# Scan Conversion

COS 426, Spring 2020

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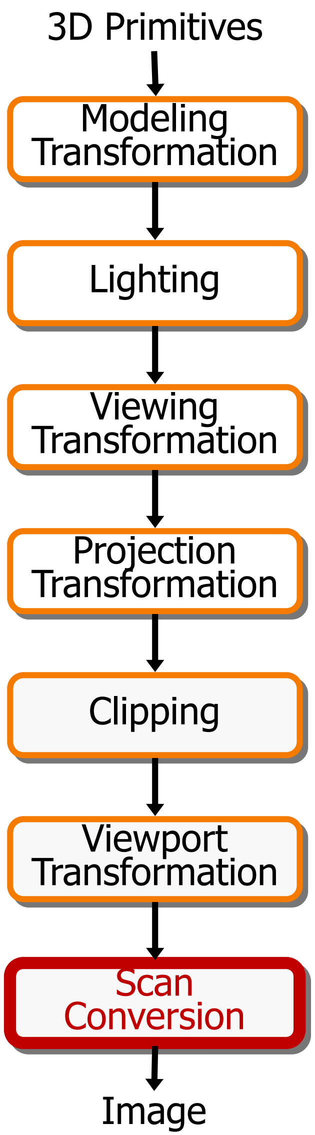
Princeton University

# 3D Rendering Pipeline (for direct illumination)



# Rasterization

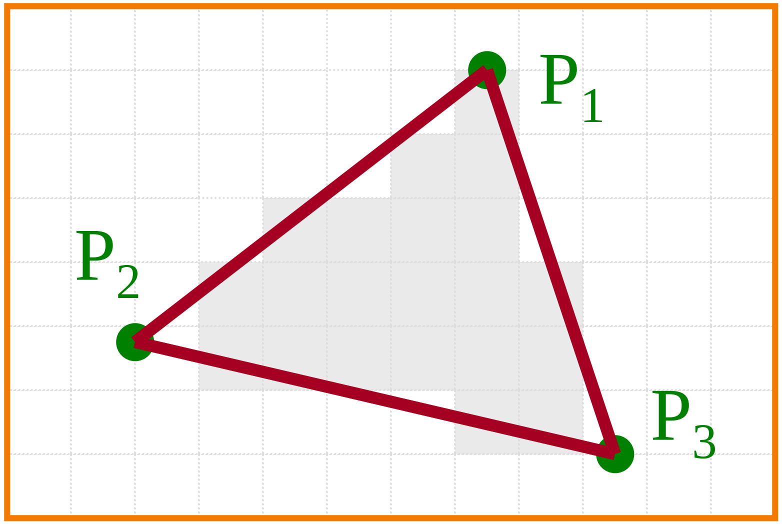
- Scan conversion
  - Determine which pixels to fill
- Shading
  - Determine a color for each filled pixel
- Texture mapping
  - Describe shading variation within polygon interiors
- Visible surface determination
  - Figure out which surface is front-most at every pixel

# Rasterization

- Scan conversion (last time)
  - Determine which pixels to fill
- Shading
  - Determine a color for each filled pixel
- Texture mapping
  - Describe shading variation within polygon interiors
- Visible surface determination
  - Figure out which surface is front-most at every pixel

# Shading

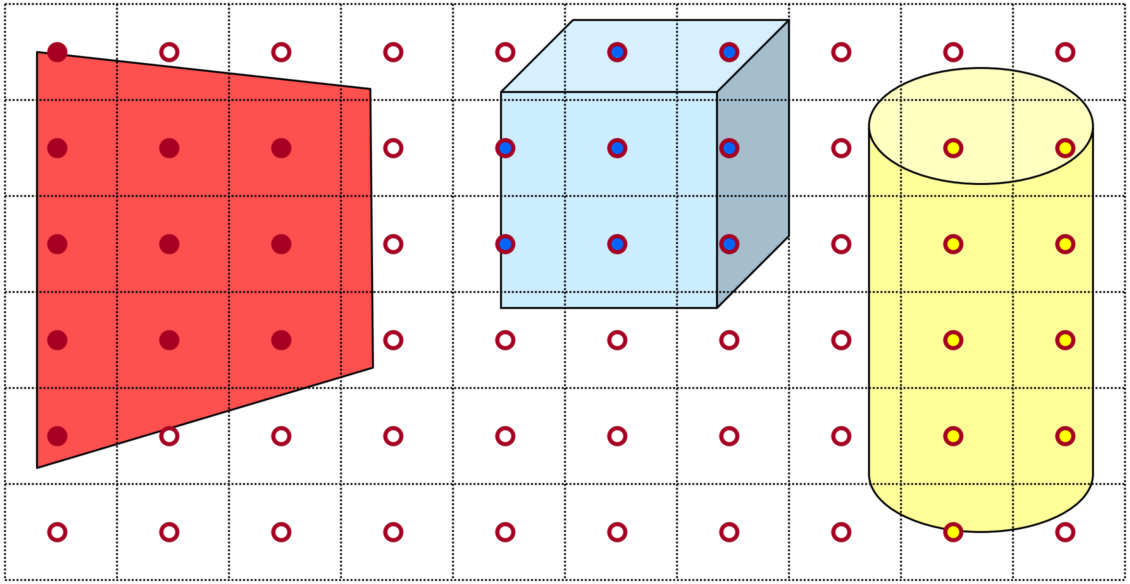
- How do we choose a color for each filled pixel?




Emphasis on methods that can be implemented in hardware

# Ray Casting

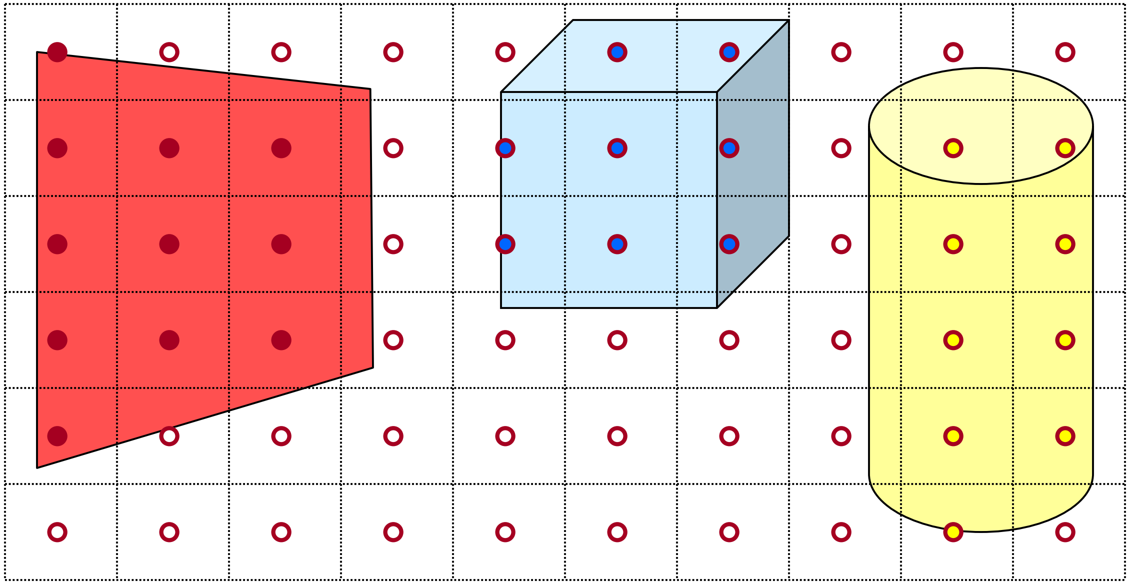
- Simplest shading approach is to perform independent lighting calculation for every pixel



$$I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)$$

# Polygon Shading

- Can take advantage of spatial coherence
  - Illumination calculations for pixels covered by same primitive are related to each other



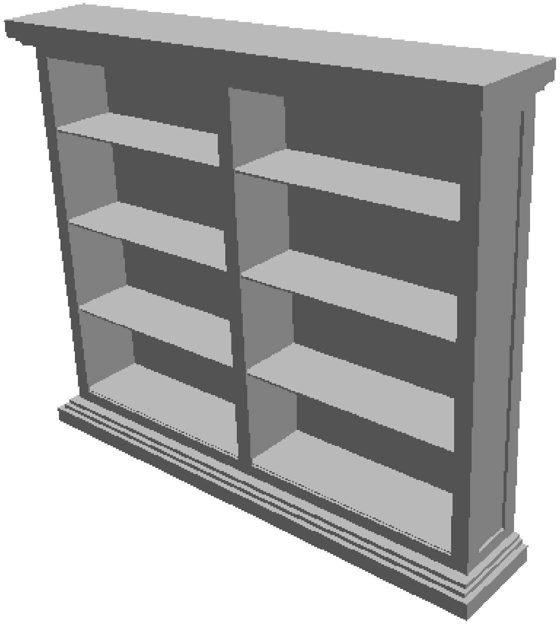
$$I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)$$

# Polygon Shading Algorithms

- **Flat Shading**
- Gouraud Shading
- Phong Shading

# Flat Shading

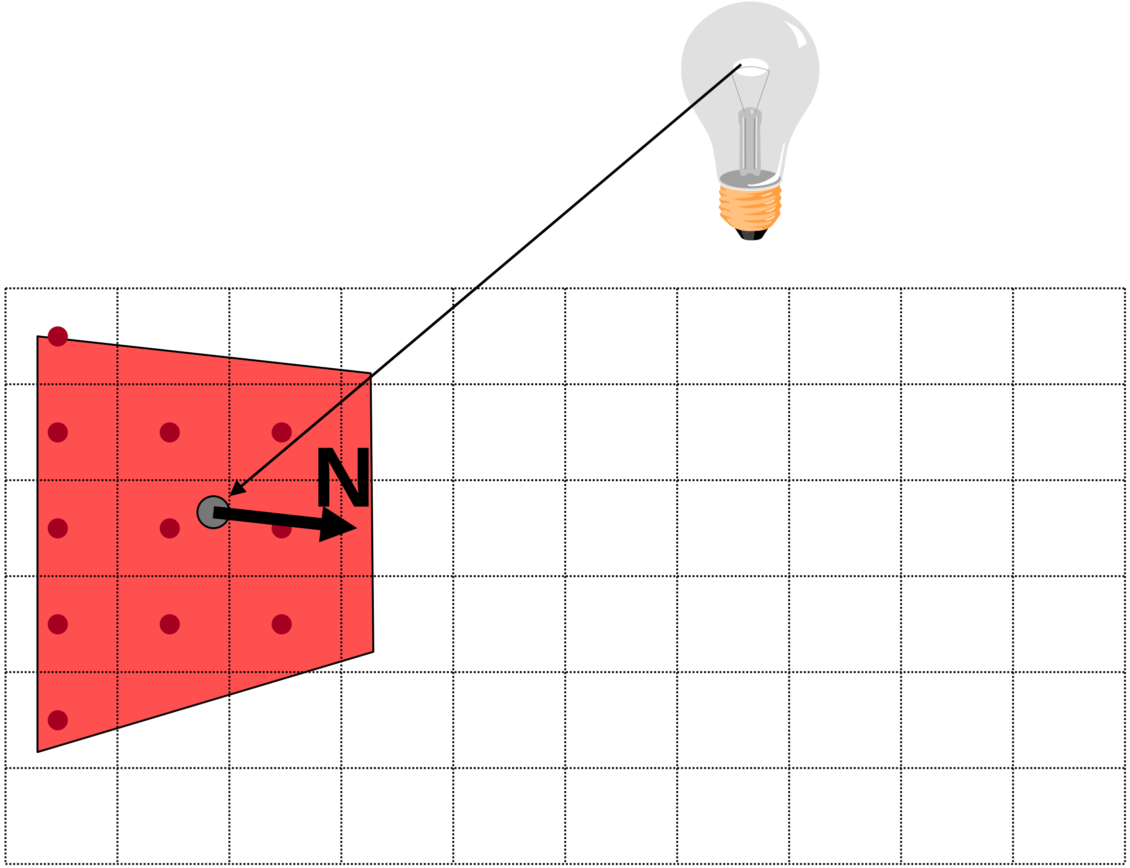
- What if a faceted object is illuminated only by directional light sources and is viewed from infinitely far away



$$I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)$$

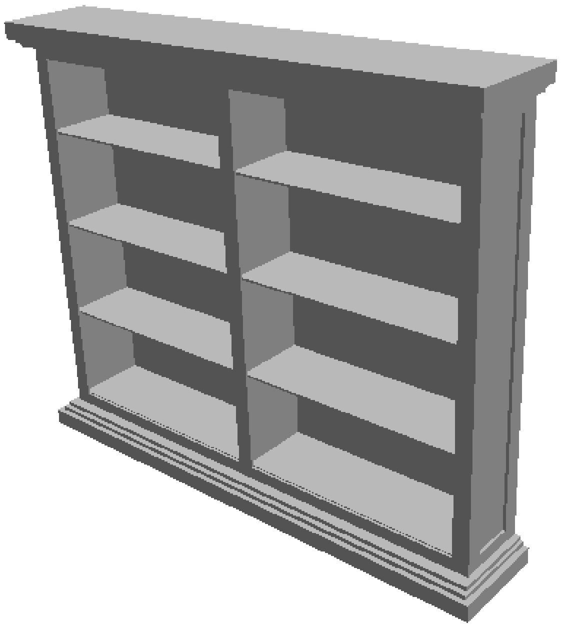
# Flat Shading

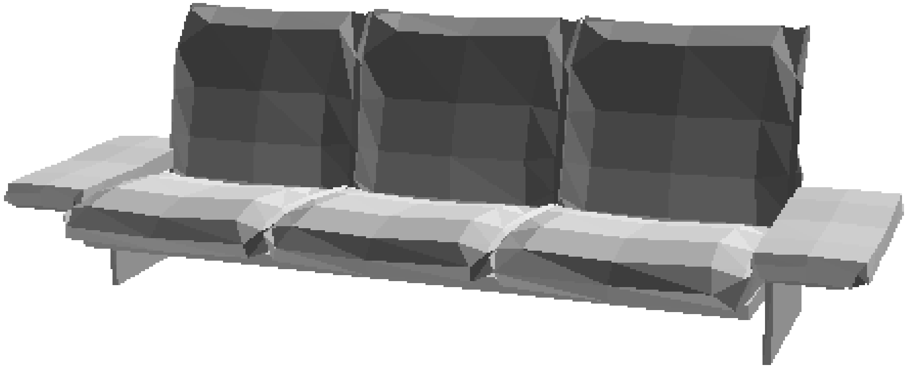
- One illumination calculation per polygon
  - Assign all pixels inside each polygon the same color



# Flat Shading

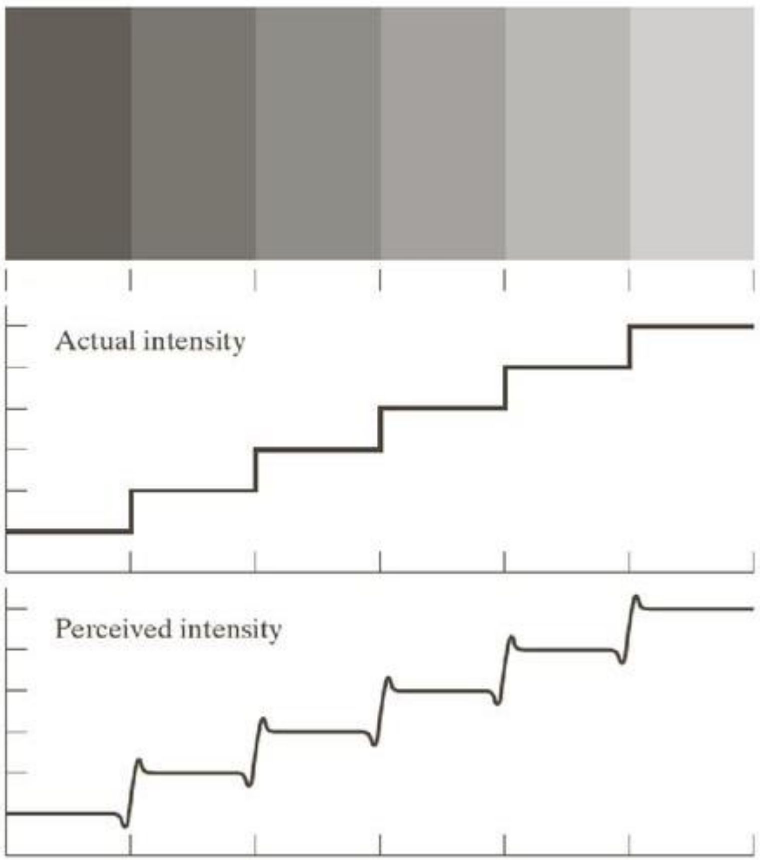
- Objects look like they are composed of polygons
  - OK for polyhedral objects
  - Not so good for smooth surfaces





# Mach Band Effect

- Edges between adjacent shades of gray are perceived as exaggerated.

