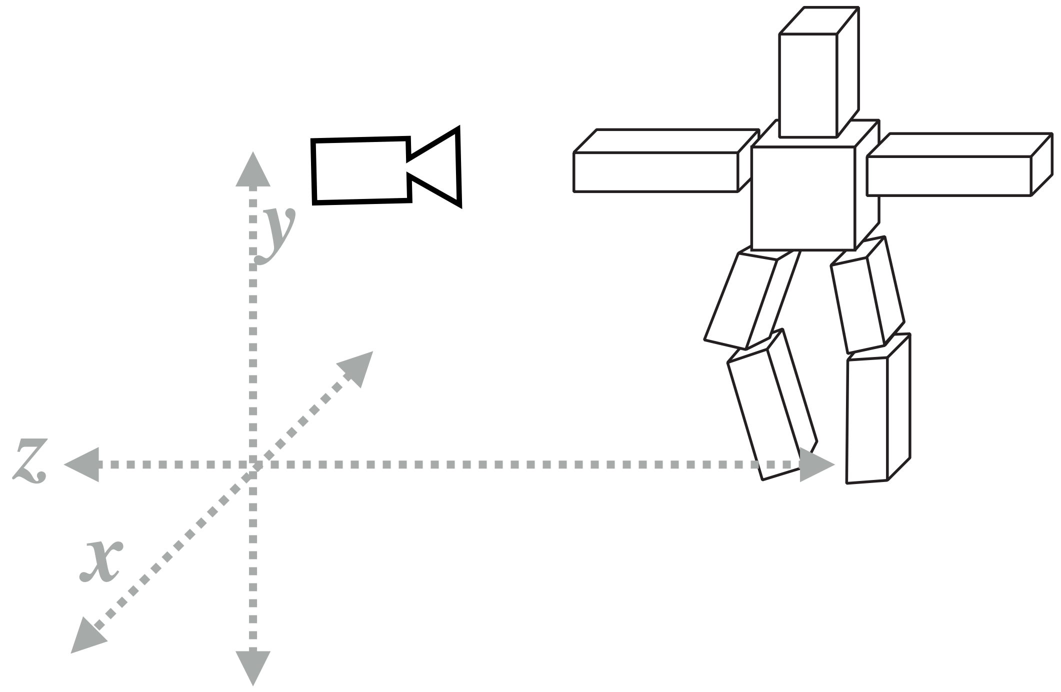
Lecture 6:

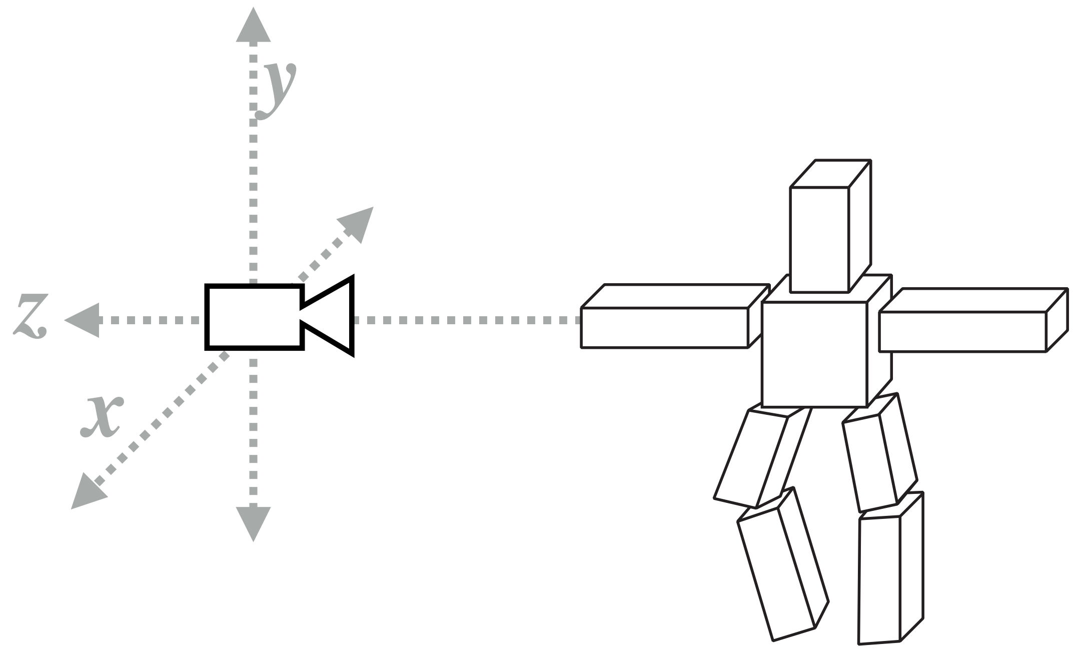
The Rasterization Pipeline

Computer Graphics and Imaging
UC Berkeley CS184/284A

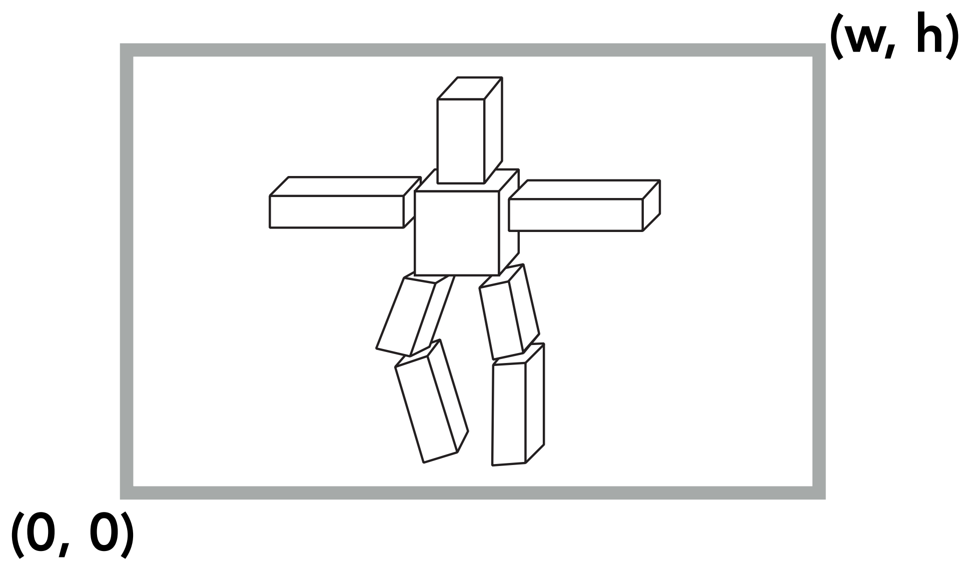
What We’ve Covered So Far



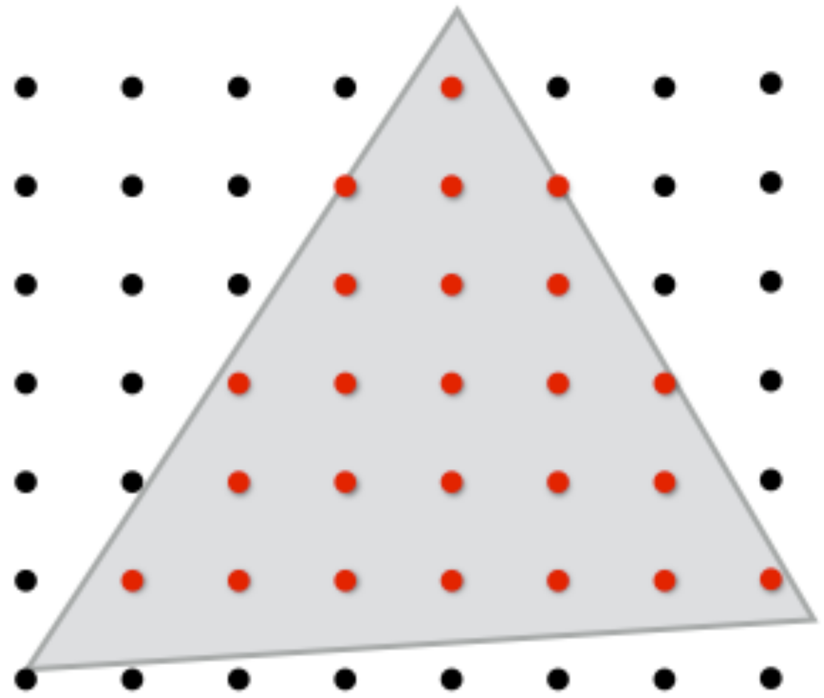
Position objects and the camera in the world



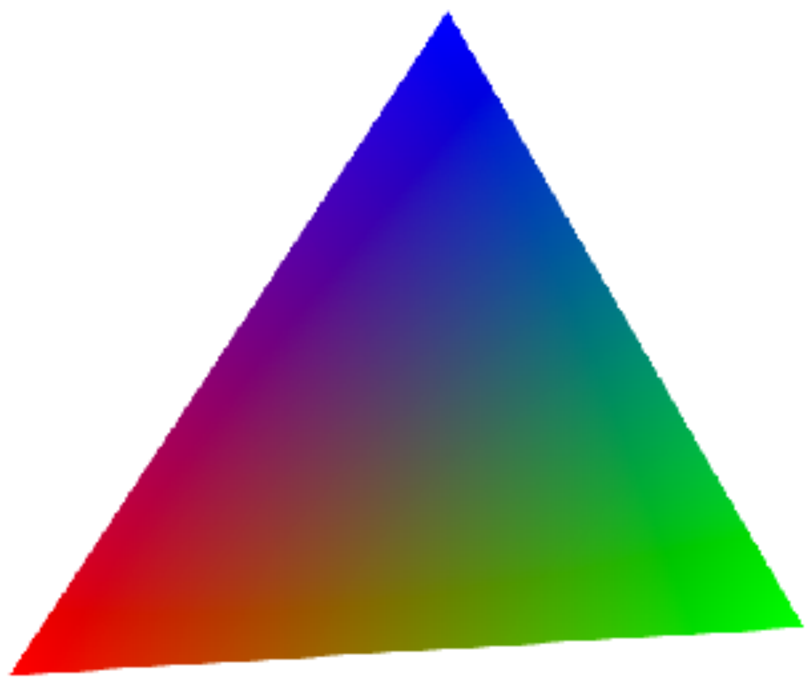
Compute position of objects relative to the camera



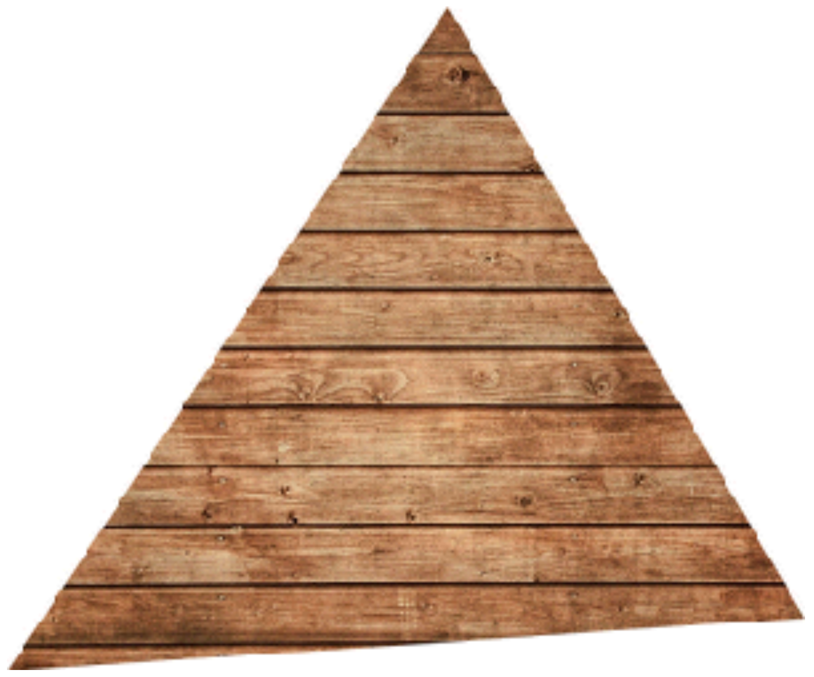
Project objects onto the screen



Sample triangle coverage

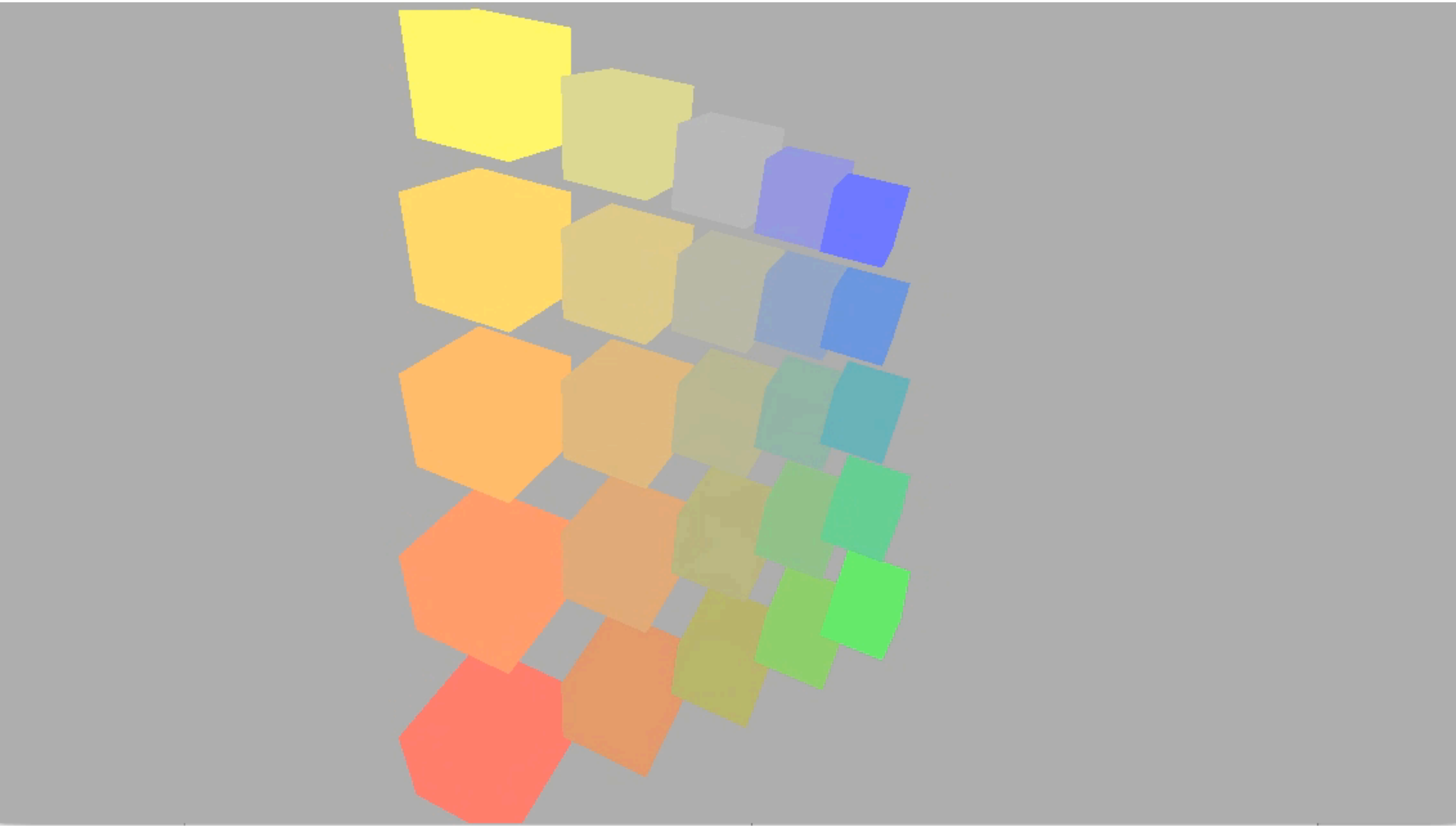


Interpolate triangle attributes

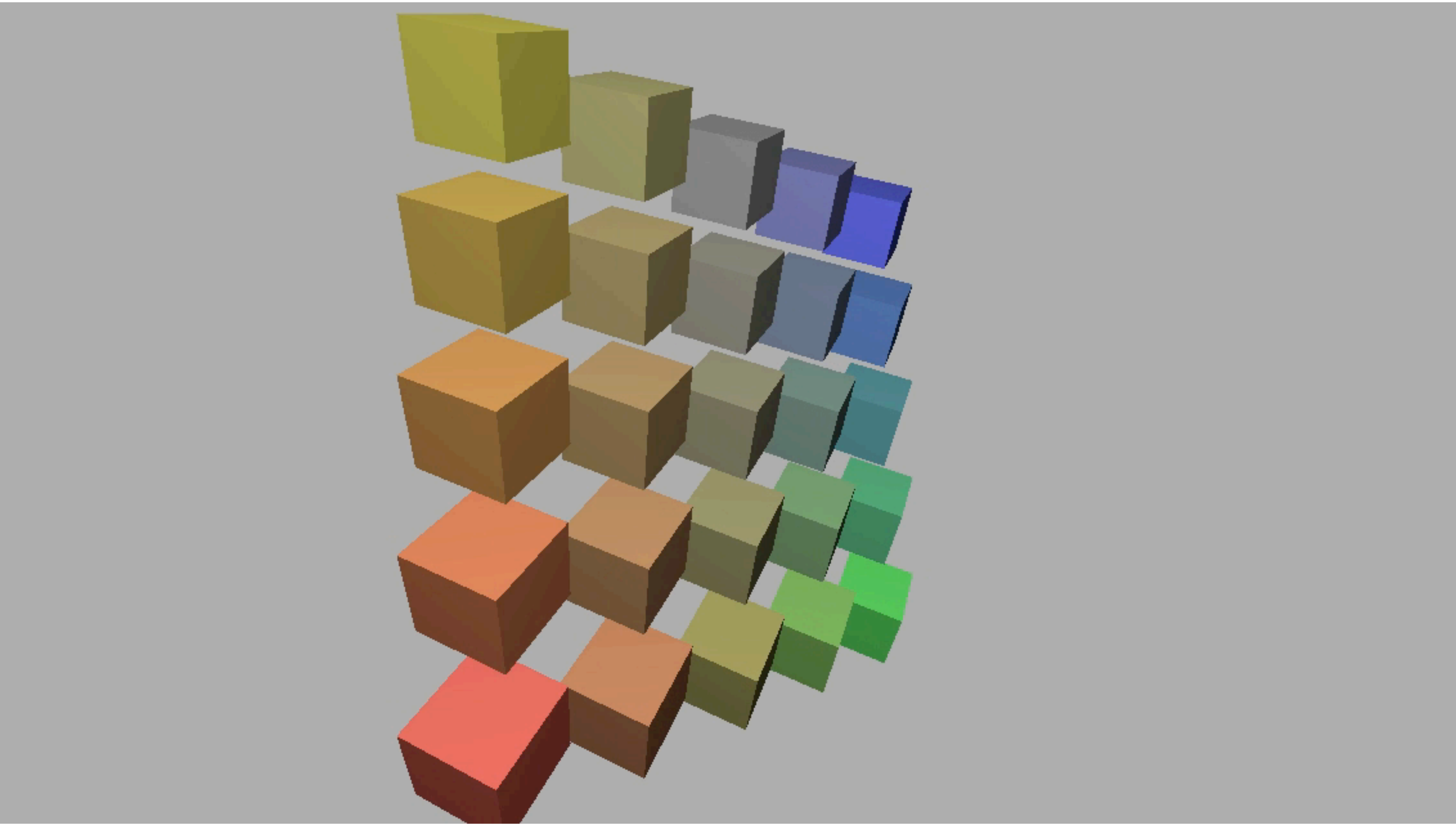


Sample texture maps

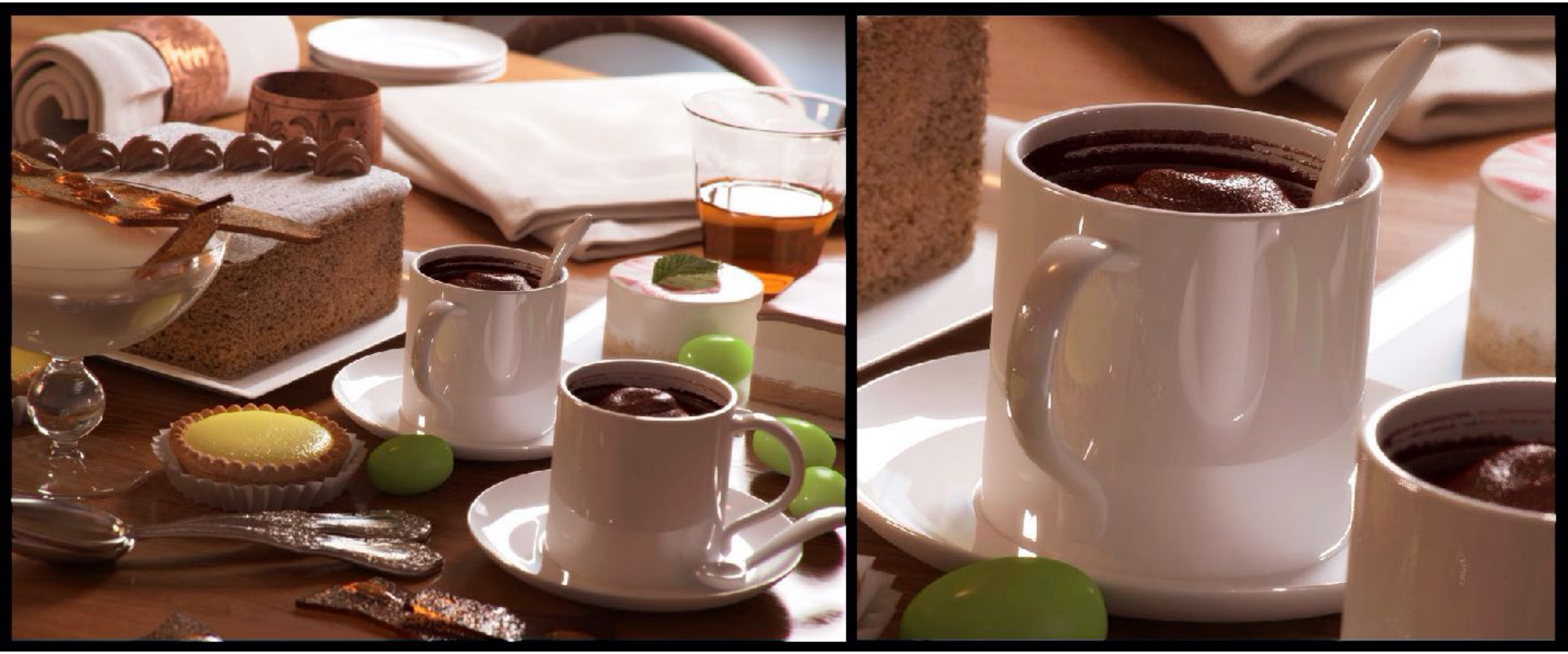
Rotating Cubes in Perspective



Rotating Cubes in Perspective



What Else Are We Missing?



