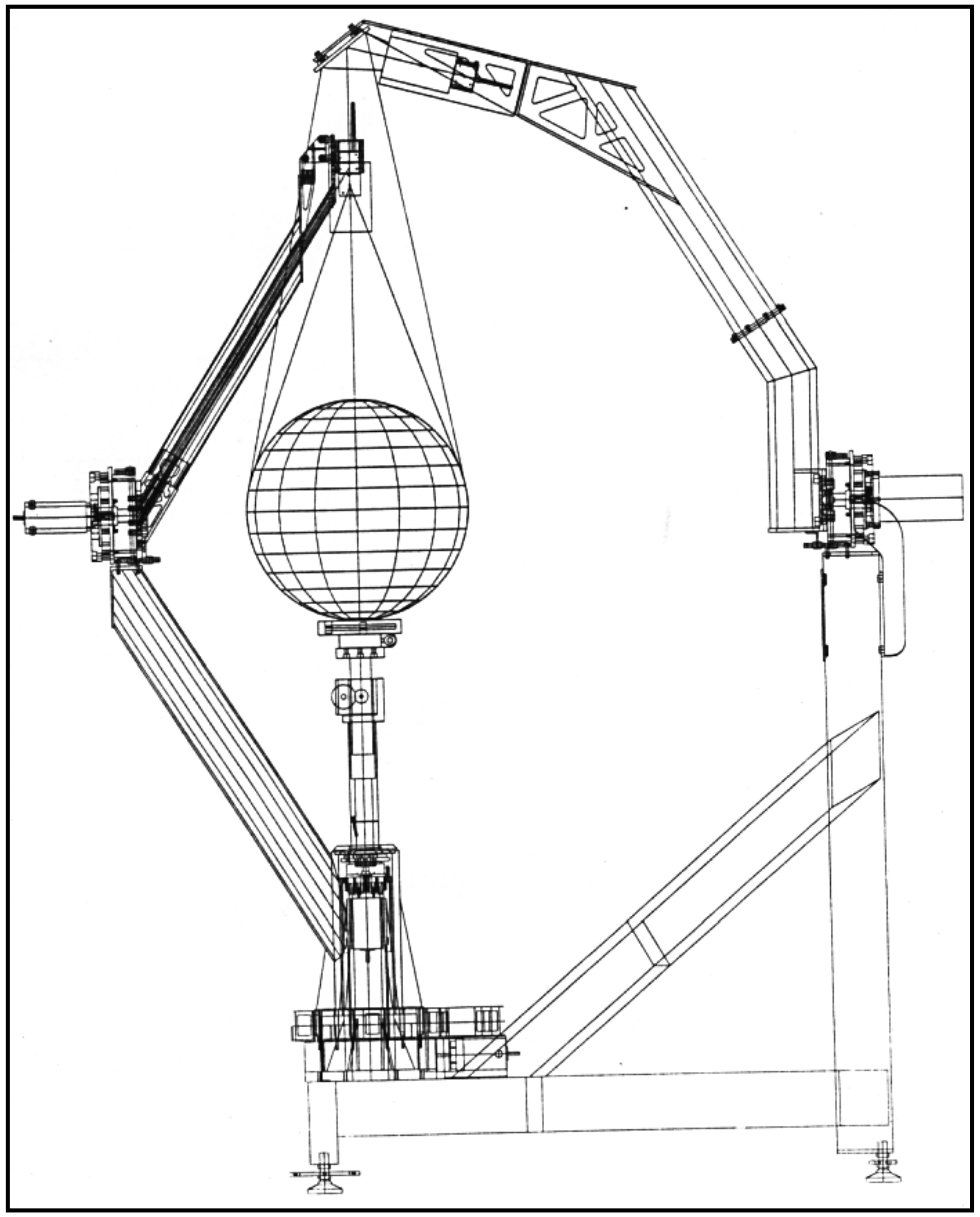


BRDFs for lucite sheet

Images from Cornell University Program of Computer Graphics

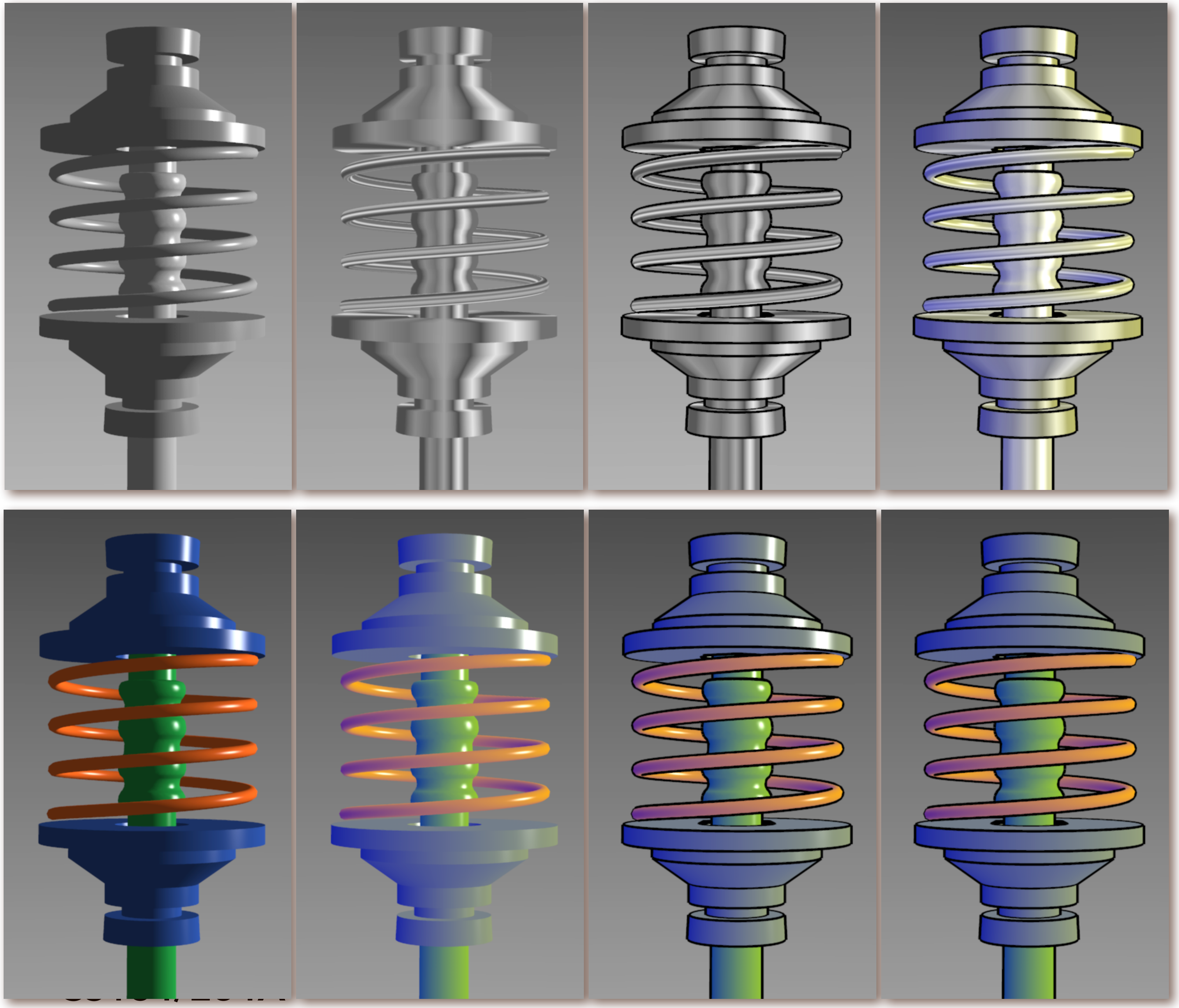
Measuring BRDF

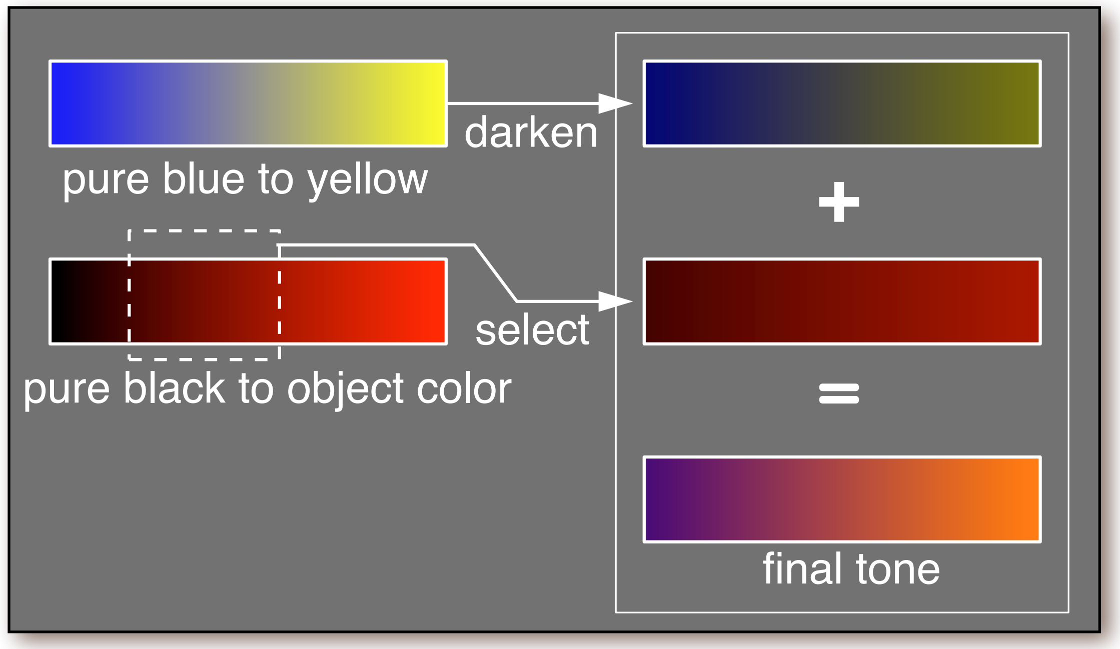




Images from Marc Levoy

Other Color Effects





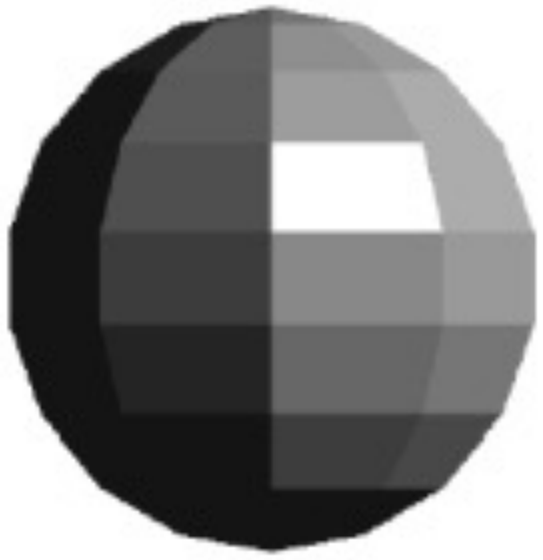
Images from Gooch *et. al, 1998*

Shading Triangle Meshes