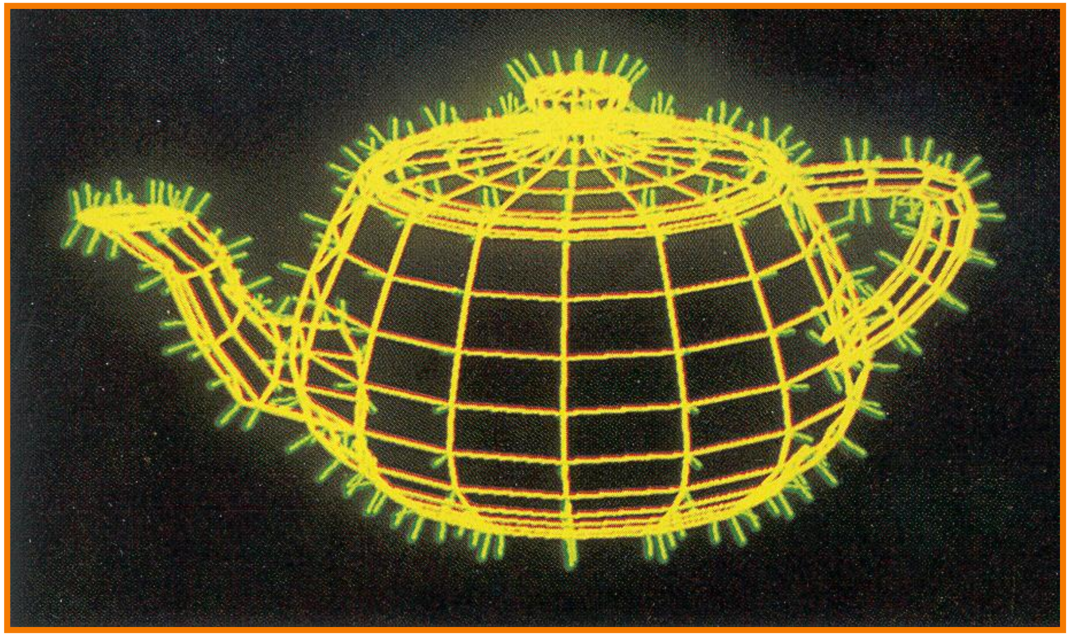


# Polygon Shading Algorithms

- Flat Shading
- **Gouraud Shading**
- Phong Shading

# Gouraud Shading

- What if smooth surface is represented by polygonal mesh with a normal at each vertex?

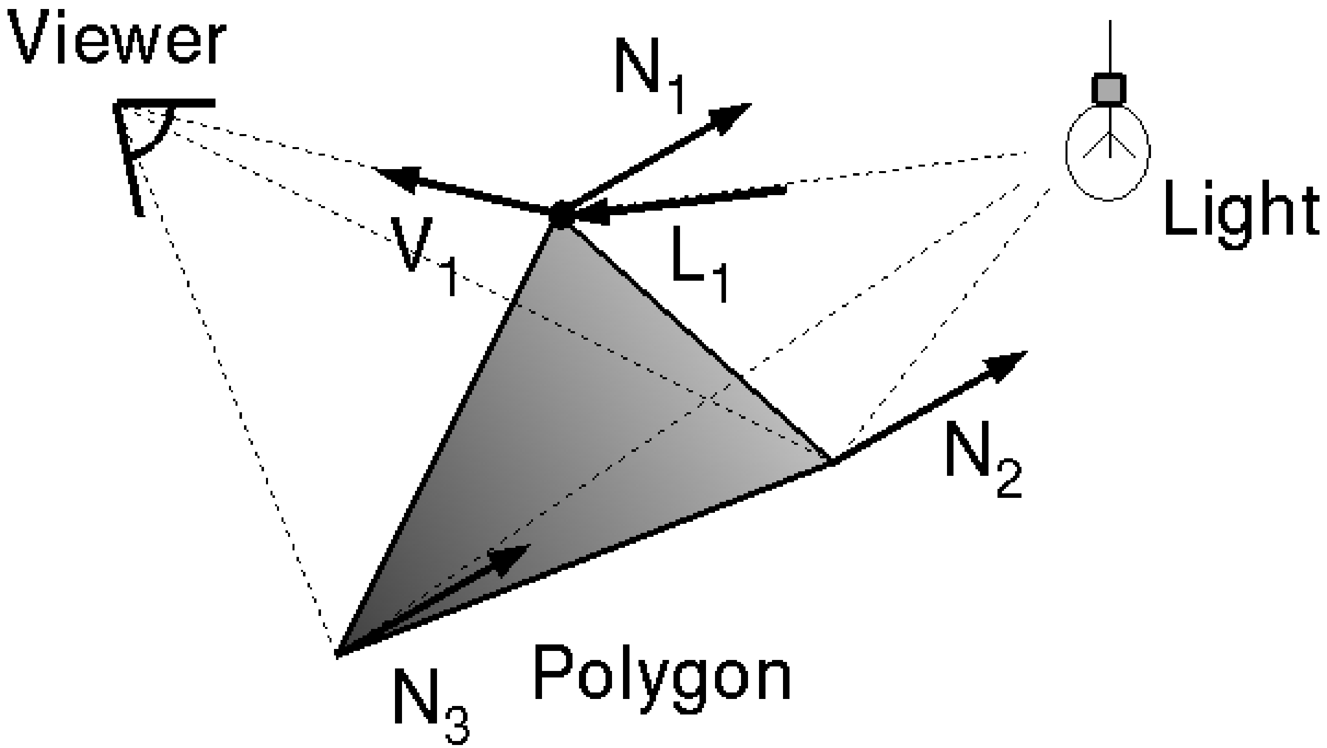


Watt Plate 7

$$I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)$$

# Gouraud Shading

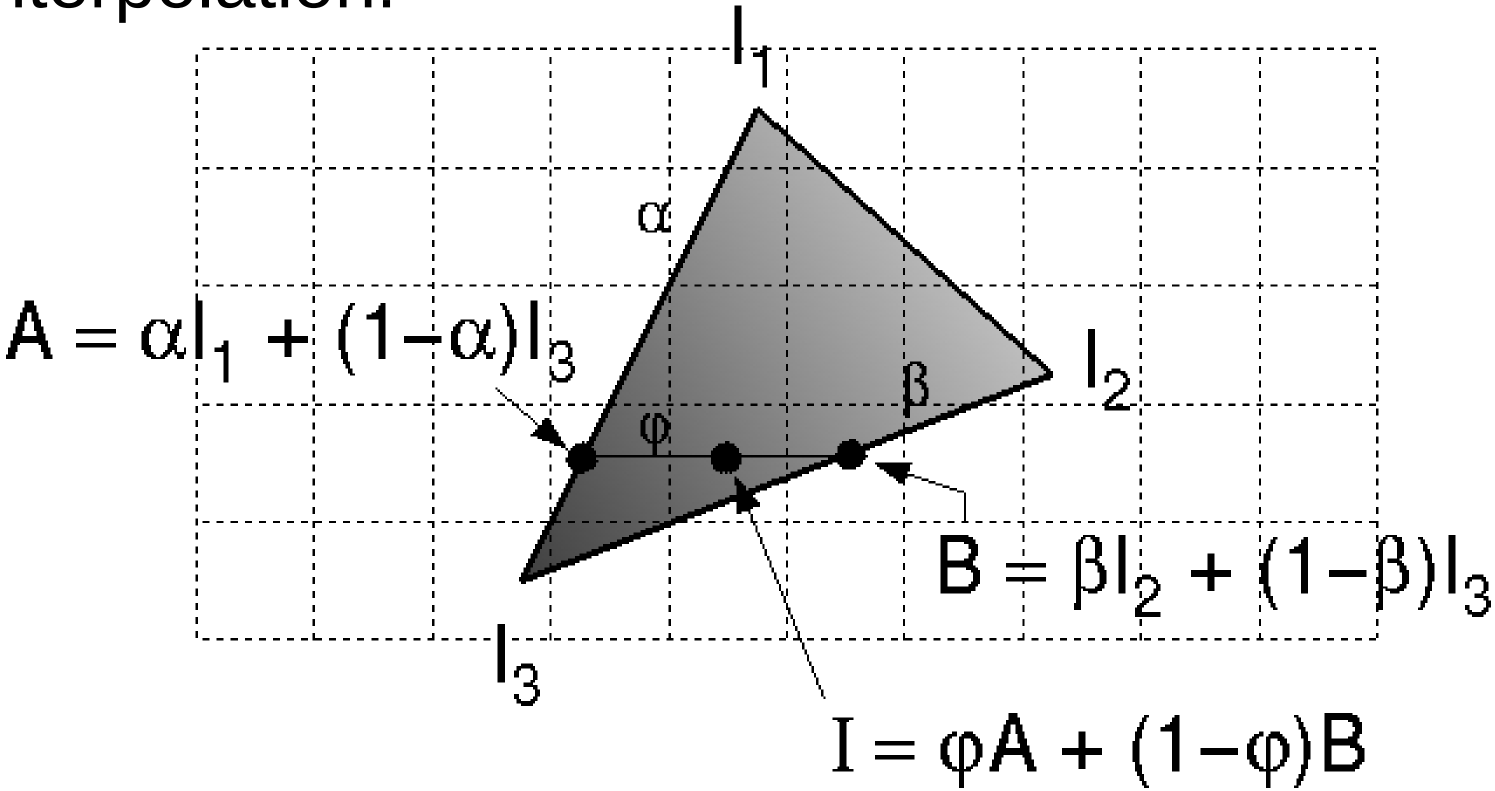
- One lighting calculation per vertex
  - Assign pixels inside polygon by interpolating colors computed at vertices



# Gouraud Shading

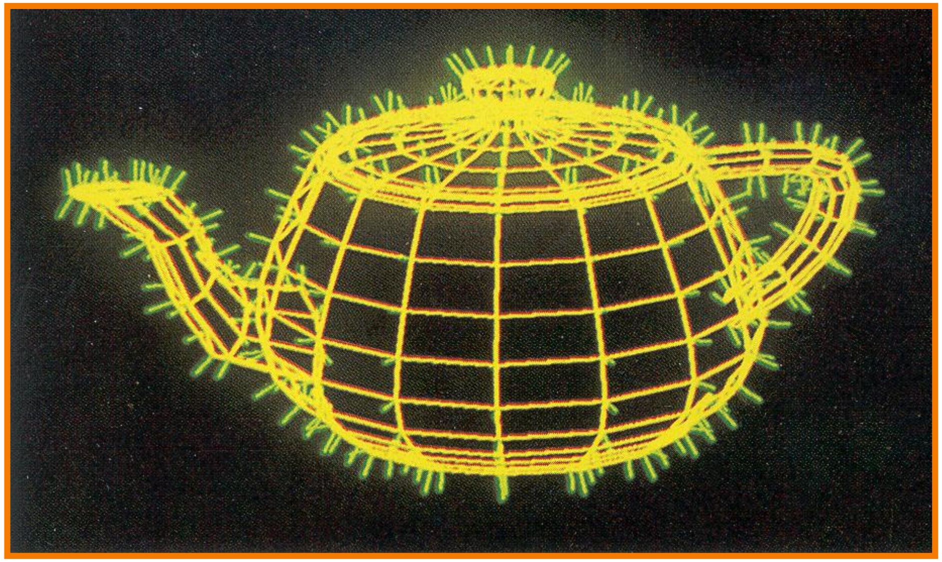
Bilinear interpolation of colors at vertices

- down and across scan lines = barycentric interpolation!



# Gouraud Shading

- Smooth shading over adjacent polygons
  - Curved surfaces
  - Illumination highlights
  - Soft shadows

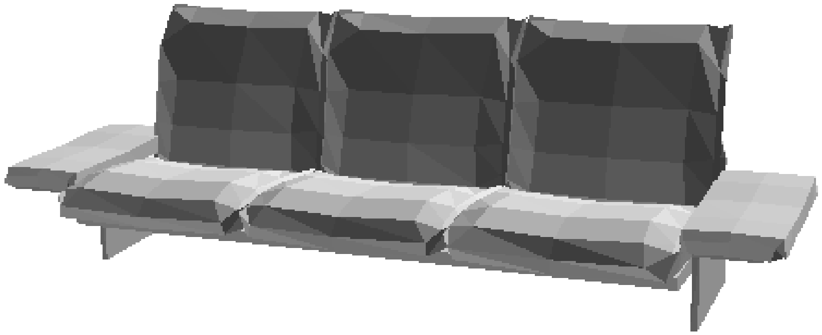


Mesh with shared normals at vertices

Watt Plate 7

# Gouraud Shading

- Produces smoothly shaded polygonal mesh
  - Piecewise linear (!) approximation
  - Need fine mesh to capture subtle lighting effects



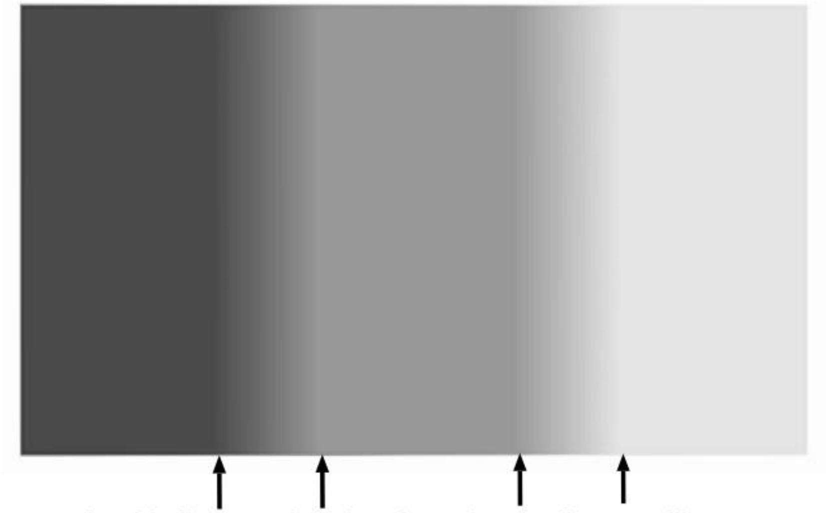
Flat Shading

Gouraud Shading

# Mach Band Effect

- Mach Band Effect also affects Gouraud Shading for piecewise linear interpolation.