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

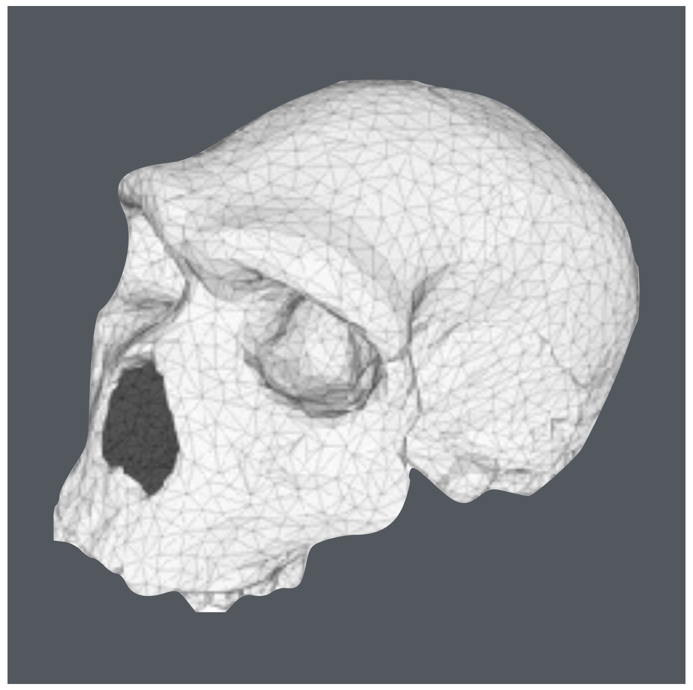
What Else Are We Missing?

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

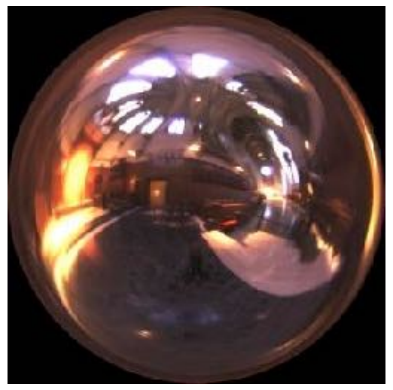
Core Concepts

- Sampling
- Antialiasing
- Transforms

- Intro
- Rasterization
- Transforms & Projection
- Texture Mapping
- Today: Visibility, Shading, Overall Pipeline

Geometric Modeling

Lighting & Materials



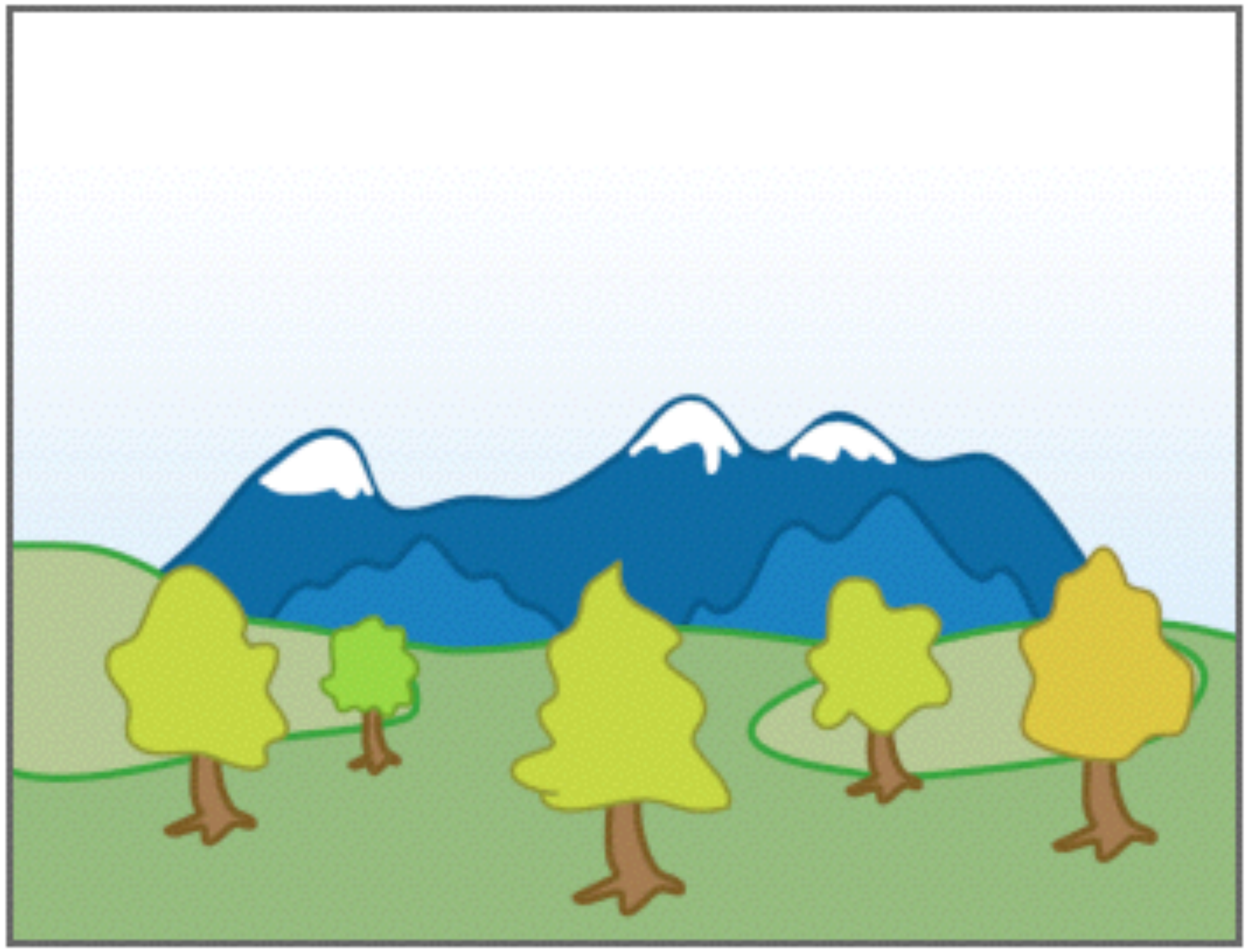
Cameras & Imaging

Visibility

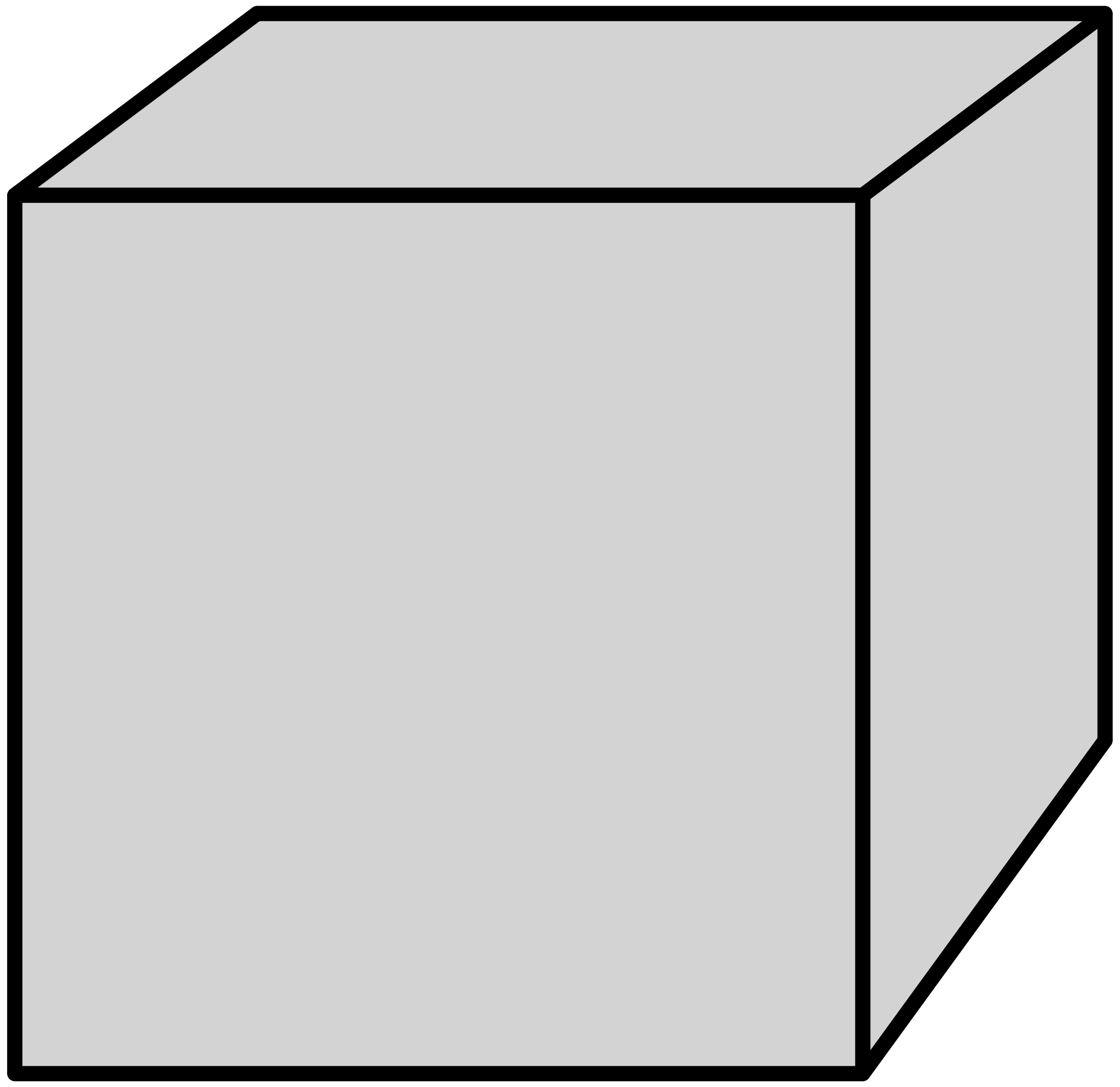
Painter's Algorithm

Inspired by how painters paint

Paint from back to front, overwrite in the framebuffer



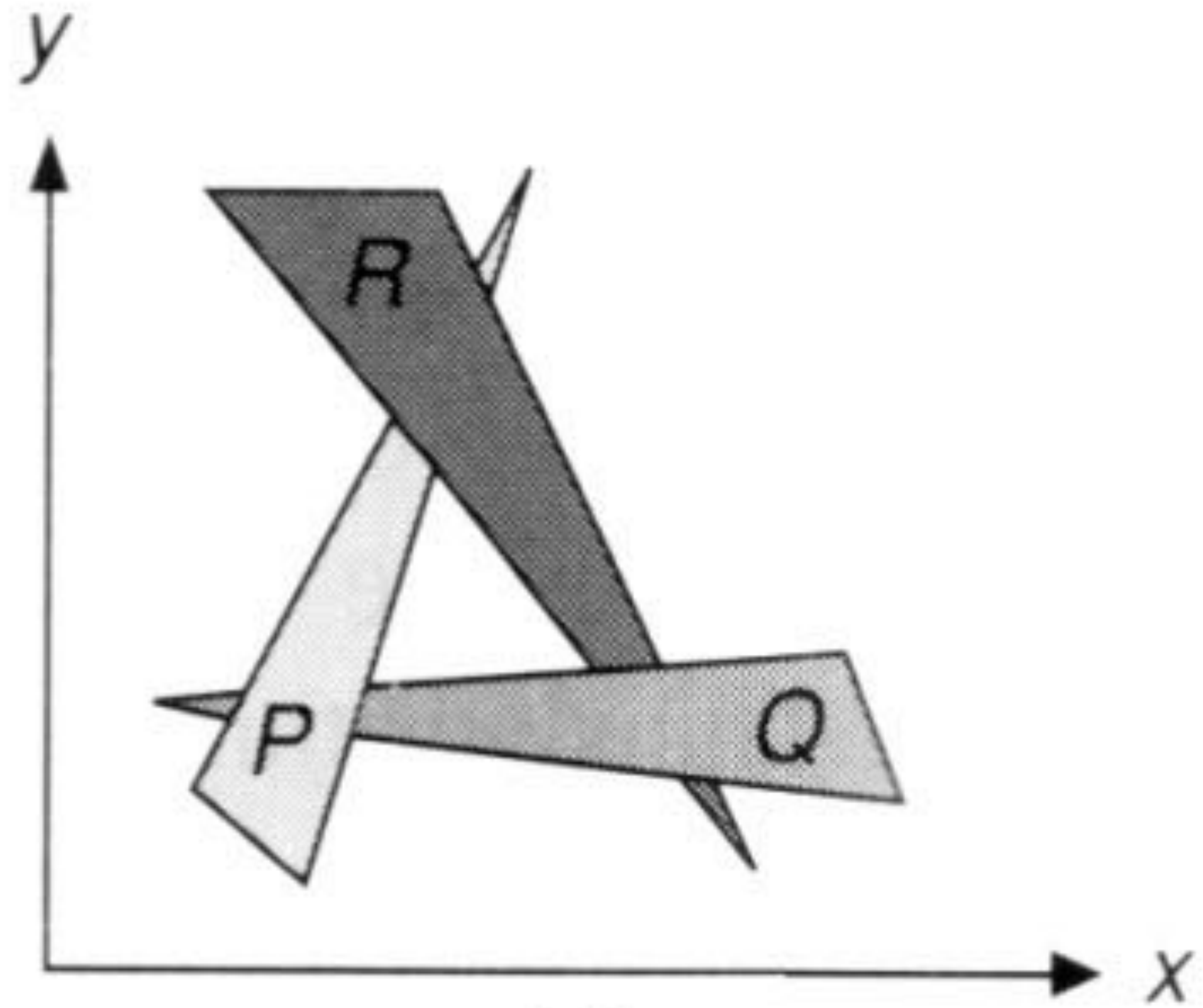
[Wikipedia]



Painter's Algorithm

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

Can have unresolvable depth order



[Foley et al.]

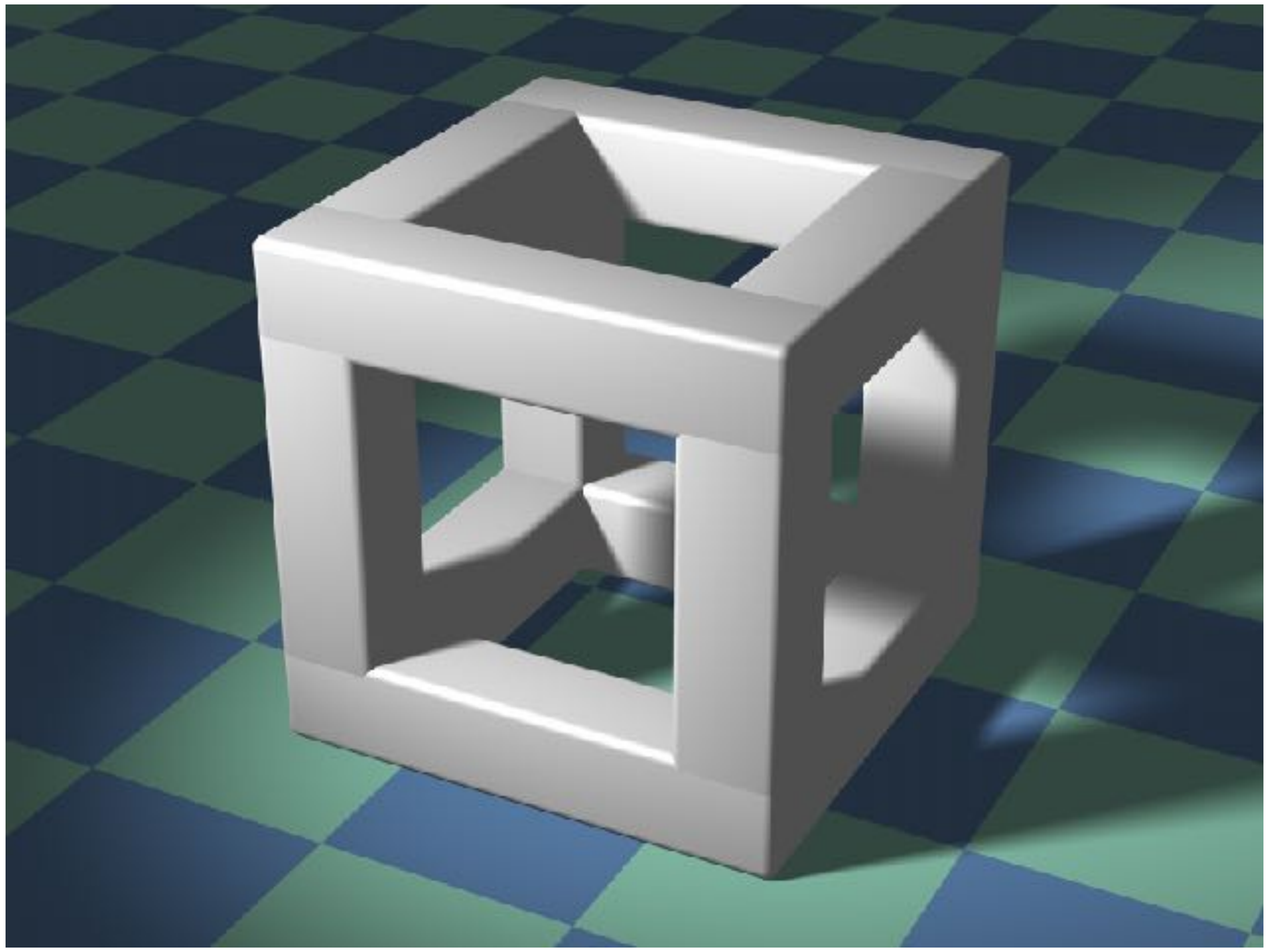
Z-Buffer

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

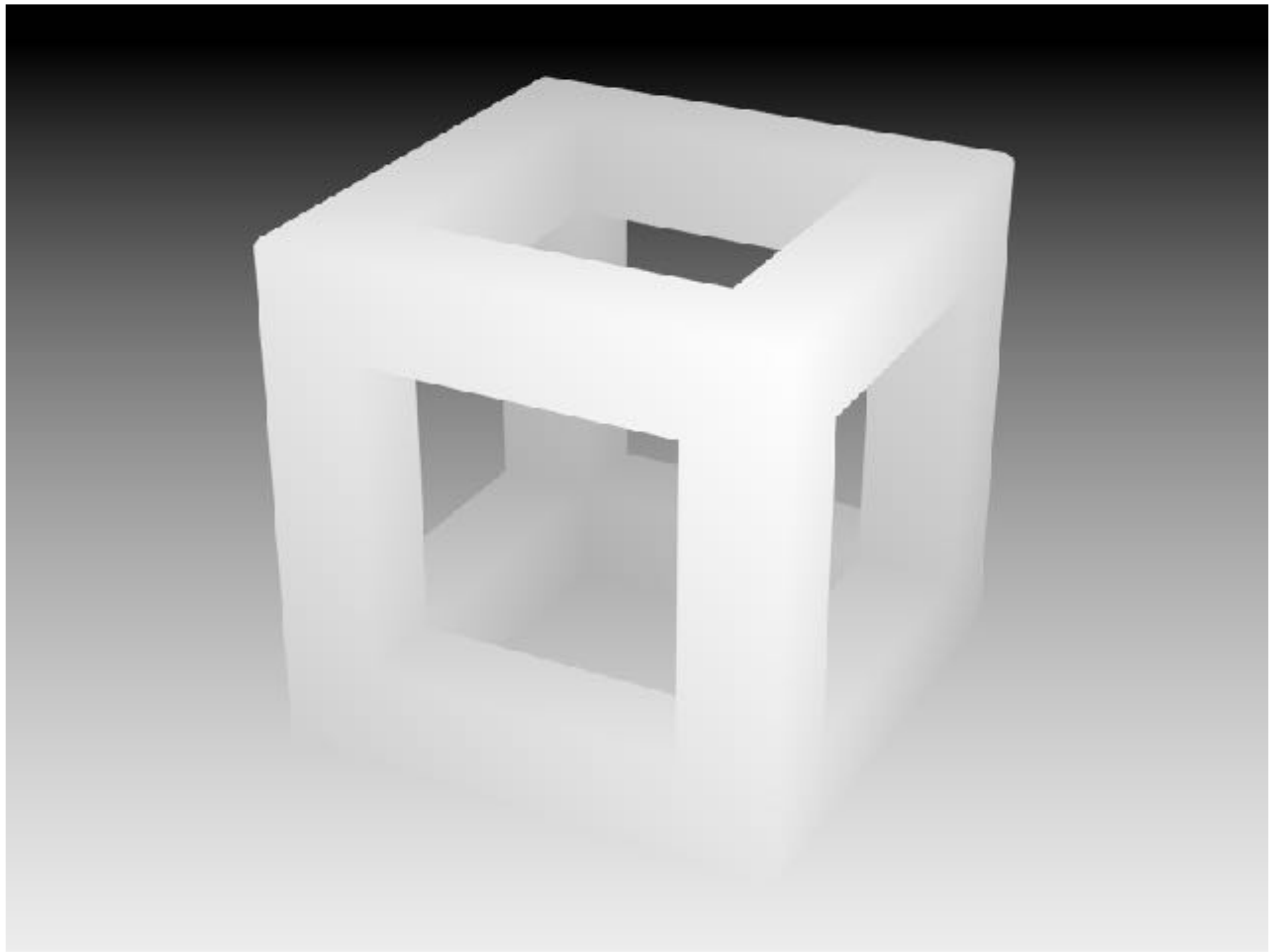
Idea:

- 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.