Shading Frequency: Triangle, Vertex or Pixel

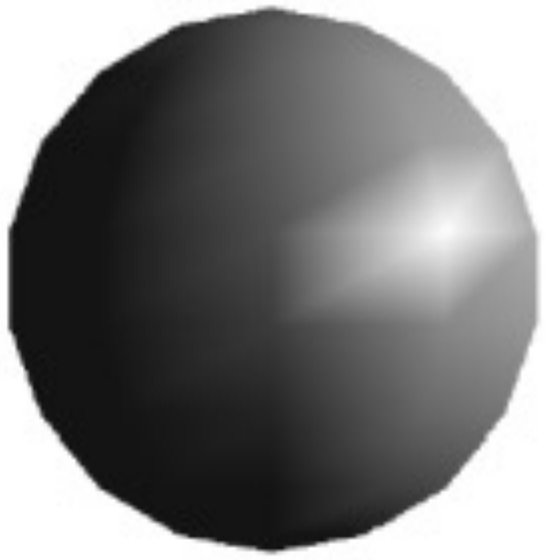
Shade each triangle (flat shading)

- Triangle face is flat — one normal vector
- Not good for smooth surfaces



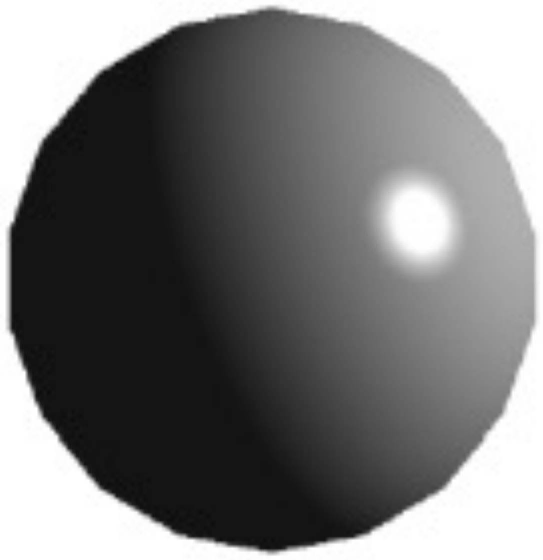
Shade each vertex ("Gouraud" shading)

- Interpolate colors from vertices across triangle
- Each vertex has a normal vector