Actual Intensity



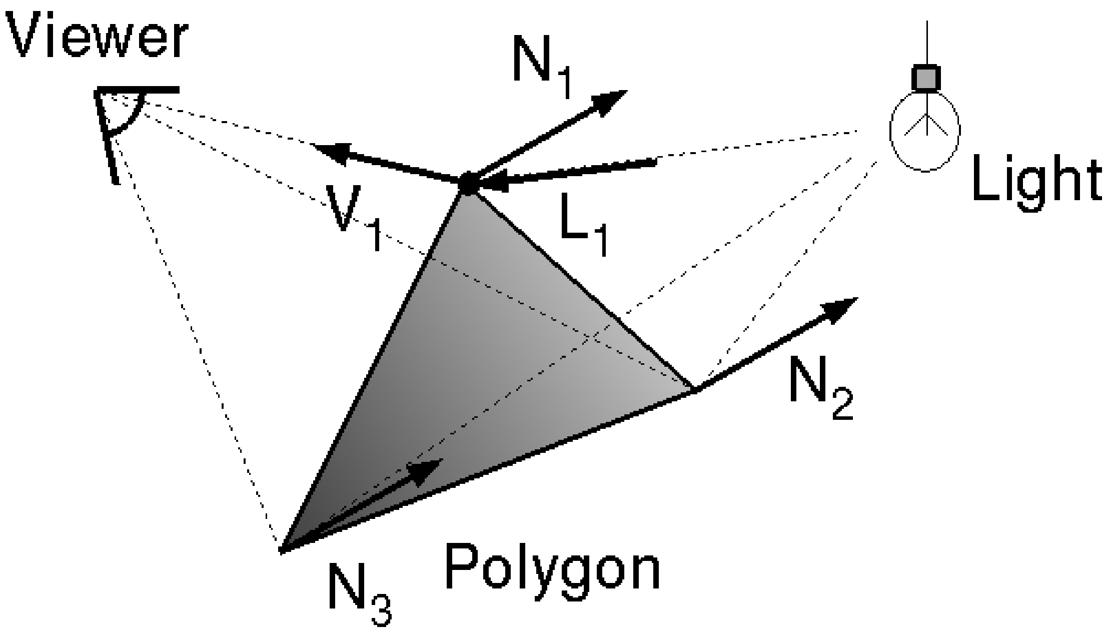
The thin lines or "bands" along the gradient are illusory.

# Polygon Shading Algorithms

- Flat Shading
- Gouraud Shading
- **Phong Shading** (≠ Phong reflectance model)

# Phong Shading

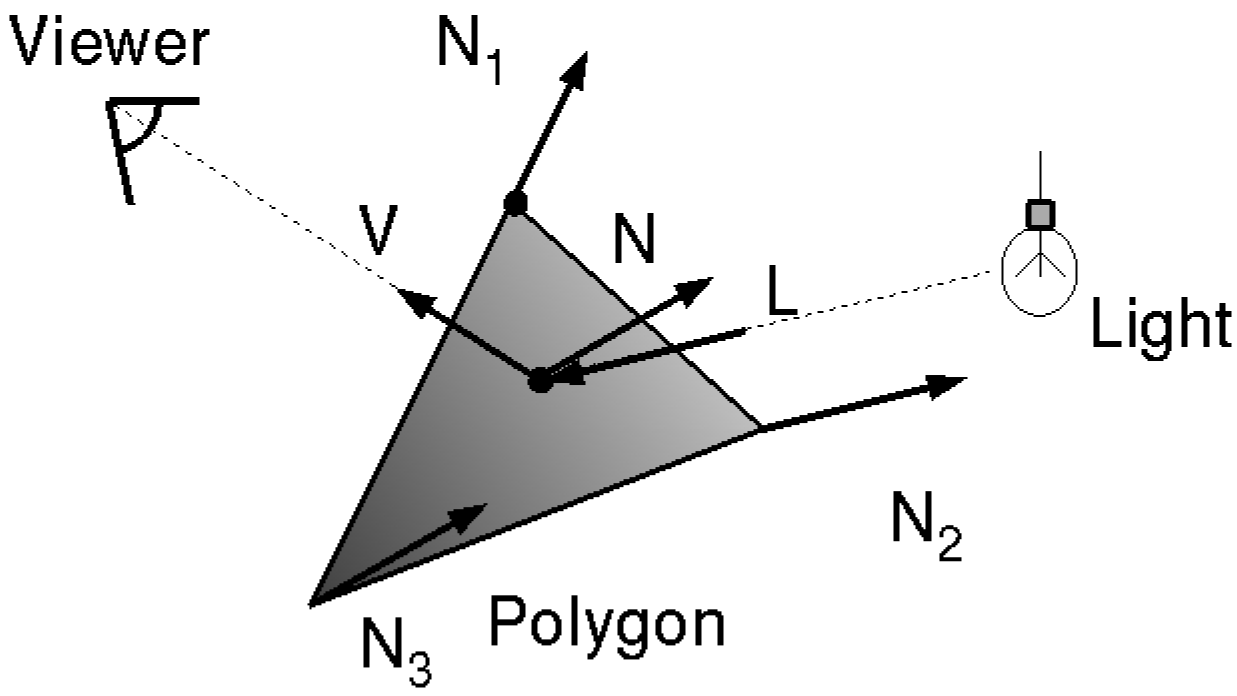
- What if polygonal mesh is too coarse to capture illumination effects in polygon interiors?




$$I = I_E + K_A I_{AL} + \sum_i \left( K_D (N \cdot L_i) I_i + K_S (V \cdot R_i)^n I_i \right)$$

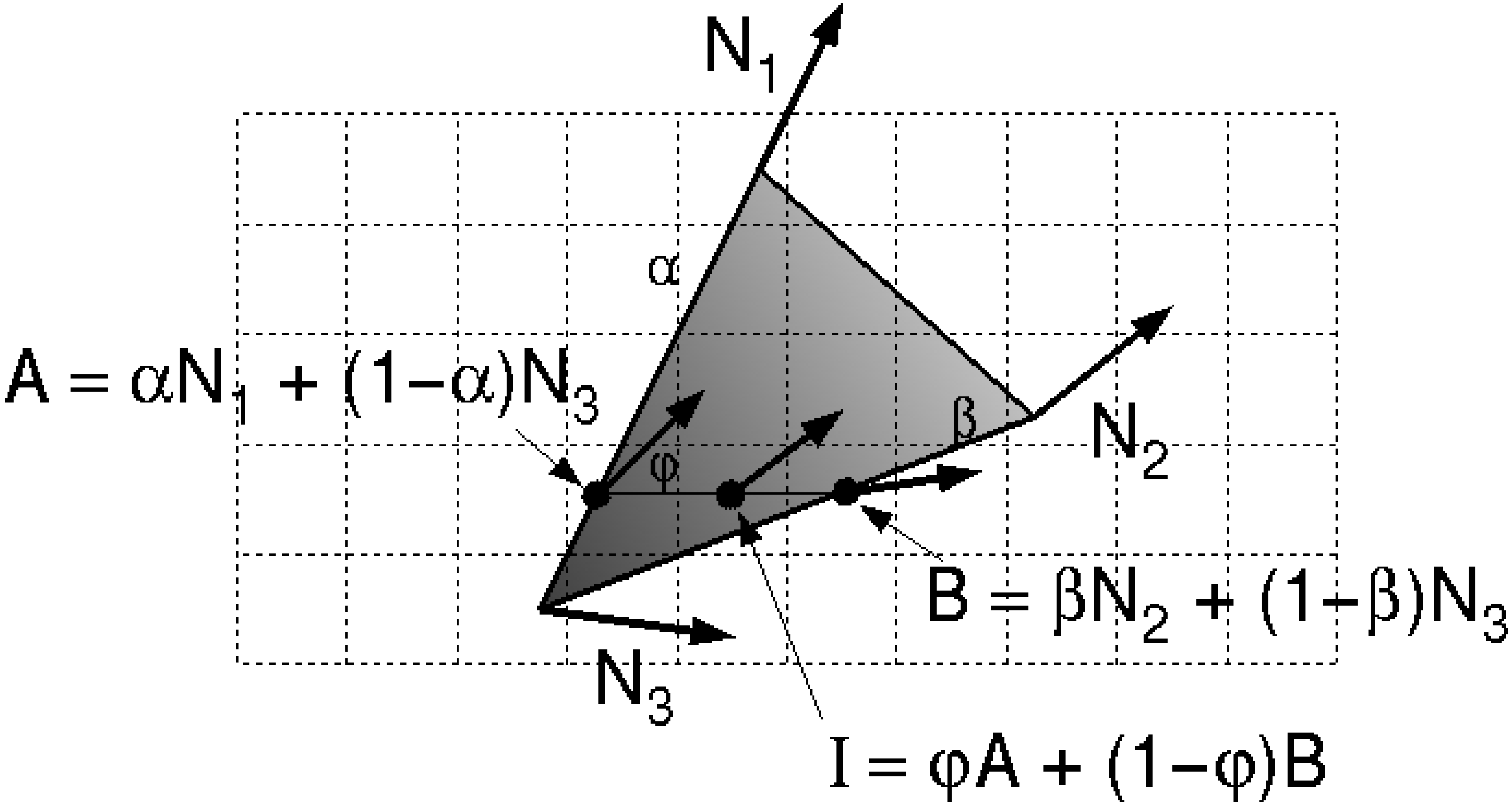
# Phong Shading

- One lighting calculation per pixel
  - Approximate surface normals for points inside polygons by bilinear interpolation of normals from vertices



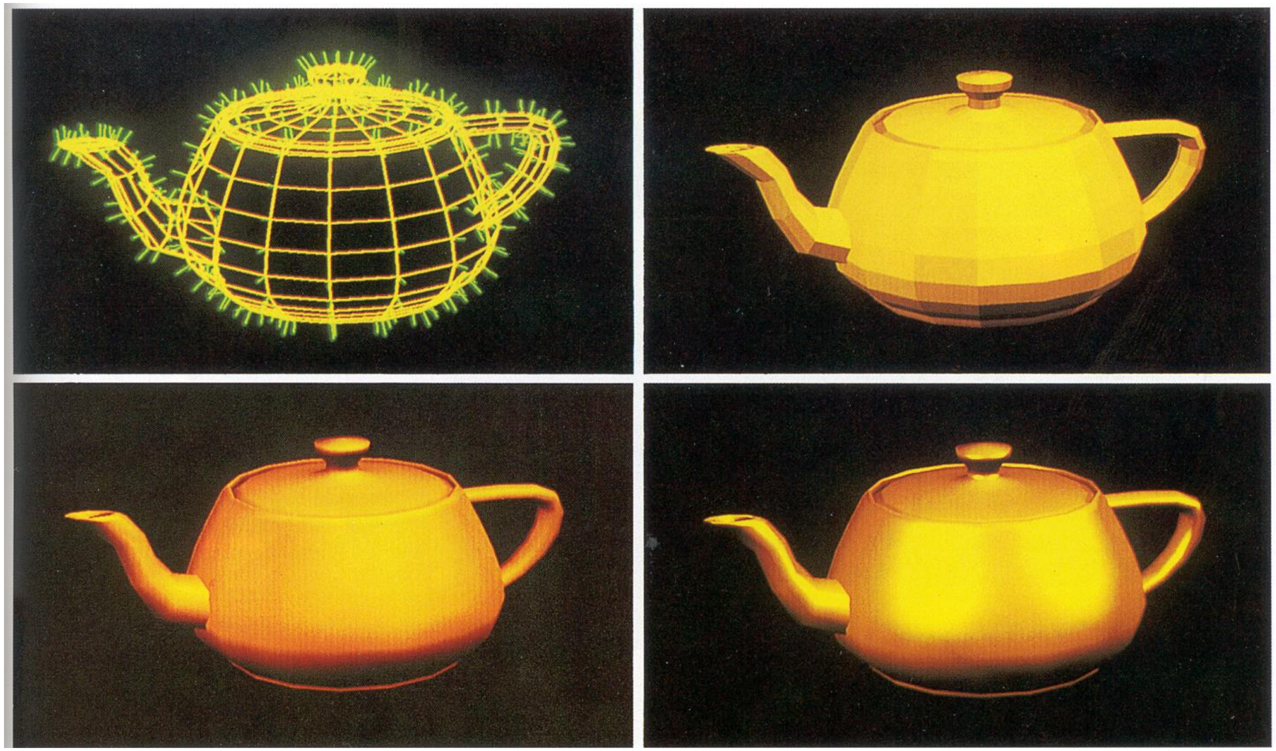
# Phong Shading

Bilinear interpolation of surface normals at vertices



# Polygon Shading Algorithms

Wireframe  Flat



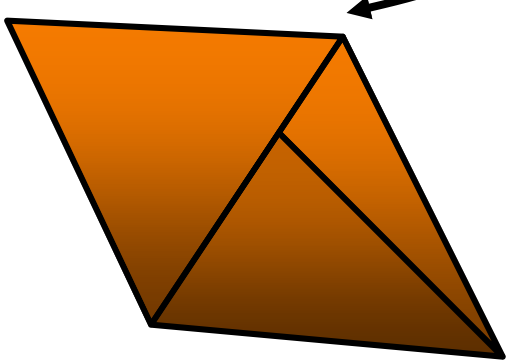
Gouraud  Phong

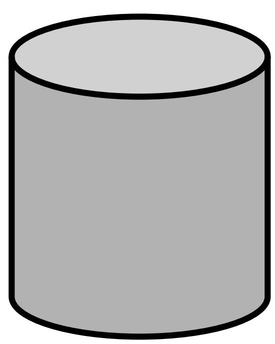
Demo: https://threejs.org/docs/scenes/material-browser.html#MeshPhongMaterial

Watt Plate 7

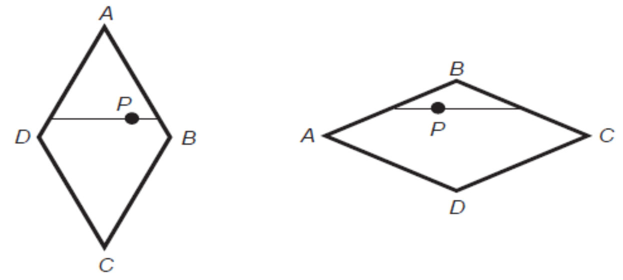
# Shading Issues

- Problems with interpolated shading:
  - Polygonal silhouettes still obvious
  - Perspective distortion (due to screen-space interpolation)
  - Problems computing shared vertex normals
  - Problems at T-junctions





The results of interpolated-shading is not independent of the projected polygons position (Foley Figure 14.22).



