Lecture 6:

# The Rasterization Pipeline

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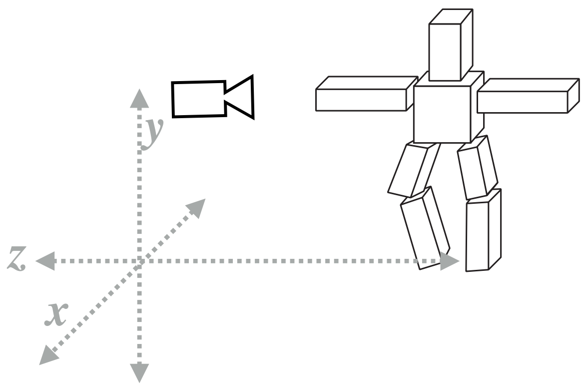
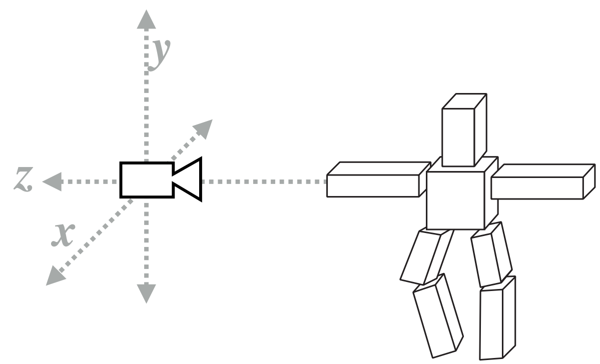
Computer Graphics and Imaging
UC Berkeley CS184/284A

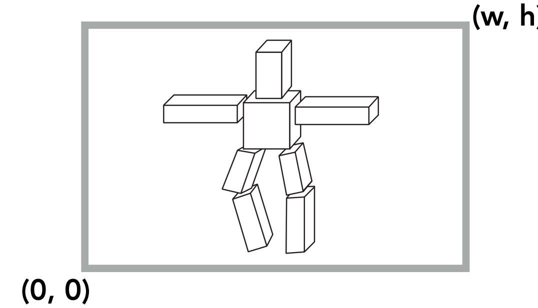
# What We've Covered So Far



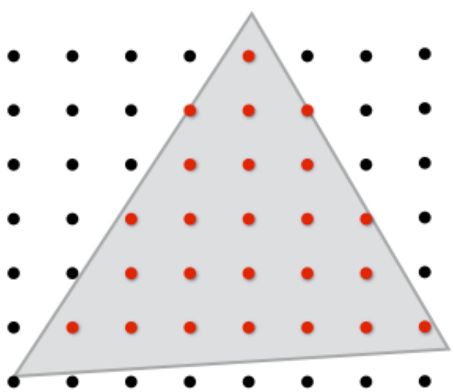

Position objects and the camera in the world



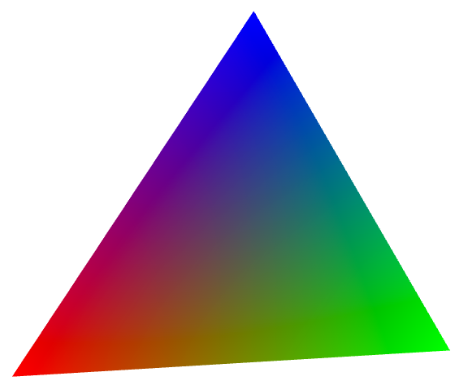

Compute position of objects relative to the camera



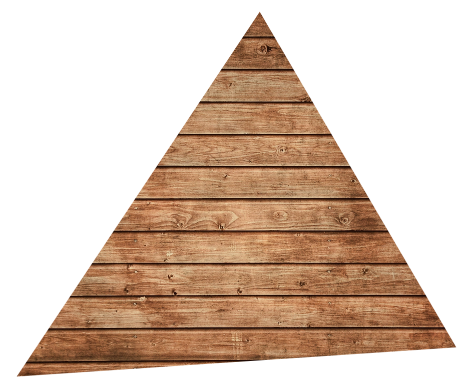

Project objects onto the screen



Sample triangle coverage

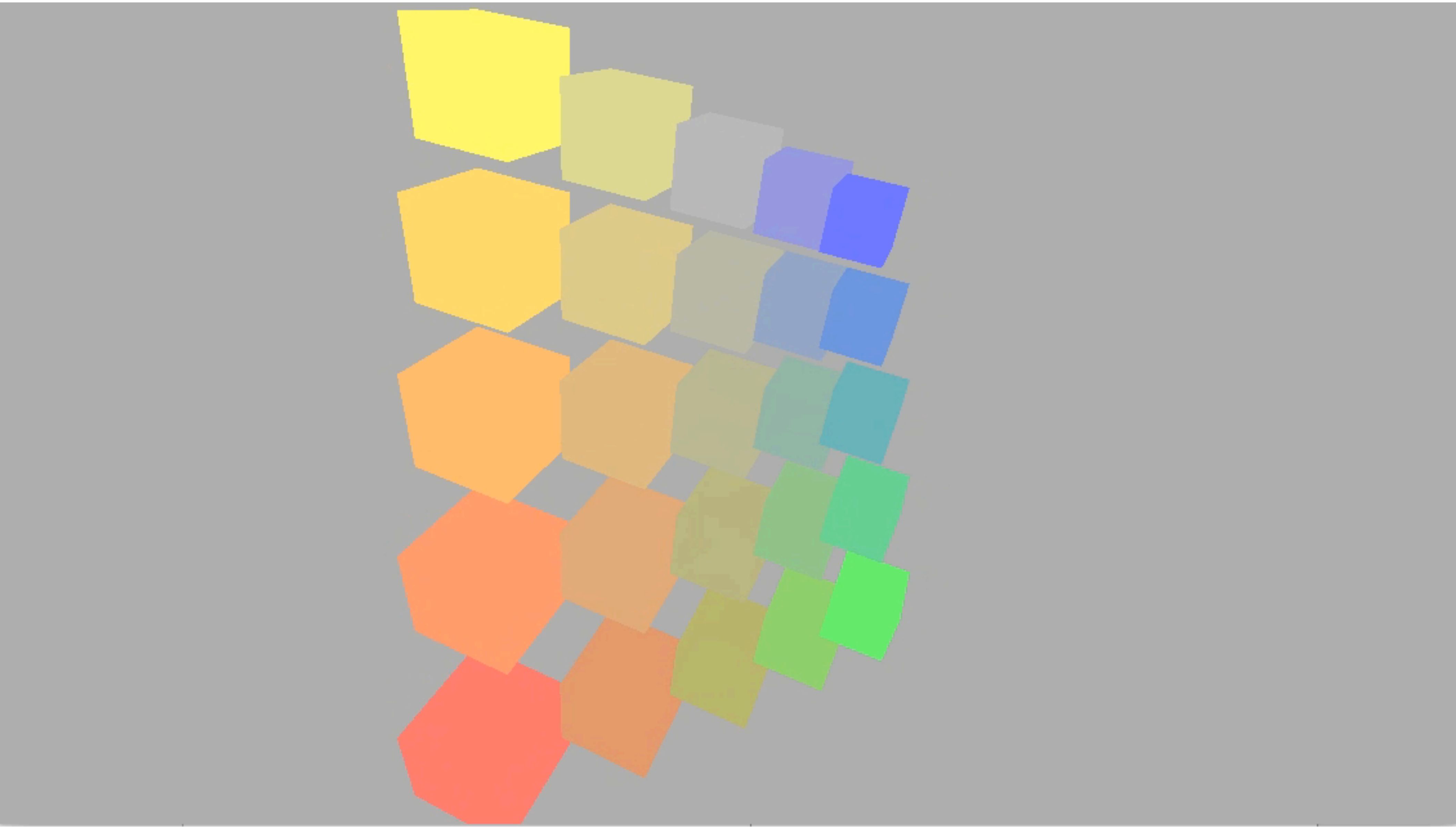


Interpolate triangle attributes

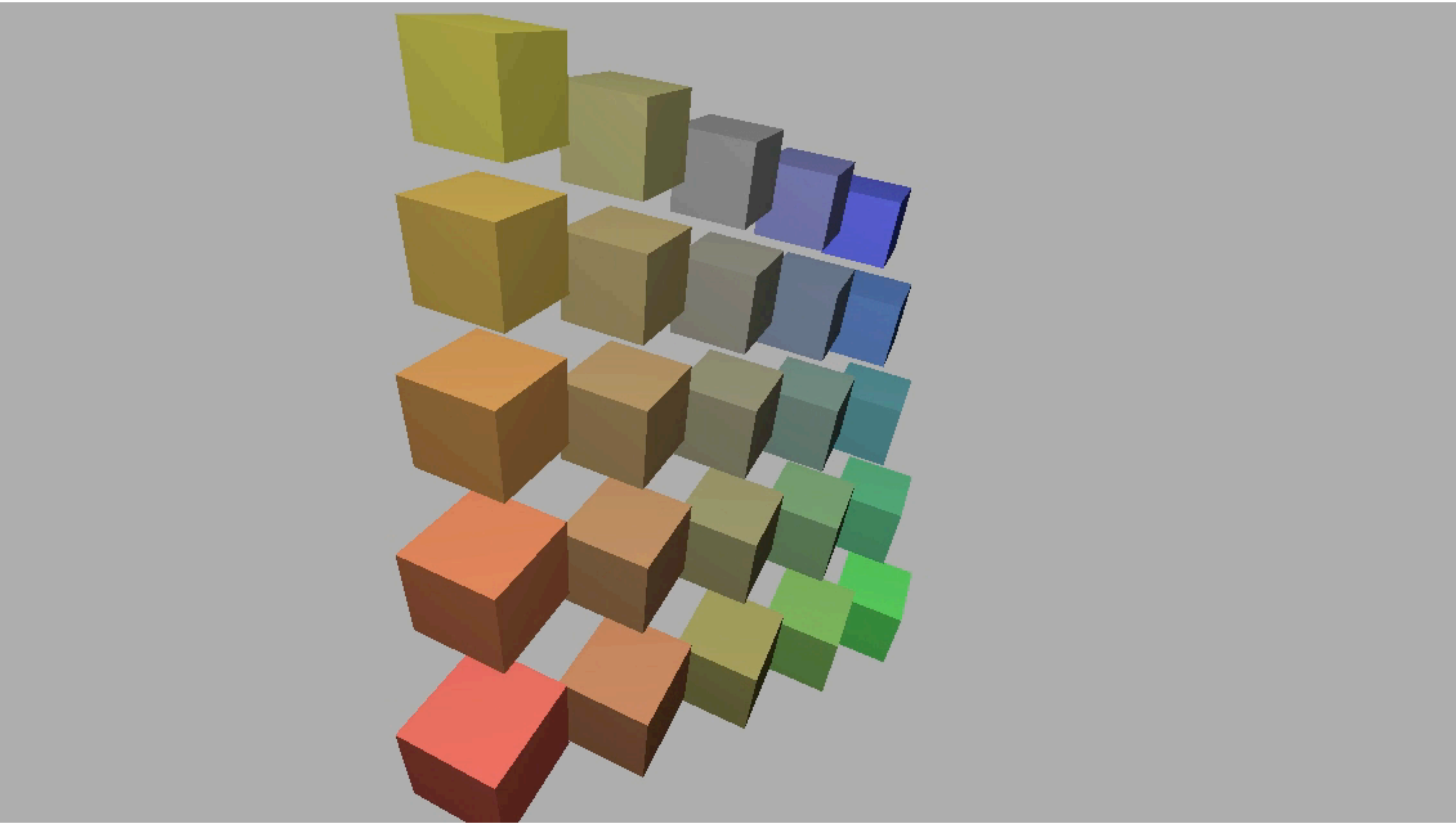


Sample texture maps

# 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

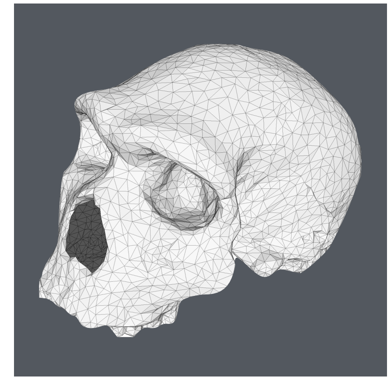
- Objects in the real world exhibit highly complex geometric details