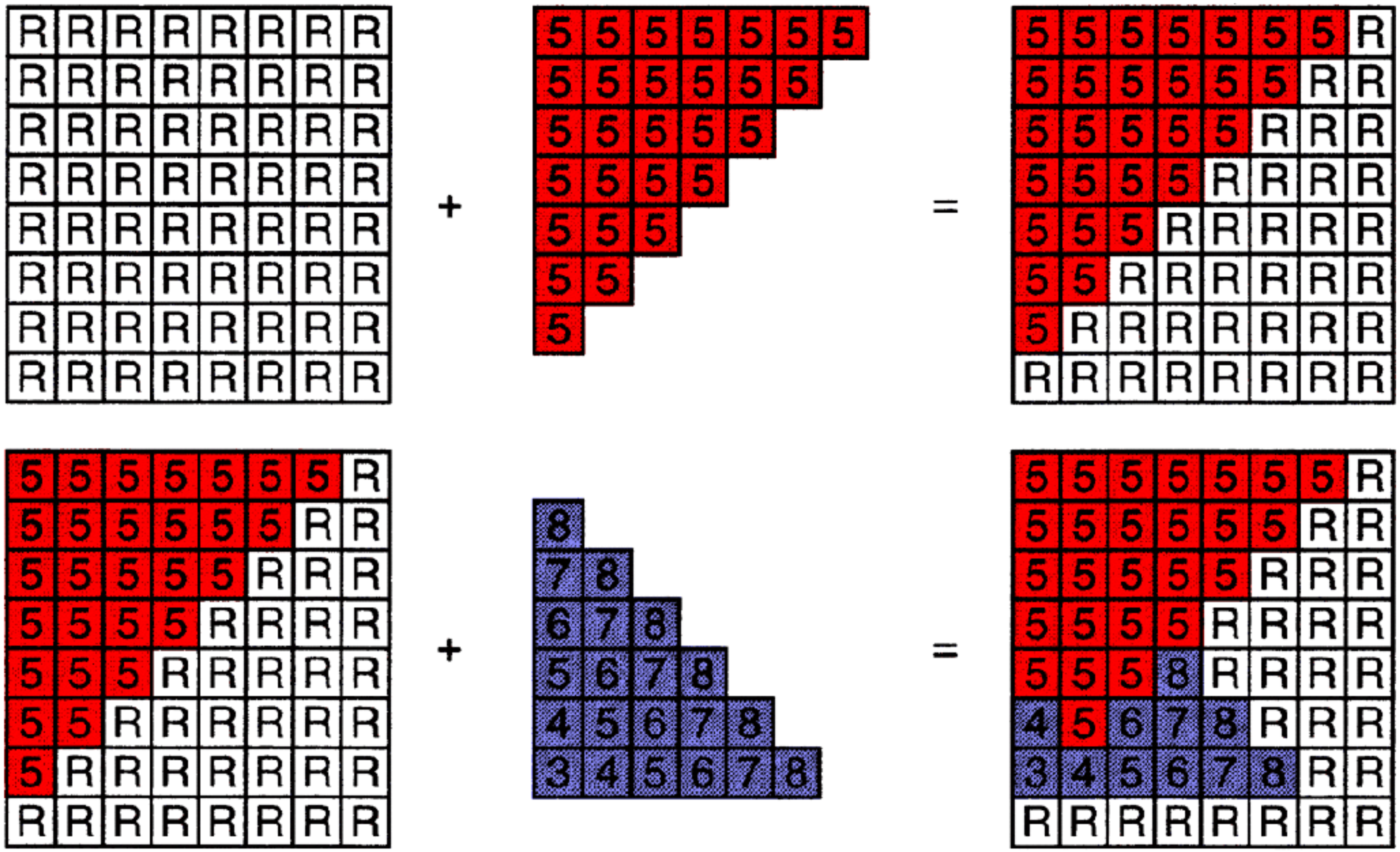
Z-Buffer Algorithm

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

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

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

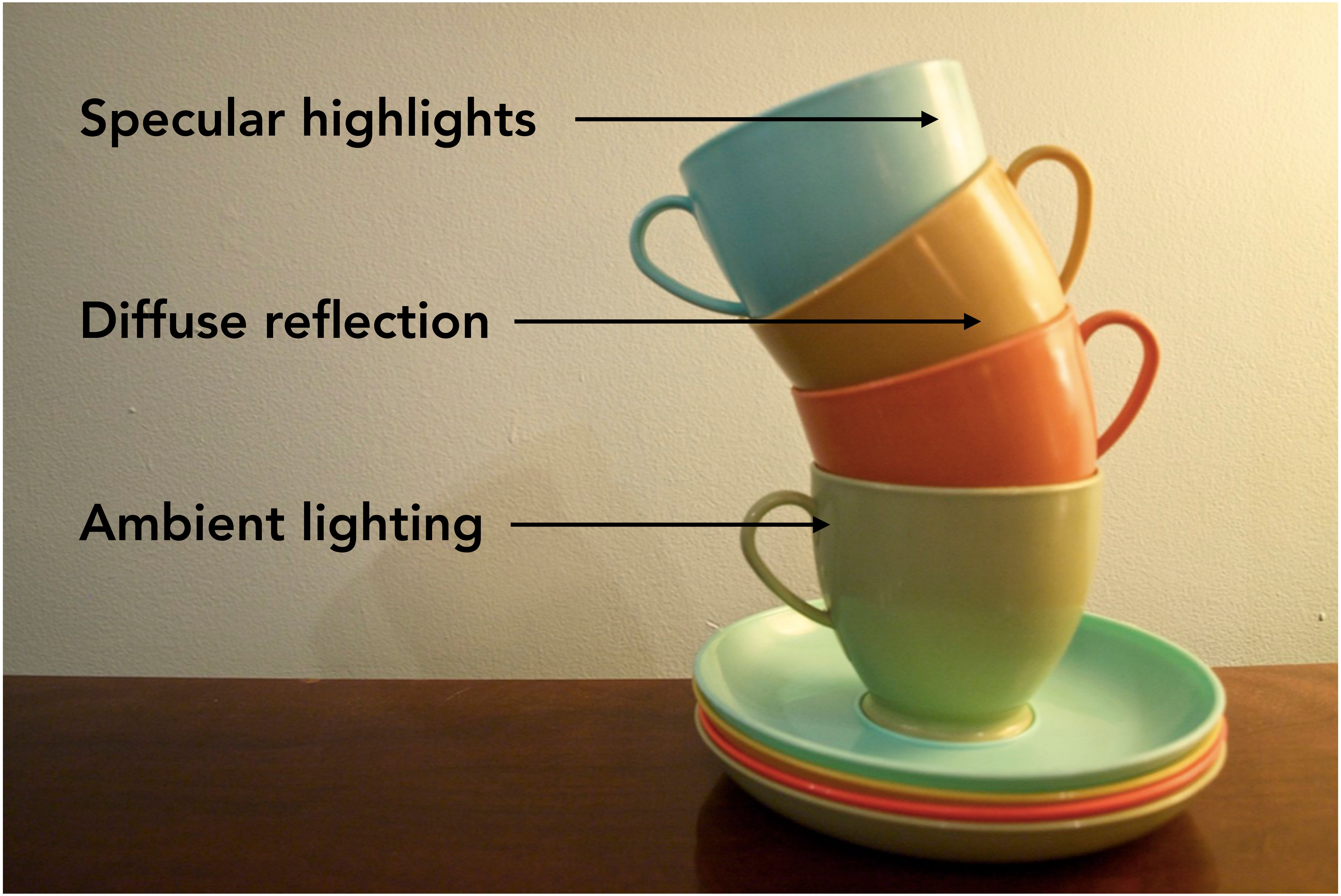


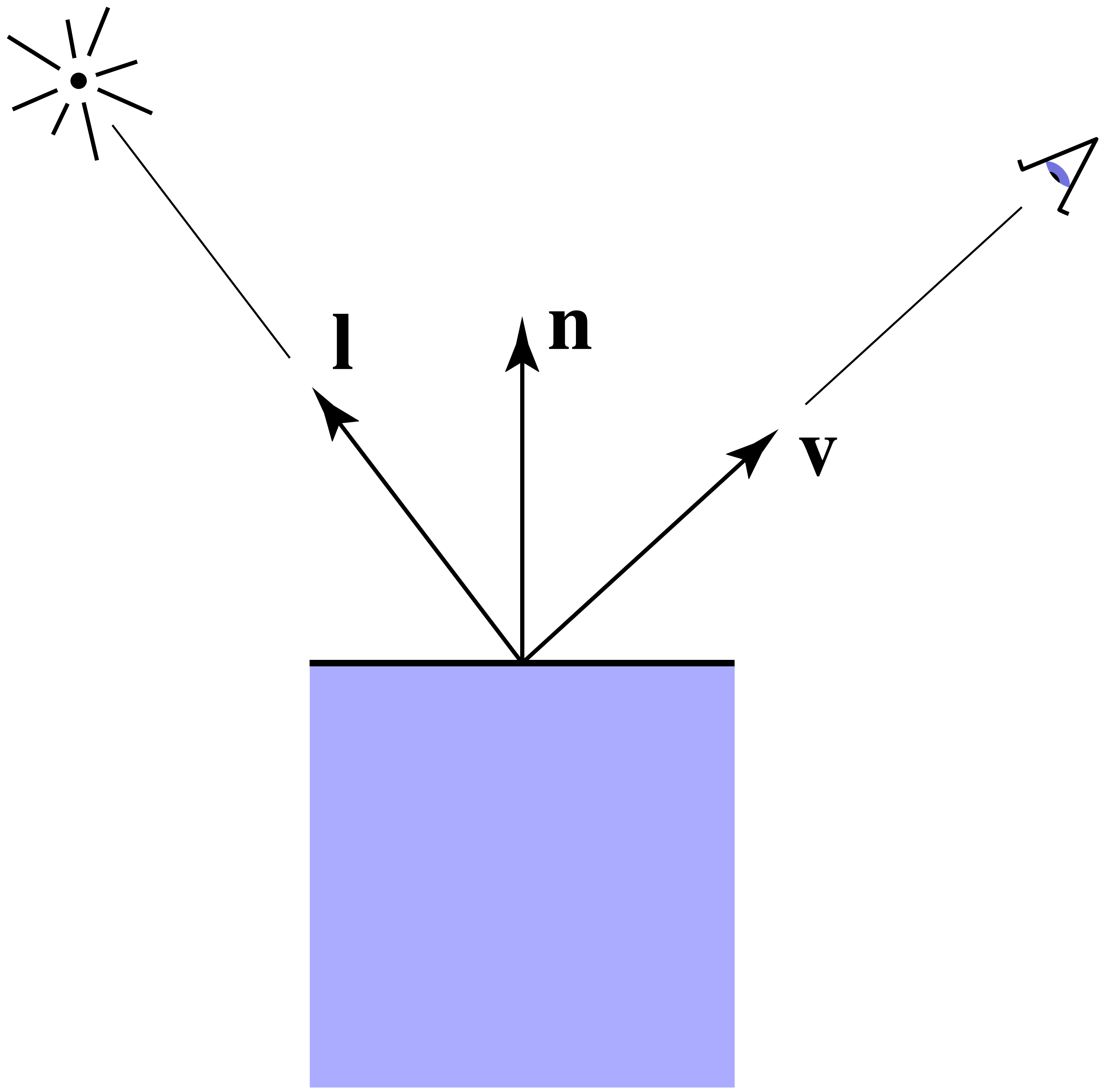
Photo credit: Jessica Andrews, flickr

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, …)

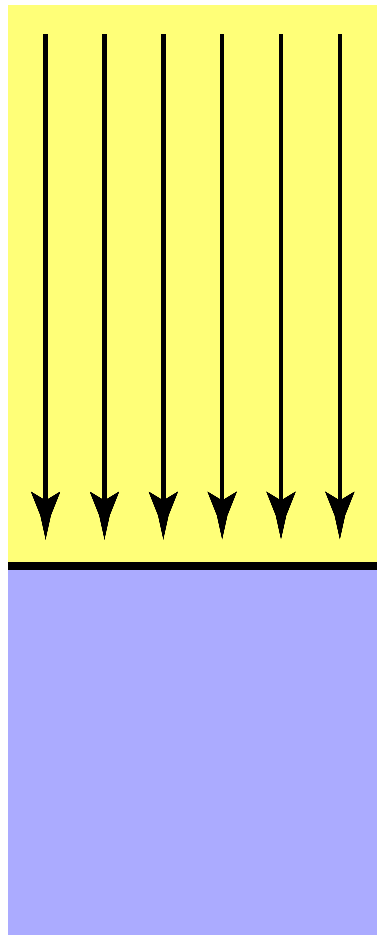


Diffuse Reflection

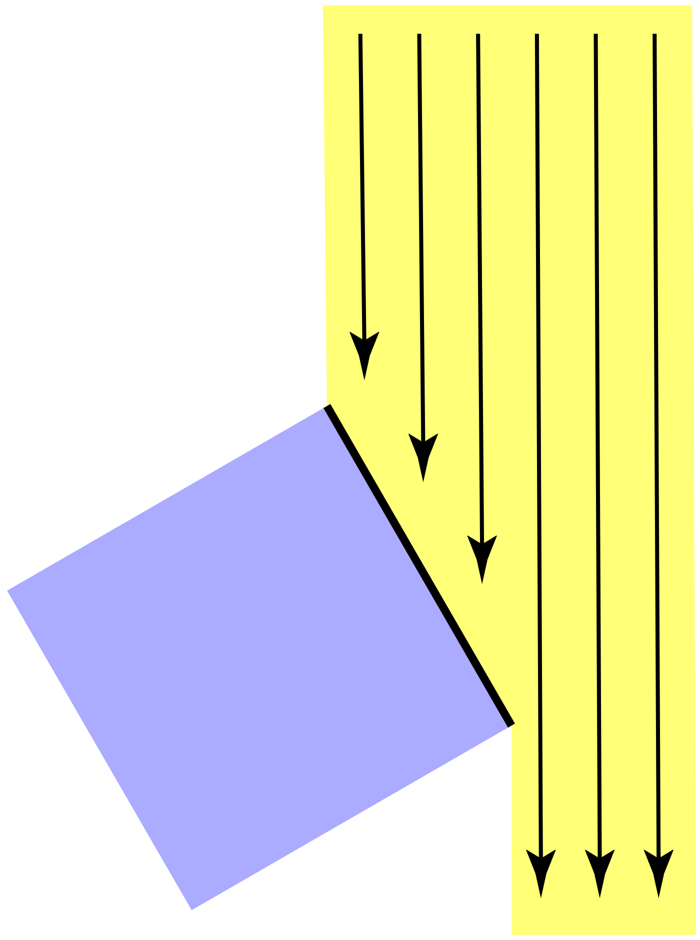
Light is scattered uniformly in all directions