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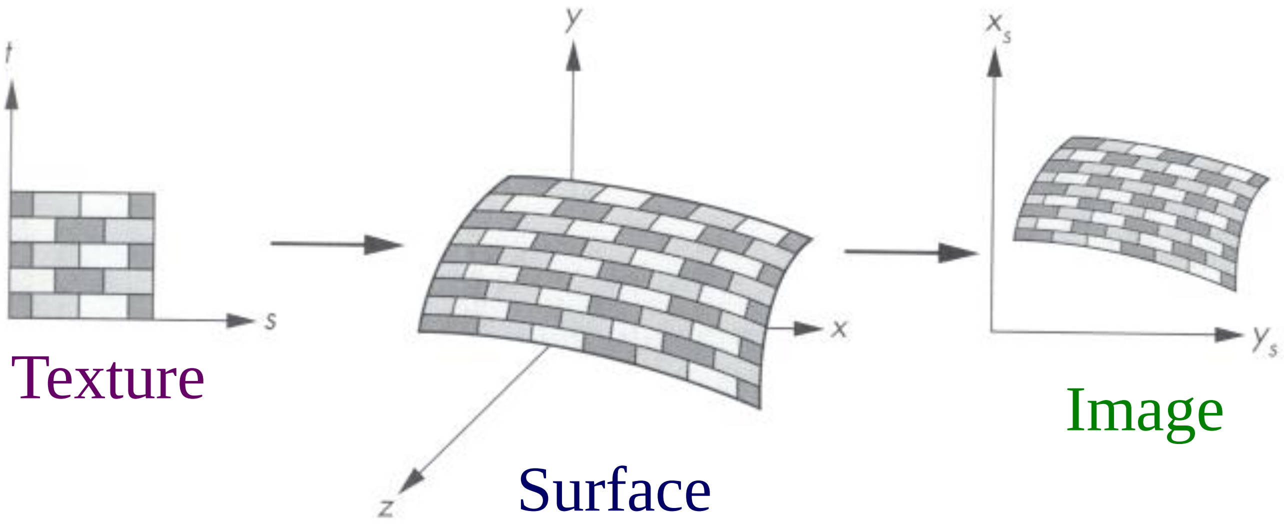
# Textures

- Describe **color variation** in interior of 3D polygon
  - When scan converting a polygon, **vary pixel colors** according to values fetched from a texture image



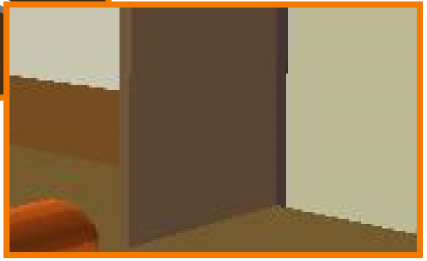

Angle Figure 9.3

# Surface Textures

- Add visual detail to surfaces of 3D objects

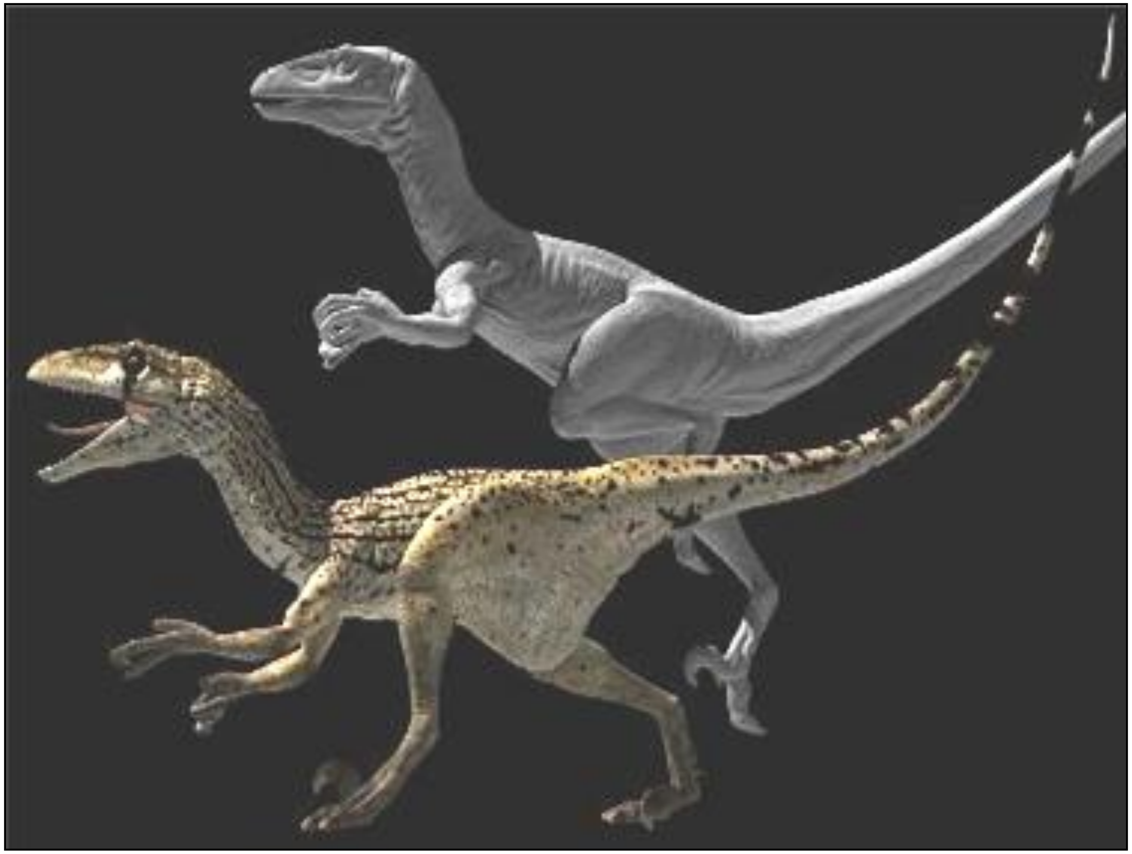
With surface texture

Polygonal model



# Textures

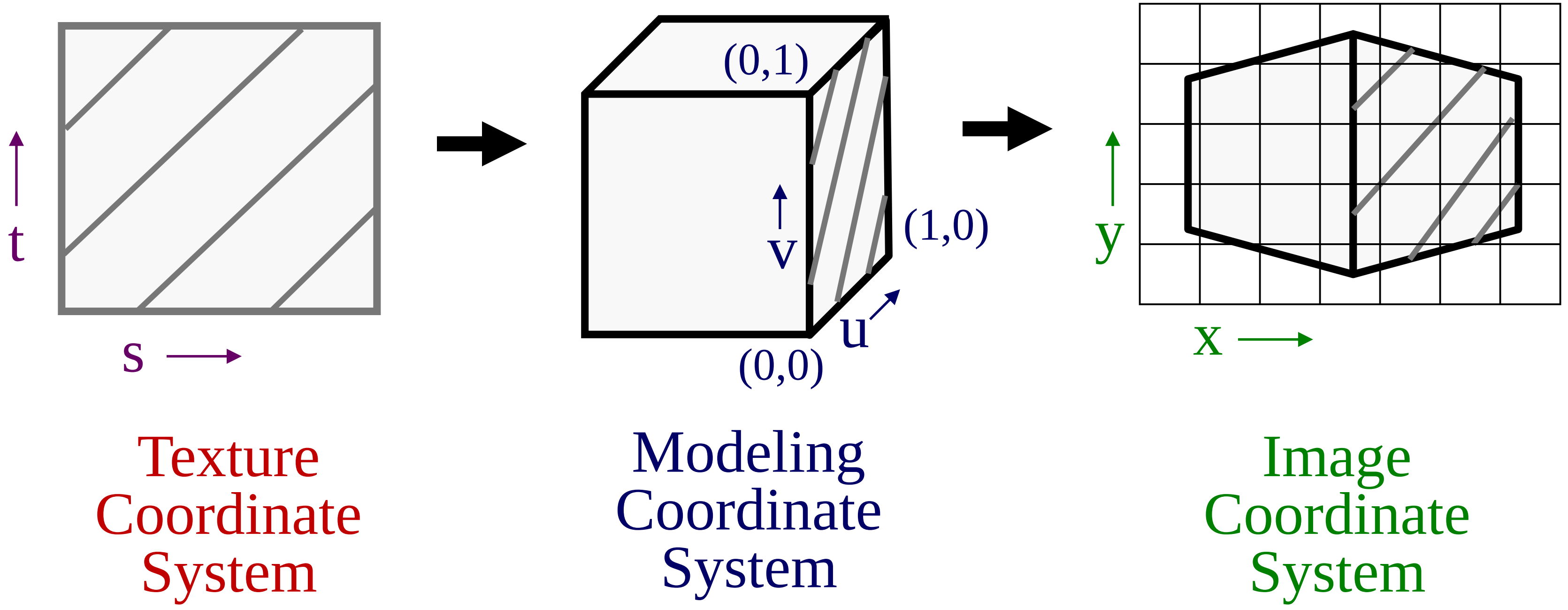
- Add visual detail to surfaces of 3D objects



[Daren Horley]

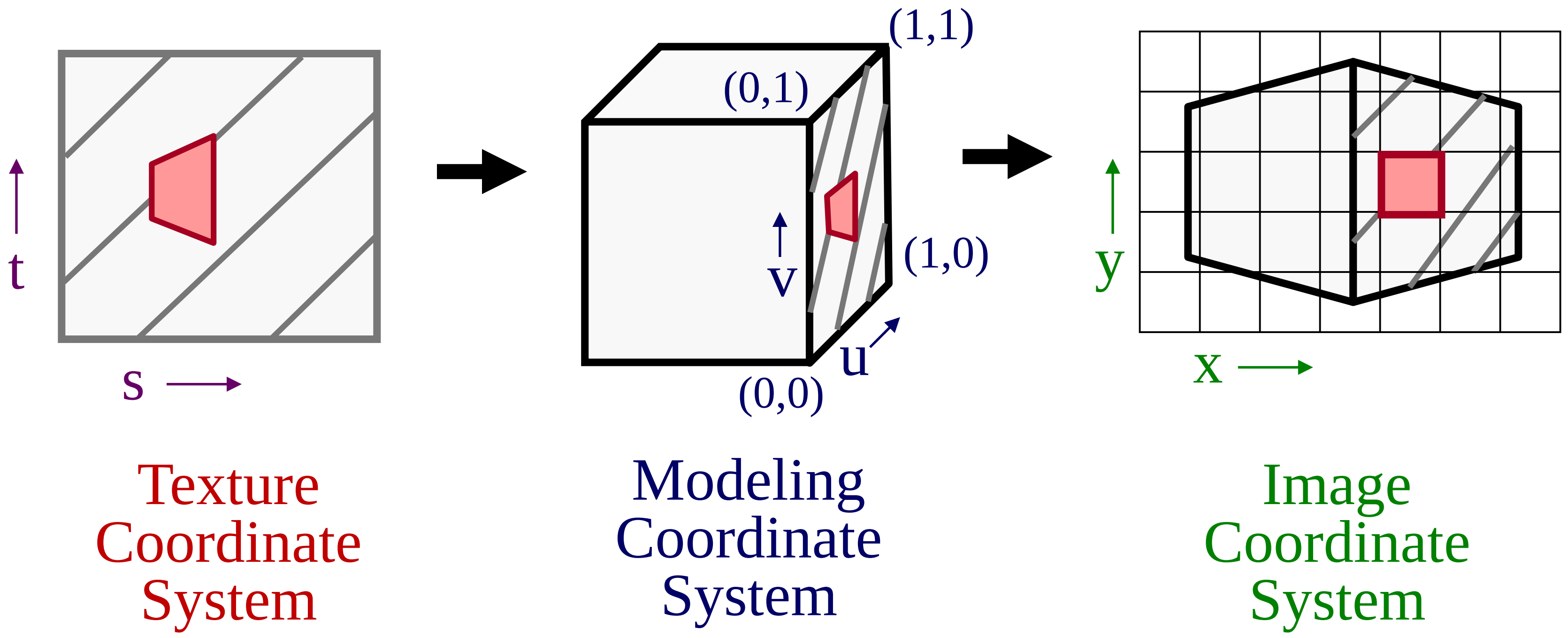
# Texture Mapping

- Steps:
  1. Define texture
  2. Specify mapping from texture to surface
  3. Look up texture values during scan conversion



# Texture Mapping

- When scan converting, map from …
  - image coordinate system (x,y) to
  - modeling coordinate system (u,v) to
  - texture image (s,t)



# Texture Overview

- Texture mapping stages
  - Parameterization
  - Mapping
  - Filtering
- Texture mapping applications
  - Modulation textures
  - Illumination mapping
  - Bump mapping
  - Environment mapping
  - Image-based rendering
  - Non-photorealistic rendering

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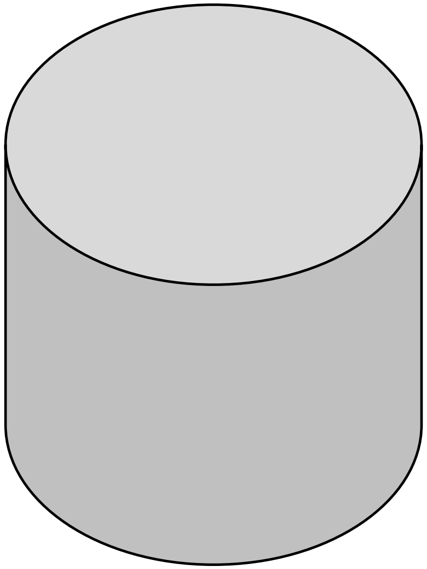
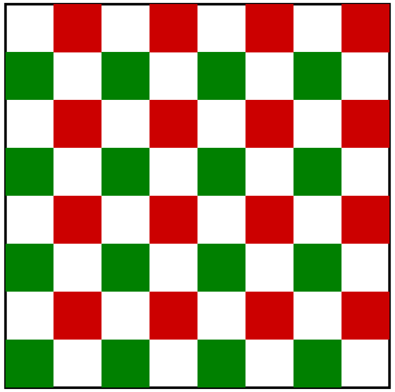
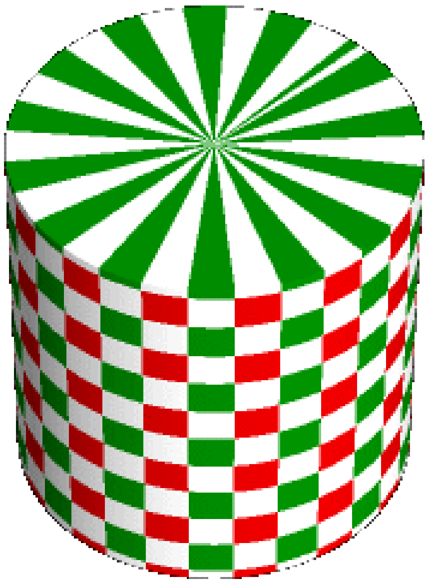
# Texture Parameterization