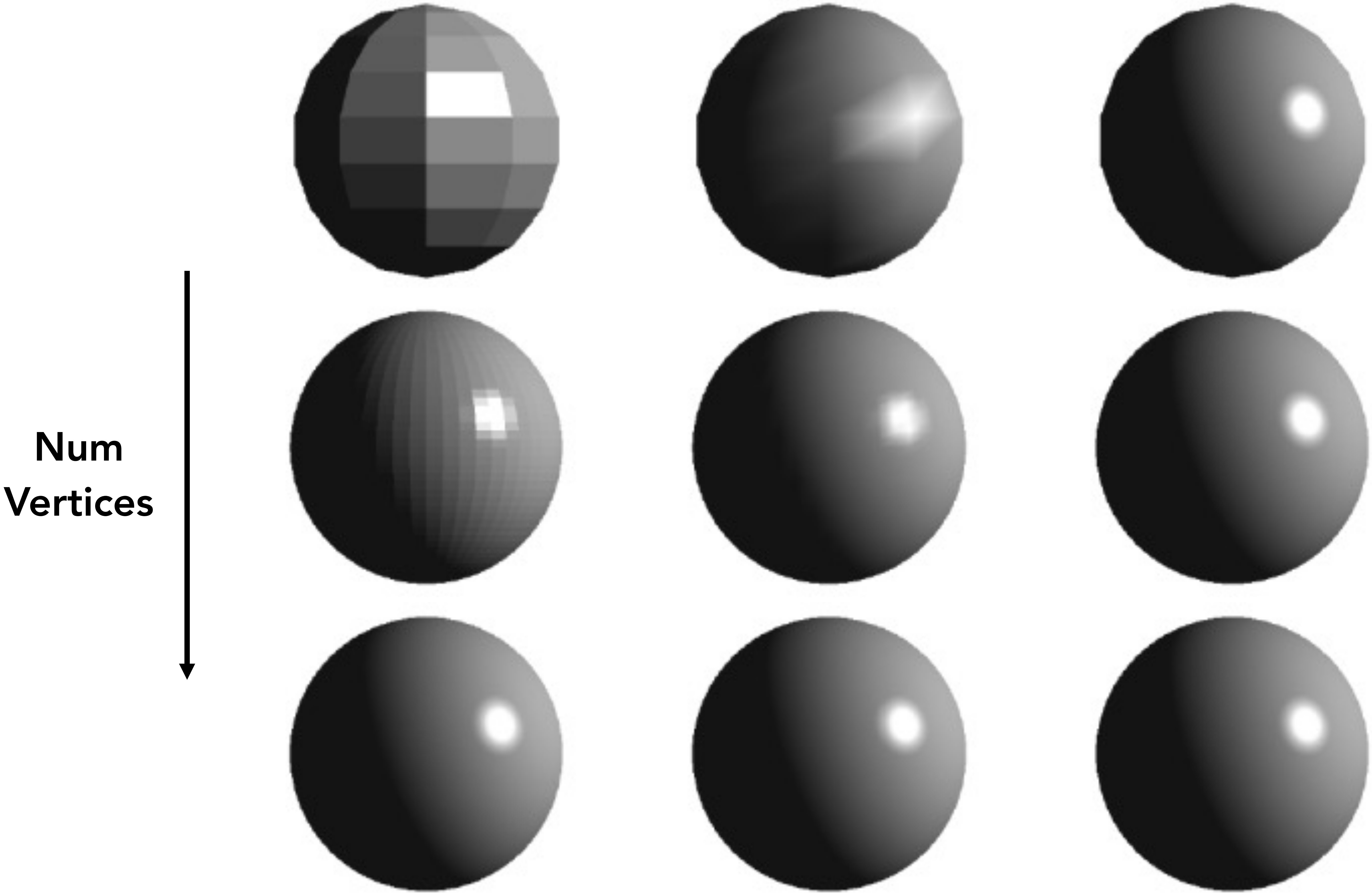


Shade each pixel ("Phong" shading)

- Interpolate normal vectors across each triangle
- Compute full shading model at each pixel



Shading Frequency: Face, Vertex or Pixel



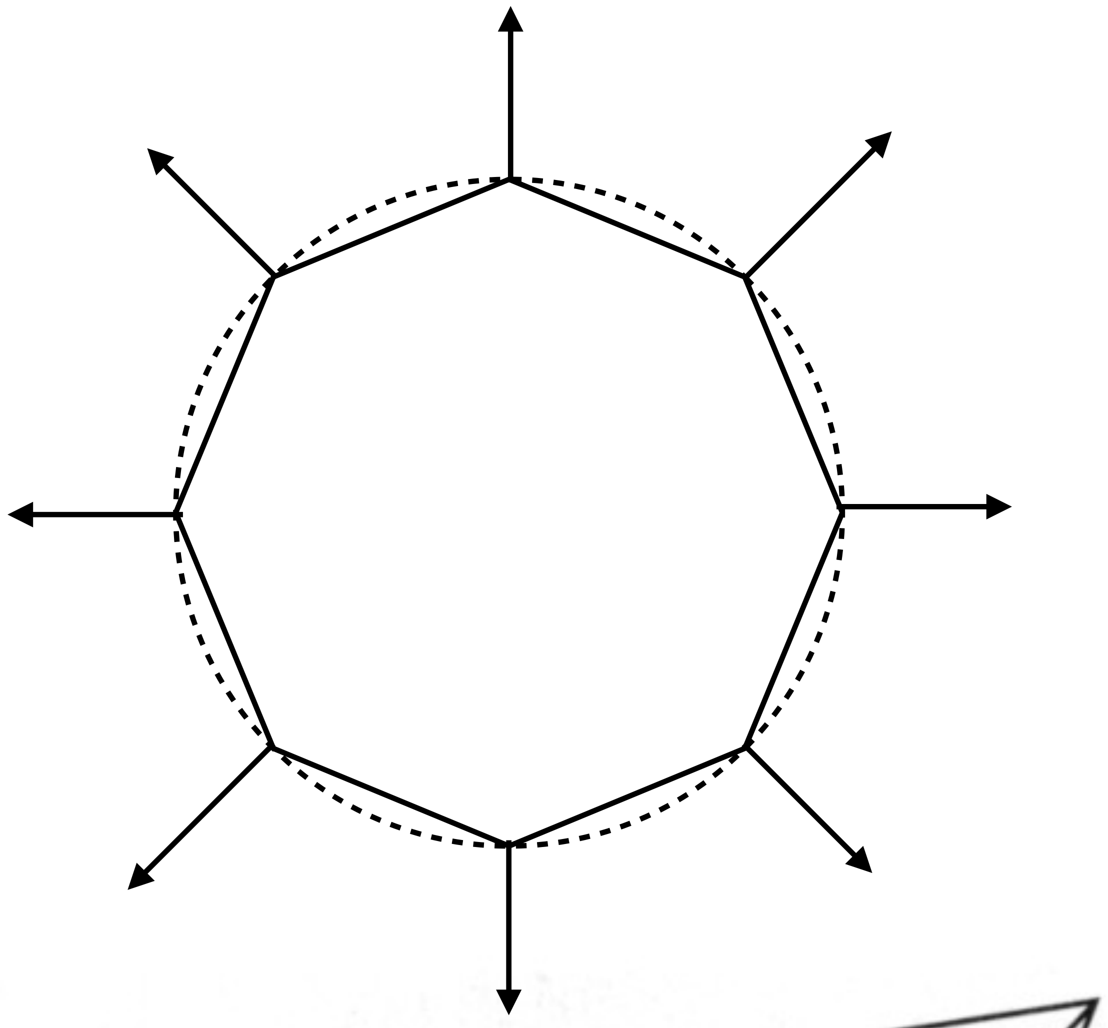
Shading freq. :	Face	Vertex	Pixel
Shading type :	Flat	Gouraud	Phong (*)