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

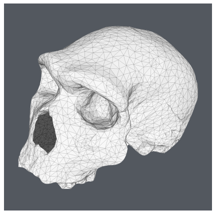
Rasterization

Transforms & Projection

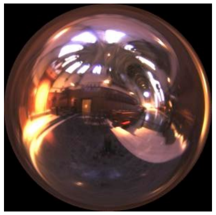
Texture Mapping

Today: Visibility, Shading, Overall Pipeline

## Geometric Modeling



## Lighting & Materials



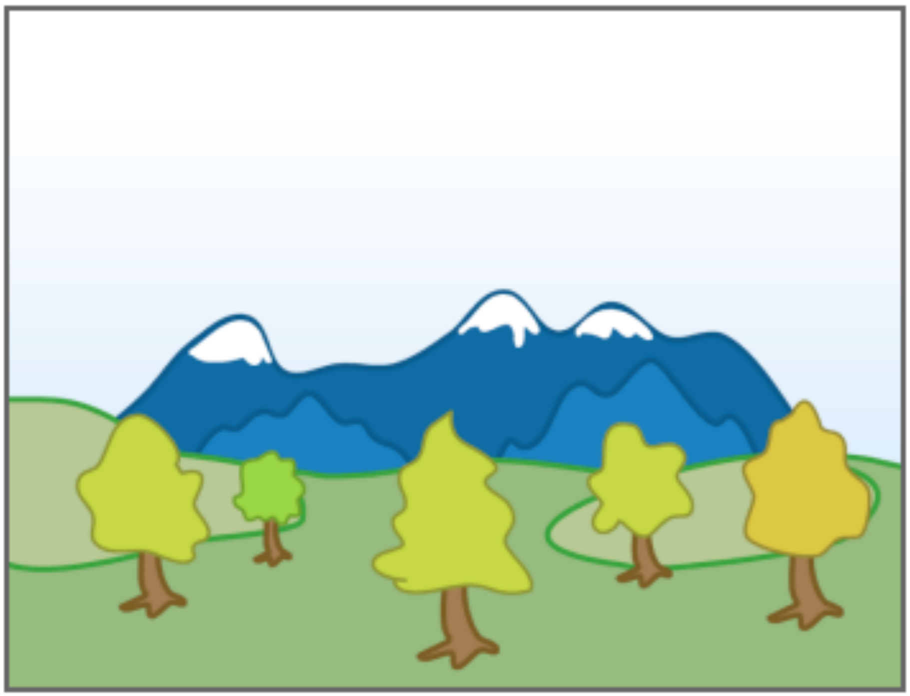
## Cameras & Imaging

# Visibility

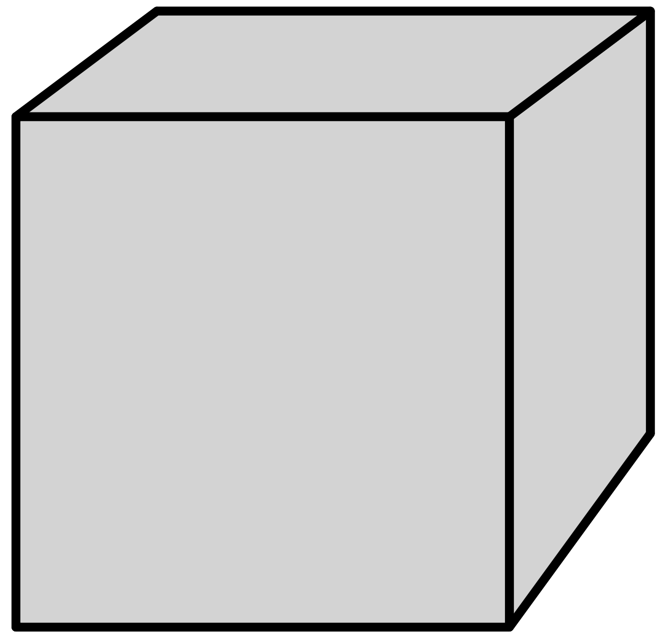
# Painter's Algorithm

Inspired by how painters paint

Paint from back to front, overwrite in the framebuffer



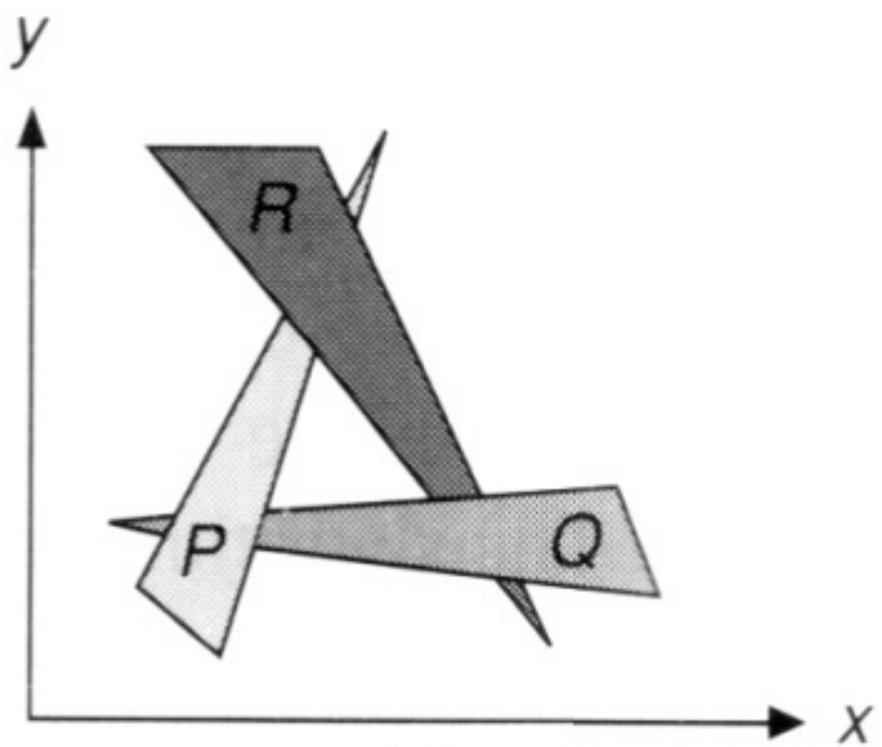
[Wikipedia]



# Painter's Algorithm

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

Can have unresolvable depth order




[Foley et al.]

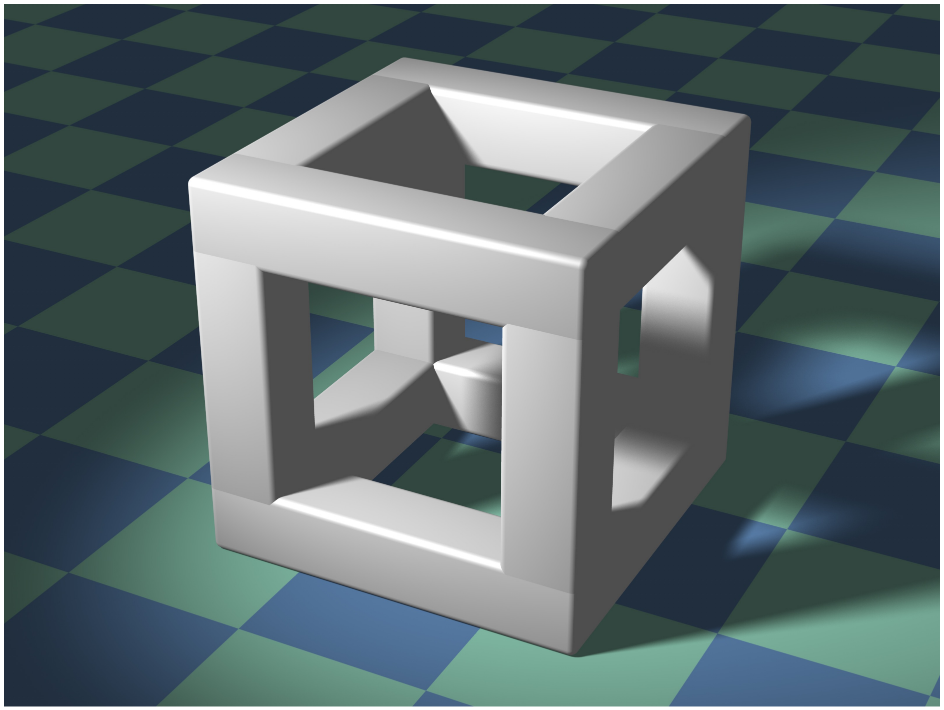
# Z-Buffer

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

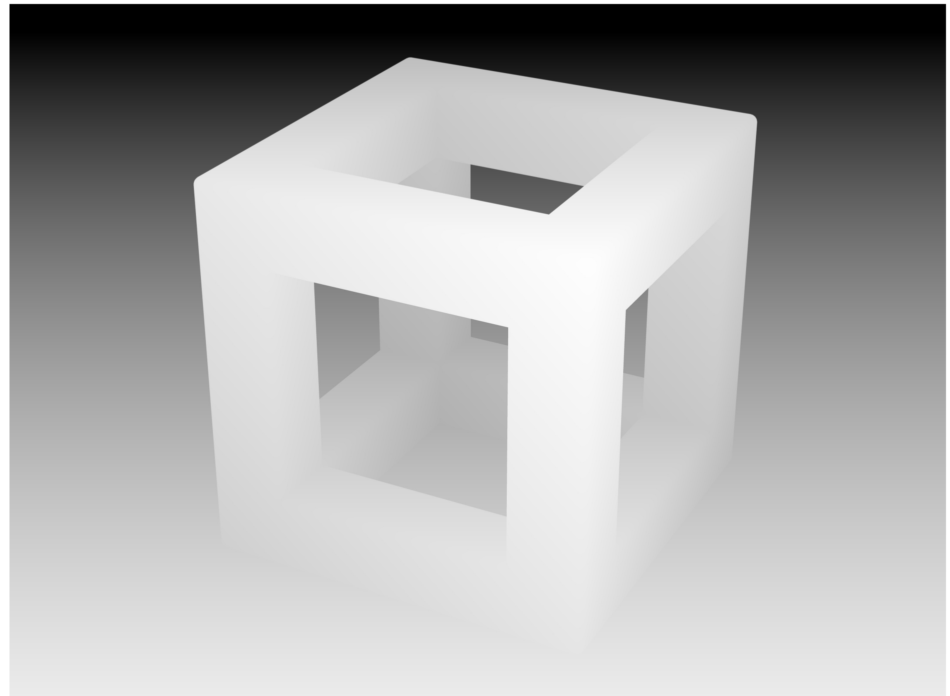
Idea:

- 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.