- Surface color is the same for all viewing directions

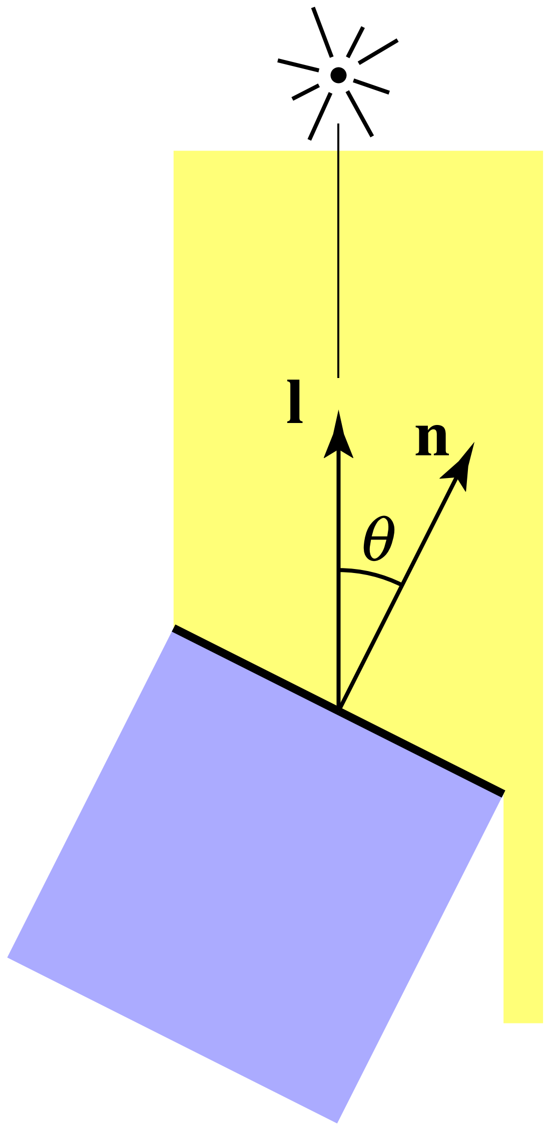
Lambert's cosine law



Top face of cube receives a certain amount of light

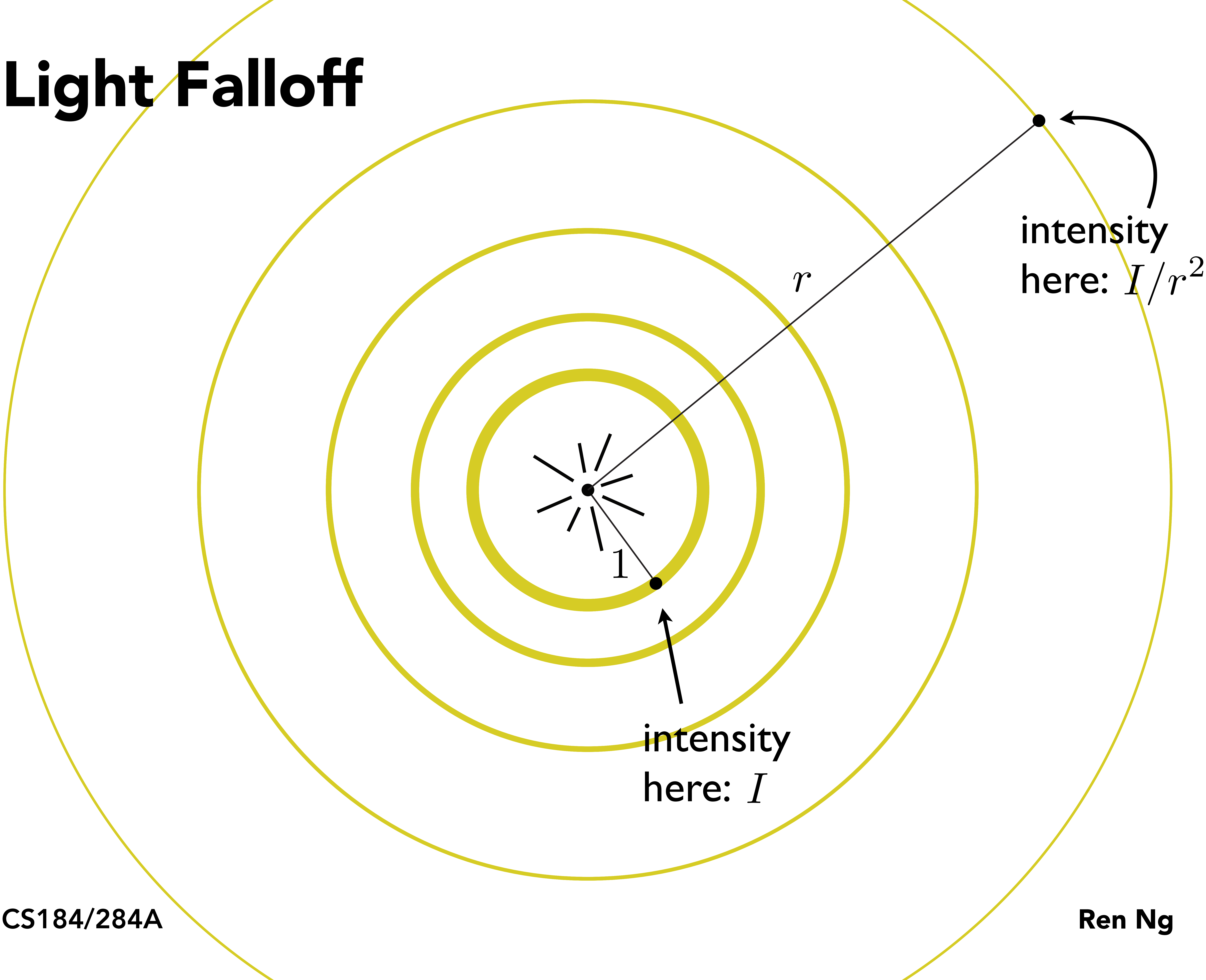


Top face of 60° rotated cube intercepts half the light

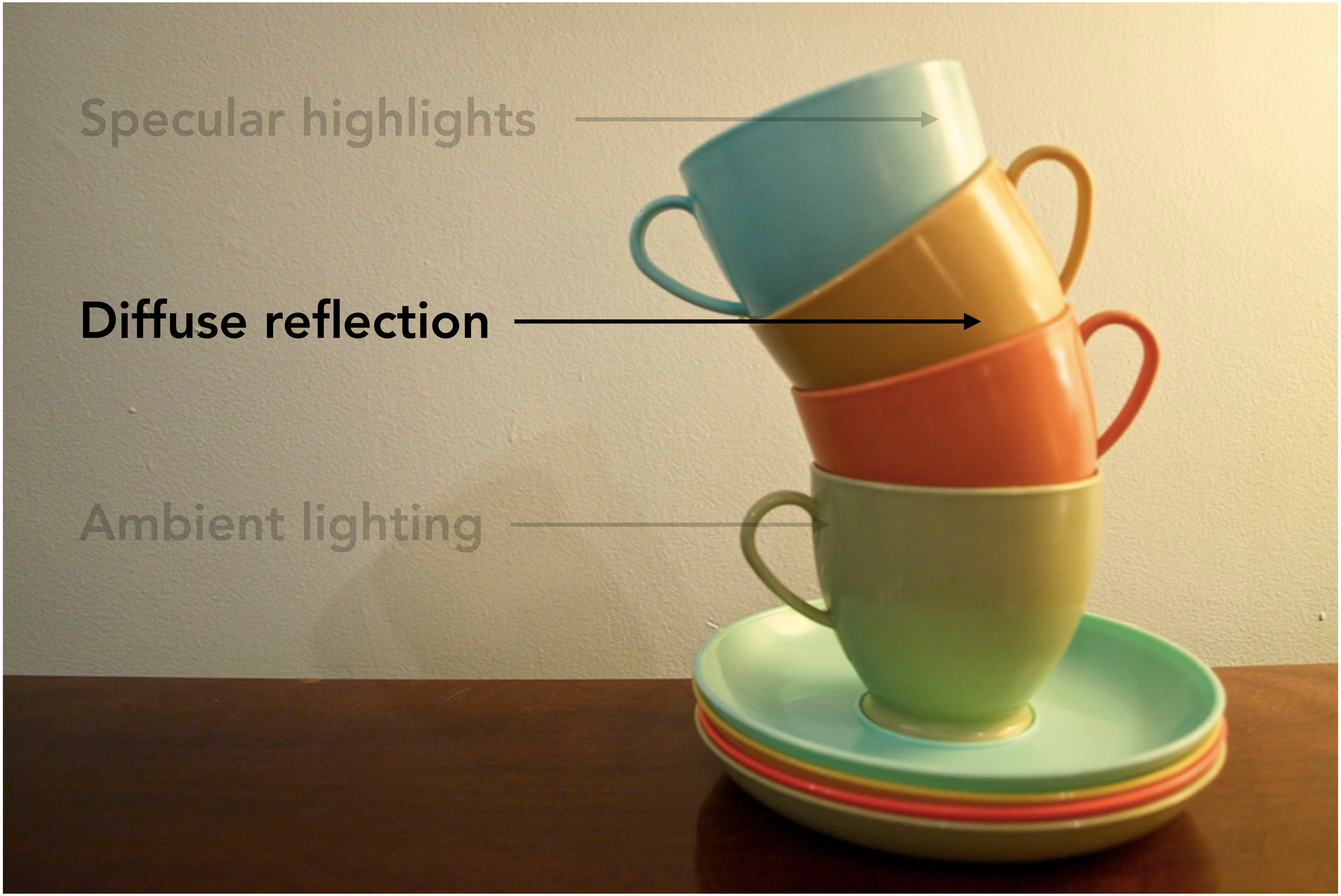


In general, light per unit area is proportional to cos θ = **l • n**

Light Falloff



Perceptual Observations



Specular highlights

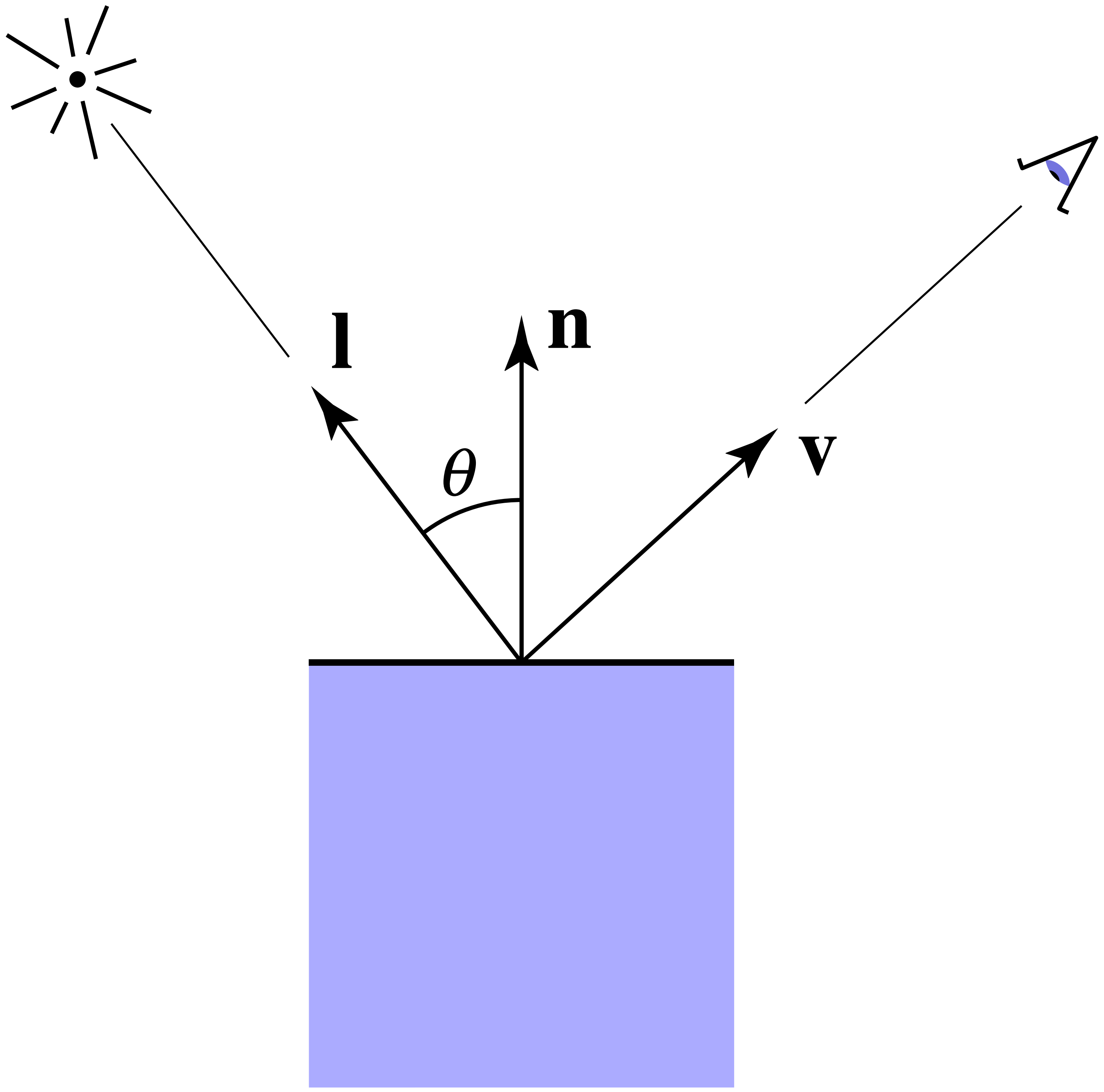
Diffuse reflection

Ambient lighting

Photo credit: Jessica Andrews, flickr

Lambertian (Diffuse) Shading

Shading independent of view direction



illumination from source

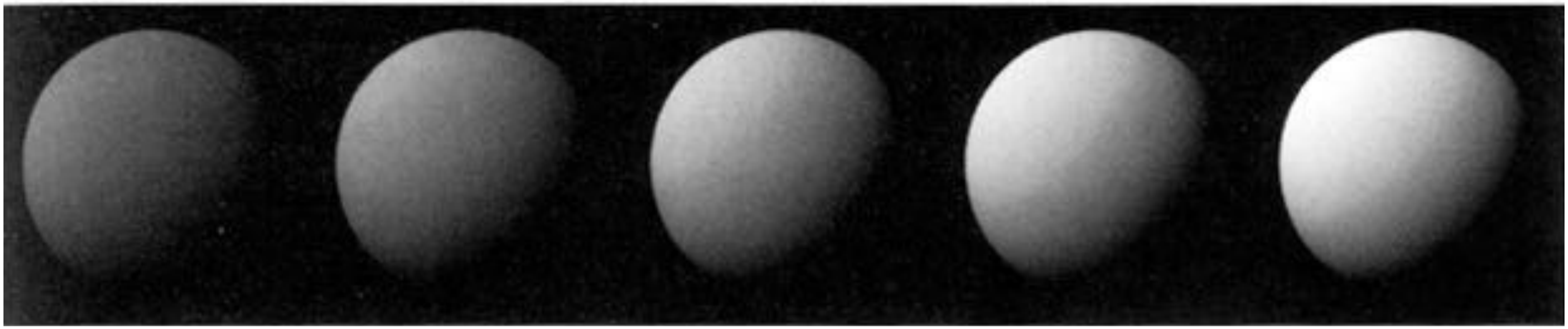
$$L_d = k_d\,(I/r^2)\max(0, \mathbf{n}\cdot\mathbf{l})$$

diffuse coefficient

diffusely reflected light

Lambertian (Diffuse) Shading

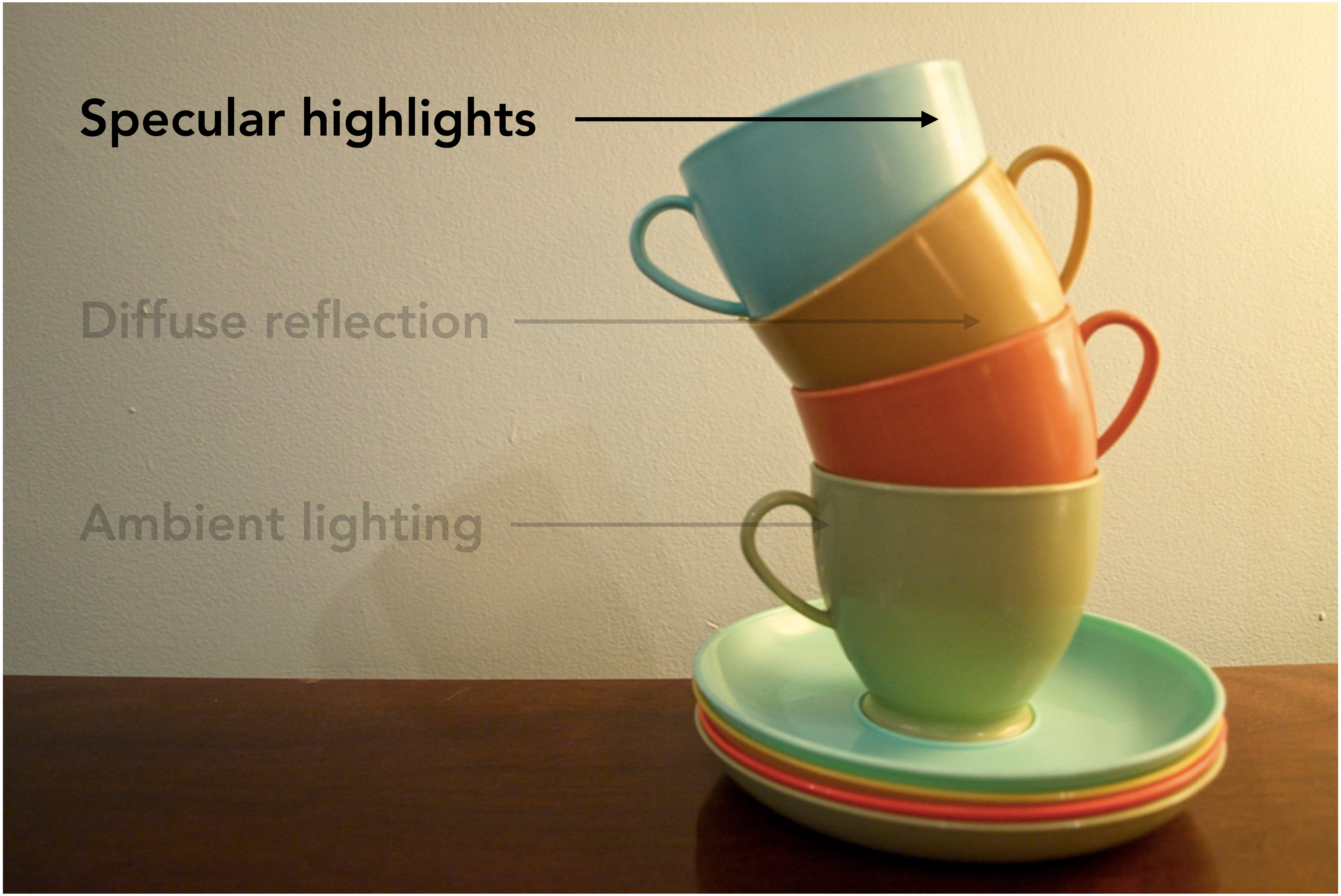
Produces matte appearance



$k_d \longrightarrow$

[Foley et al.]

Perceptual Observations



Specular highlights

Diffuse reflection

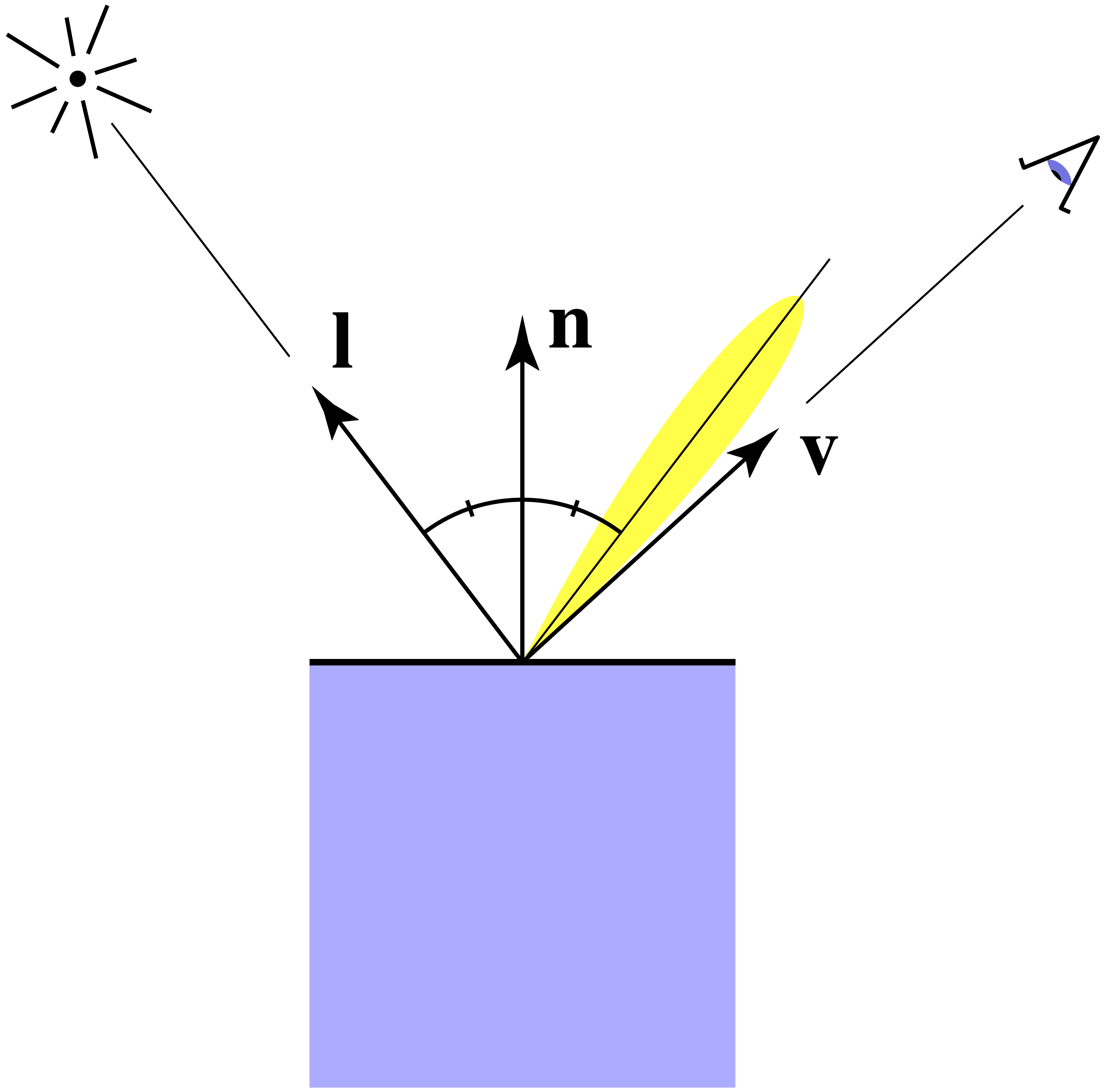
Ambient lighting

Photo credit: Jessica Andrews, flickr

Specular Shading (Blinn-Phong)

Intensity depends on view direction

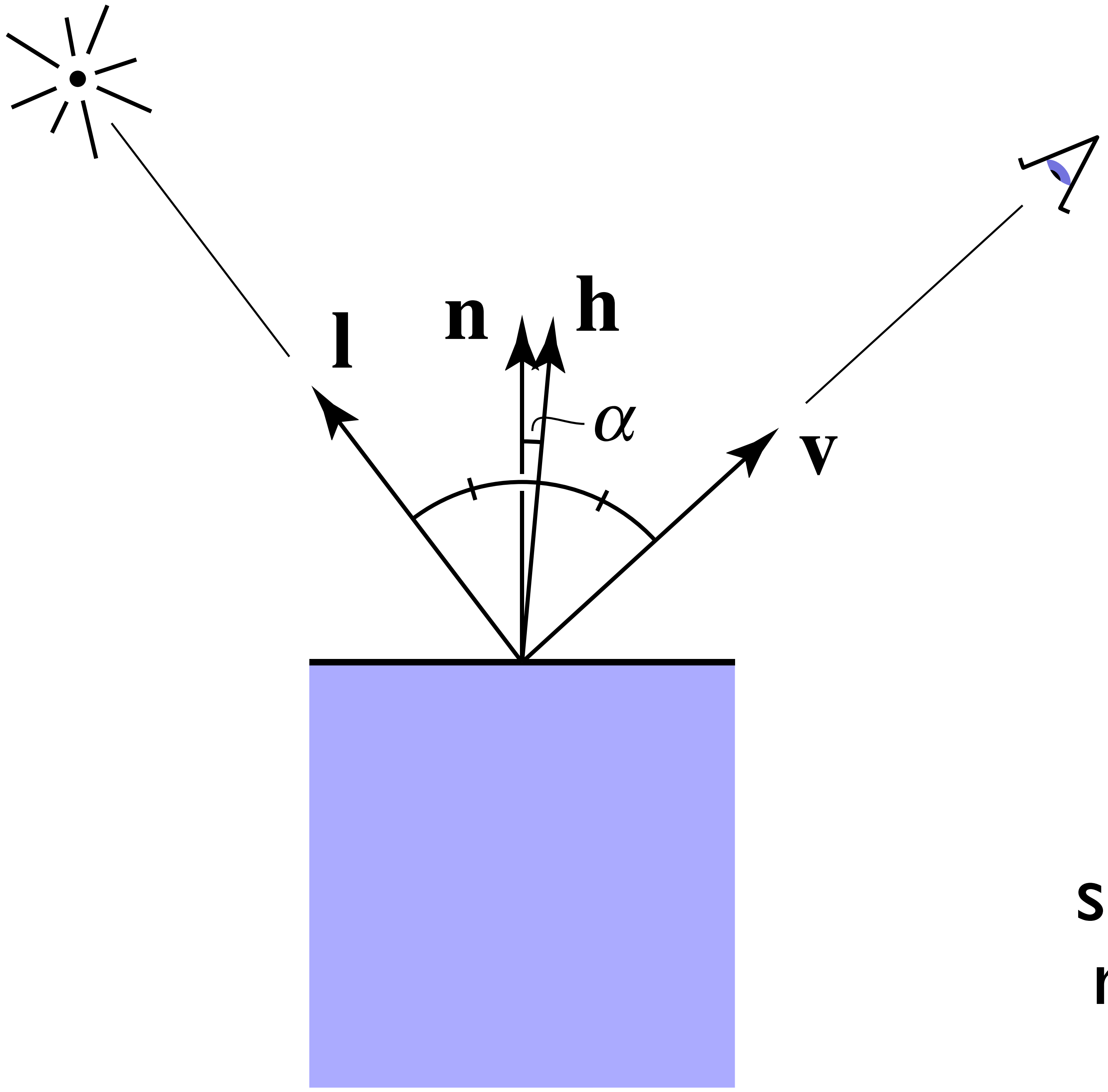
- Bright near mirror reflection direction



Specular Shading (Blinn-Phong)