Image credit: Happyman, http://cg2010studio.com/

Defining Per-Vertex Normal Vectors

Best to get vertex normals from the underlying geometry

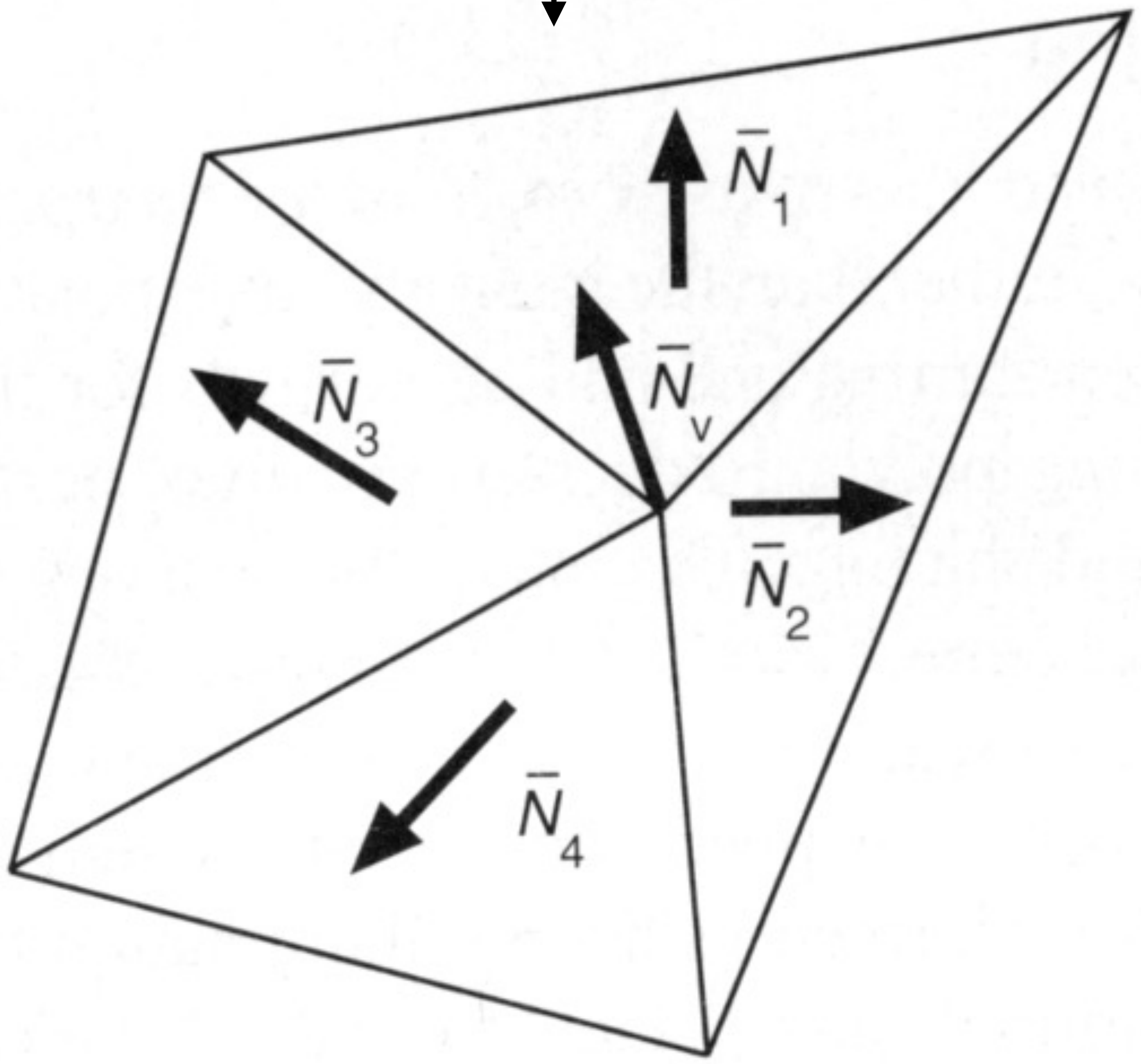
- e.g. consider a sphere



Otherwise have to infer vertex normals from triangle faces

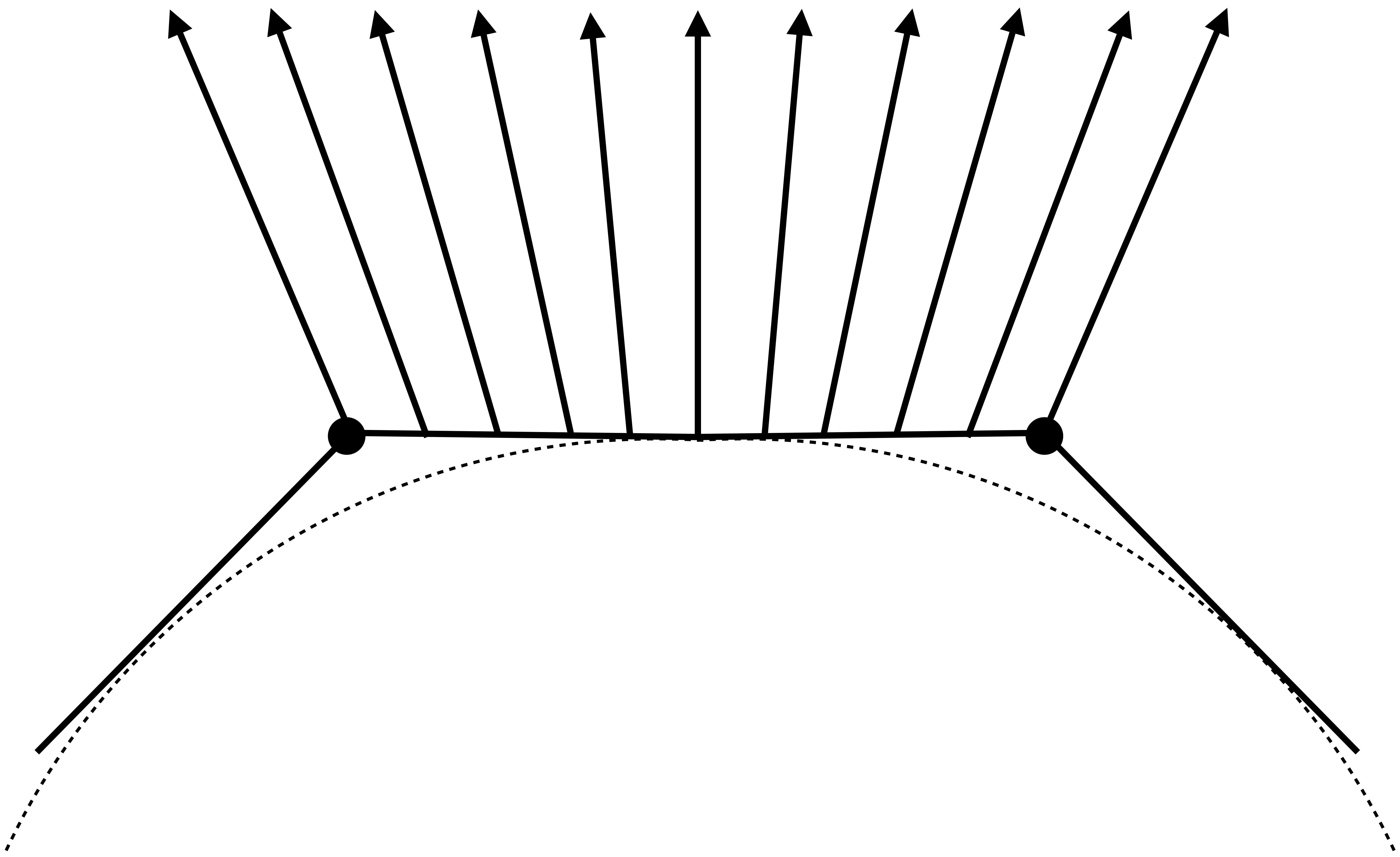
- Simple scheme: average surrounding face normals