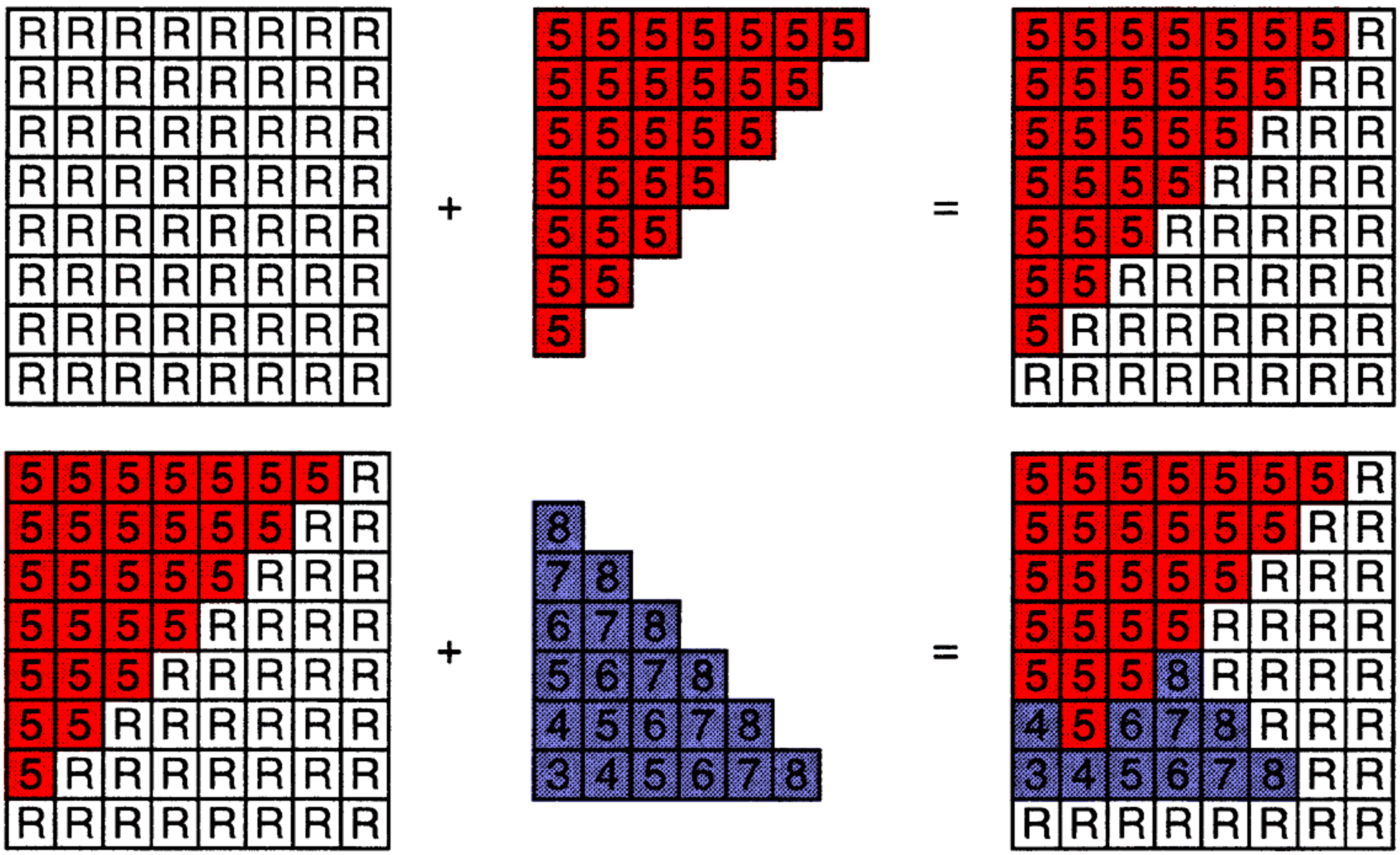
# Z-Buffer Algorithm

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



# 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

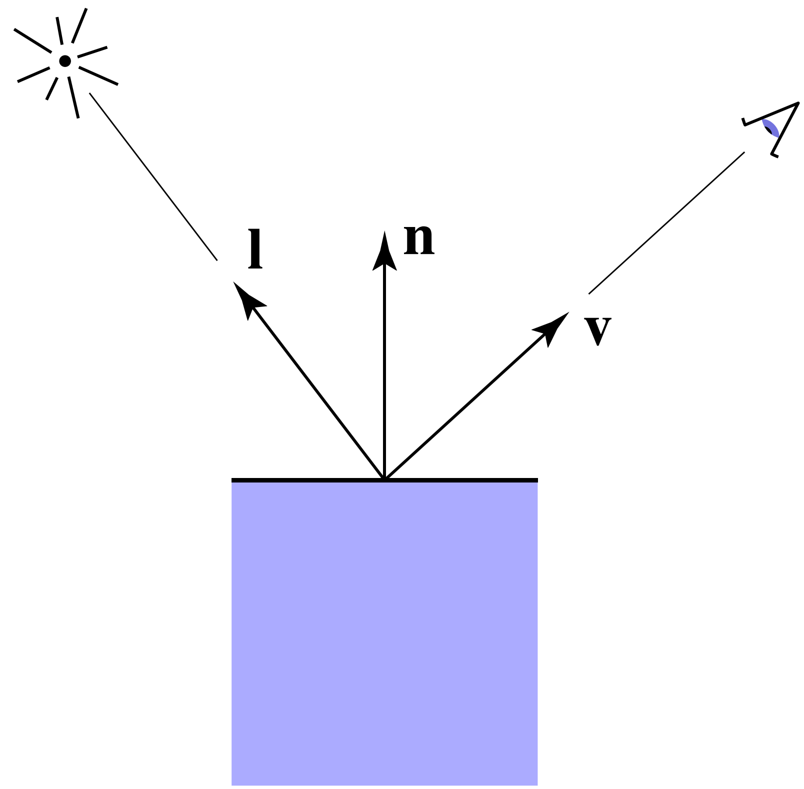
Photo credit: Jessica Andrews, flickr

# 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, …)

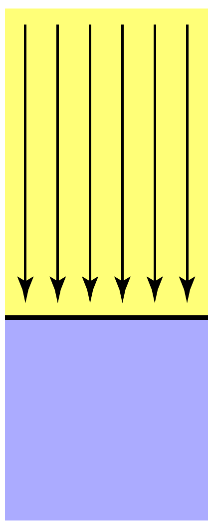


# Diffuse Reflection

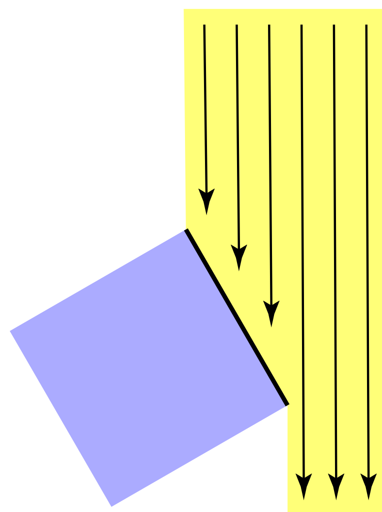
## Light is scattered uniformly in all directions

- Surface color is the same for all viewing directions

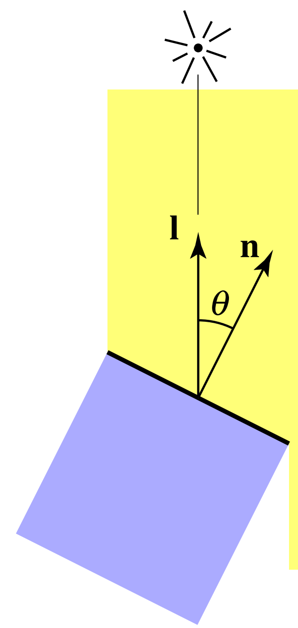
## Lambert's cosine law



Top face of cube receives a certain amount of light

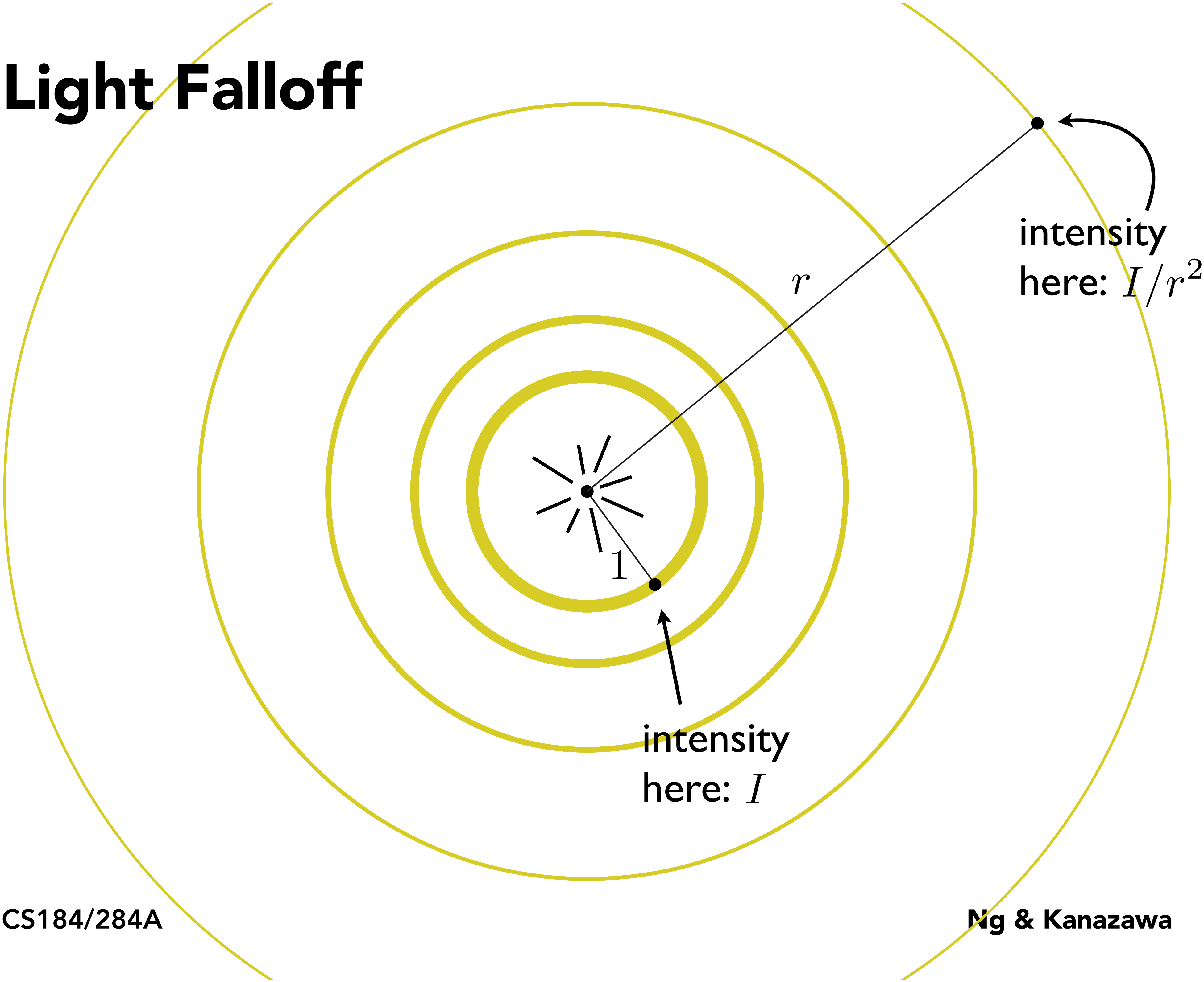


Top face of 60° rotated cube intercepts half the light



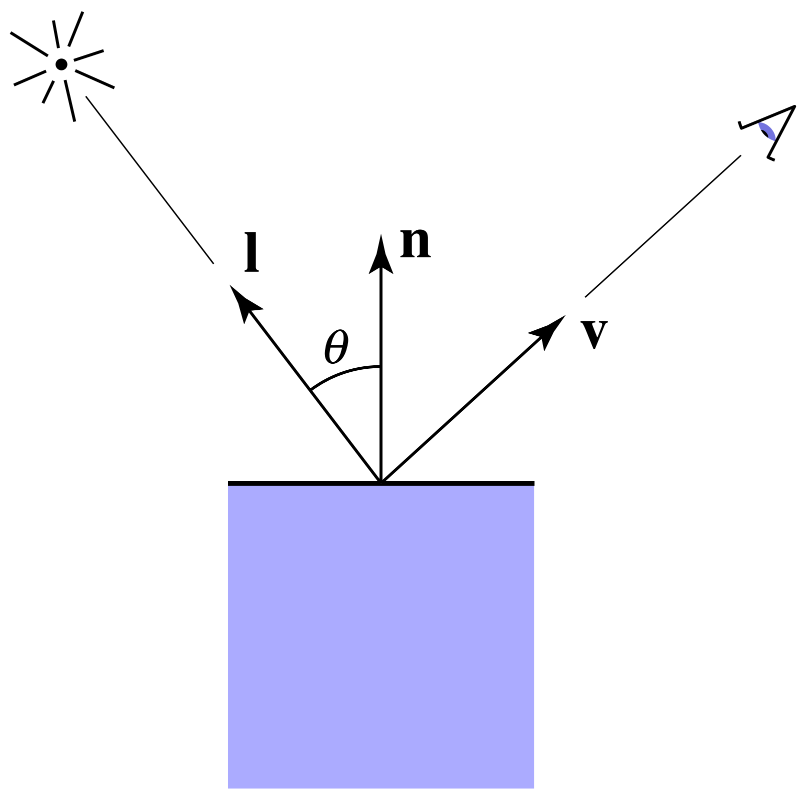

In general, light per unit area is proportional to $\cos\theta = \mathbf{l} \cdot \mathbf{n}$

# Light Falloff



# Lambertian (Diffuse) Shading

## Shading independent of view direction




illumination
from source

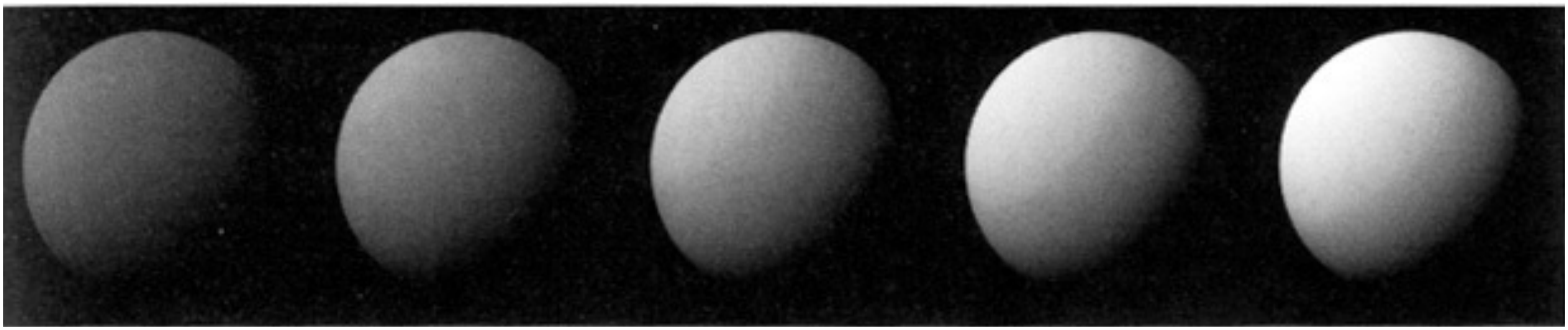
$$L_d = k_d \, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{l})$$

diffuse
coefficient

diffusely
reflected
light

# Lambertian (Diffuse) Shading

Produces matte appearance



$k_d \longrightarrow$

[Foley et al.]

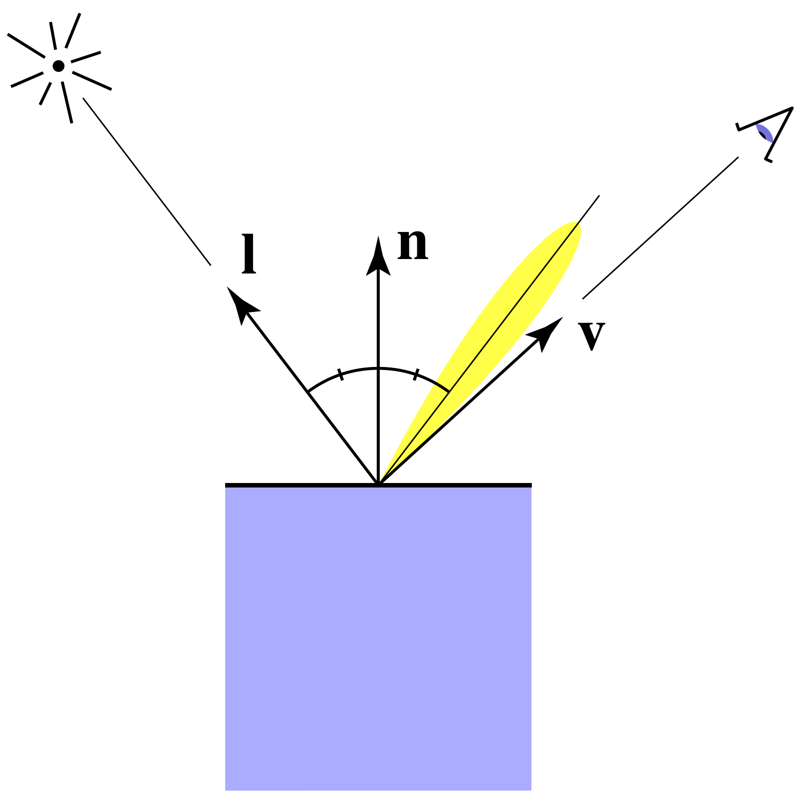
# Perceptual Observations


Photo credit: Jessica Andrews, flickr

# Specular Shading (Blinn-Phong)

Intensity depends on view direction

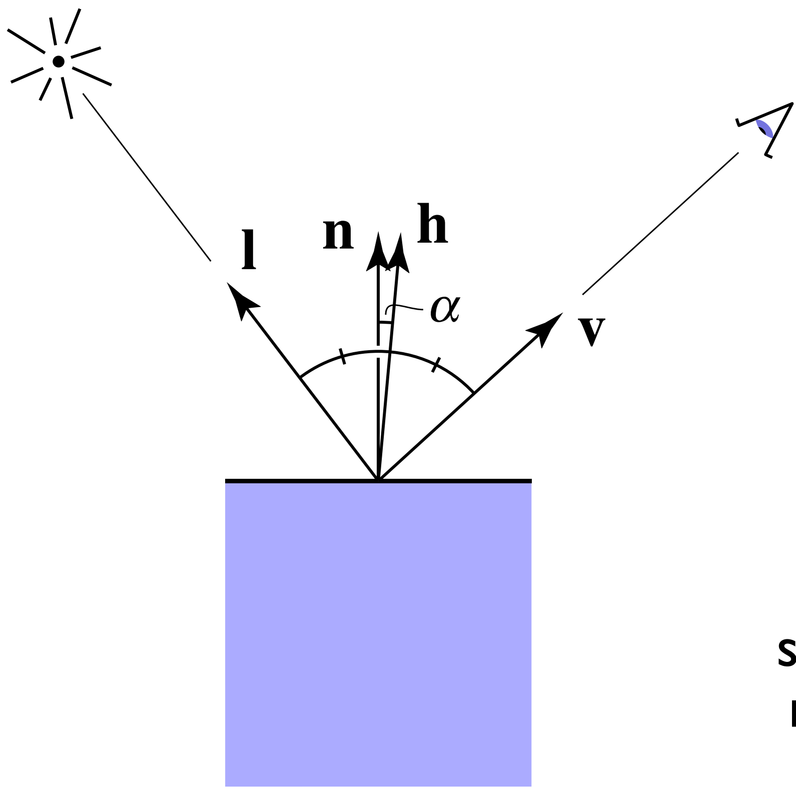
- Bright near mirror reflection direction