Close to mirror direction ⇔ half vector near normal

- Measure "near" by dot product of unit vectors

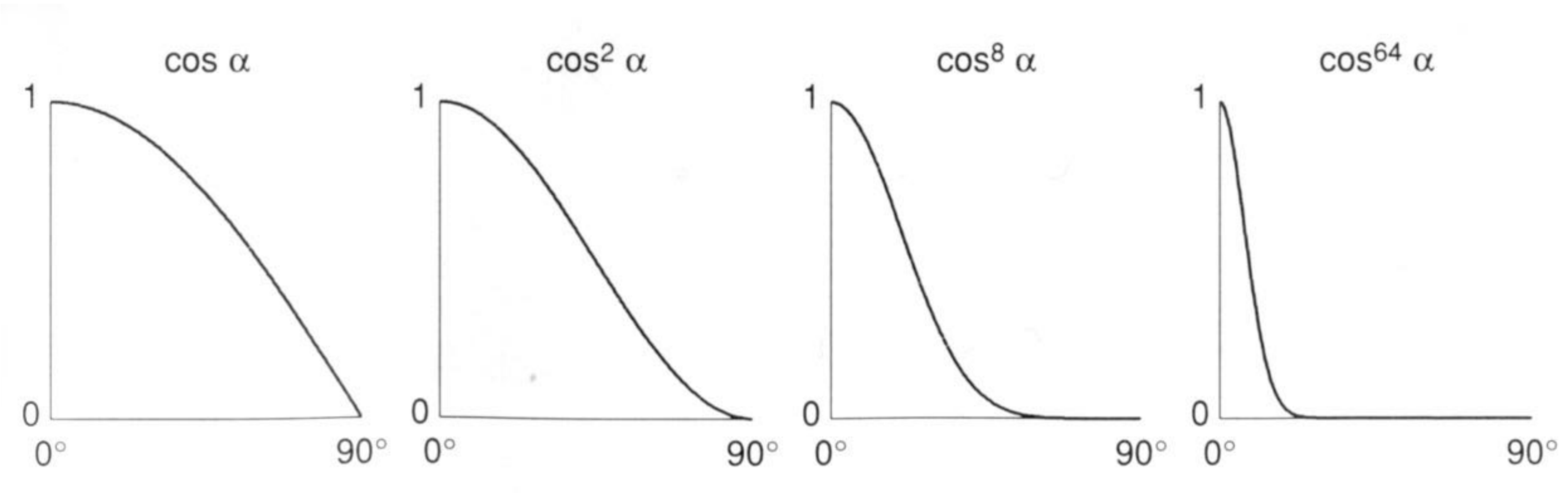


$$\mathbf{h} = \text{bisector}(\mathbf{v}, \mathbf{l}) = \frac{\mathbf{v} + \mathbf{l}}{\|\mathbf{v} + \mathbf{l}\|}$$

$$\underset{\uparrow \text{ specularly reflected light}}{L_s} = k_s\,(I/r^2)\max(0, \cos\alpha)^p = \underset{\uparrow \text{ specular coefficient}}{k_s}\,(I/r^2)\max(0, \mathbf{n}\cdot\mathbf{h})^p$$

Cosine Power Plots

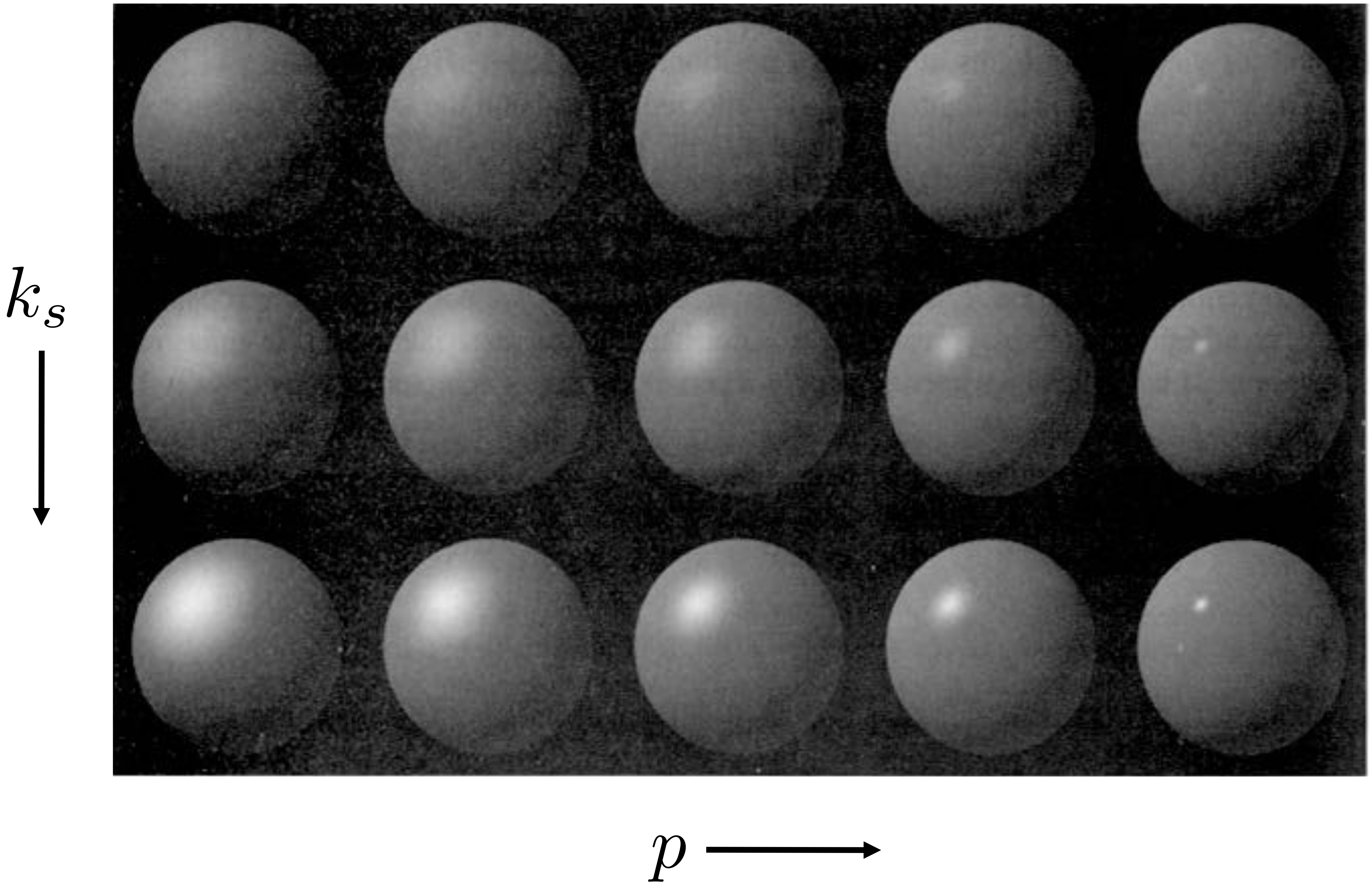
Increasing p narrows the reflection lobe



[Foley et al.]

Specular Shading (Blinn-Phong)

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



[Foley et al.]

Perceptual Observations

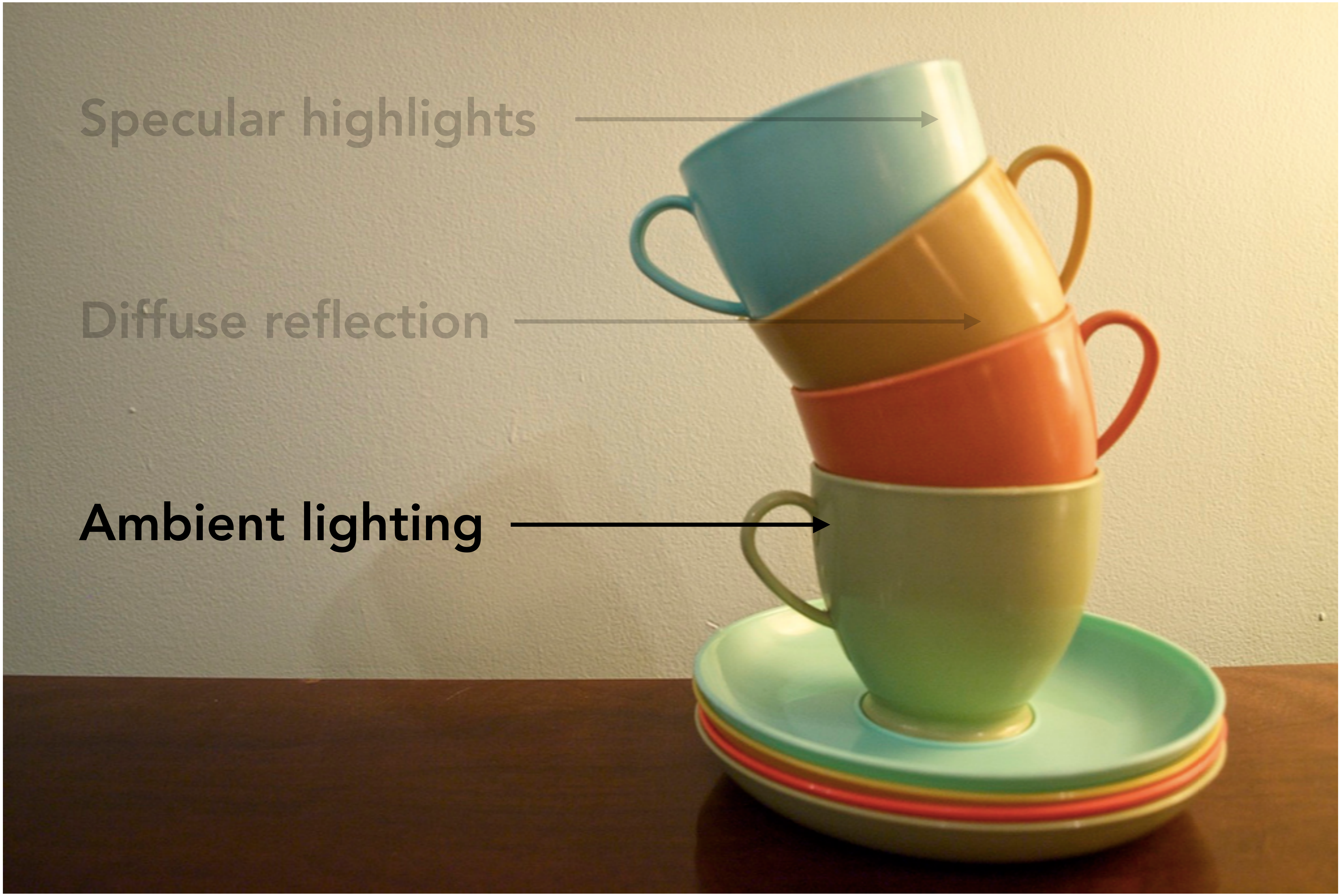
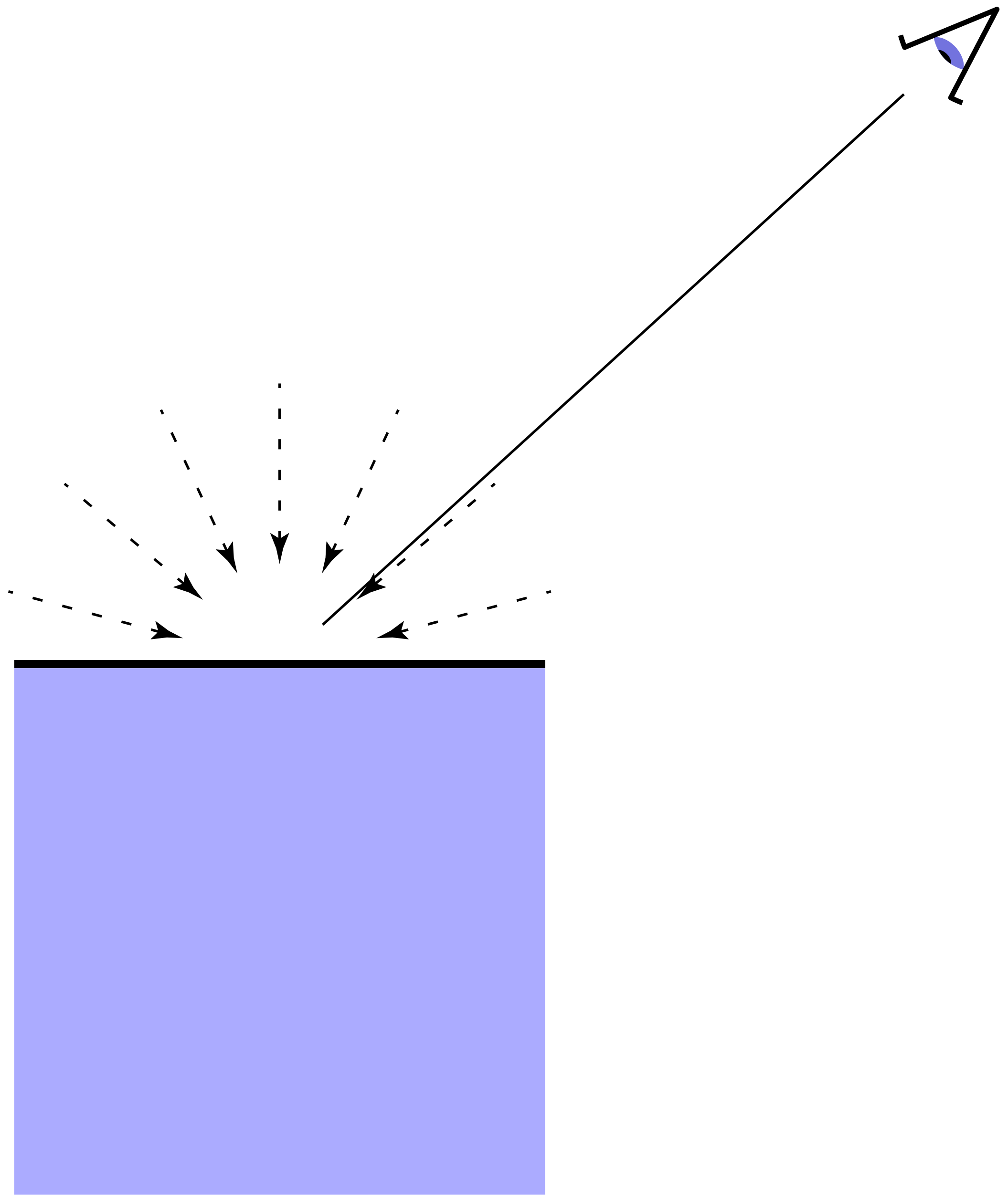


Photo credit: Jessica Andrews, flickr

Ambient Shading

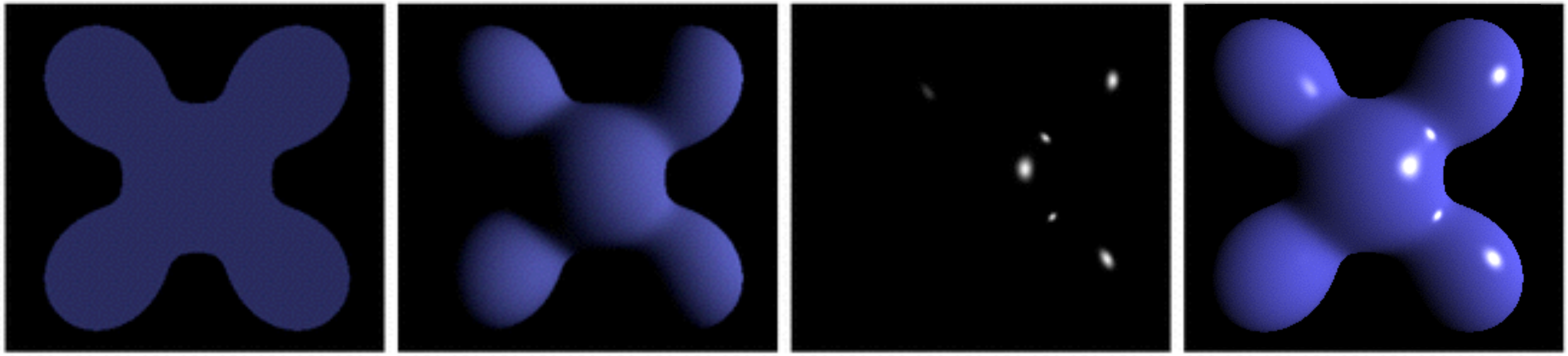
Shading that does not depend on anything

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



$$\underset{\substack{\uparrow \\ \text{reflected} \\ \text{ambient} \\ \text{light}}}{L_a} = \underset{\substack{\uparrow \\ \text{ambient} \\ \text{coefficient}}}{k_a}\, I_a$$

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

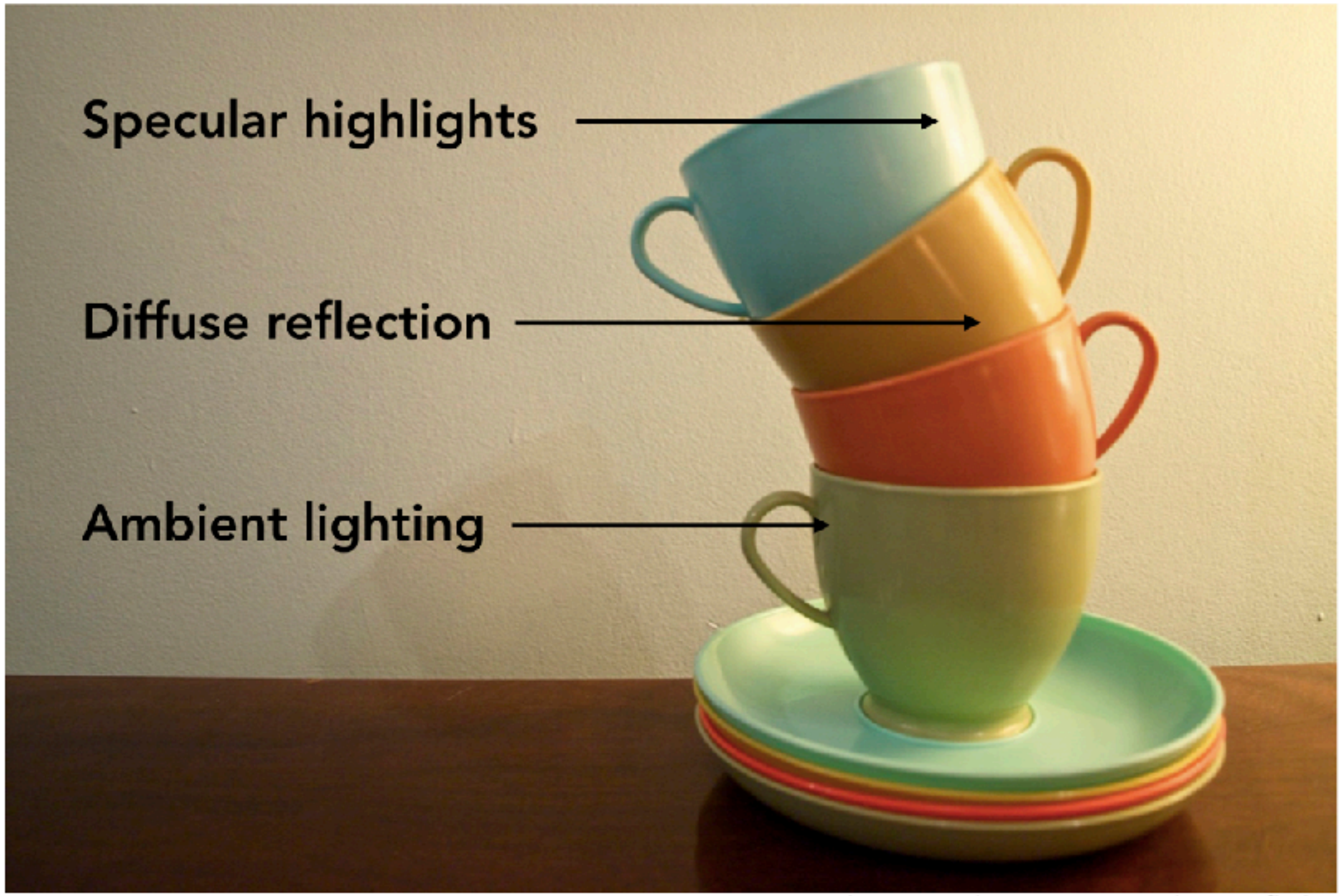


Photo credit: Jessica Andrews, flickr

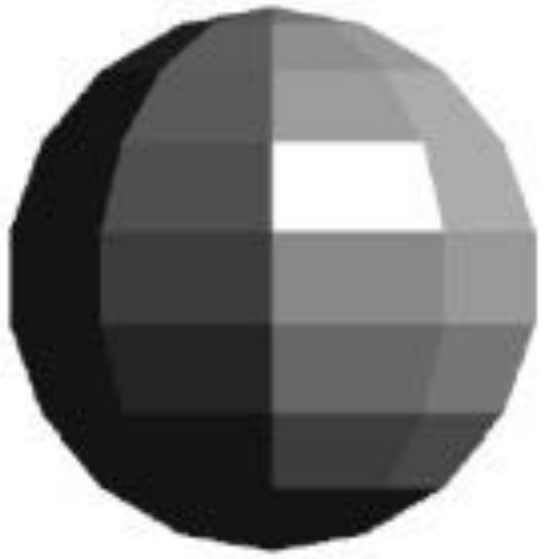
$$
\begin{aligned}
L &= L_a + L_d + L_s \\
&= k_a\, I_a + k_d\, (I/r^2)\max(0, \mathbf{n}\cdot\mathbf{l}) + k_s\, (I/r^2)\max(0, \mathbf{n}\cdot\mathbf{h})^p
\end{aligned}
$$

Shading Triangle Meshes

Shading Frequency: Triangle, Vertex or Pixel

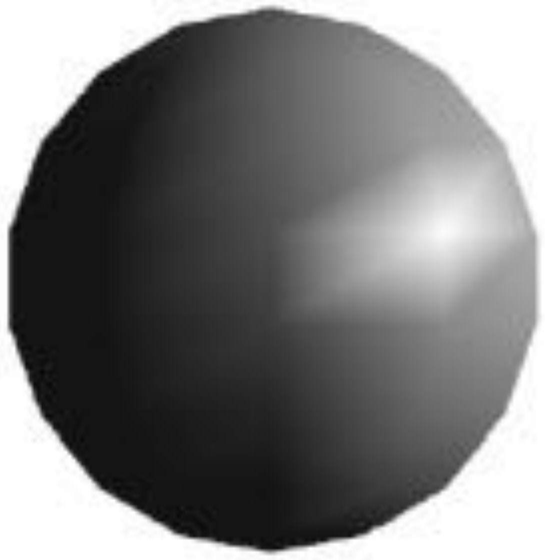
Shade each triangle (flat shading)