$$N_v = \frac{\sum_i N_i}{\|\sum_i N_i\|}$$



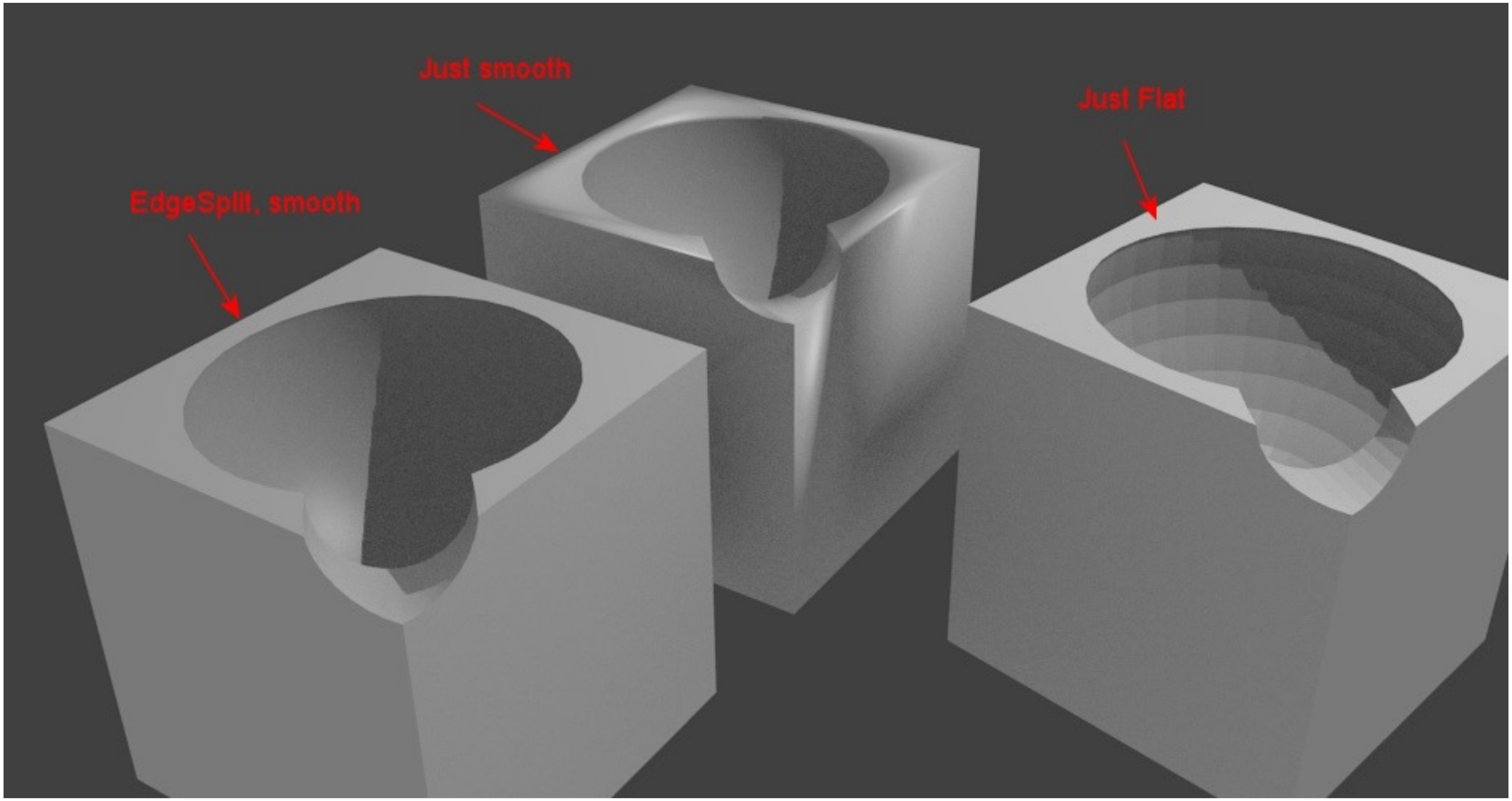
Defining Per-Pixel Normal Vectors

Barycentric interpolation of vertex normals



Problem: length of vectors?