# Specular Shading (Blinn-Phong)

Close to mirror direction ⇔ half vector near normal

- Measure "near" by dot product of unit vectors




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

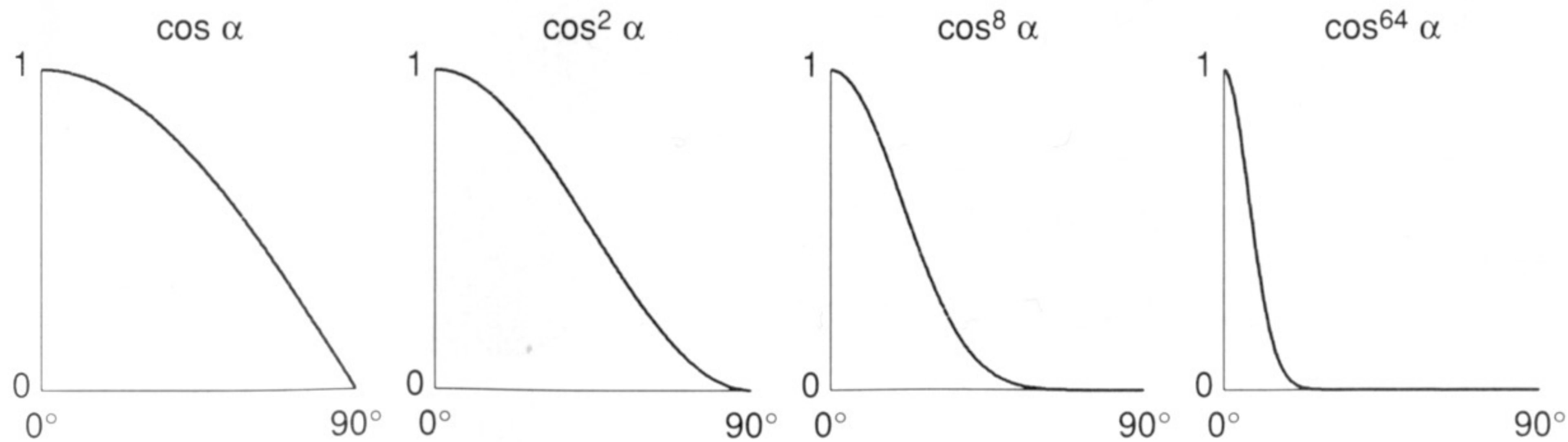
$$L_s = k_s \, (I/r^2) \max(0, \cos\alpha)^p = k_s \, (I/r^2) \max(0, \mathbf{n} \cdot \mathbf{h})^p$$

specularly reflected light ($L_s$)

specular coefficient ($k_s$)

# Cosine Power Plots

## Increasing p narrows the reflection lobe

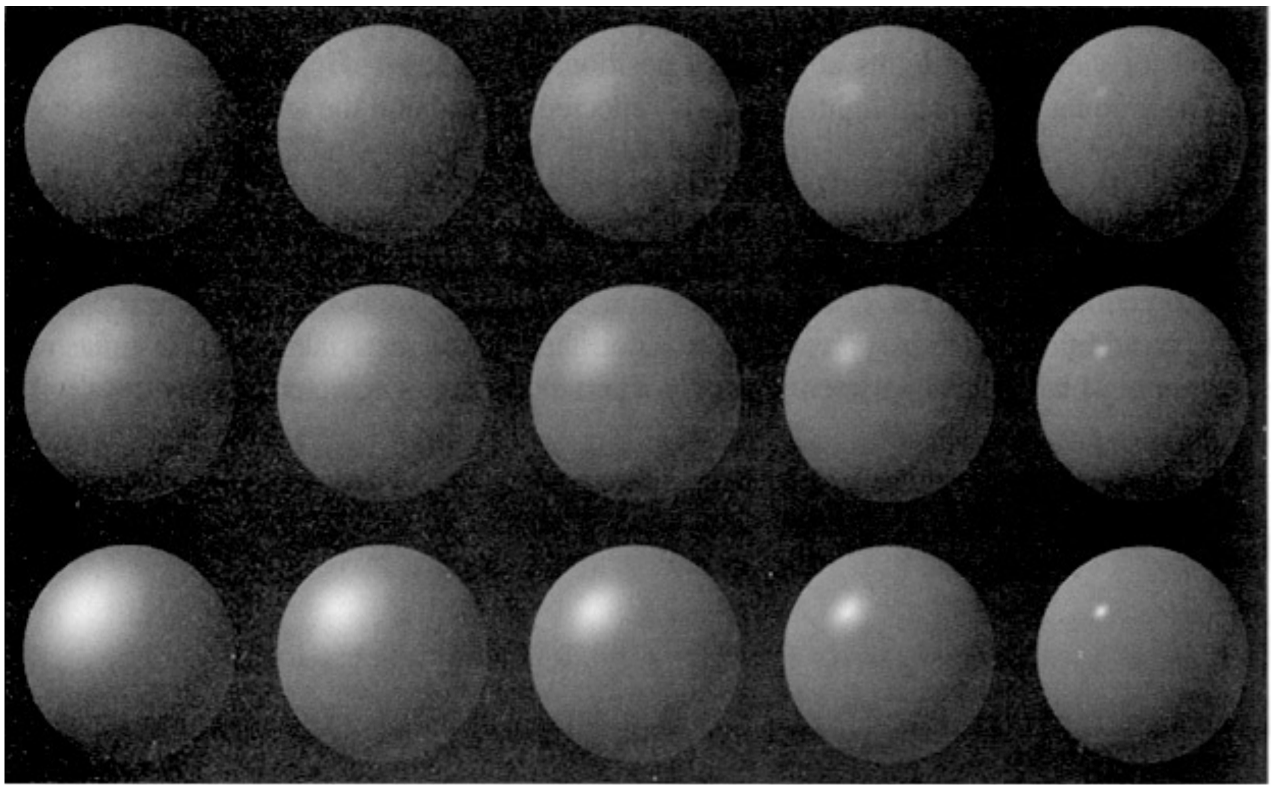



[Foley et al.]

# 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.]

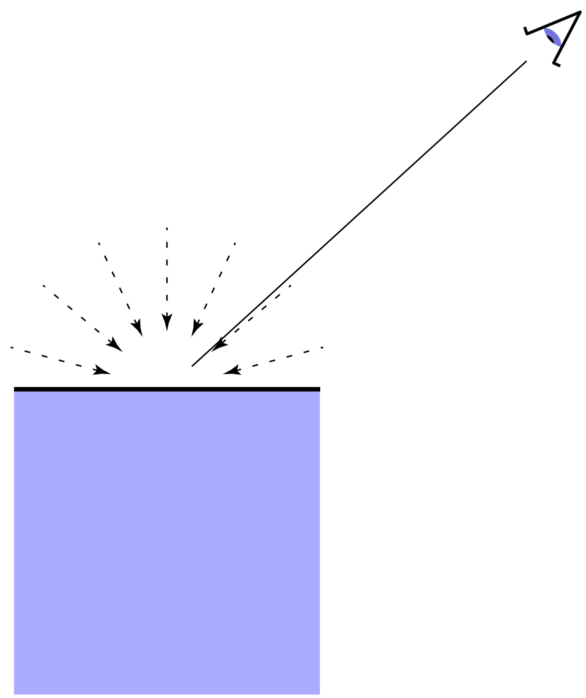
# Perceptual Observations


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

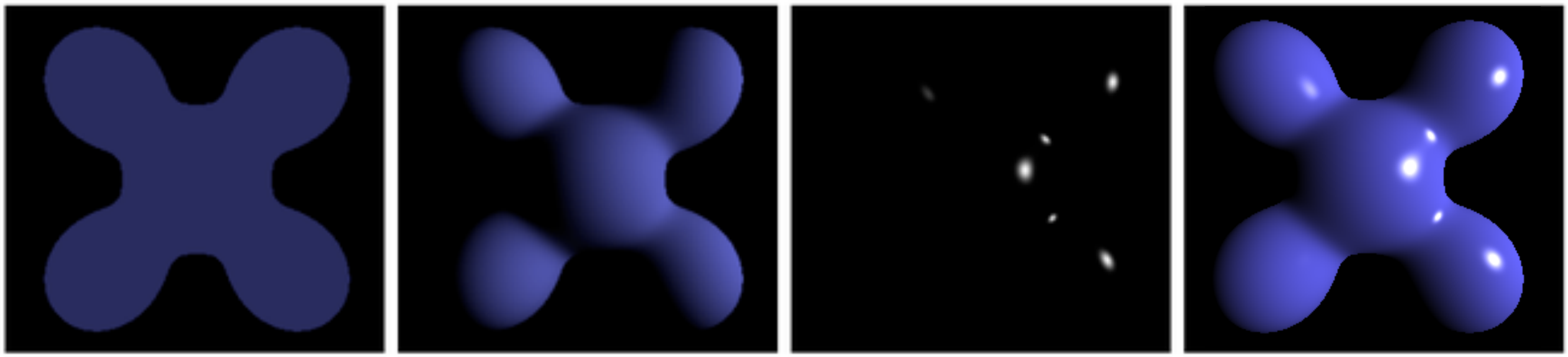


$$L_a = k_a \, I_a$$

reflected ambient light

ambient coefficient

# 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

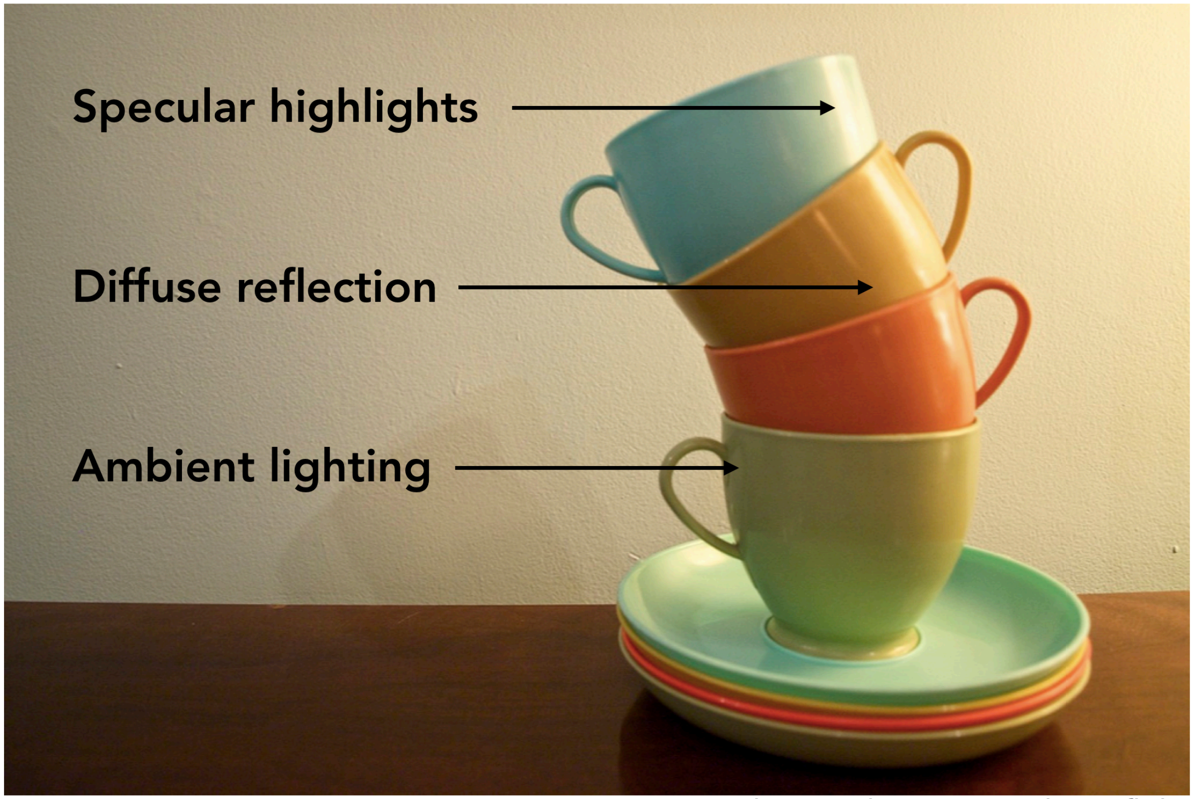



Photo credit: Jessica Andrews, flickr

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

# Shading Triangle Meshes

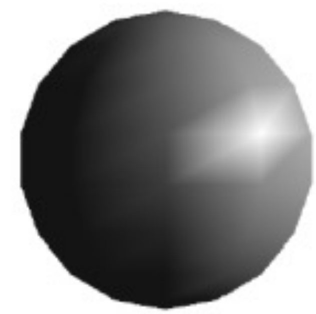
# Shading Frequency: Triangle, Vertex or Pixel