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



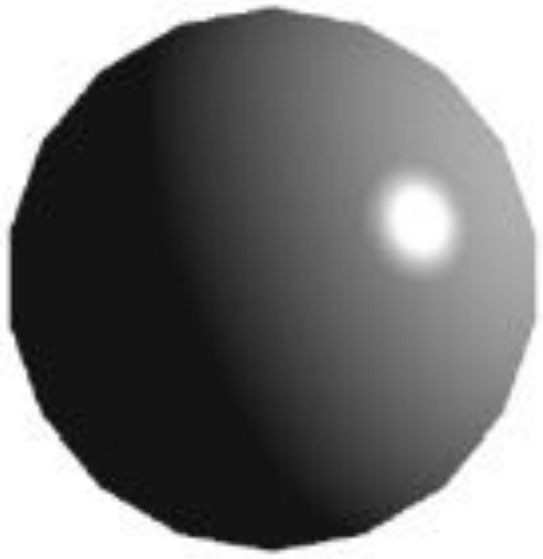
Shade each vertex ("Gouraud" shading)

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

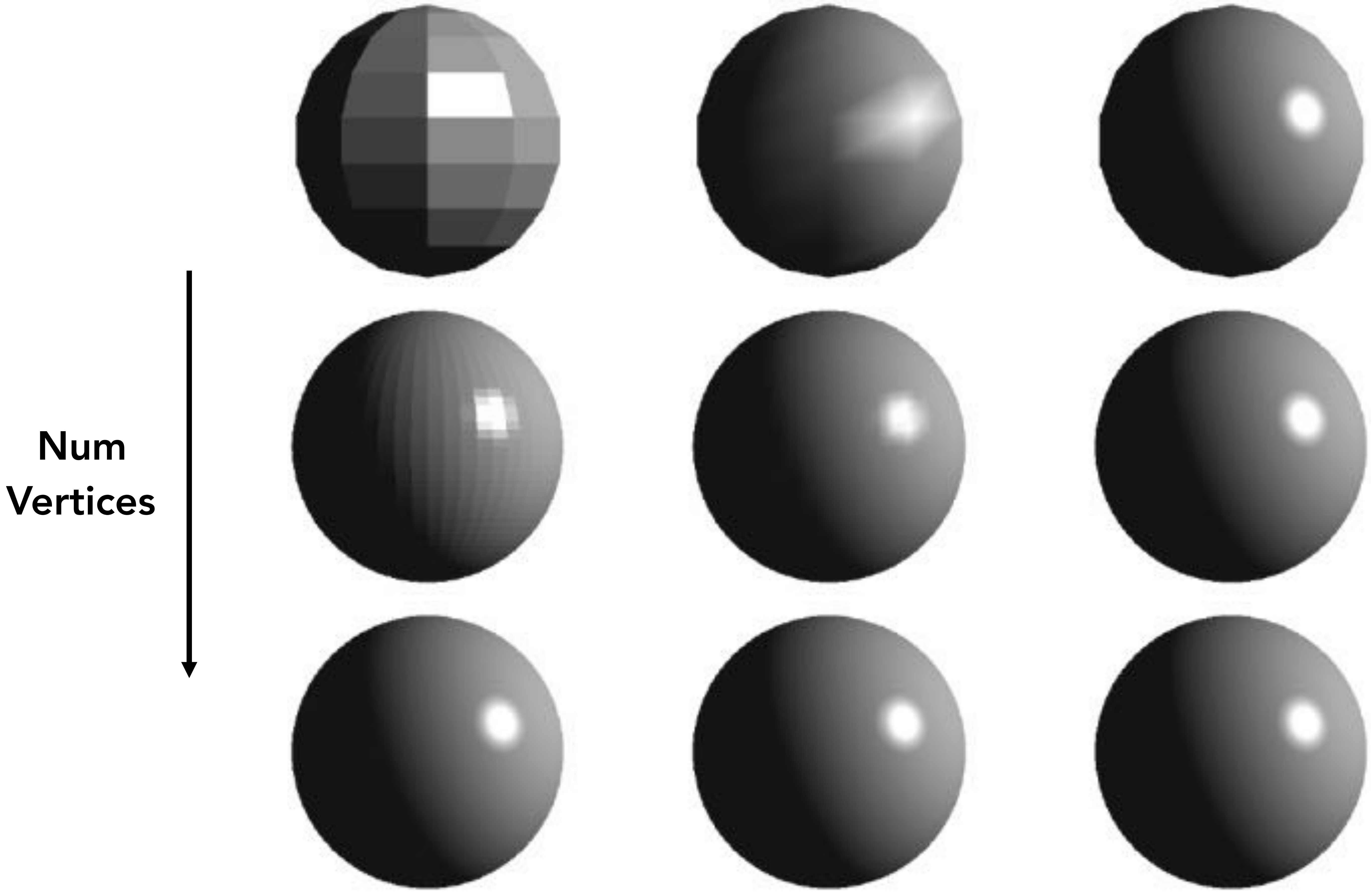


Shade each pixel ("Phong" shading)

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



Shading Frequency: Face, Vertex or Pixel



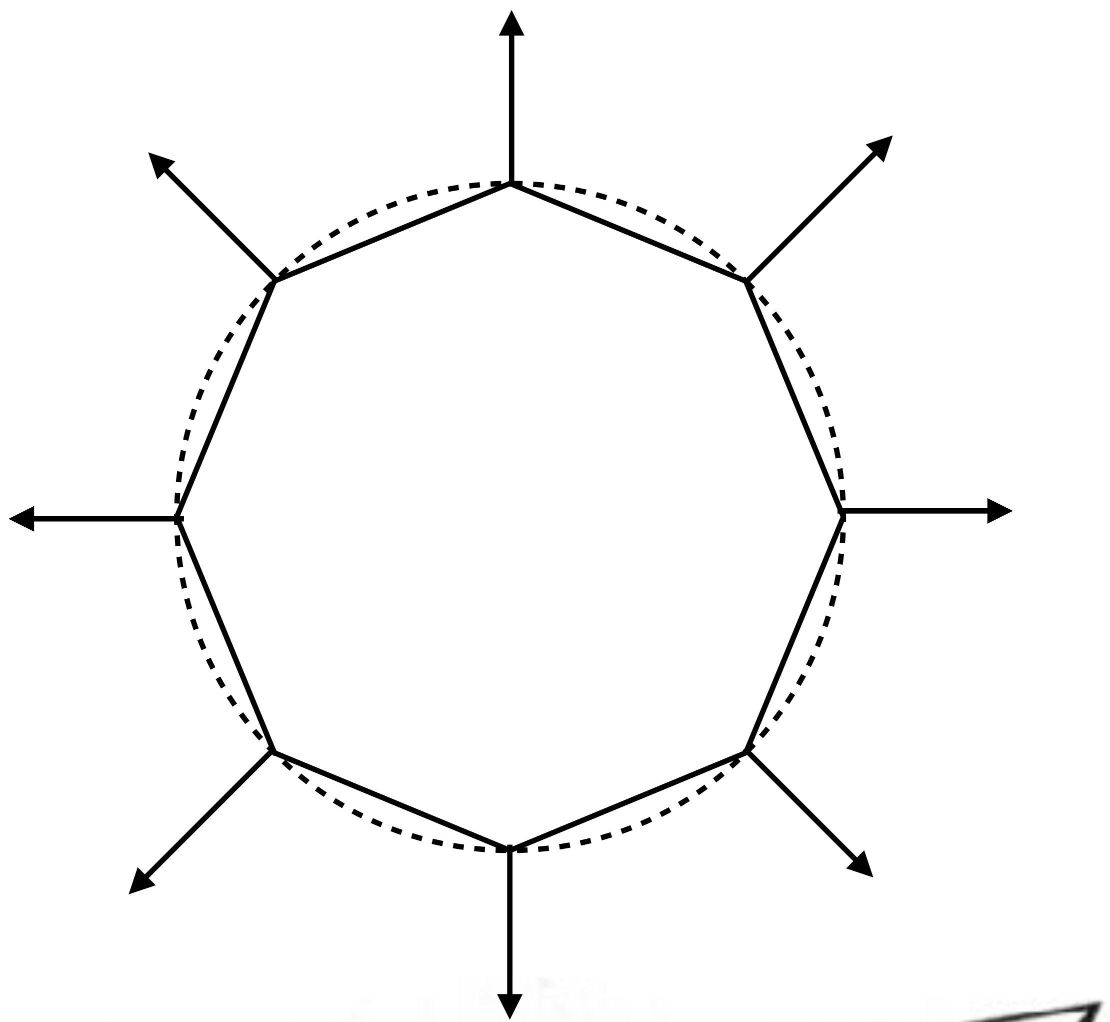
Shading freq. :	Face	Vertex	Pixel
Shading type :	Flat	Gouraud	Phong (*)

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

Defining Per-Vertex Normal Vectors

Best to get vertex normals from the underlying geometry

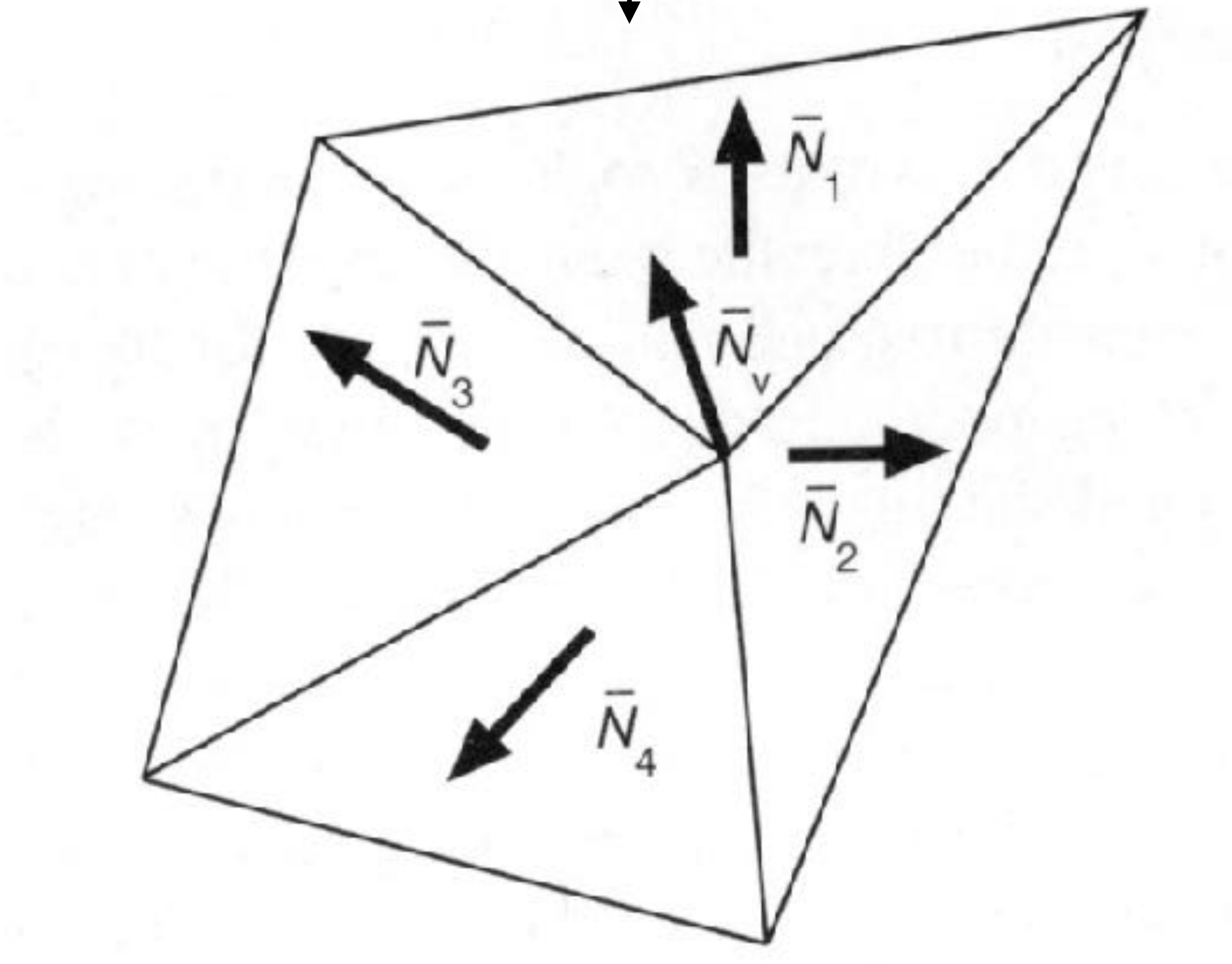
- e.g. consider a sphere



Otherwise have to infer vertex normals from triangle faces

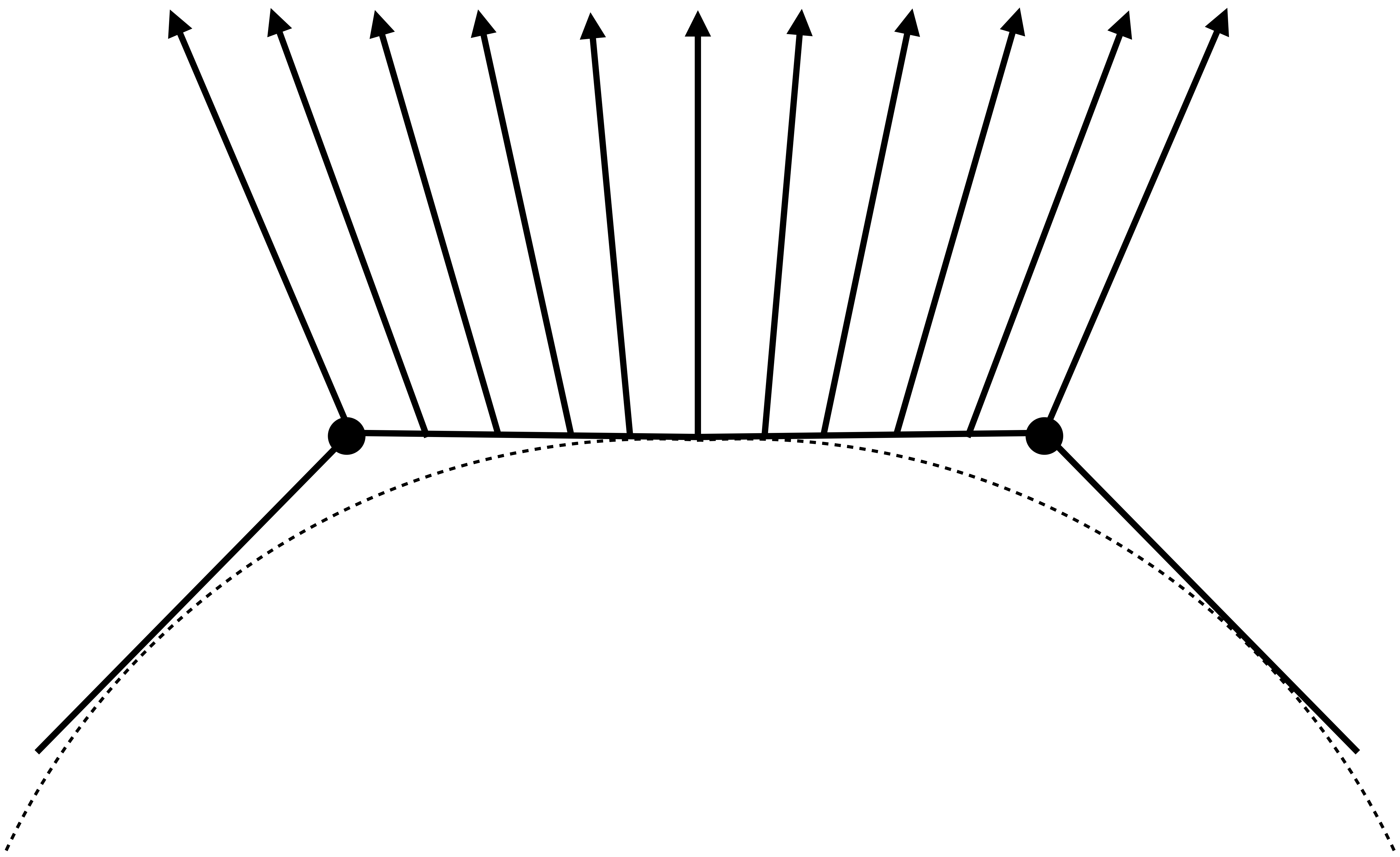
- Simple scheme: average surrounding face normals

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



Defining Per-Pixel Normal Vectors

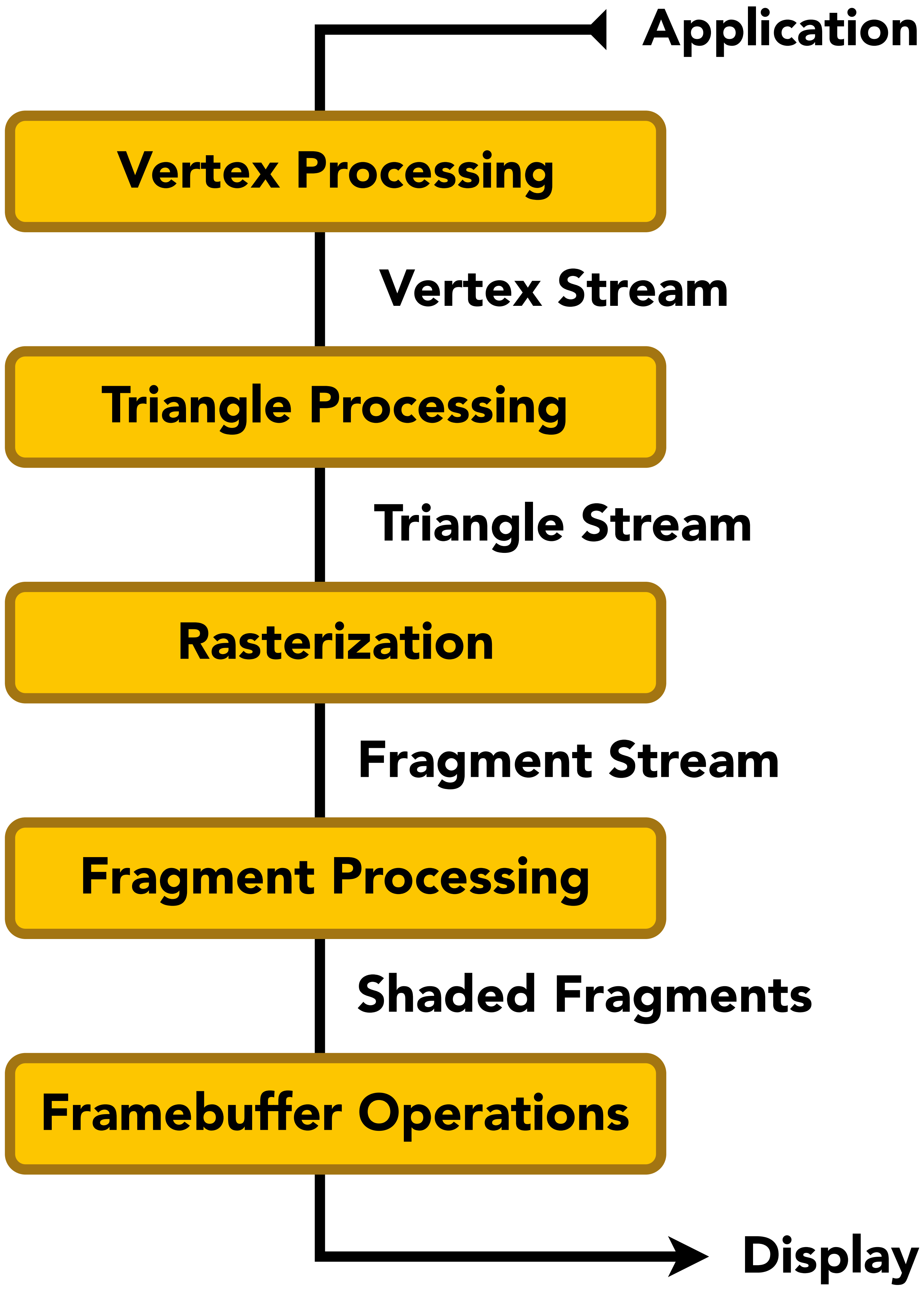
Barycentric interpolation of vertex normals



Problem: length of vectors?