+



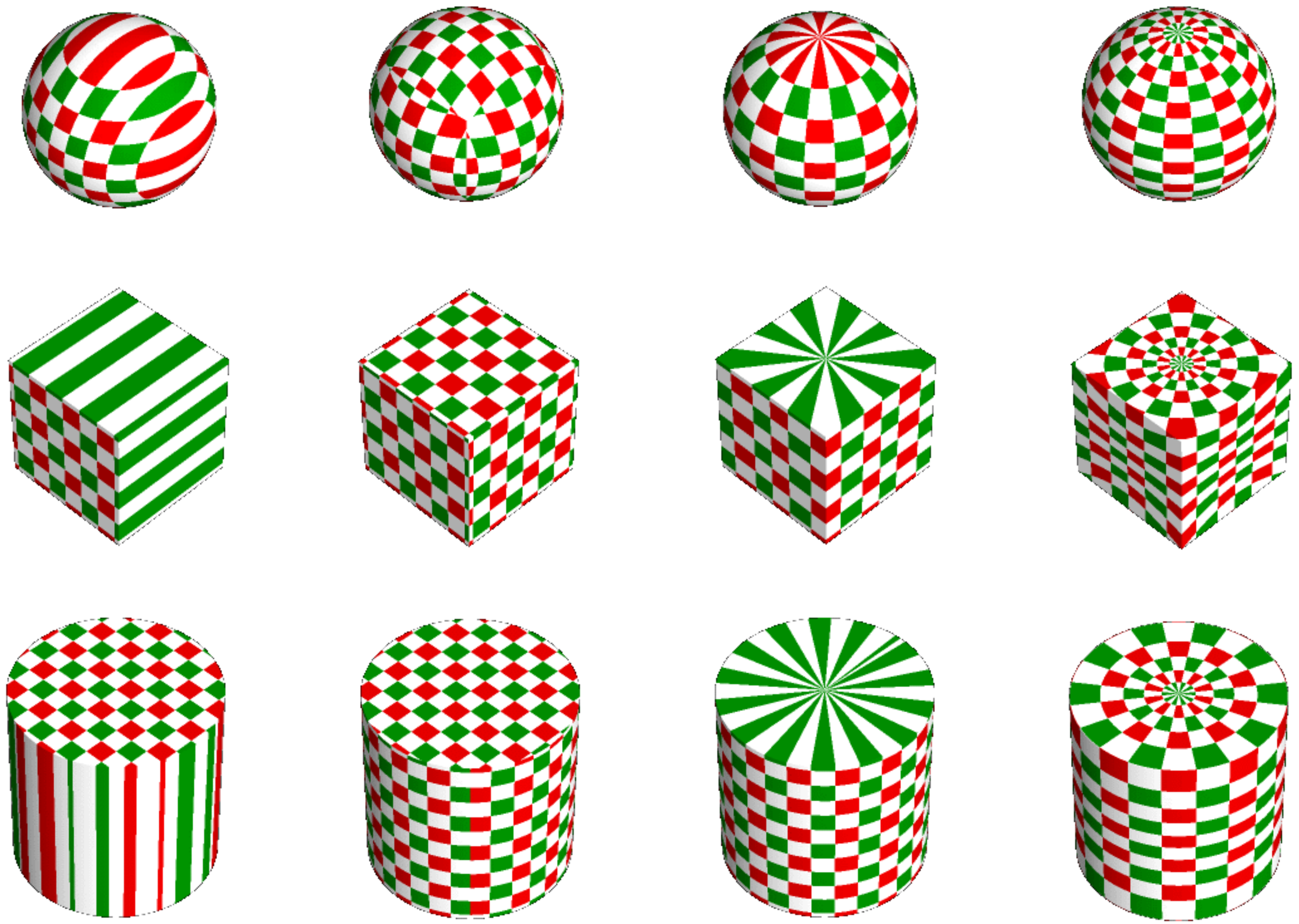
=



geometry image texture map

- Q: How do we decide ***where* on the geometry** each color from the image should go?

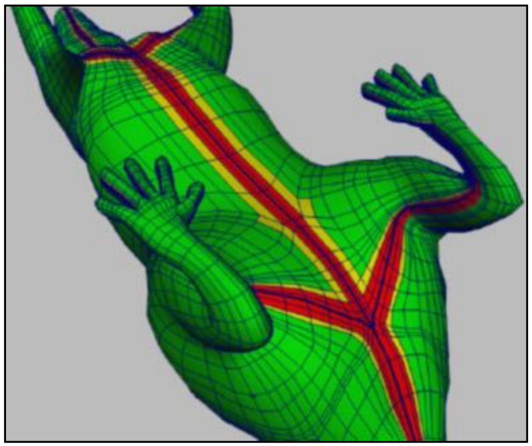
# Texture Parameterization

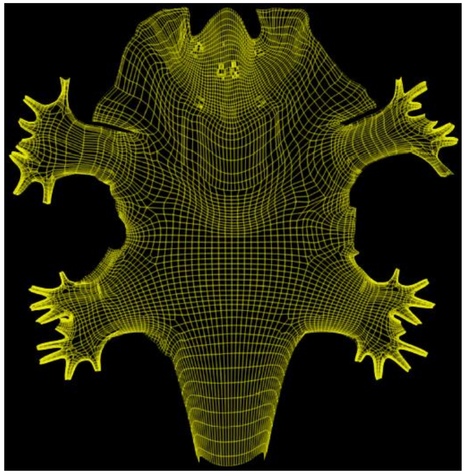


[Paul Bourke]

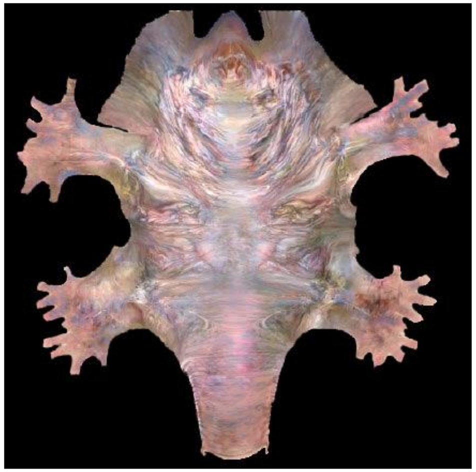
# Texture Parameterization

## Option1: unfold the surface





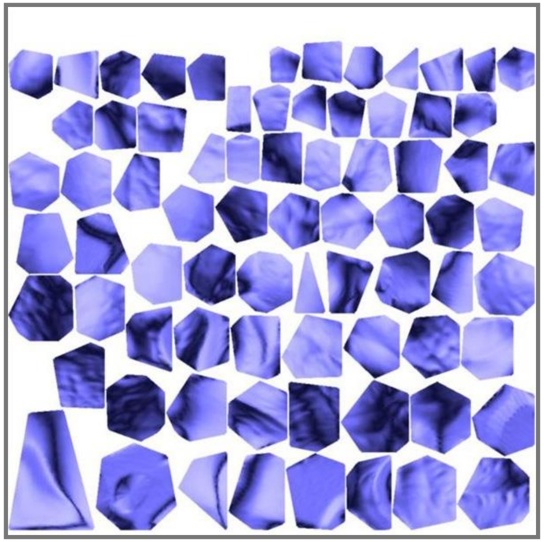
[Piponi2000]



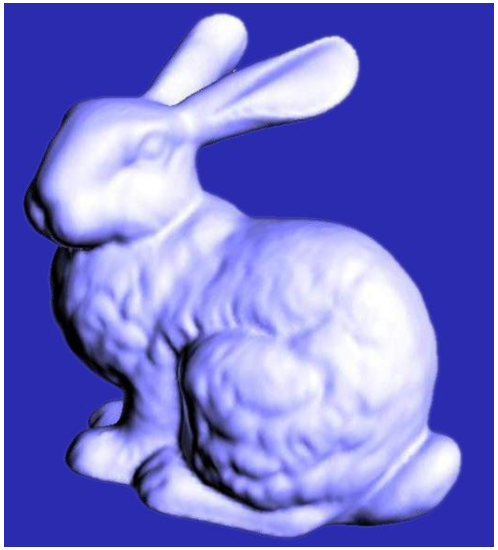
# Texture Parameterization

**Option2: make an atlas**

charts



atlas



surface

[Sander2001]

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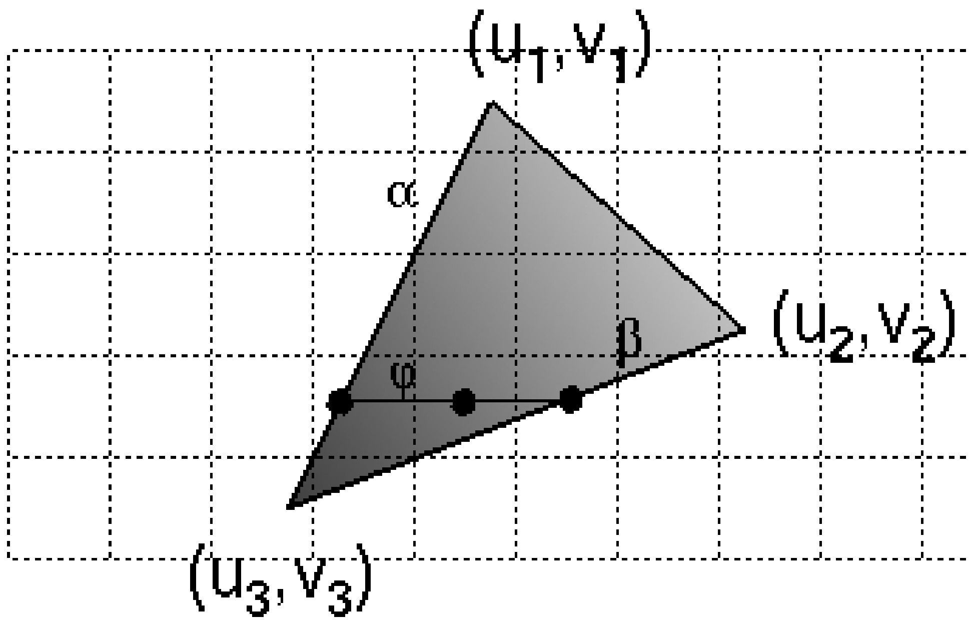
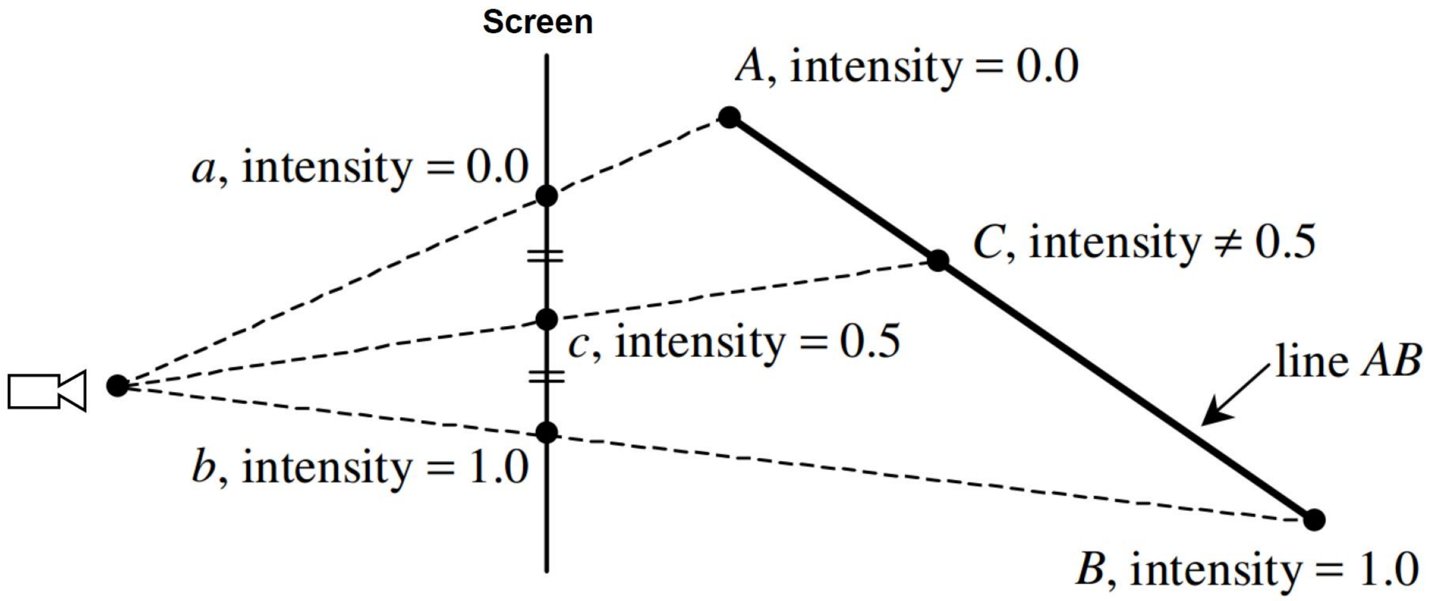
# Texture Mapping

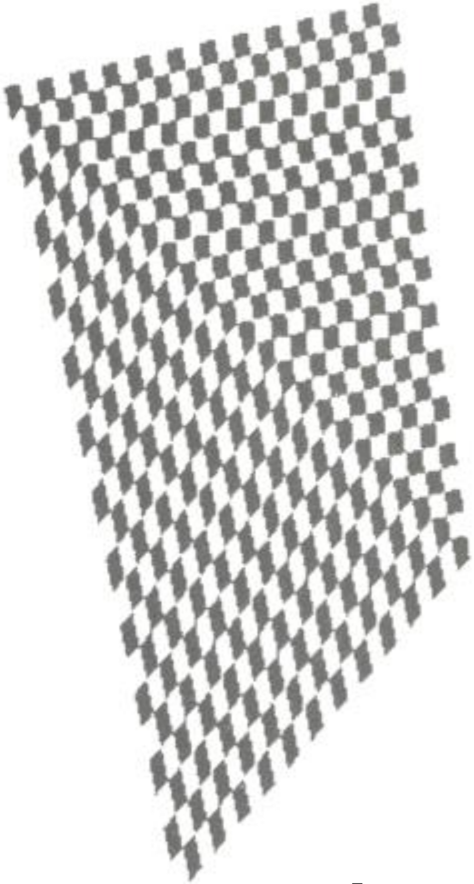
- Scan conversion
  - Interpolate texture coordinates down/across scan lines
  - Distortion due to bilinear interpolation approximation
    - » Cut polygons into smaller ones, or
    - » Perspective divide at each pixel