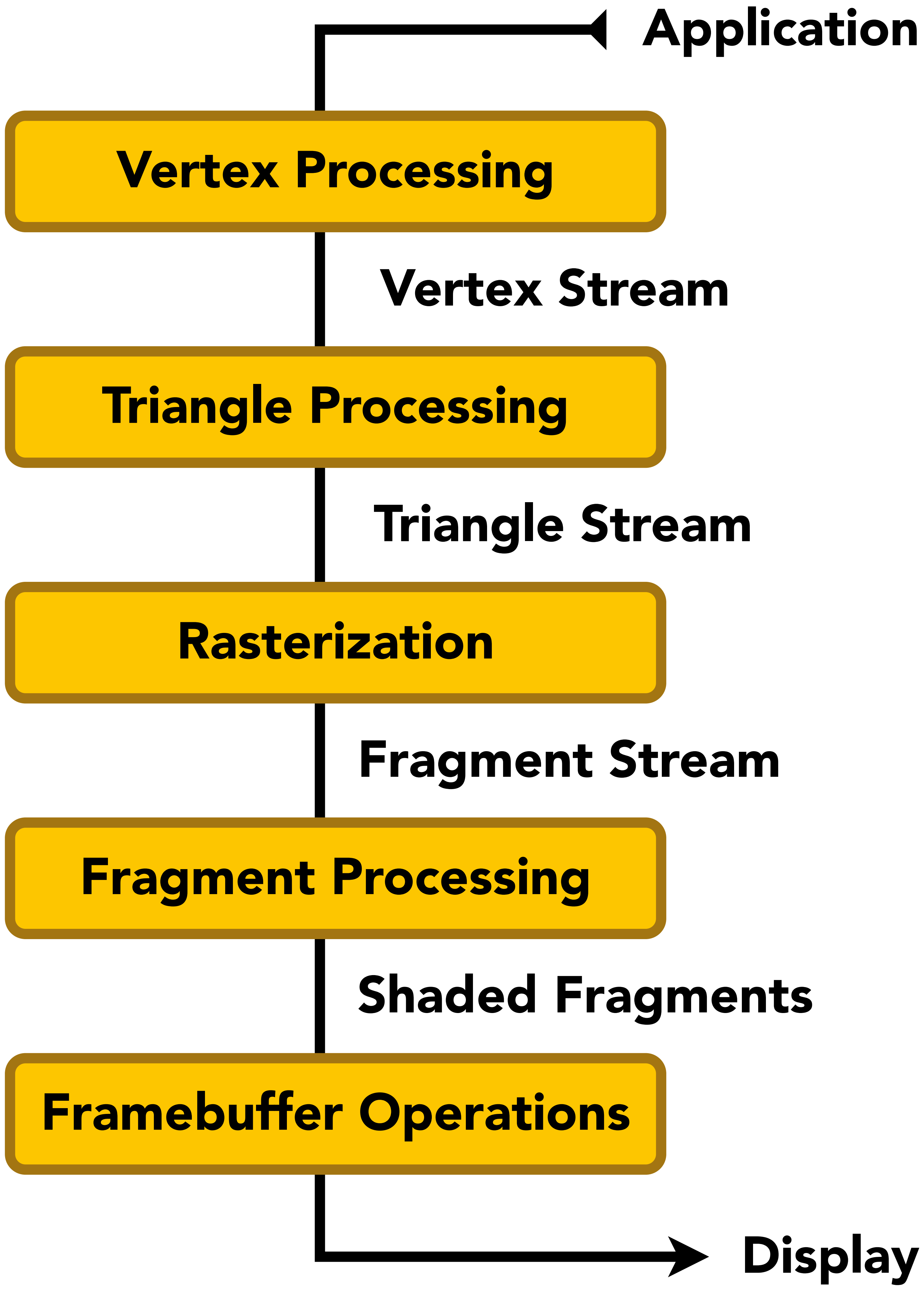
Smooth Shading



From blender.stackexchange.com

Rasterization Pipeline

Rasterization Pipeline



Application

Vertex Processing

Vertex Stream

Triangle Processing

Triangle Stream

Rasterization

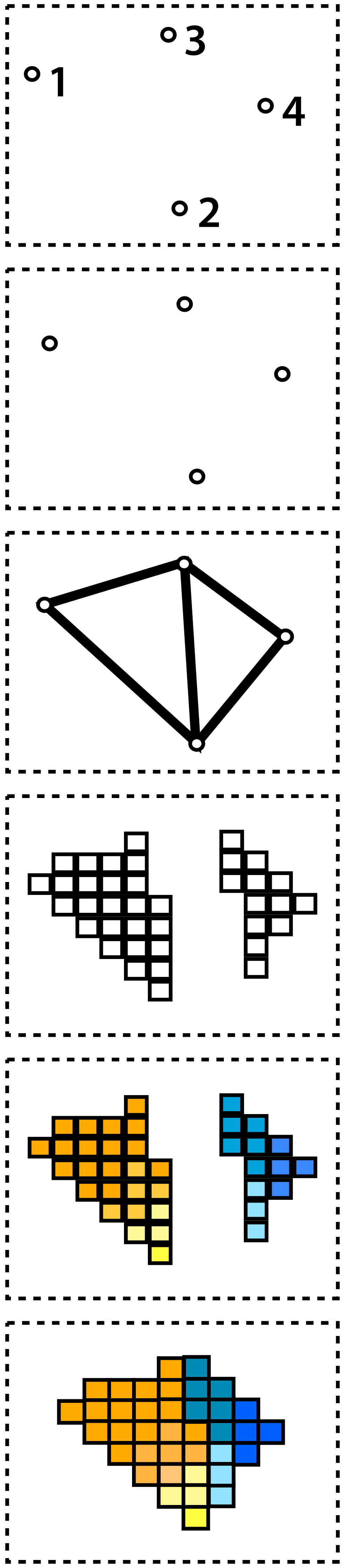
Fragment Stream

Fragment Processing

Shaded Fragments

Framebuffer Operations

Display



Input: vertices in 3D space

Vertices positioned in screen space

Triangles positioned in screen space

Fragments (one per covered sample)

Shaded fragments

Output: image (pixels)

Shader Programs

- Program vertex and fragment processing stages
- Describe operation on a single vertex (or fragment)

Example GLSL fragment shader program

```
uniform sampler2D myTexture;
uniform vec3 lightDir;
varying vec2 uv;
varying vec3 norm;

void diffuseShader()
{
  vec3 kd;
  kd = texture2d(myTexture, uv);
  kd *= clamp(dot(–lightDir, norm), 0.0, 1.0);
  gl_FragColor = vec4(kd, 1.0);
}
```

- Shader function executes once per fragment.
- Outputs color of surface at the current fragment’s screen sample position.
- This shader performs a texture lookup to obtain the surface’s material color at this point, then performs a diffuse lighting calculation.

Shader Programs

- Program vertex and fragment processing stages
- Describe operation on a single vertex (or fragment)

Example GLSL fragment shader program

```
uniform sampler2D myTexture;    // program parameter
uniform vec3 lightDir;          // program parameter
varying vec2 uv;                // per fragment value (interp. by rasterizer)
varying vec3 norm;              // per fragment value (interp. by rasterizer)

void diffuseShader()
{
  vec3 kd;
  kd = texture2d(myTexture, uv);                // material color from texture
  kd *= clamp(dot(–lightDir, norm), 0.0, 1.0);  // Lambertian shading model
  gl_FragColor = vec4(kd, 1.0);                 // output fragment color
}
```