Rasterization Pipeline

Rasterization Pipeline



Application

Vertex Processing

Vertex Stream

Triangle Processing

Triangle Stream

Rasterization

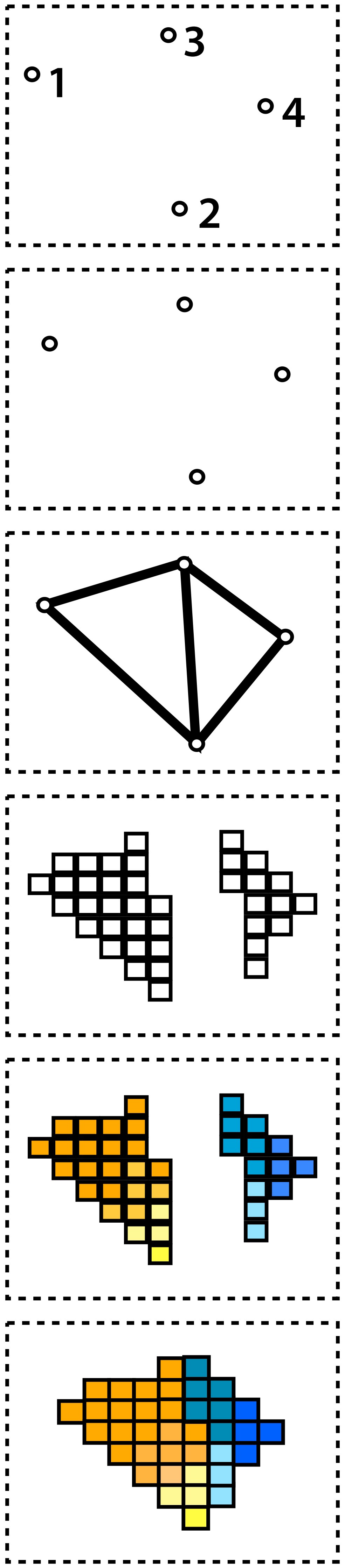
Fragment Stream

Fragment Processing

Shaded Fragments

Framebuffer Operations

Display



Input: vertices in 3D space

Vertices positioned in screen space

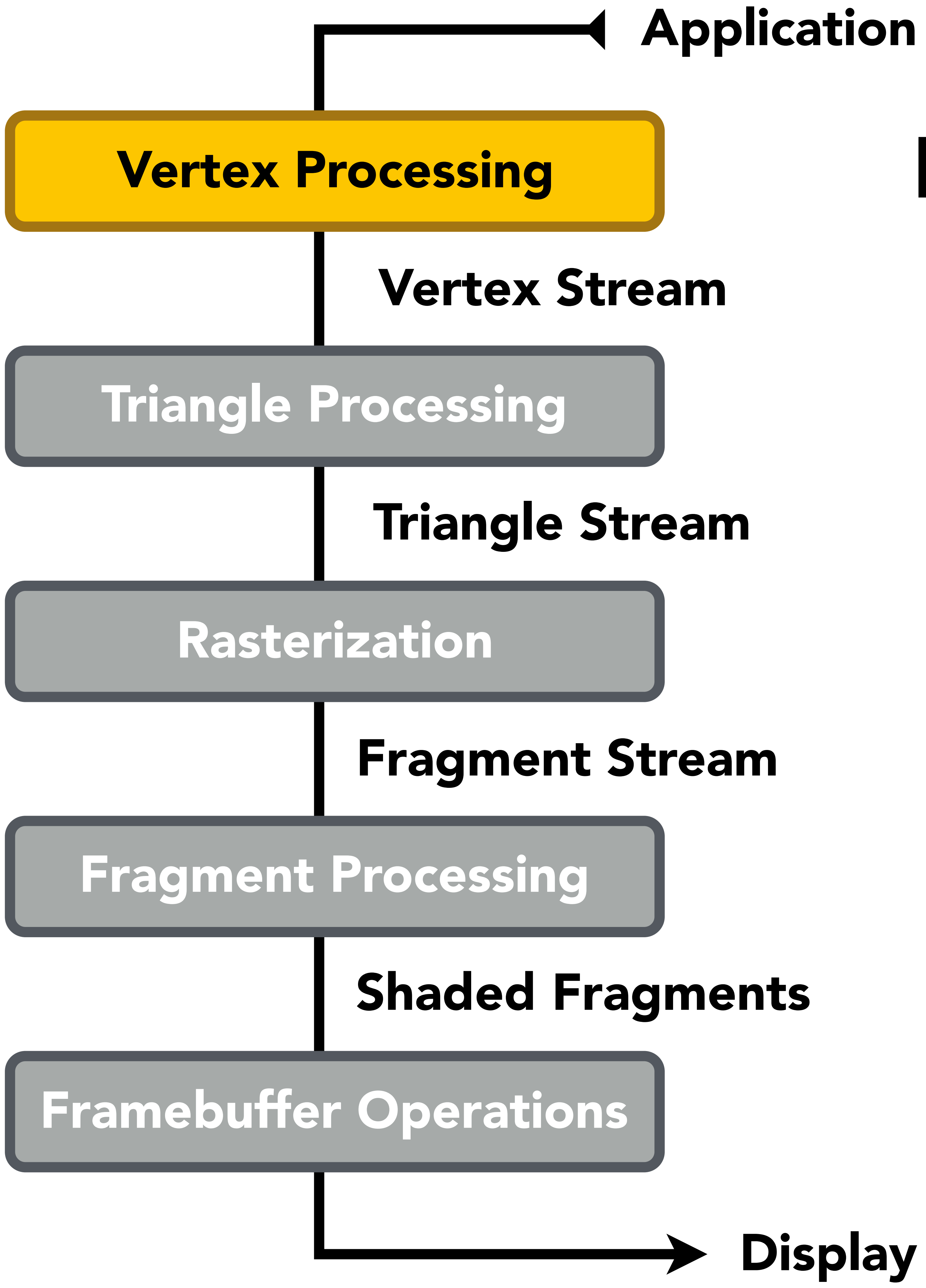
Triangles positioned in screen space

Fragments (one per covered sample)

Shaded fragments

Output: image (pixels)

Rasterization Pipeline



Application

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Vertex Stream

Triangle Processing

Triangle Stream

Rasterization

Fragment Stream

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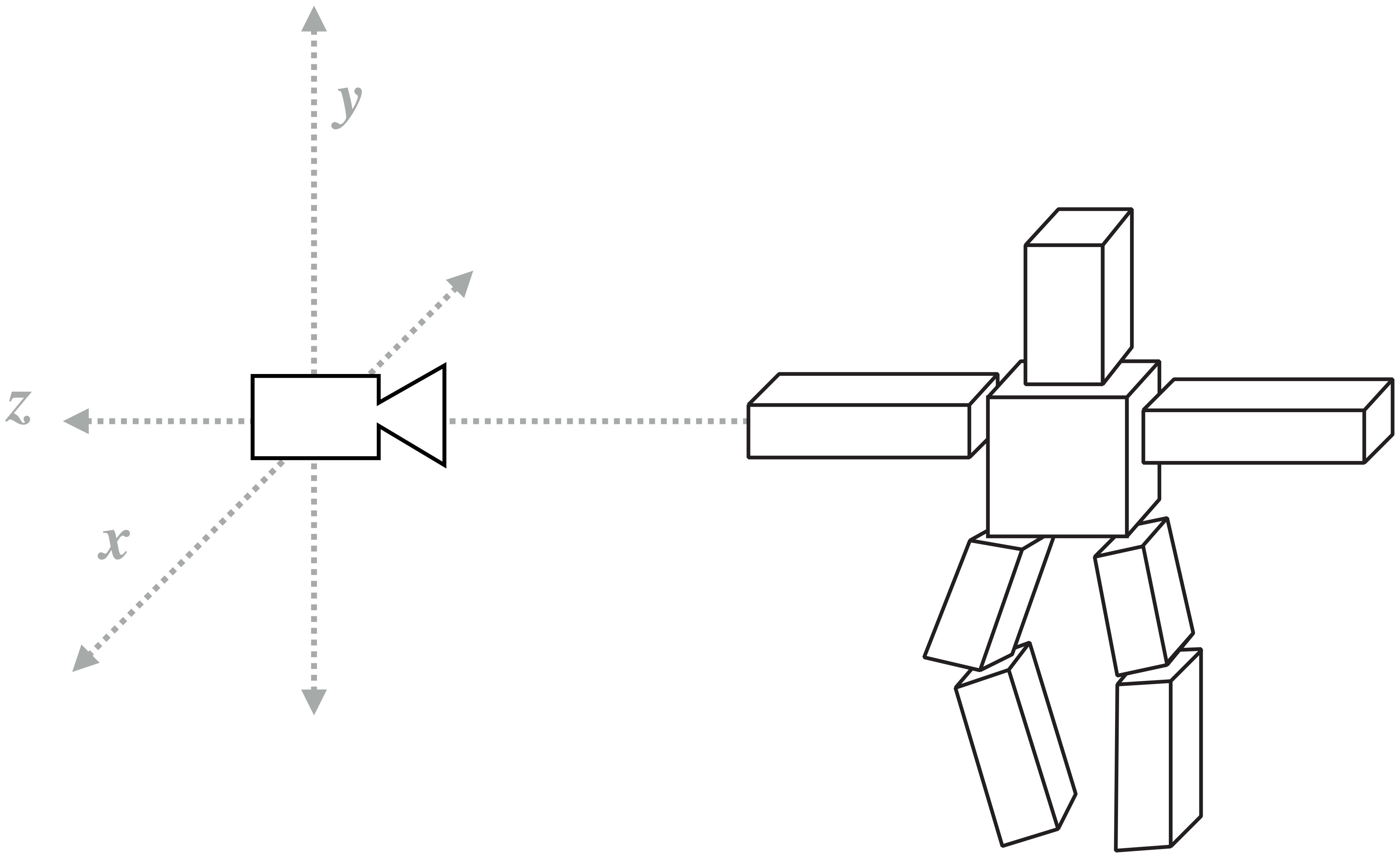
Shaded Fragments

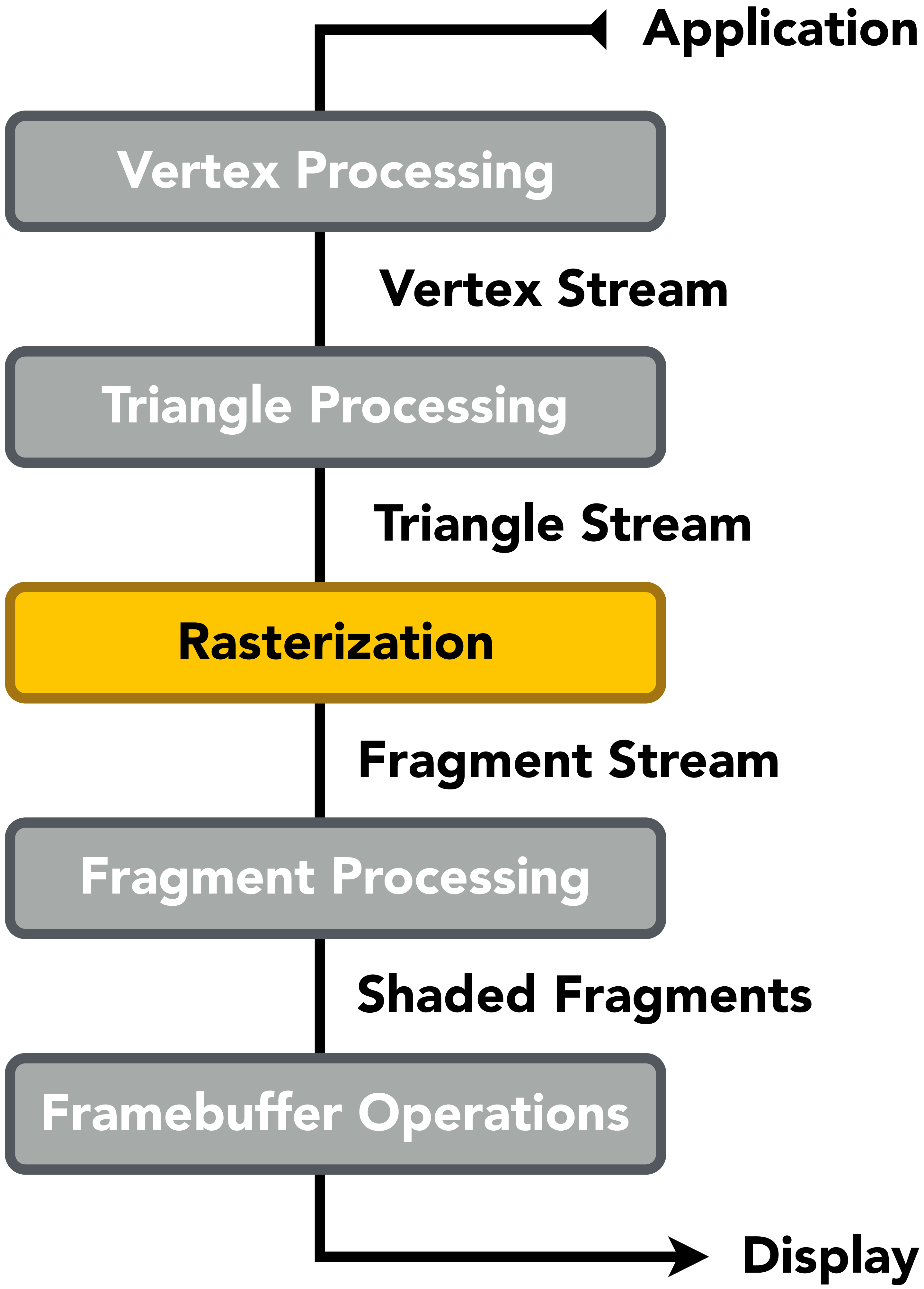
Framebuffer Operations

Display

Modeling & viewing transforms



Rasterization Pipeline



Application

Vertex Processing

Vertex Stream

Triangle Processing

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Rasterization

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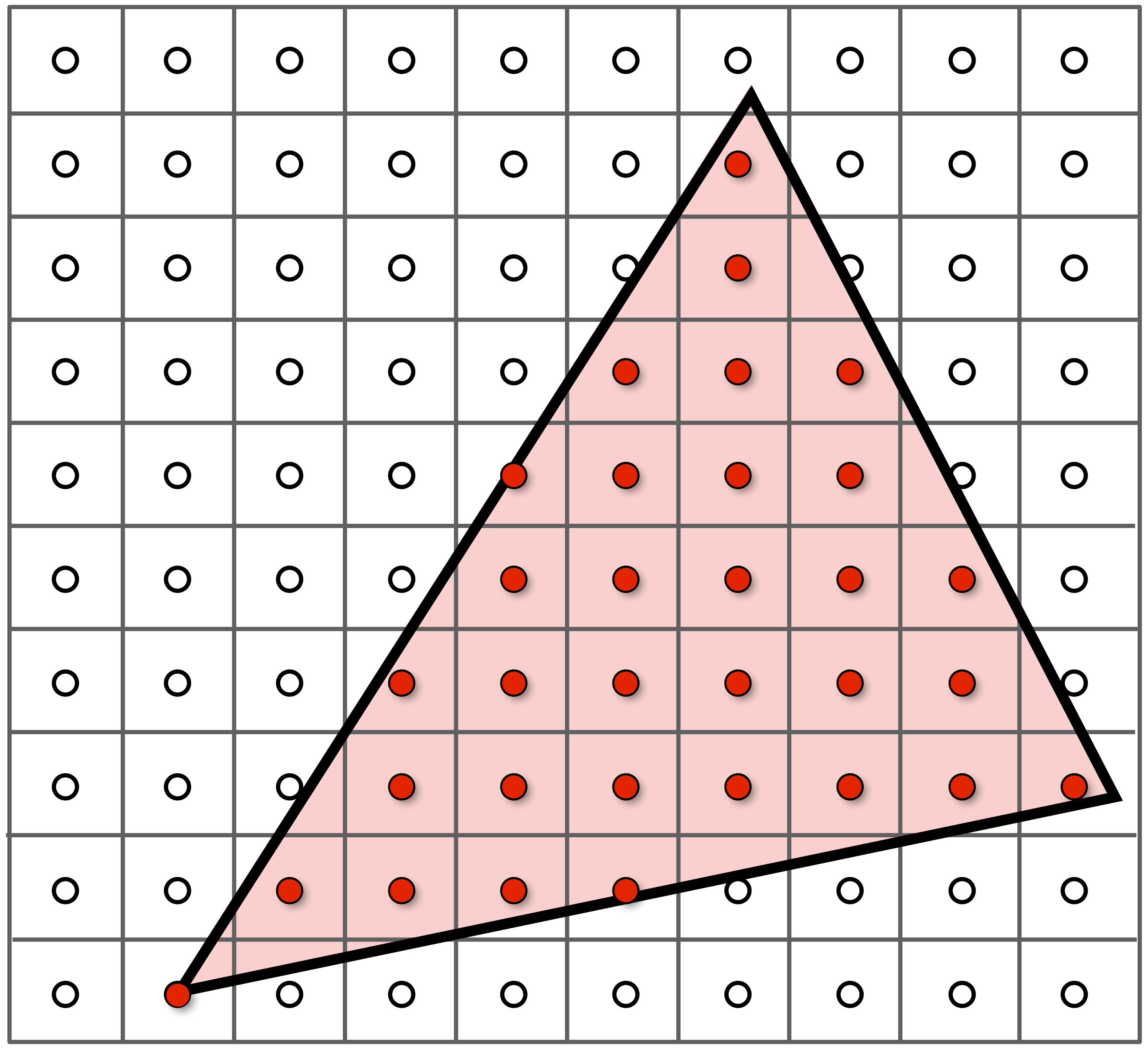
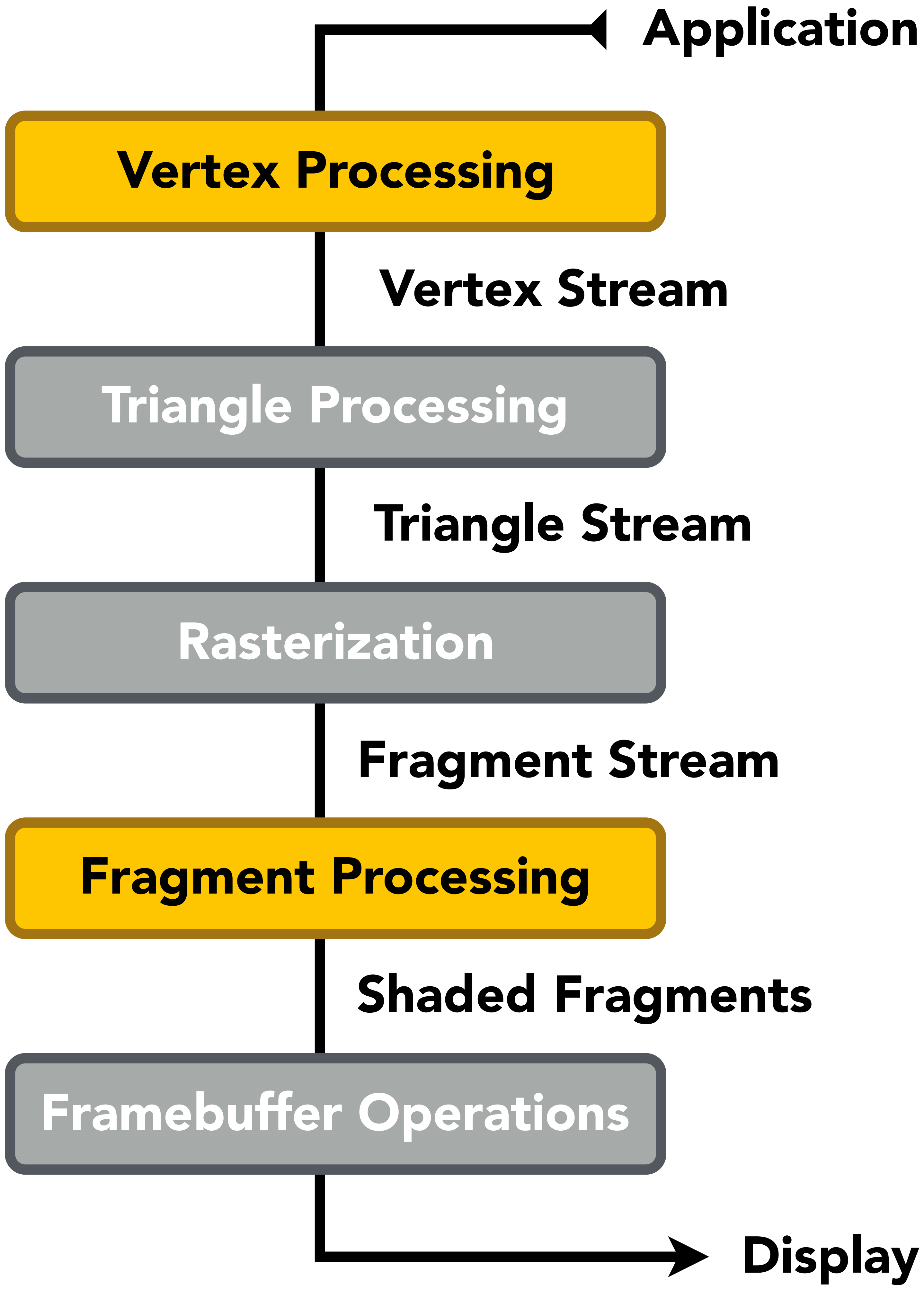
Framebuffer Operations