Shade each triangle (flat shading)

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

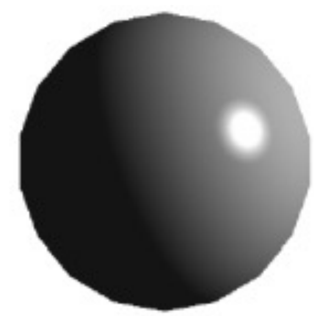
Shade each vertex ("Gouraud" shading)

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

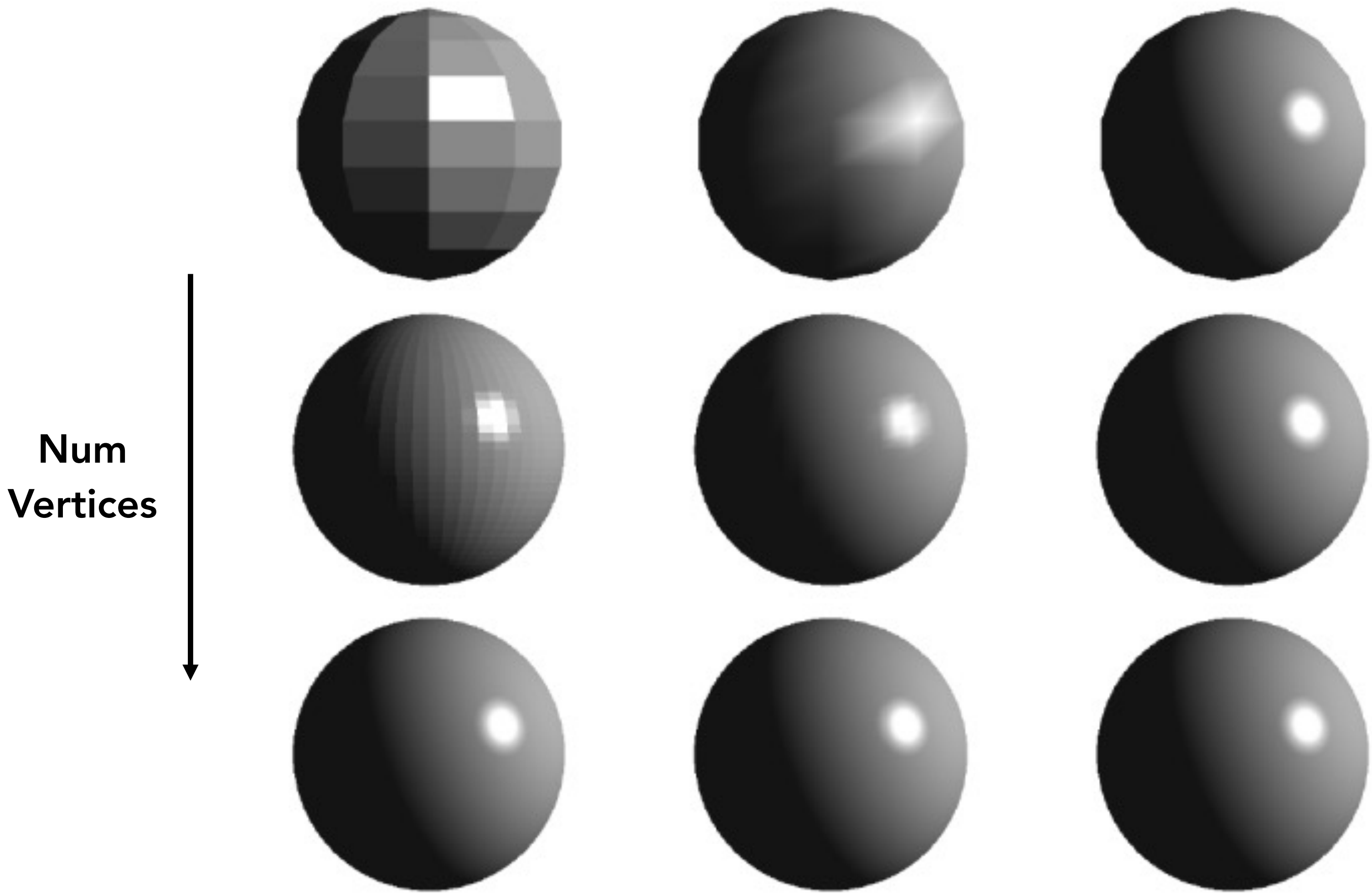


Shade each pixel ("Phong" shading)

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



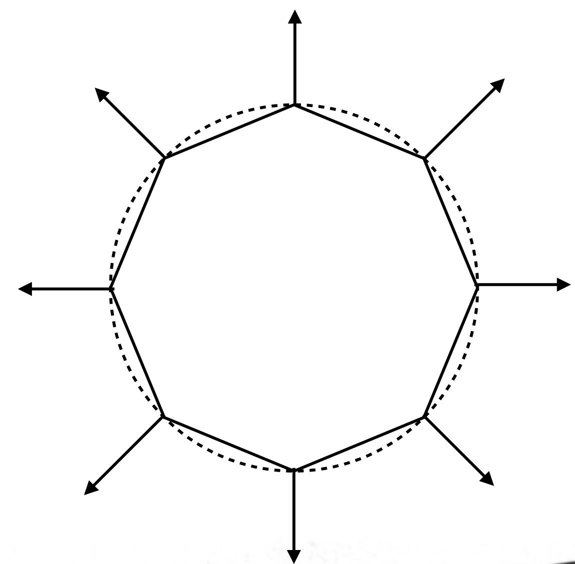
# Shading Frequency: Face, Vertex or Pixel




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

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

# Defining Per-Vertex Normal Vectors



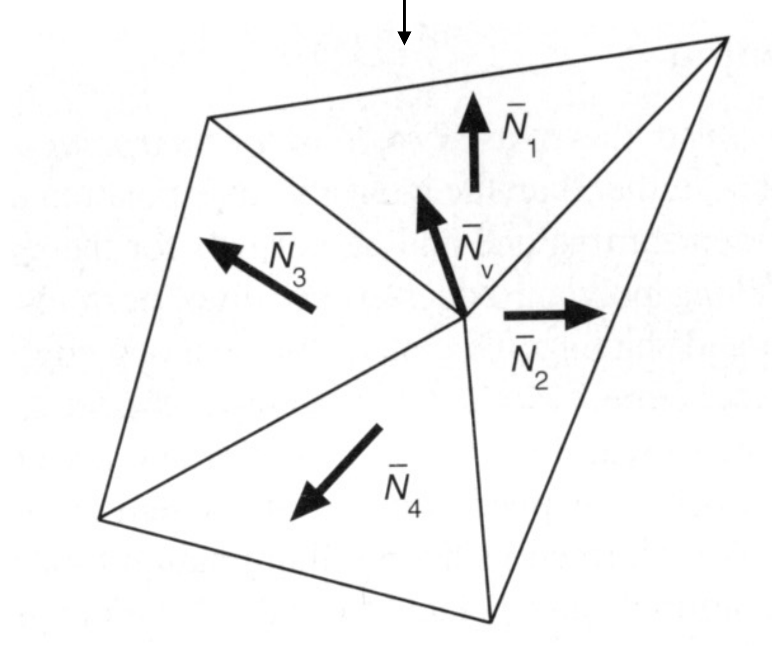
Best to get vertex normals from the underlying geometry

- e.g. consider a sphere

Otherwise have to infer vertex normals from triangle faces

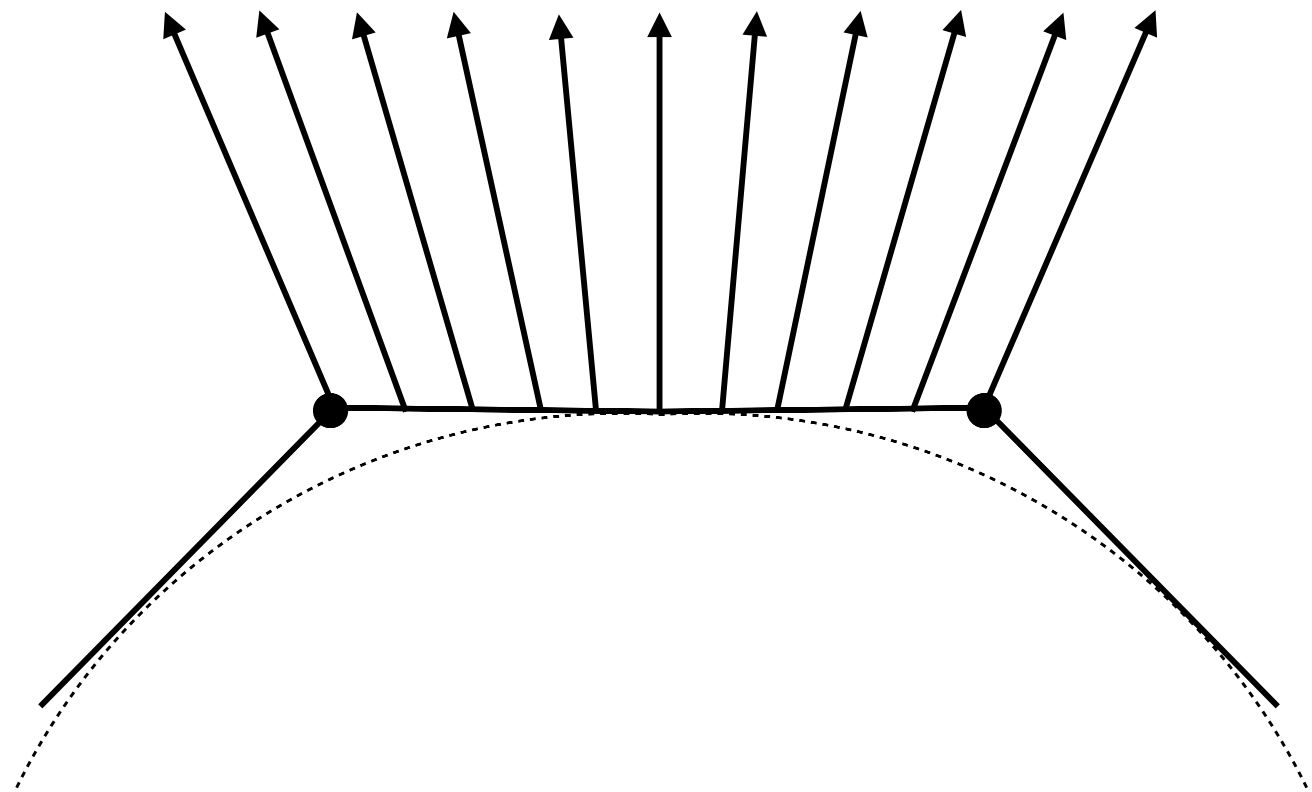
- Simple scheme: average surrounding face normals

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



# Defining Per-Pixel Normal Vectors

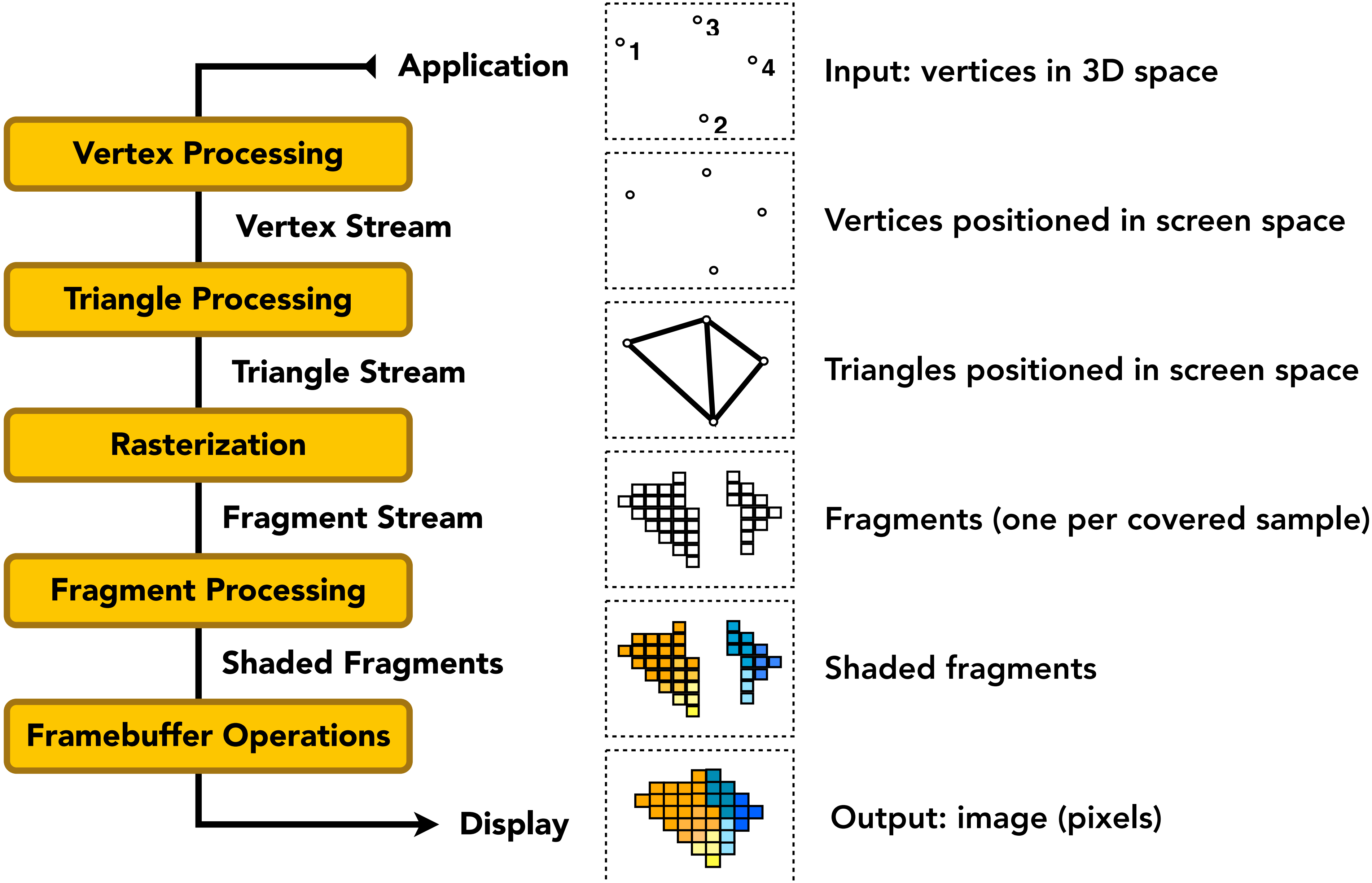
## Barycentric interpolation of vertex normals