Shader Programs

- Program vertex and fragment processing stages
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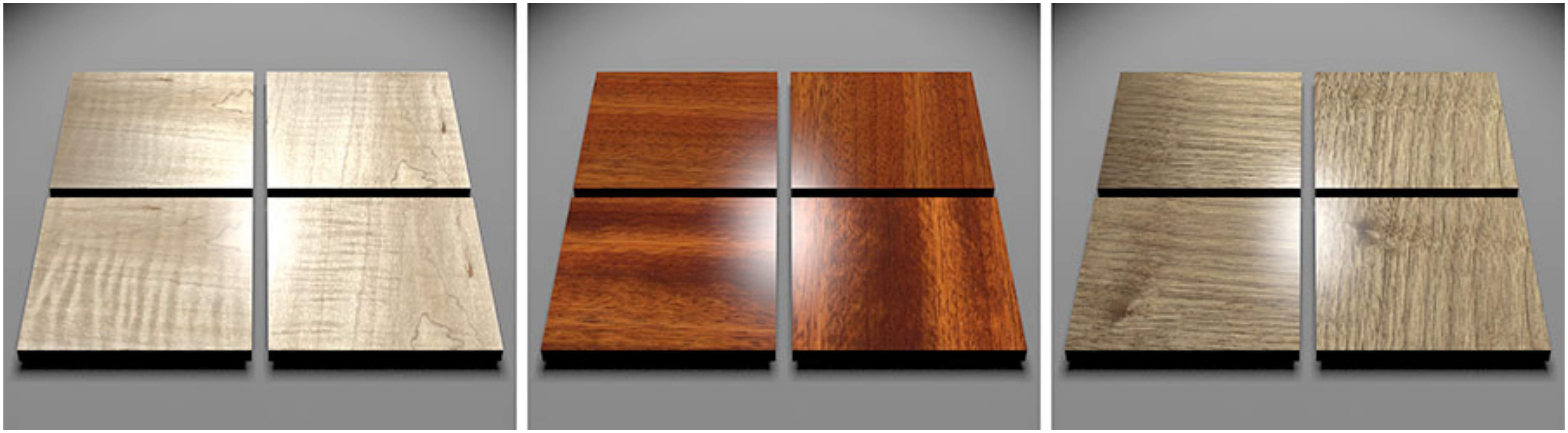
```

Shader Programs



Measuring and Modeling the Appearance of Finished Wood

Stephen R. Marschner, Stephen H. Westin, Adam Arbree, and Jonathan T. Moon.
In Proceedings of *SIGGRAPH 2005*. Held in Los Angeles, California, July 2005.

Code on GitHub: https://github.com/mckennapsean/wood-shader

Goal: Highly Complex 3D Scenes in Realtime

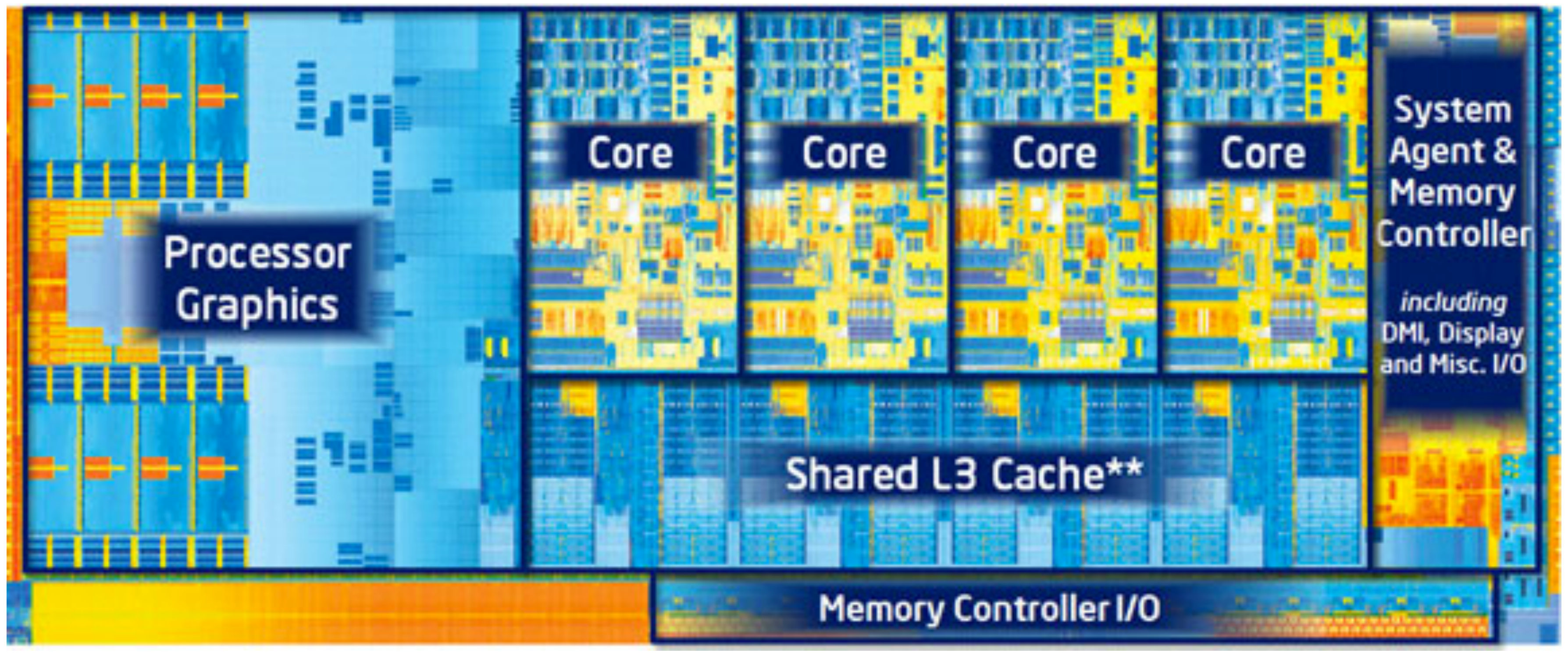
- 100's of thousands to millions of triangles in a scene
- Complex vertex and fragment shader computations
- High resolution (3-5+ megapixel + supersampling)
- 30-60 frames per second (even higher for VR)

Unreal Engine Kite Demo (Epic Games 2015)

Graphics Pipeline Implementation: GPUs

Specialized processors for executing graphics pipeline computations

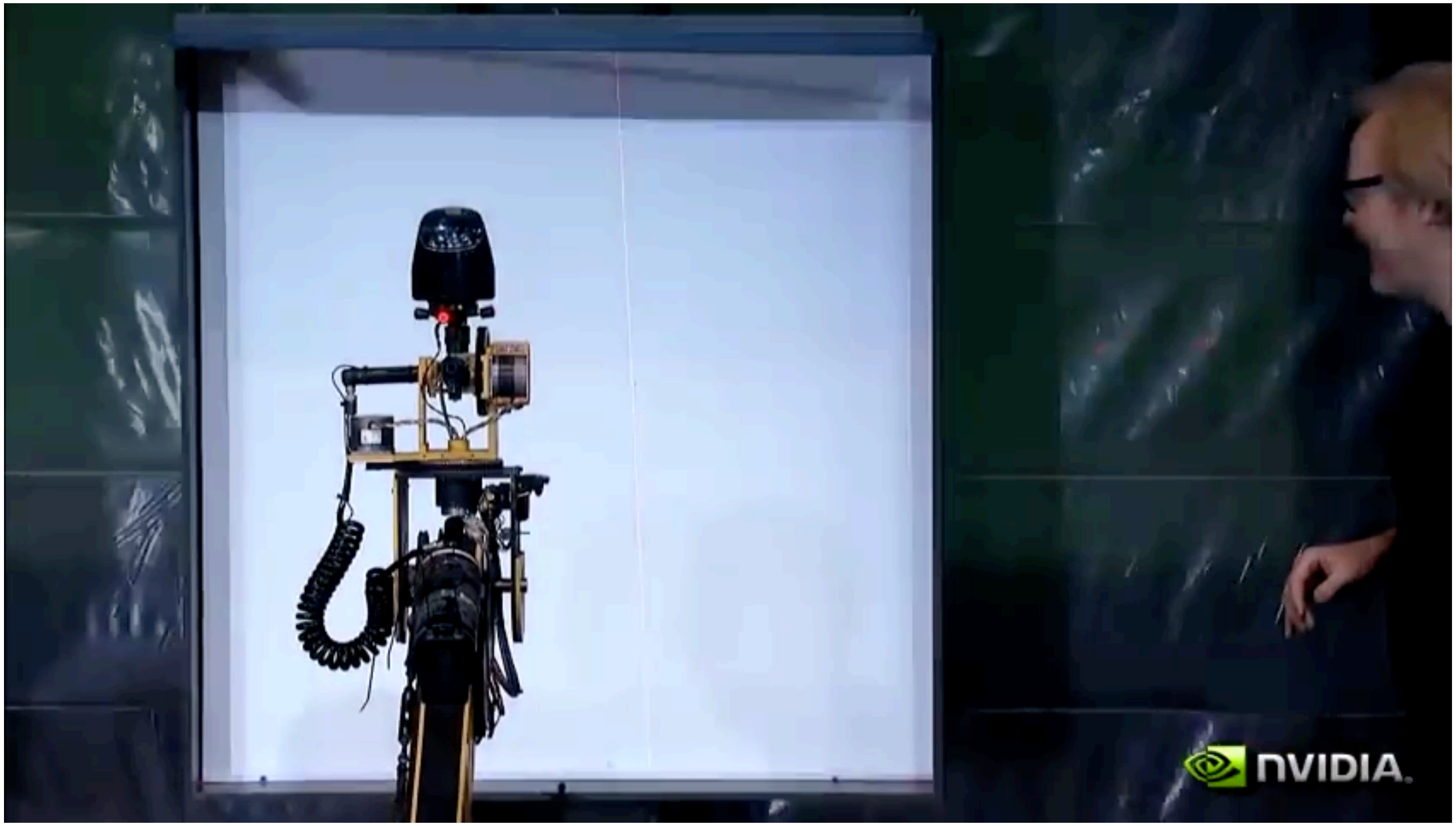
Discrete GPU Card
(NVIDIA GeForce Titan X)



Integrated GPU:
(Part of Intel CPU die)