Display

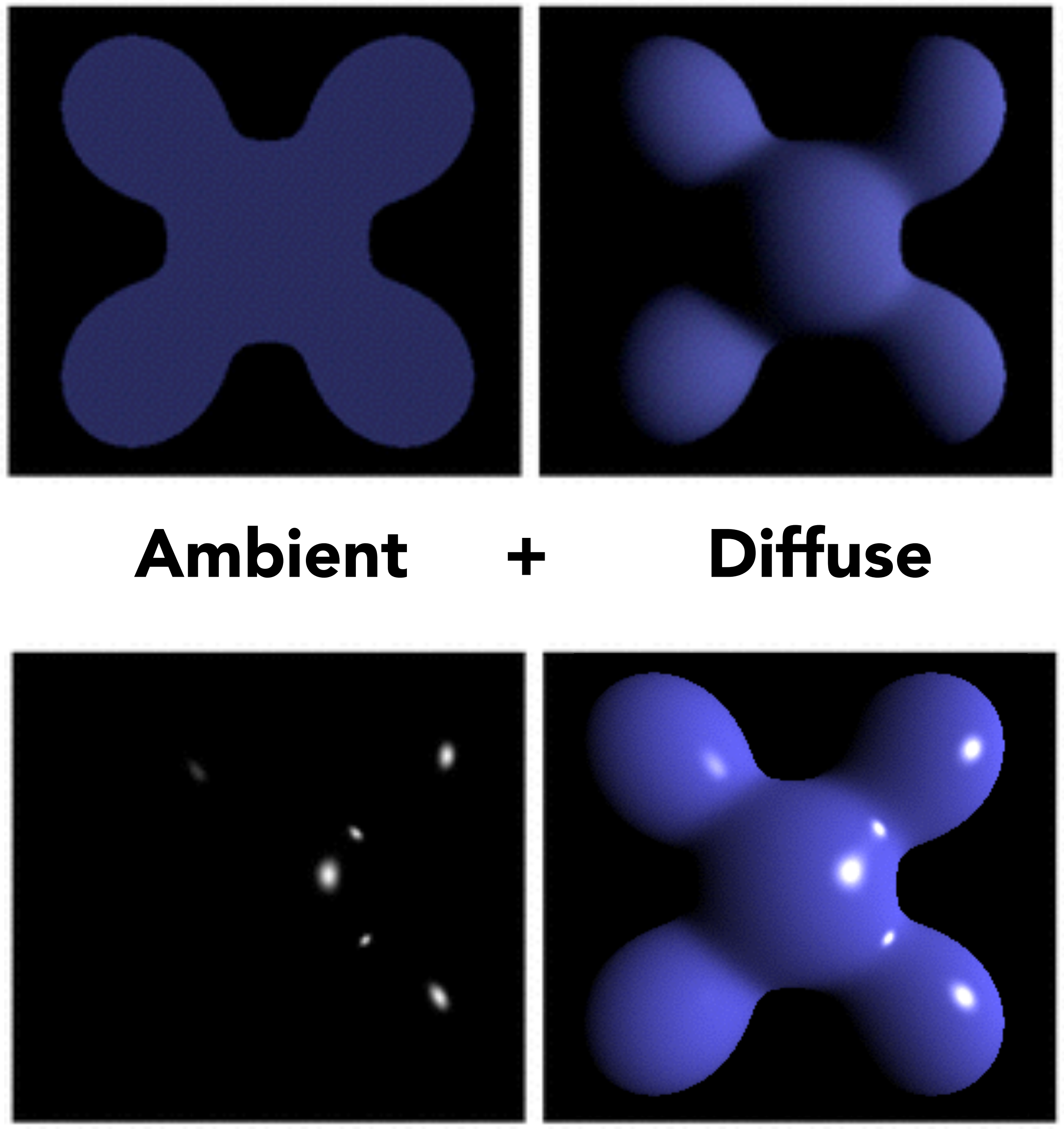
Sampling triangle coverage



Rasterization Pipeline



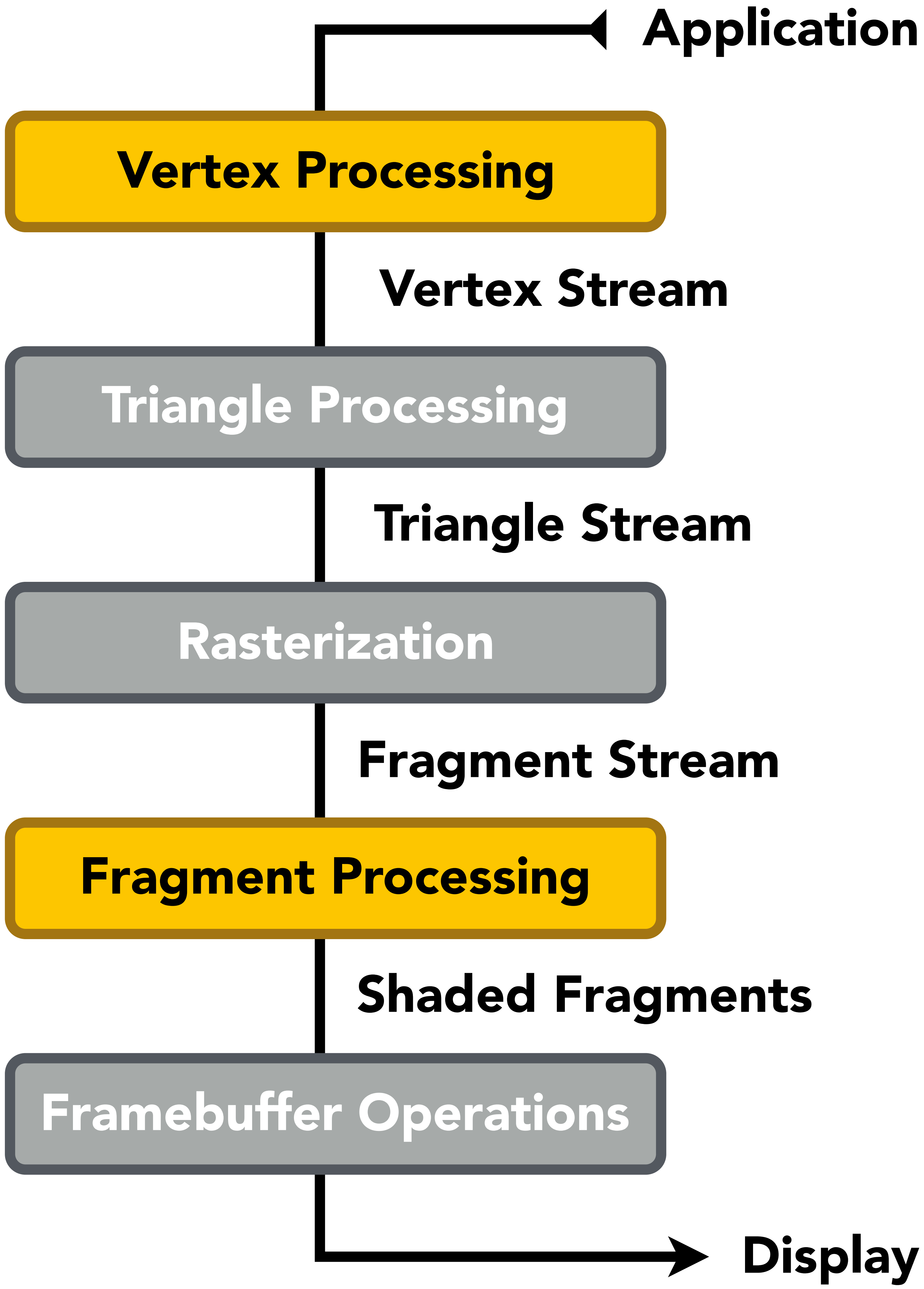
Evaluating shading functions



Ambient + Diffuse

+ Specular = Phong Reflection

Rasterization Pipeline



Application

Vertex Processing

Vertex Stream

Triangle Processing

Triangle Stream

Rasterization

Fragment Stream

Fragment Processing

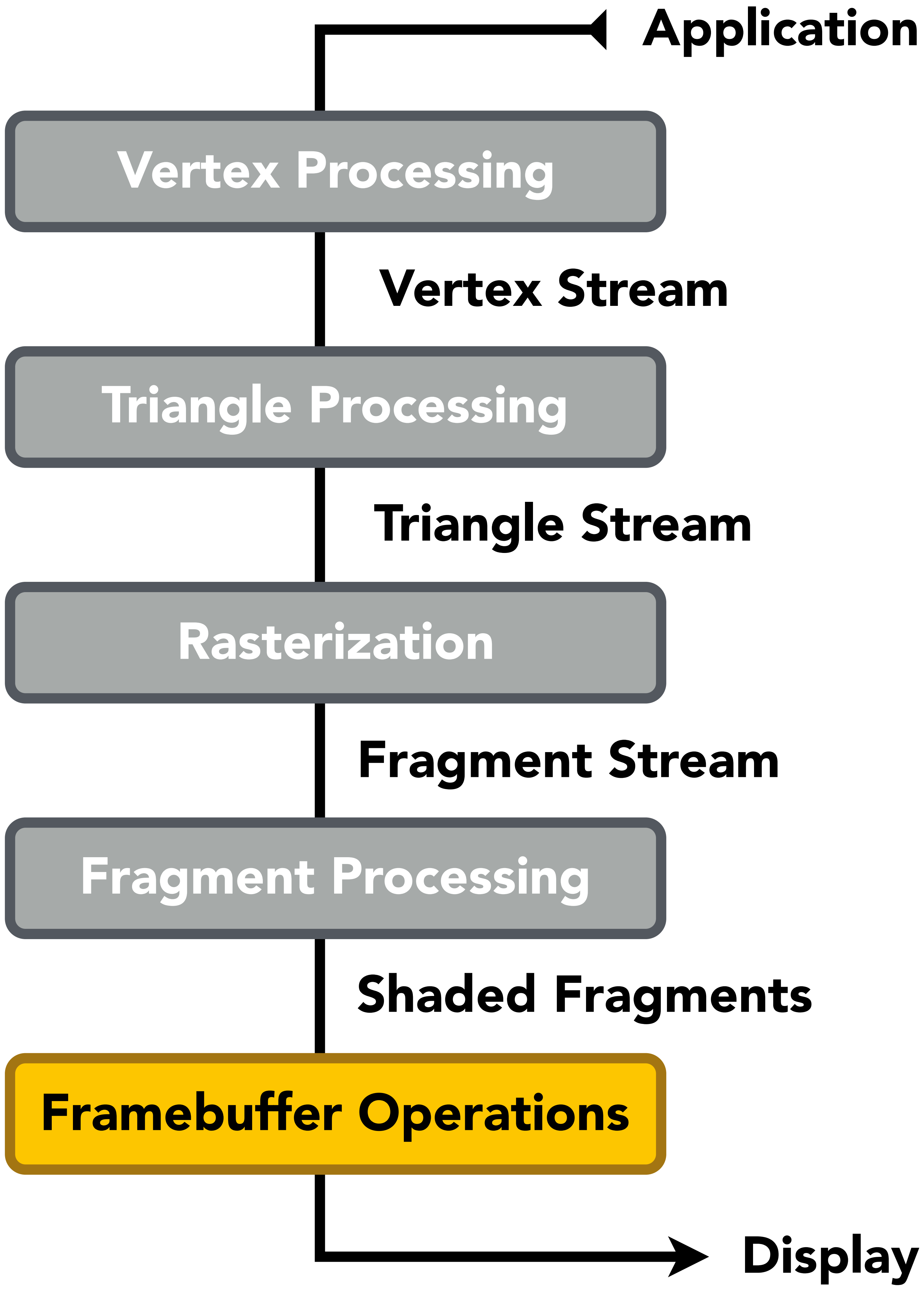
Shaded Fragments

Framebuffer Operations

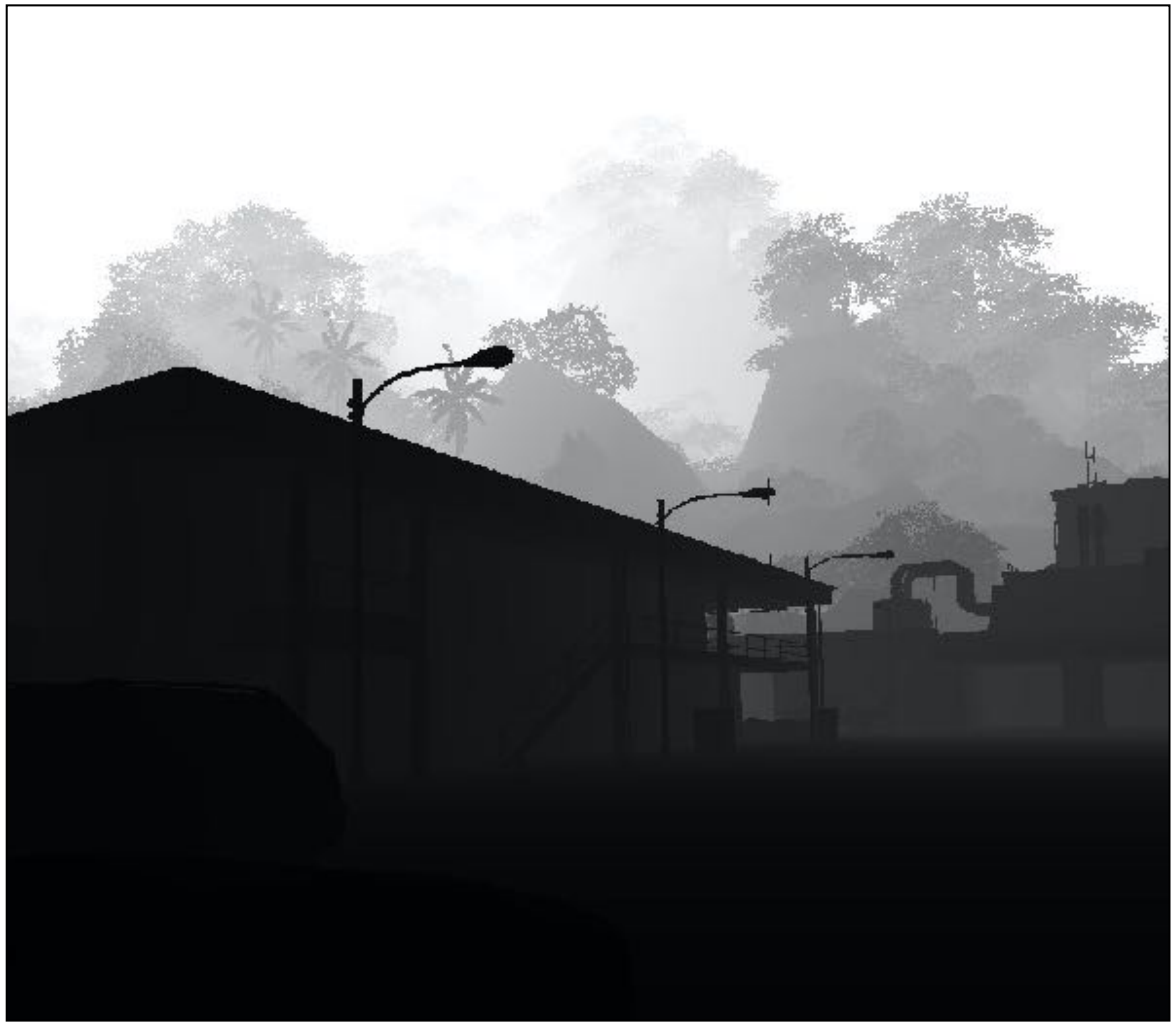
Display

Texture mapping

Rasterization Pipeline



Z-Buffer Visibility Tests



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
}
```

Goal: Highly Complex 3D Scenes in Realtime

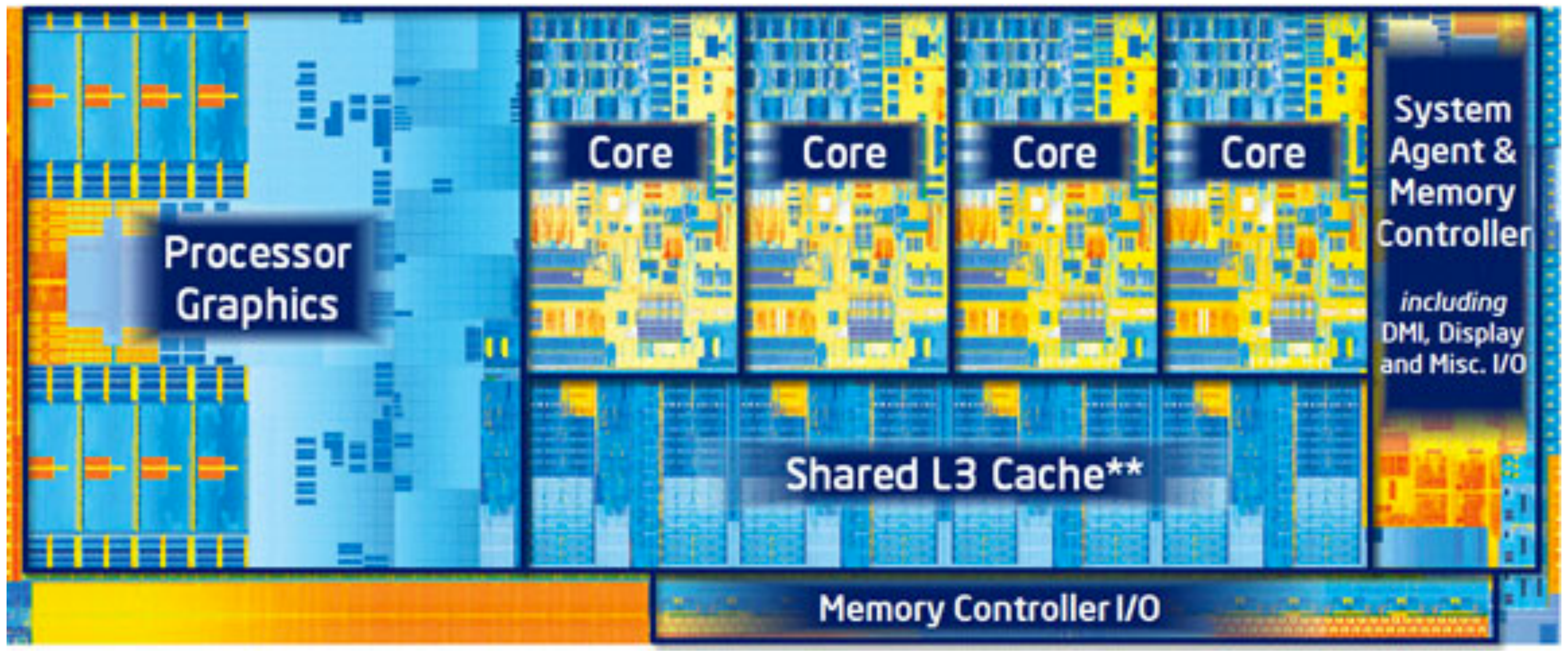
- 100's of thousands to millions of triangles in a scene
- Complex vertex and fragment shader computations
- High resolution (2-4 megapixel + supersampling)
- 30-60 frames per second (even higher for VR)

Unreal Engine Kite Demo (Epic Games 2015)

Graphics Pipeline Implementation: GPUs

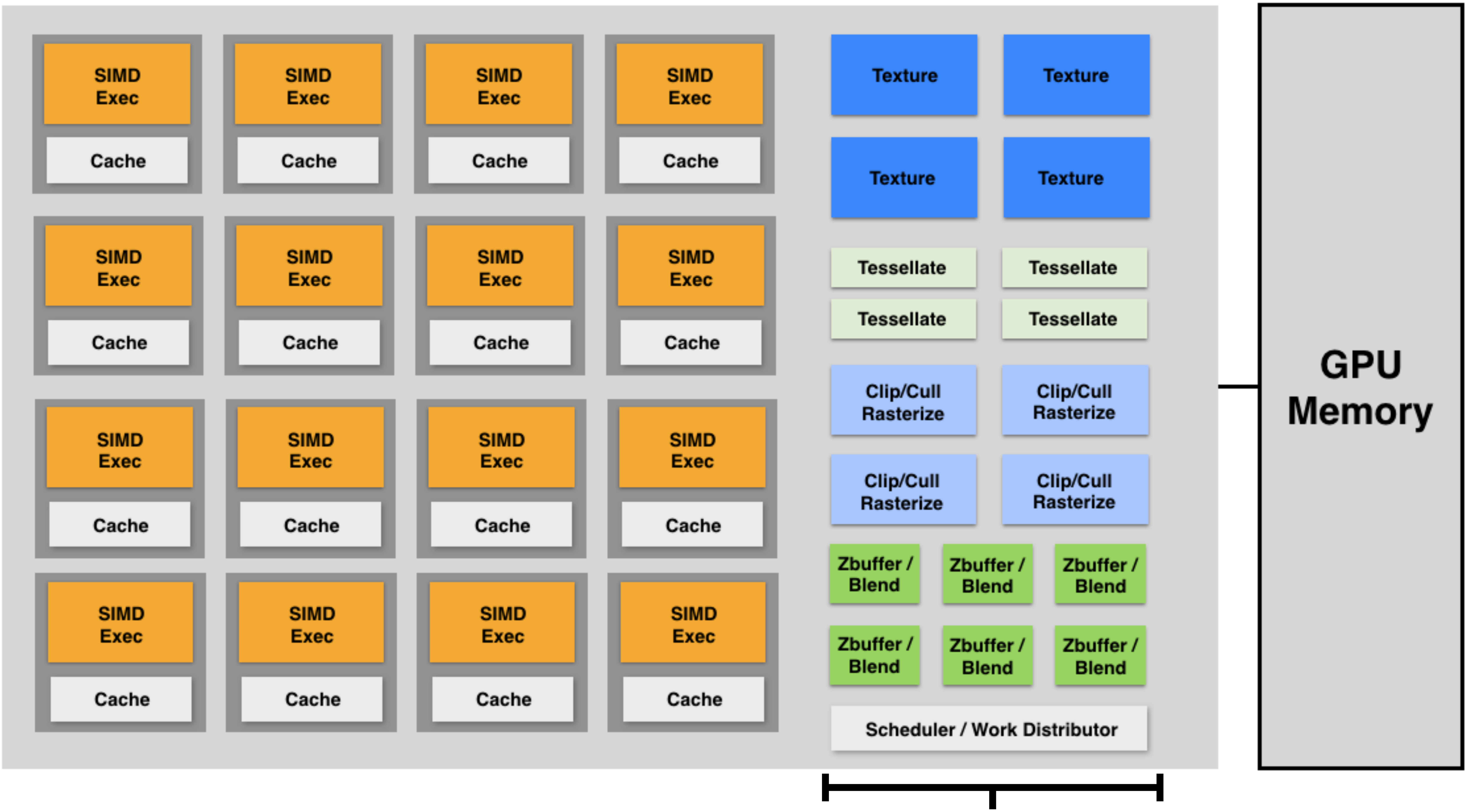
Specialized processors for executing graphics pipeline computations

Discrete GPU Card
(NVIDIA GeForce Titan X)



Integrated GPU:
(Part of Intel CPU die)

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

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