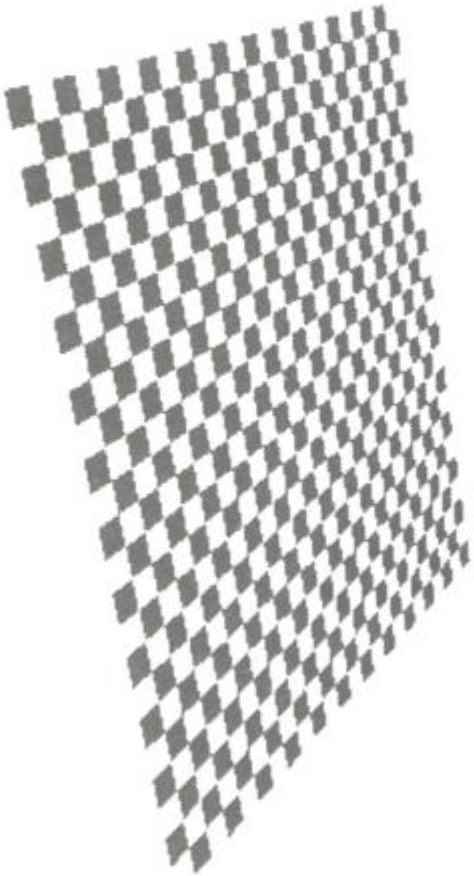
# Perspective Divide



# Perspective Divide



Linear interpolation
of texture coordinates



Correct interpolation
with perspective divide

Hill Figure 8.42

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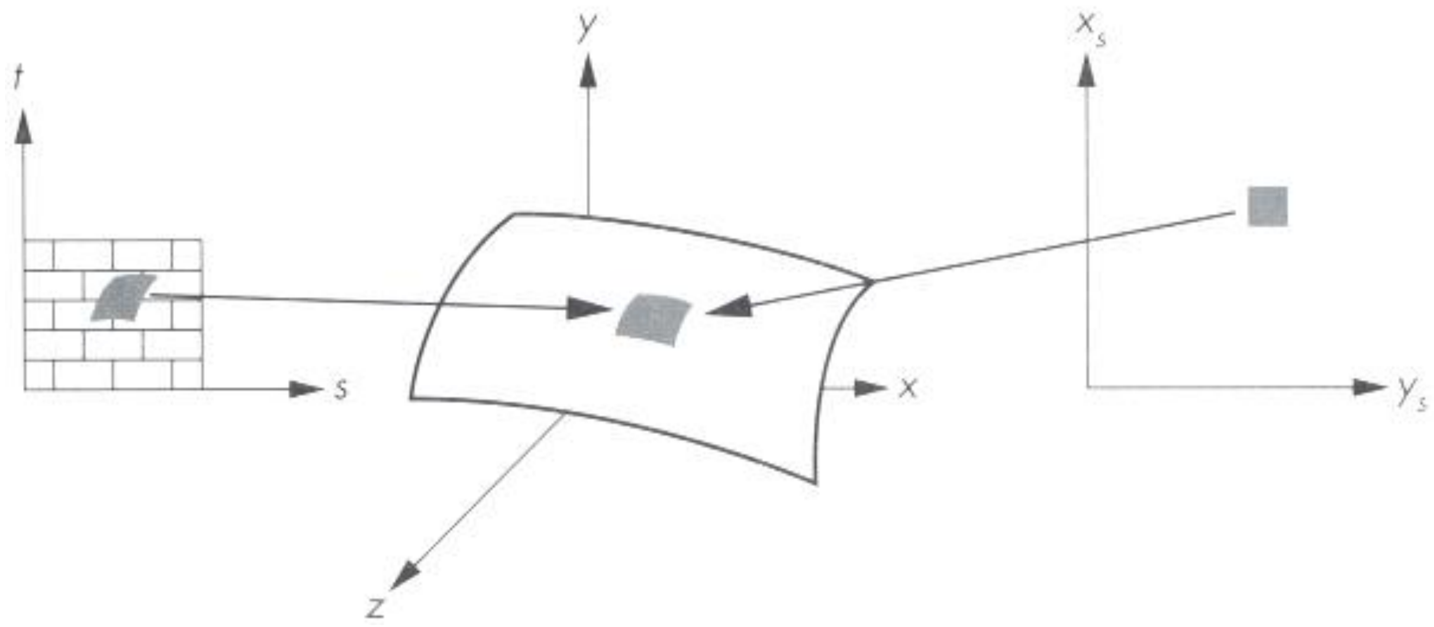
# Texture Filtering

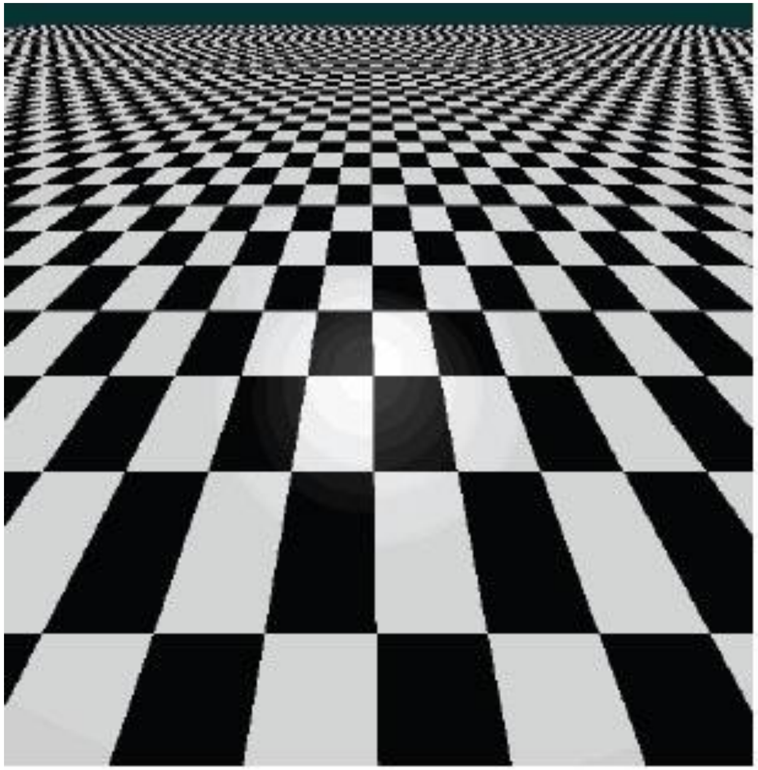
- Must sample texture to determine color at each pixel in image



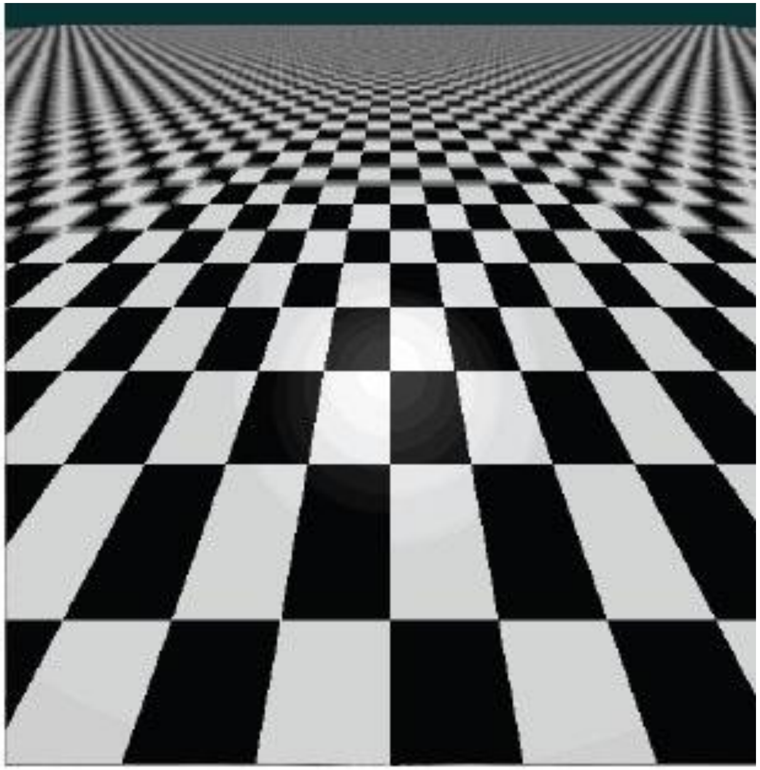

Angel Figure 9.4

# Texture Filtering

- Aliasing is a problem



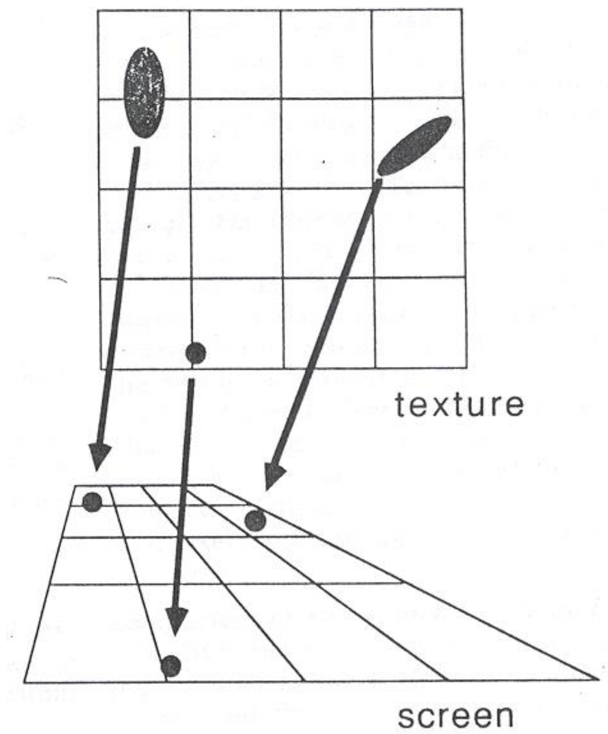
Point sampling



Area filtering

# Texture Filtering

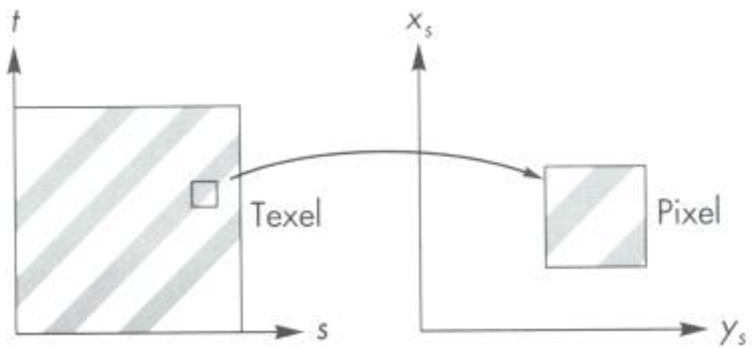
- Ideally, use elliptically shaped convolution filters



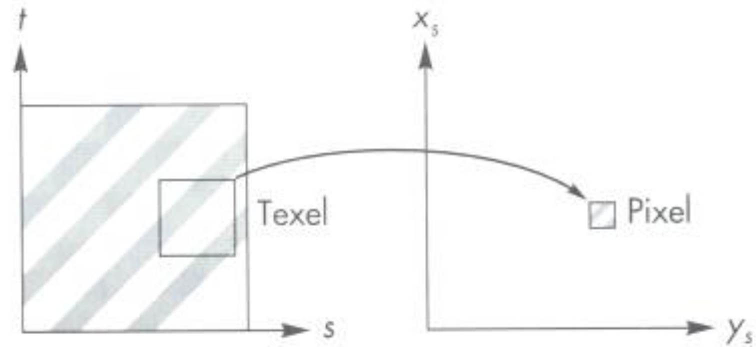

In practice, use rectangles or squares

# Texture Filtering

- Size of filter depends on projective warp
  - Compute prefiltered images to avoid run-time cost
    - » Mipmaps
    - » Summed area tables




Magnification

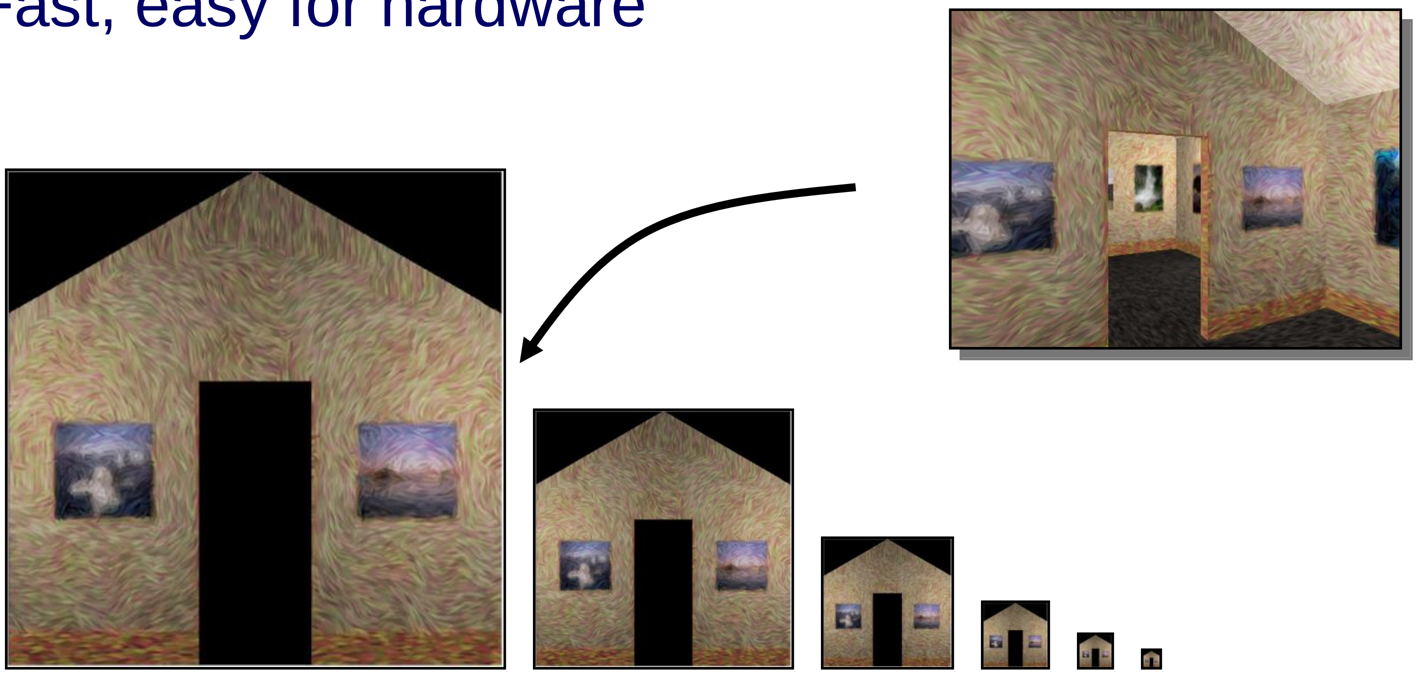



Minification

Angel Figure 9.14

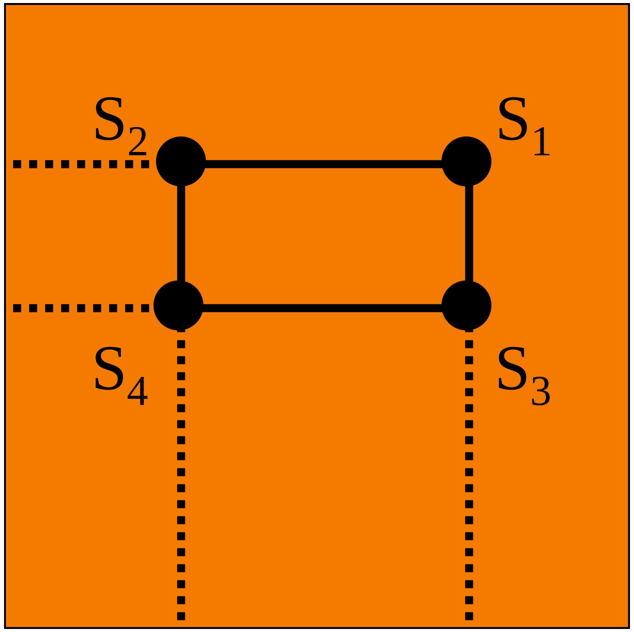
# Mipmaps

- Keep textures prefiltered at multiple resolutions
  - Usually powers of 2
  - For each pixel, linearly interpolate between two closest levels (i.e., trilinear filtering)
  - Fast, easy for hardware



# Summed-area tables

- At each texel keep sum of all values down & left
  - To compute sum of all values within a rectangle, simply combine four entries: $S_1 - S_2 - S_3 + S_4$
  - Better ability to capture oblique projections, but still not perfect




  - (Mipmaps are more common.)