CPU vs GPU

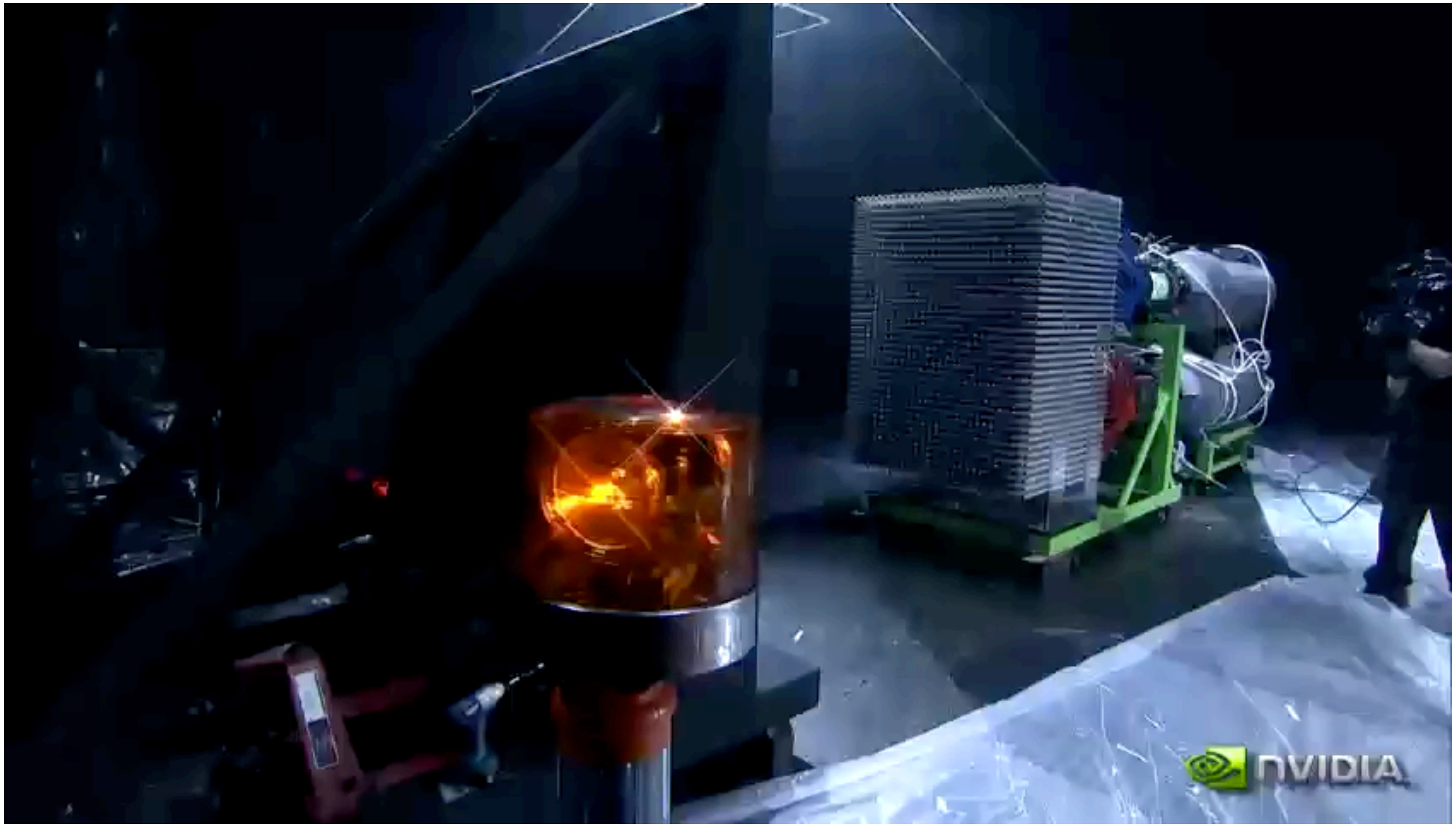
CPU



https://www.youtube.com/watch?v=ZrJeYFxpUyQ

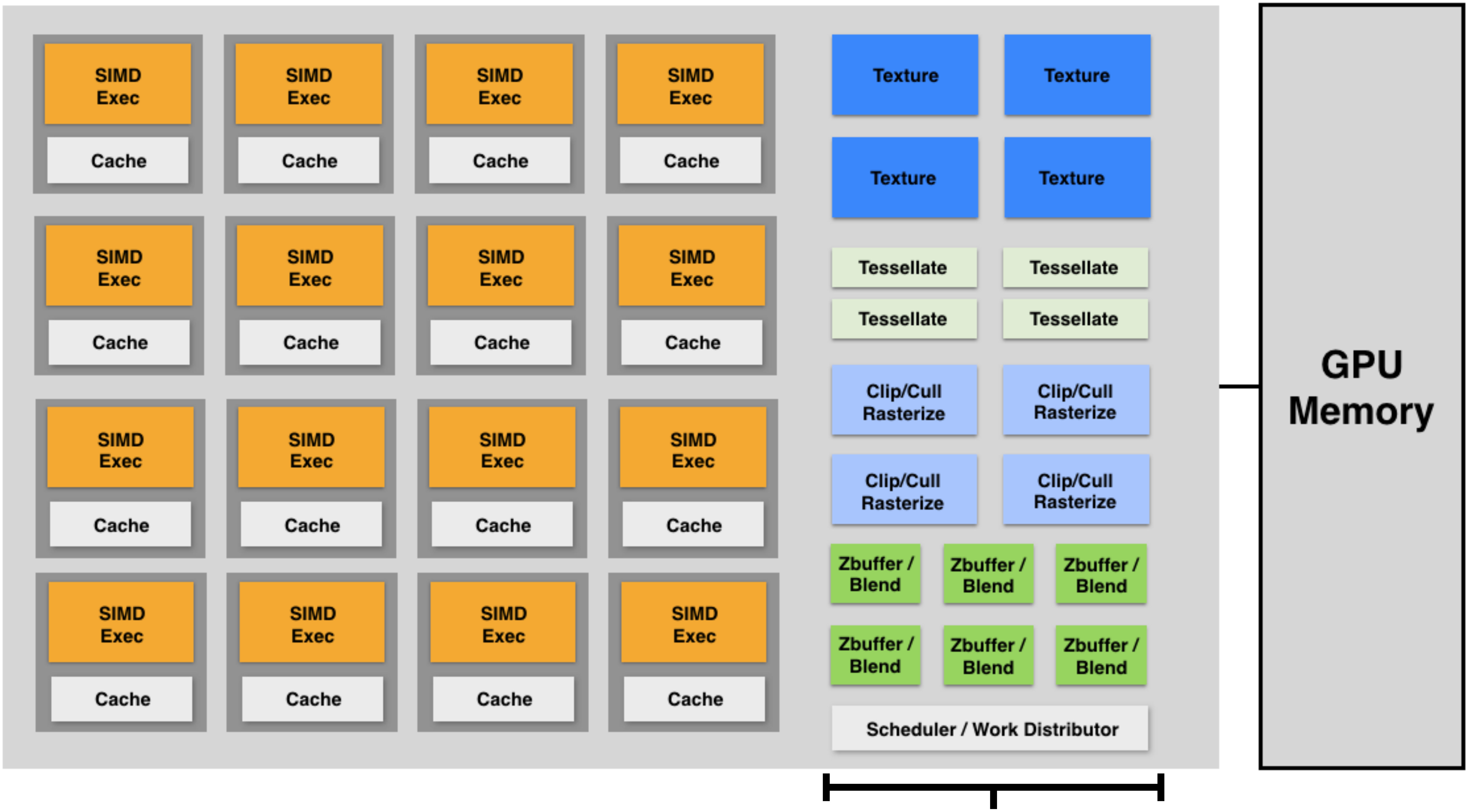
CPU vs GPU

GPU



https://www.youtube.com/watch?v=ZrJeYFxpUyQ

GPU: Heterogeneous, Multi-Core Procesor



Modern GPUs offer ~2-4 Tera-FLOPs of performance for executing vertex and fragment shader programs

Tera-Op's of fixed-function compute capability over here

Things to Remember

Visibility

- Painter's algorithm and Z-Buffer algorithm

Simple Shading Model

- Key geometry: lighting, viewing & normal vectors
- Ambient, diffuse & specular reflection functions
- Shading frequency: triangle, vertex or fragment

Graphics Rasterization Pipeline

- Where do transforms, rasterization, shading, texturing and visibility computations occur?
- GPU = parallel processor implementing graphics pipeline

Acknowledgments

This slide set contain contributions from:

- Kayvon Fatahalian
- David Forsyth
- Pat Hanrahan
- Angjoo Kanazawa
- Ren Ng
- James O'Brien
- Mark Pauly