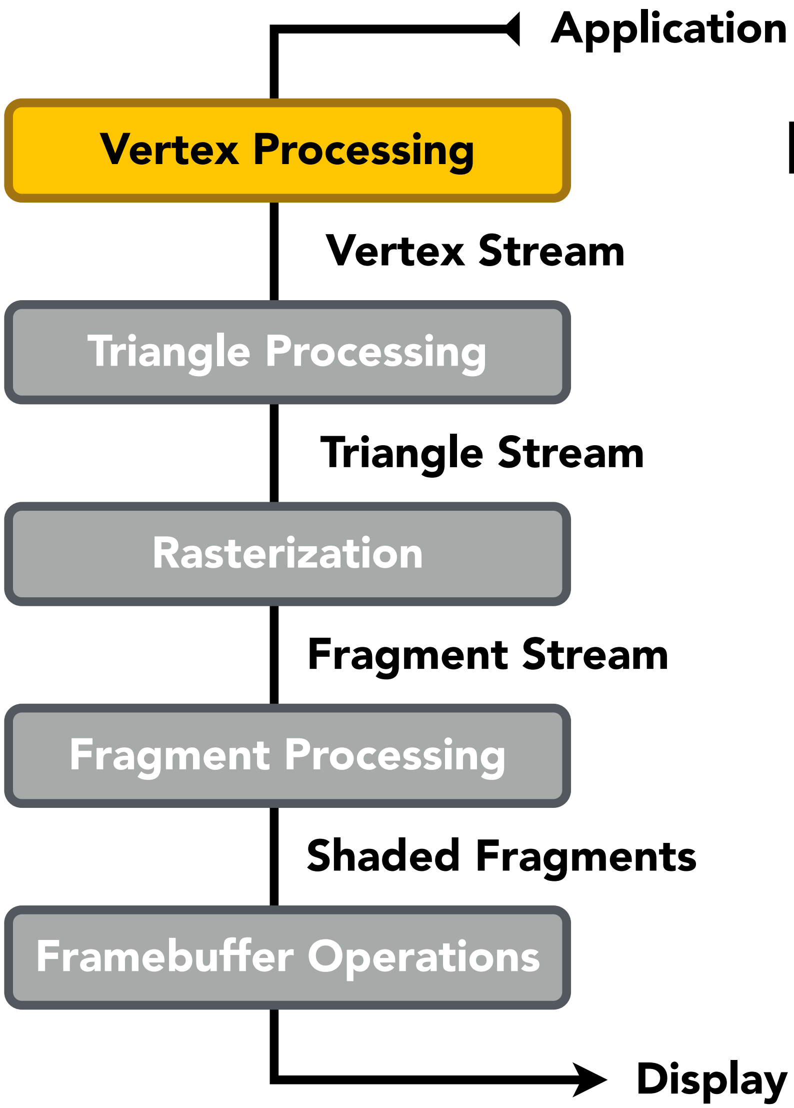
Problem: length of vectors?