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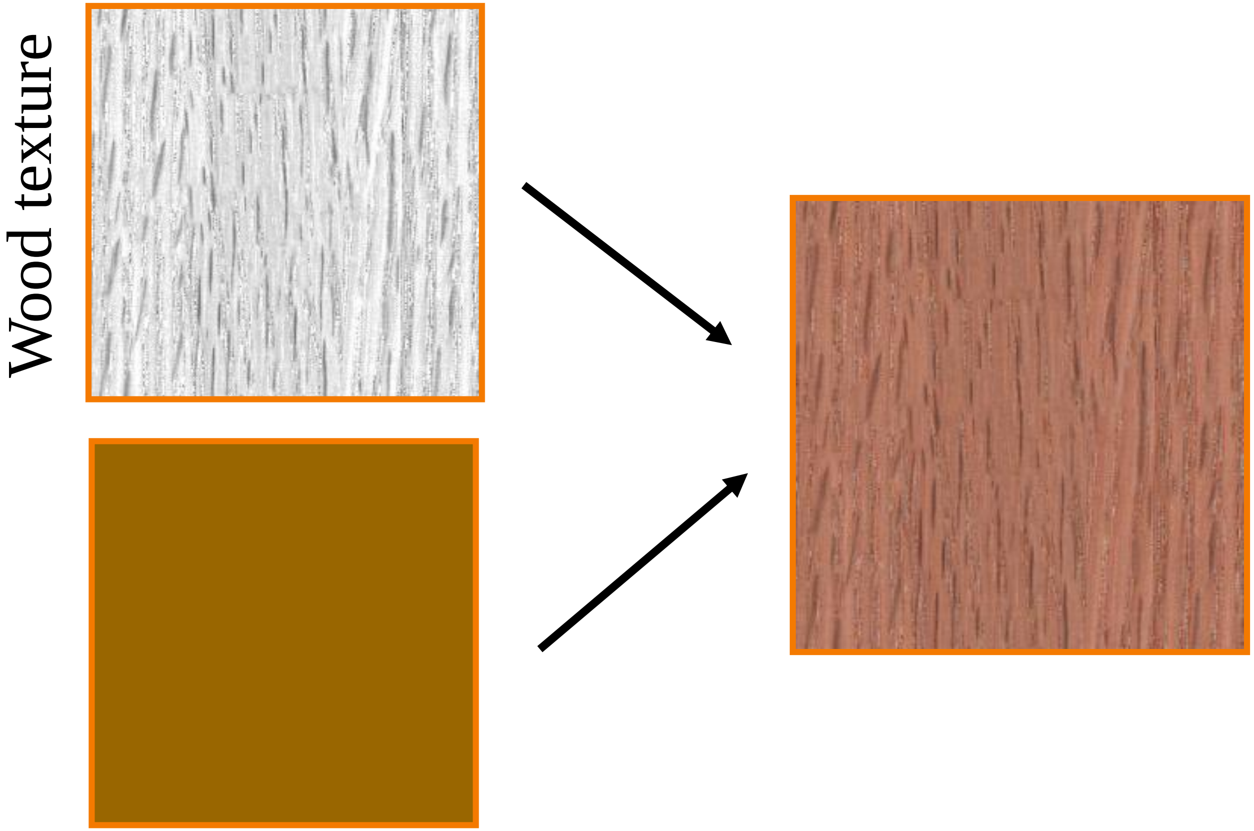
# Modulation textures

Texture values scale result of lighting calculation




Texture value

$$I = T(s,t)\left(I_E + K_A I_A + \sum_L \left(K_D (N \cdot L) + K_S (V \cdot R)^n\right) S_L I_L + K_T I_T + K_S I_S\right)$$

# Illumination Mapping

Map texture values to surface material parameter

- $K_A$
- $K_D$
- $K_S$
- $K_T$
- $n$

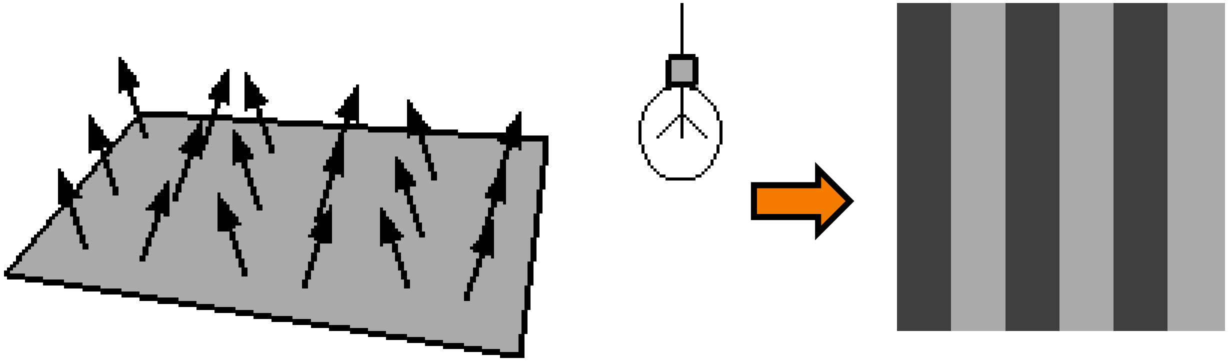
Texture value

$$I = I_E + K_A I_A + \sum_L \left( K_D(s,t)(N \cdot L) + K_S (V \cdot R)^n \right) S_L I_L + K_T I_T + K_S I_S$$

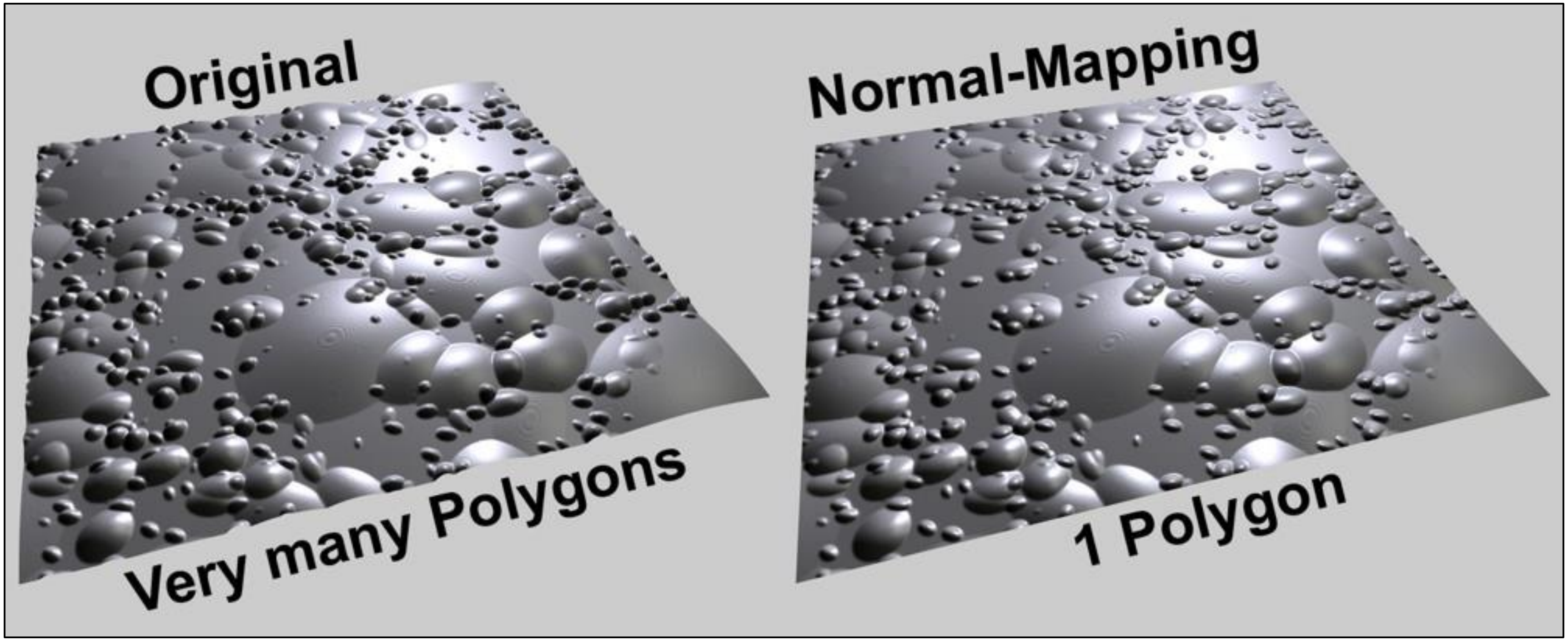
# Bump/Normal Mapping

Texture values perturb surface normals:

- Encode normals (or offsets) in RGB
- Use gradient of grayscale image (“bump”)



# Normal Mapping

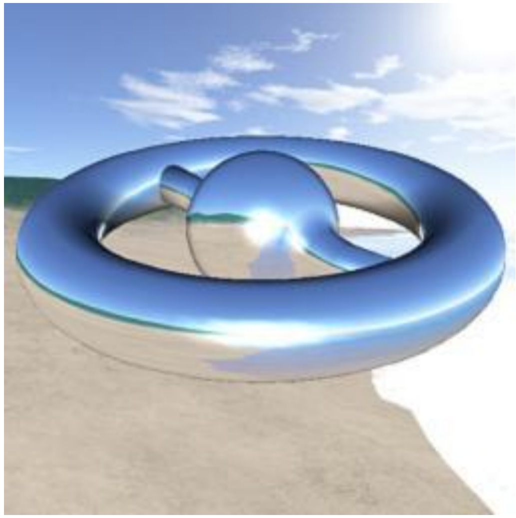


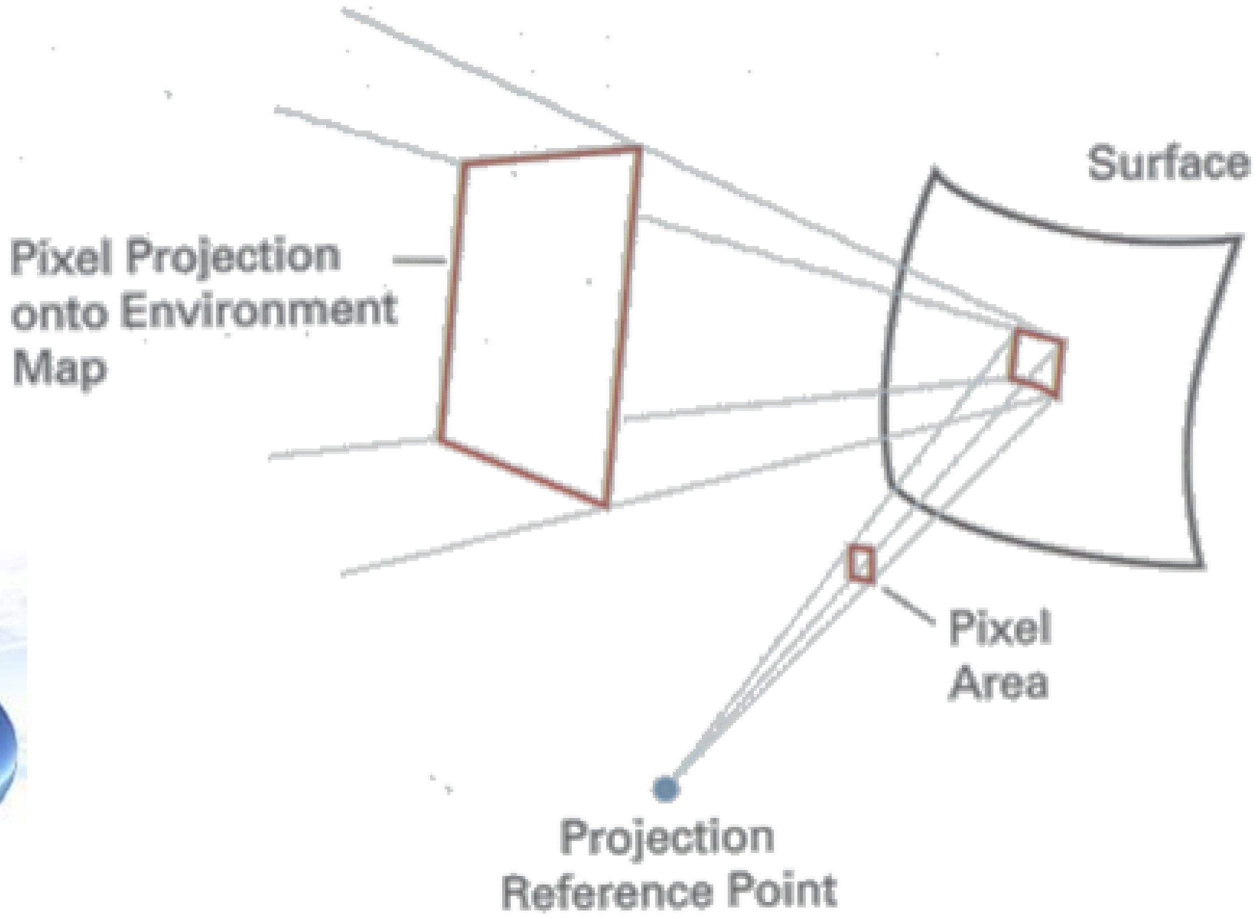

Graphisoft.com

# Environment Mapping

Texture values are reflected off surface patch

Gamer3D/Wikipedia

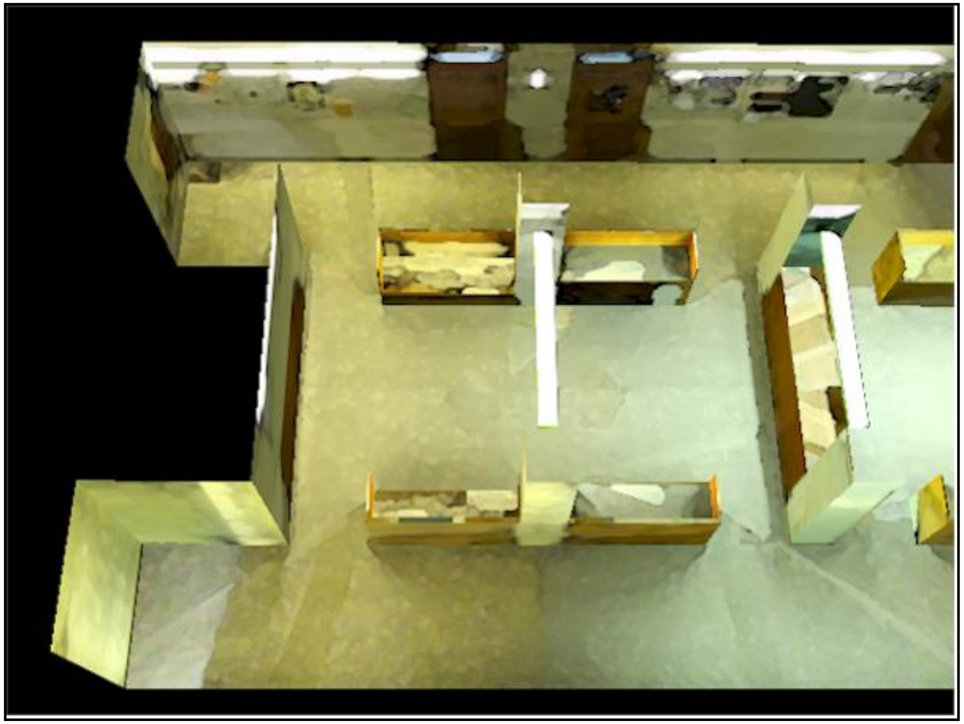





H&B Figure 14.93

# Image-Based Rendering

Map photographic textures to provide details for coarsely detailed polygonal model