# Rasterization Pipeline

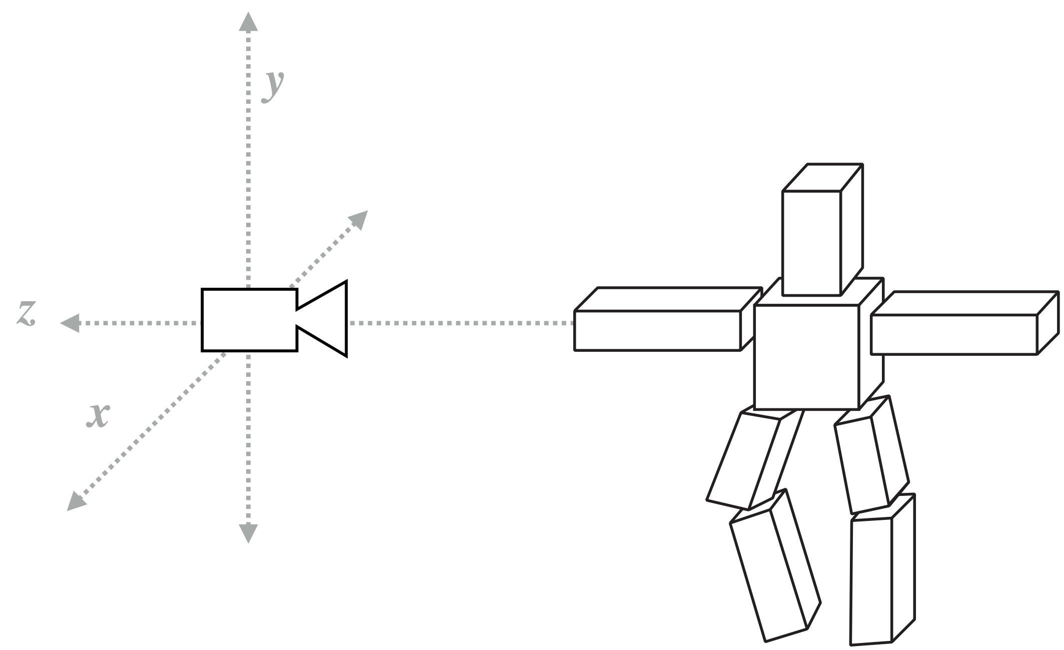
# Rasterization Pipeline



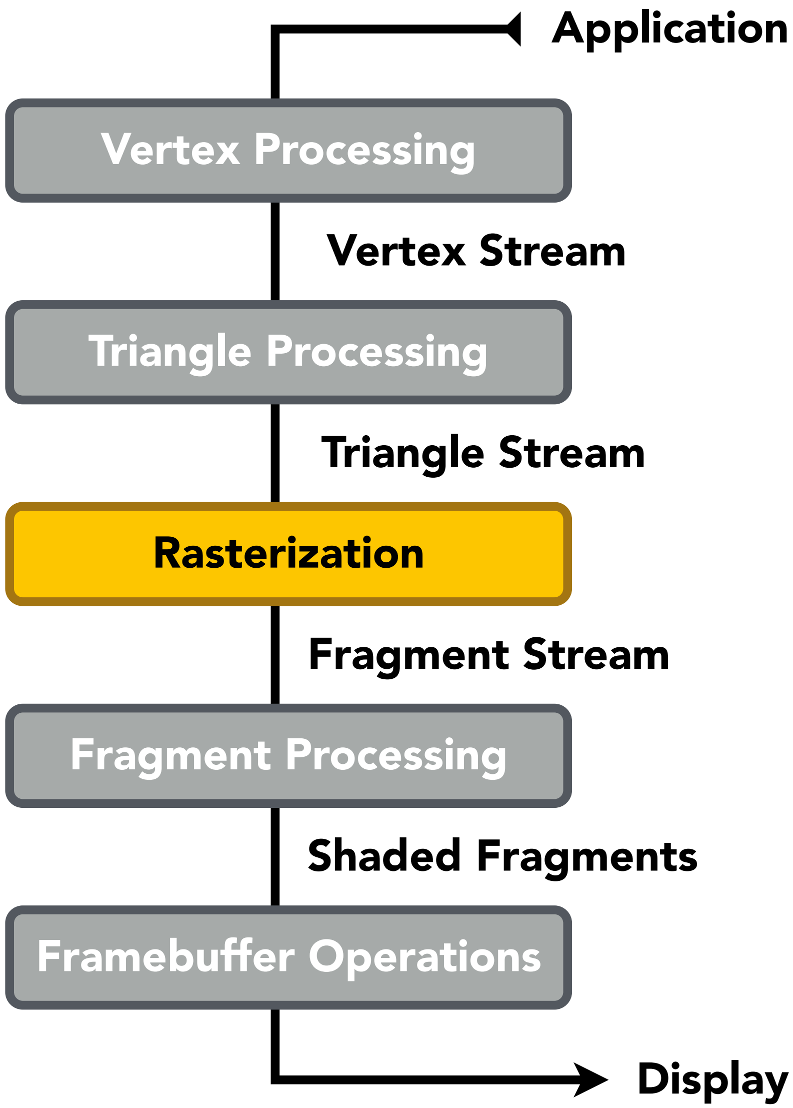
# Rasterization Pipeline



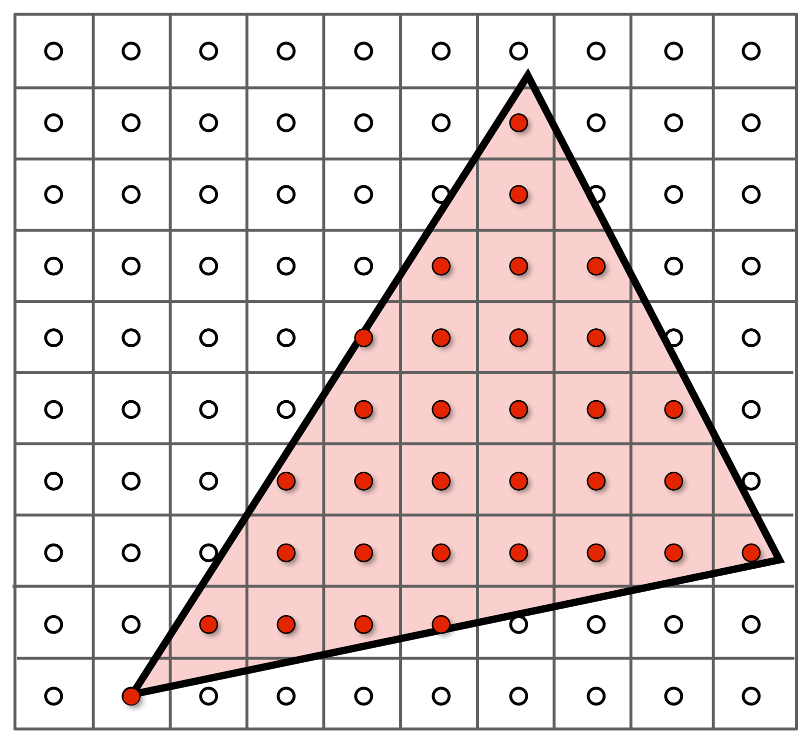

## Modeling & viewing transforms



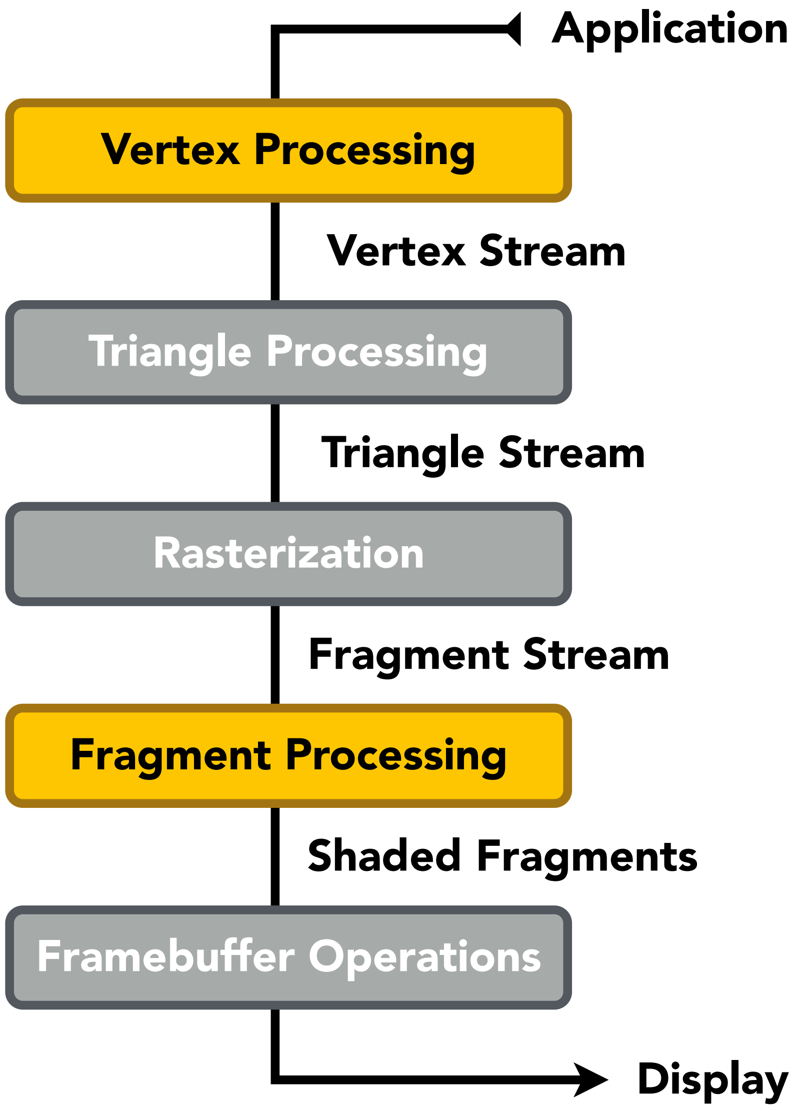
# Rasterization Pipeline



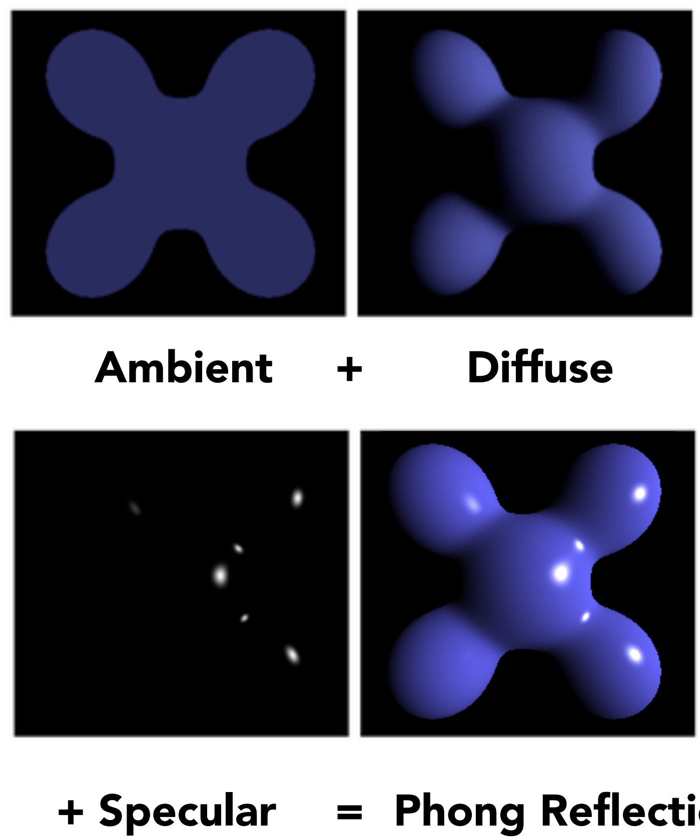

## Sampling triangle coverage



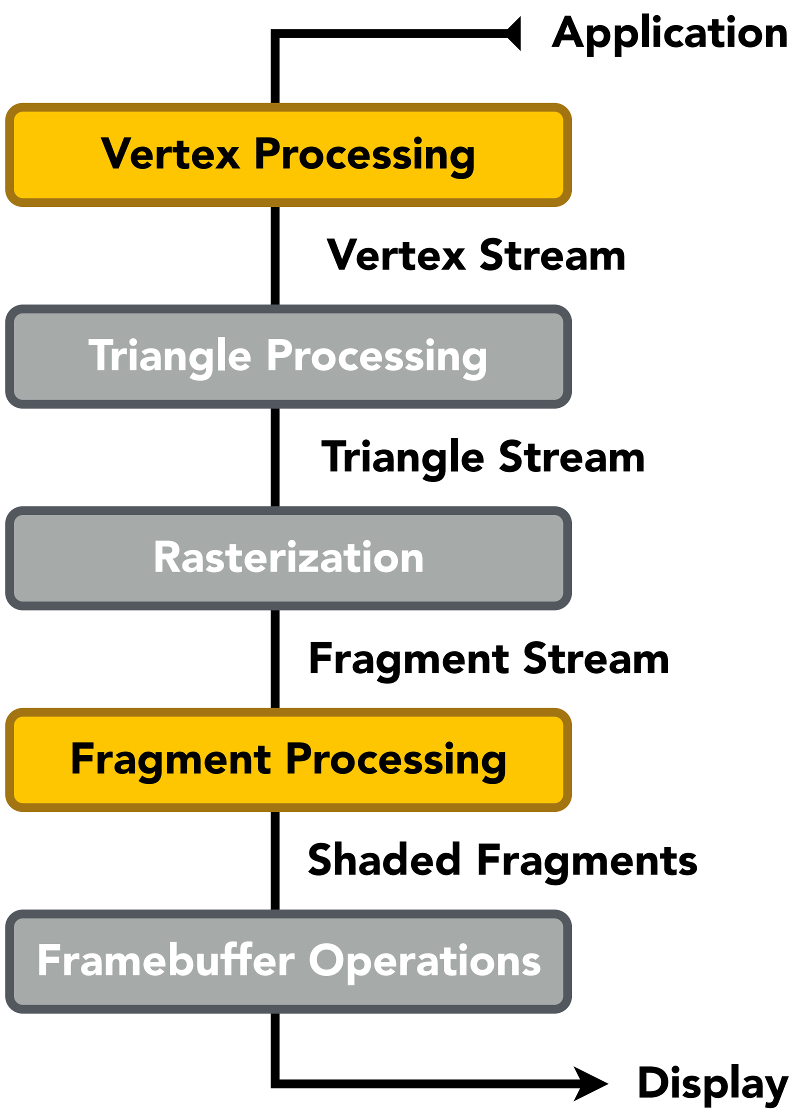
# Rasterization Pipeline



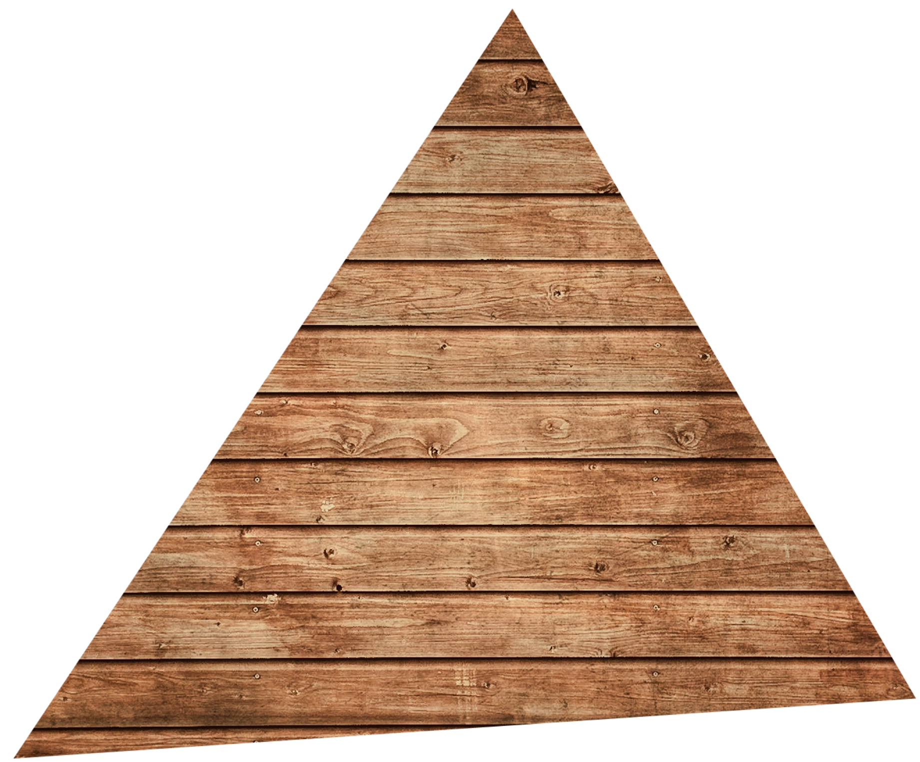

## Evaluating shading functions



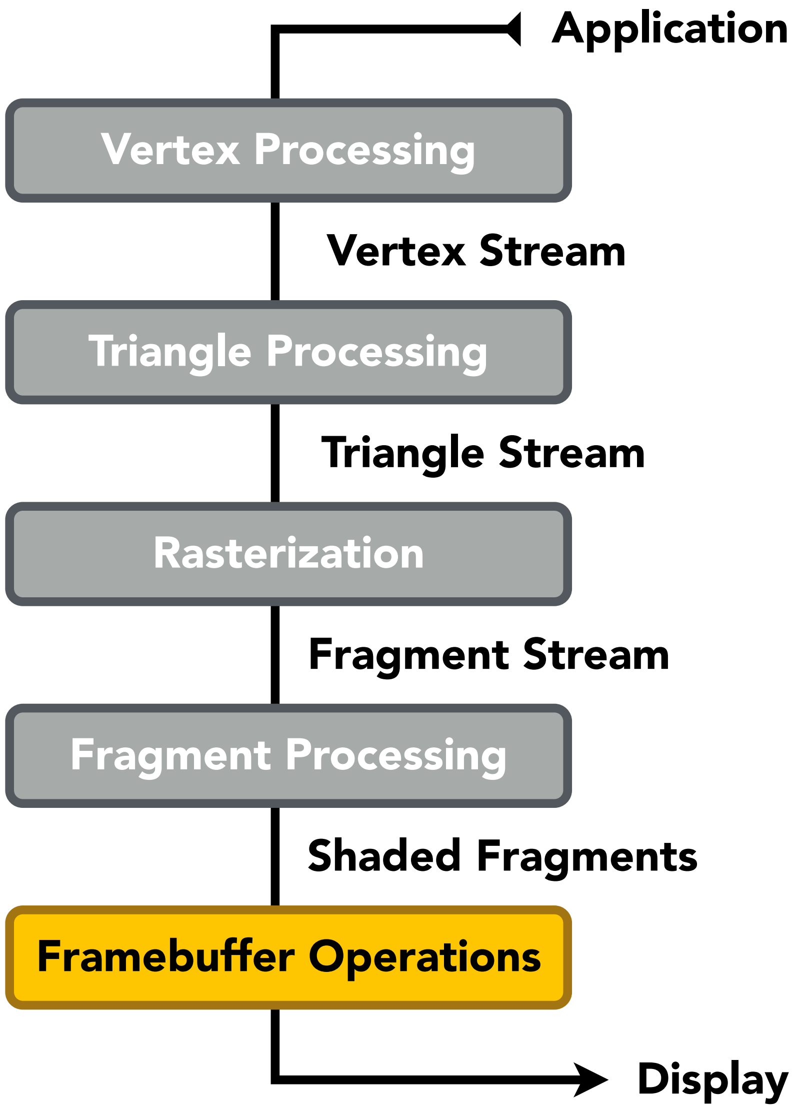
# Rasterization Pipeline




## 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

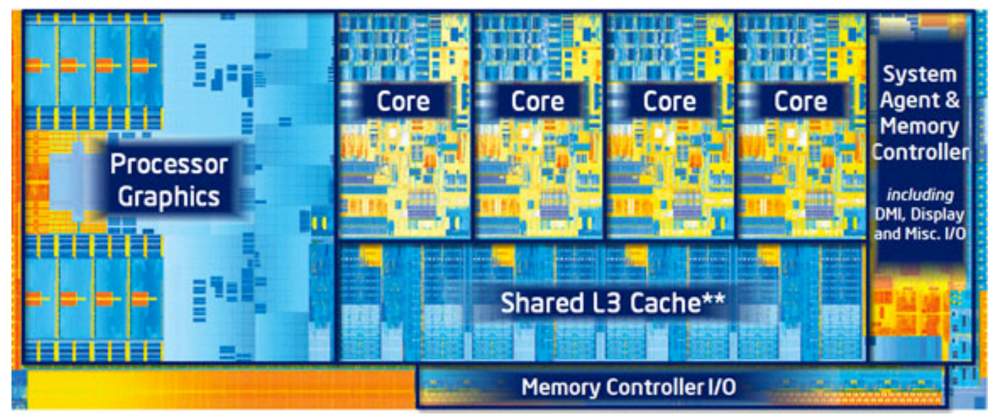
- 100's of thousands to millions of triangles in a scene
- Complex vertex and fragment shader computations
- High resolution (3-5+ megapixel + supersampling)
- 30-60 frames per second (even higher for VR)

**Unreal Engine Kite Demo (Epic Games 2015)**

# Graphics Pipeline Implementation: GPUs

Specialized processors for executing graphics pipeline computations

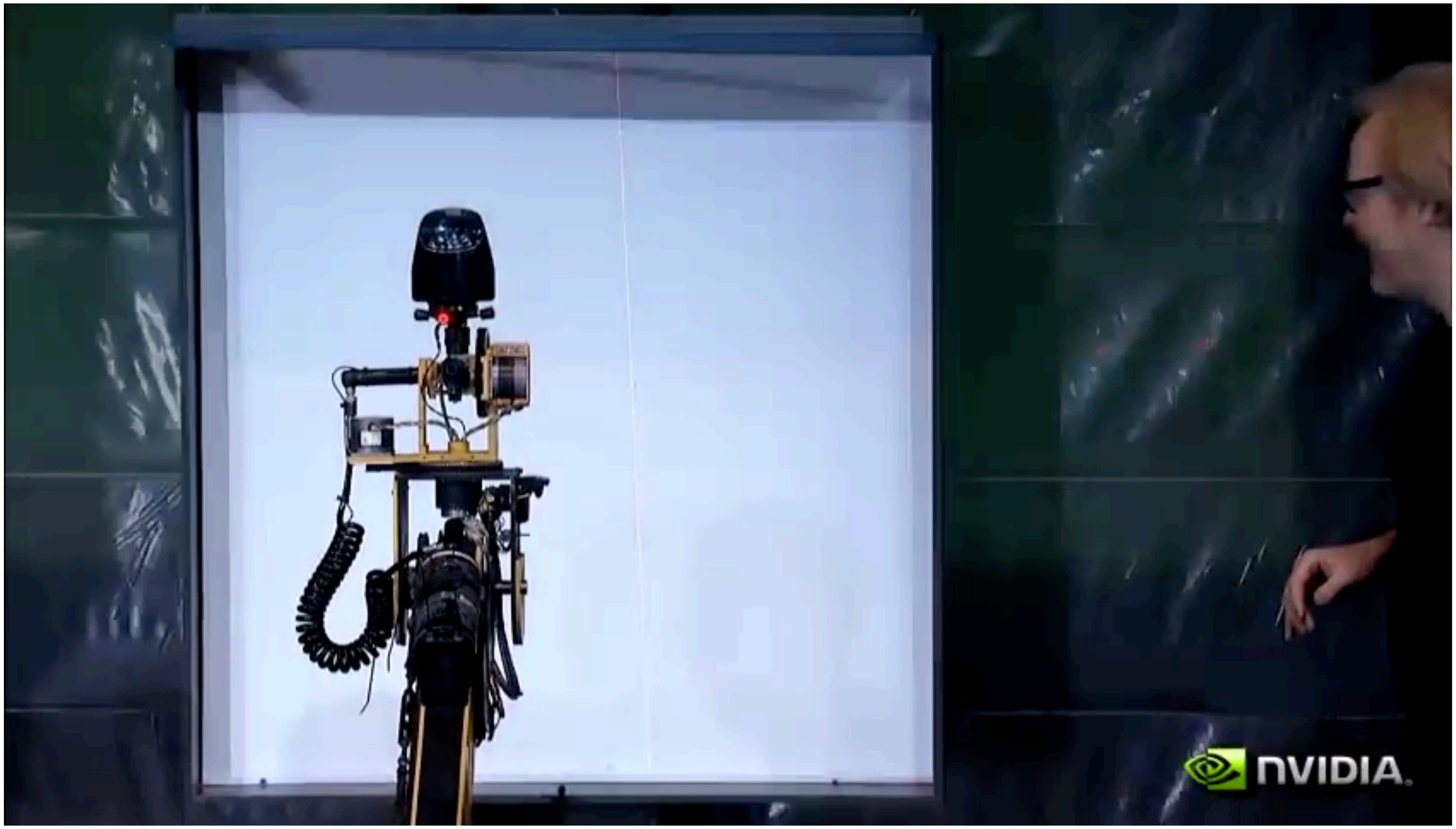

Discrete GPU Card
(NVIDIA GeForce Titan X)




Integrated GPU:
(Part of Intel CPU die)

# CPU vs GPU

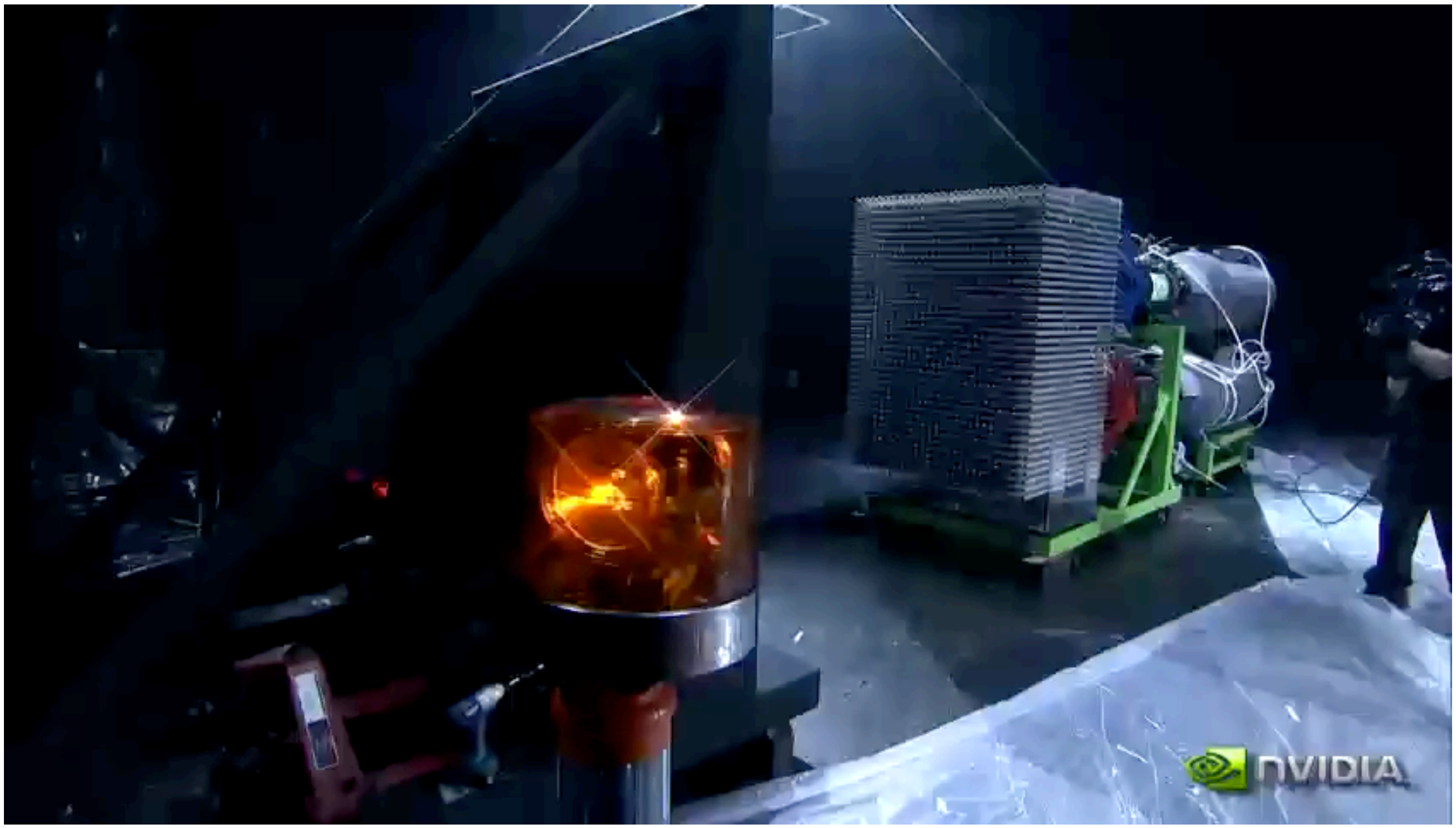
CPU




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

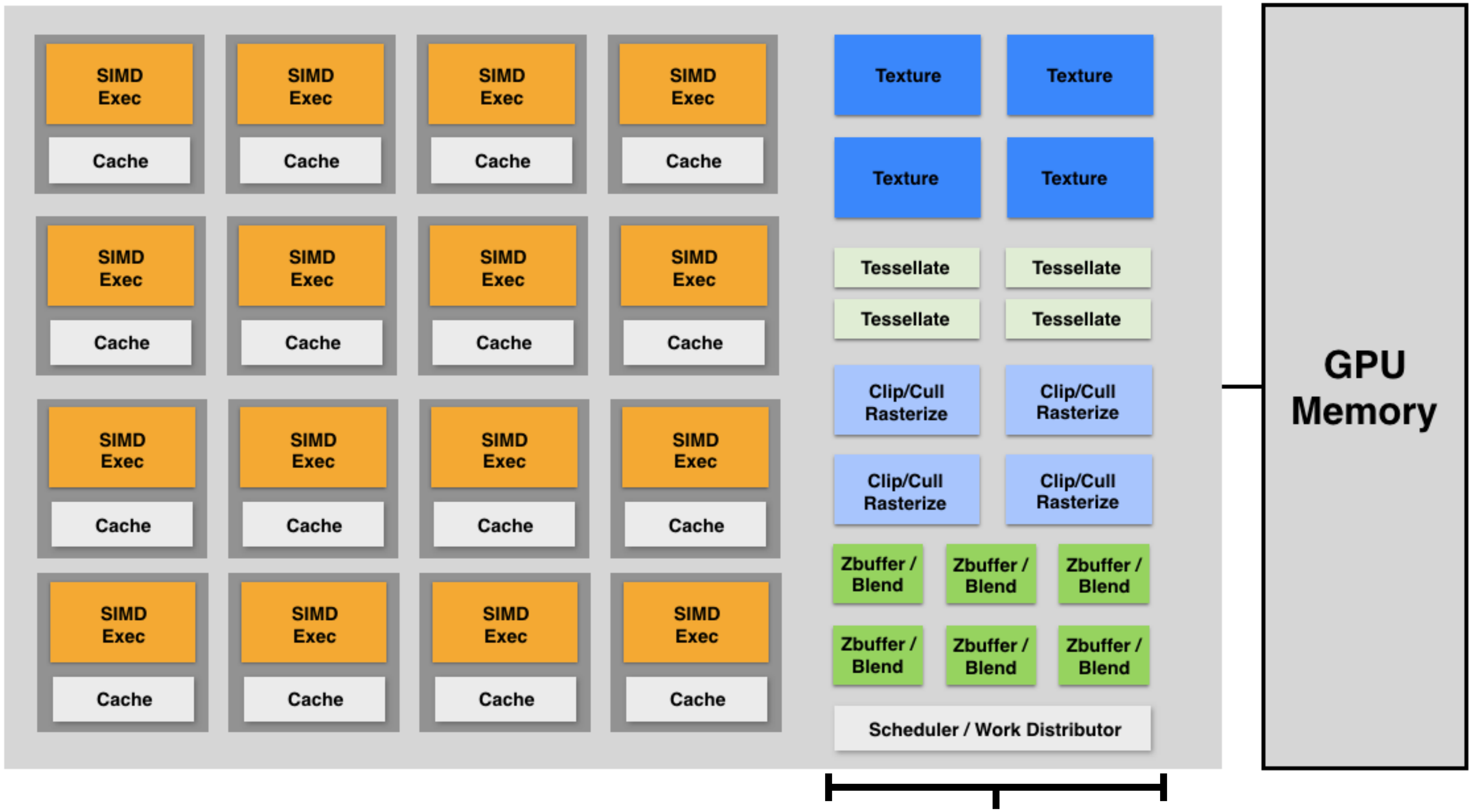
# CPU vs GPU

GPU




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

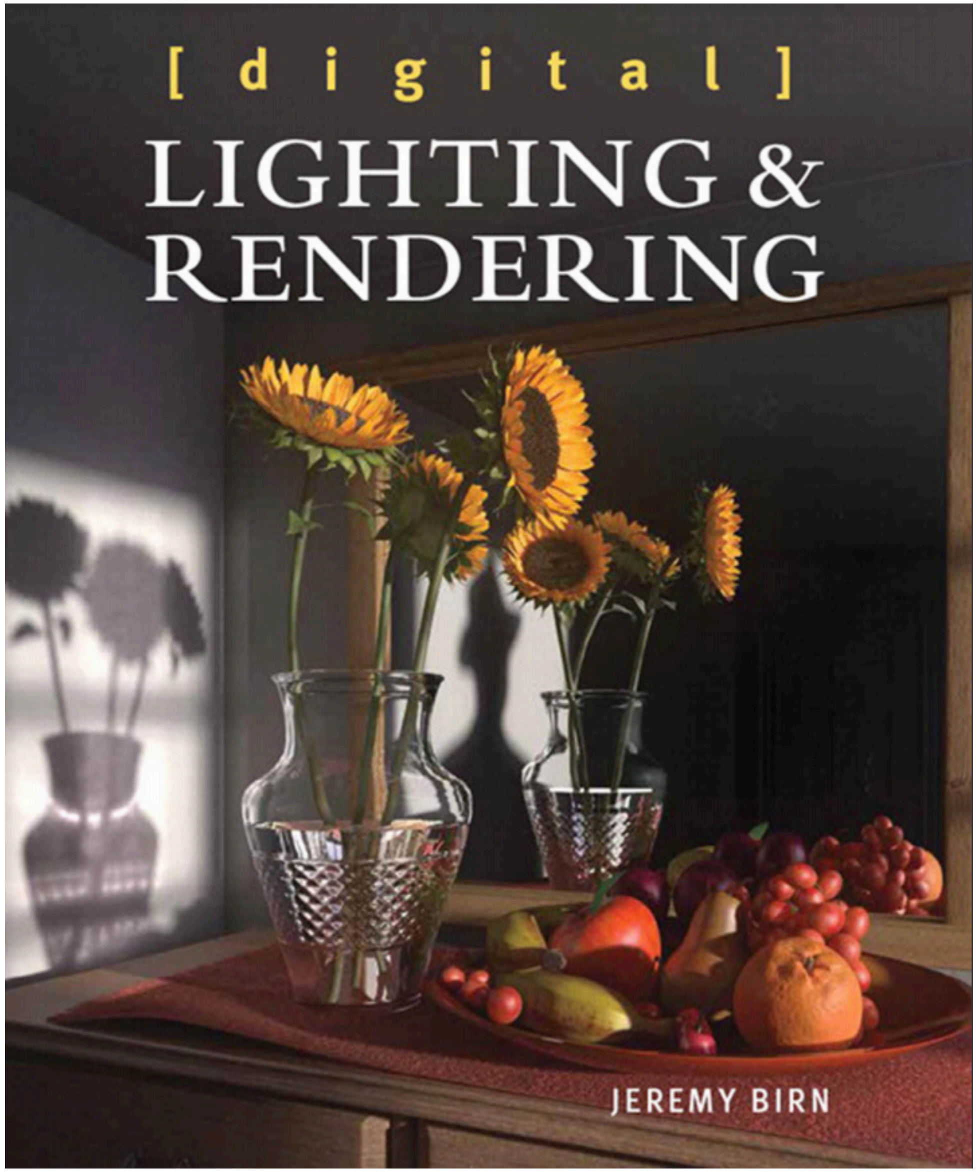
# GPU: Heterogeneous, Multi-Core Procesor




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

# Shading from today is phenomenological (hack)



# 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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