# Solid textures

Texture values indexed by 3D location (x,y,z)

- Expensive storage, or
- Compute on the fly, e.g. Perlin noise →

# Texture Summary

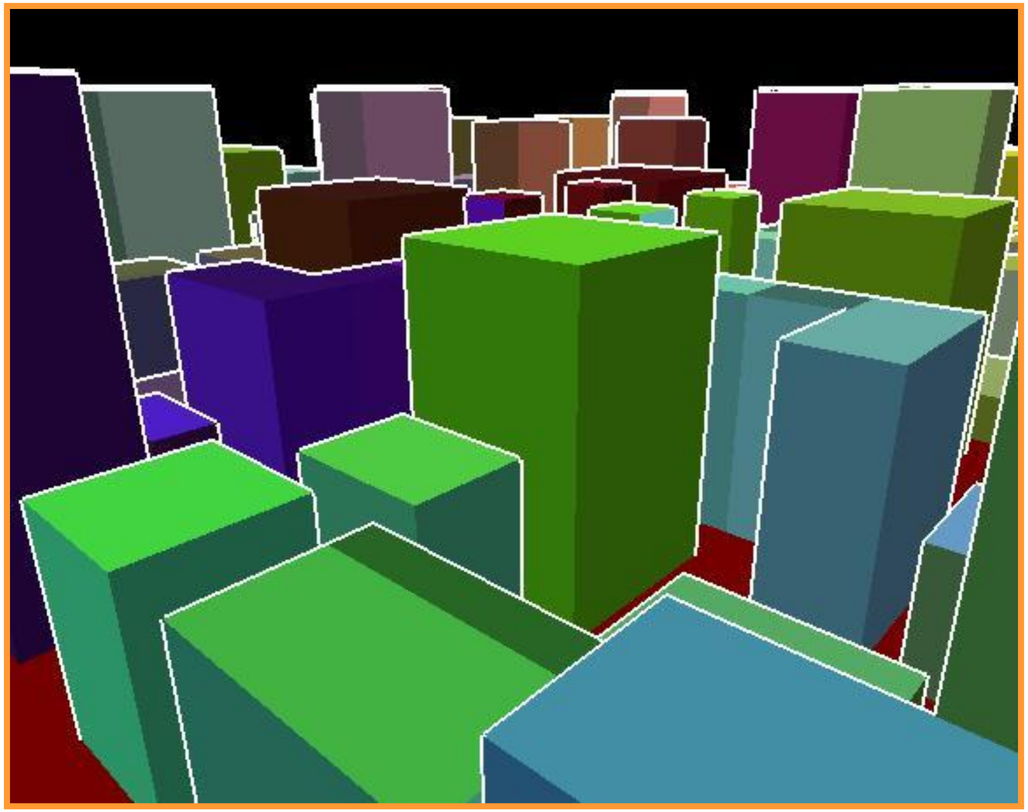
- Texture mapping stages
  - Parameterization
  - Mapping
  - Filtering
- Texture mapping applications
  - Modulation textures
  - Illumination mapping
  - Bump mapping
  - Environment mapping
  - Image-based rendering
  - Volume textures

# Rasterization

- Scan conversion
  - Determine which pixels to fill
- Shading
  - Determine a color for each filled pixel
- Texture mapping
  - Describe shading variation within polygon interiors
- Visible surface determination
  - Figure out which surface is front-most at every pixel

# Visible Surface Determination

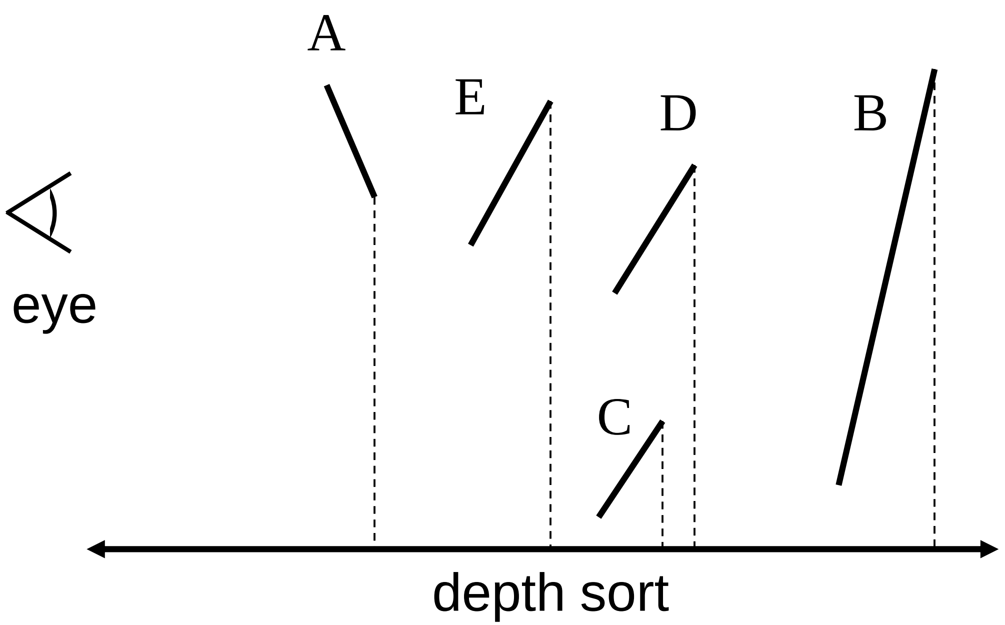
Make sure only front-most surface contributes to color at every pixel

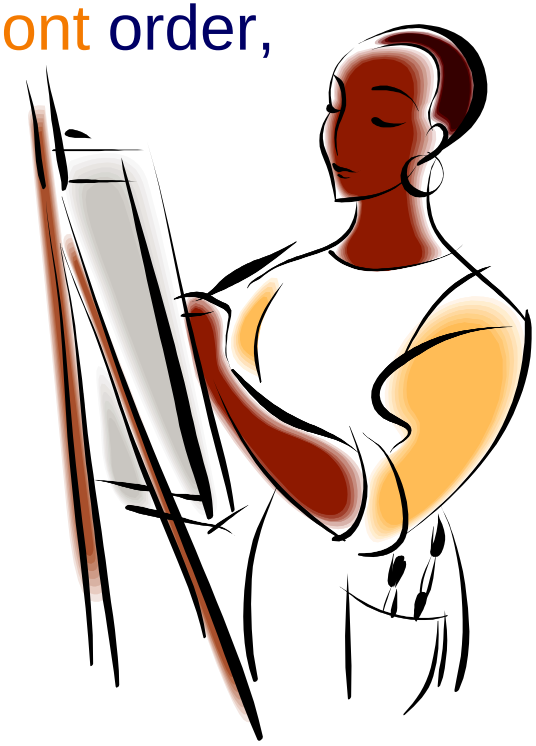


# Depth sort

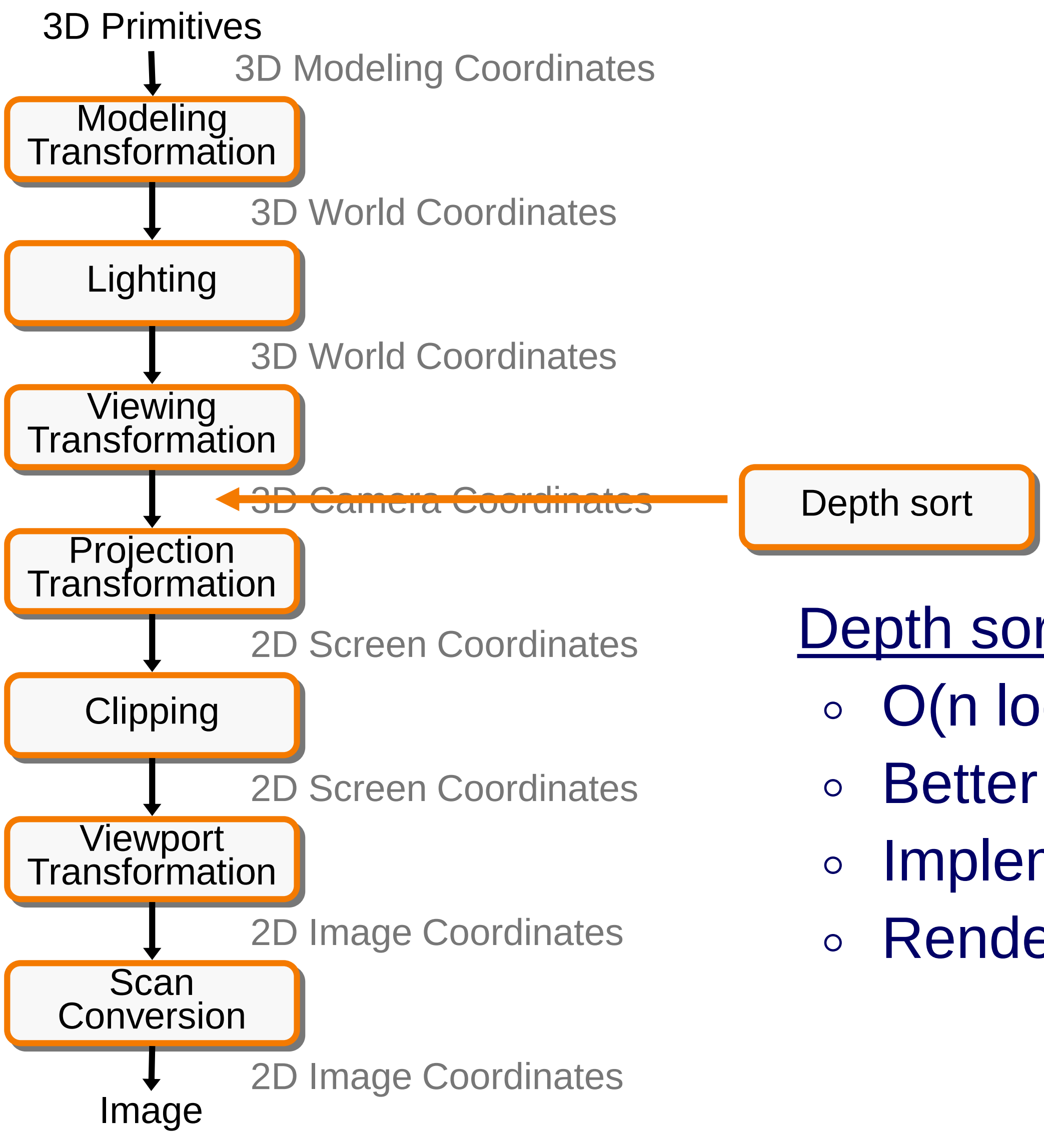
"Painter's algorithm"

1. First **sort surfaces** in order of decreasing maximum depth
2. Scan convert surfaces in back-to-front order, overwriting pixels



# 3D Rendering Pipeline



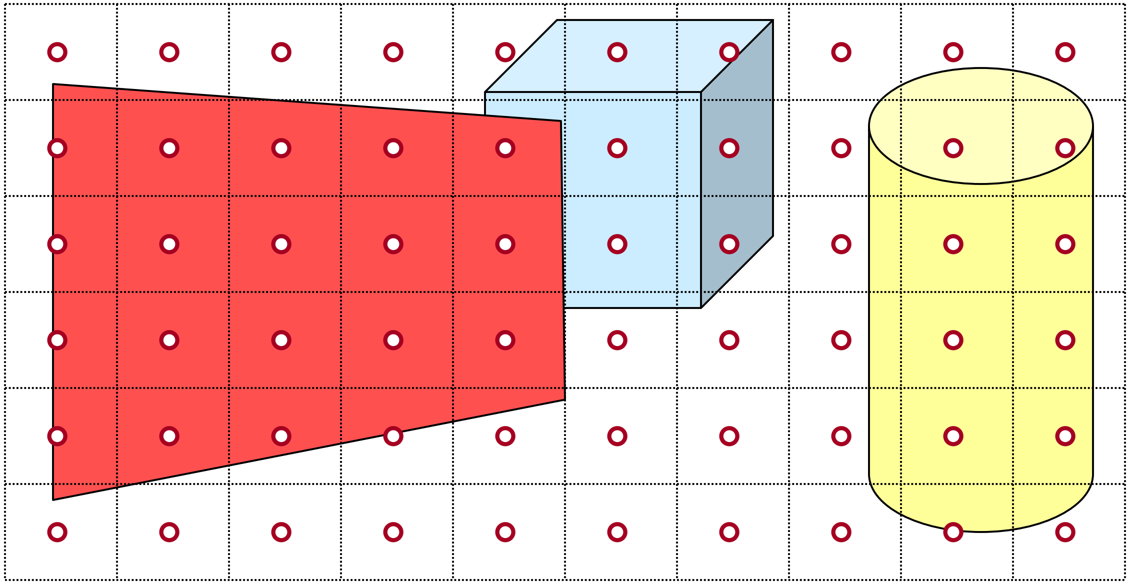

## Depth sort comments

- O(n log n)
- Better with frame coherence?
- Implemented in software
- Render every polygon

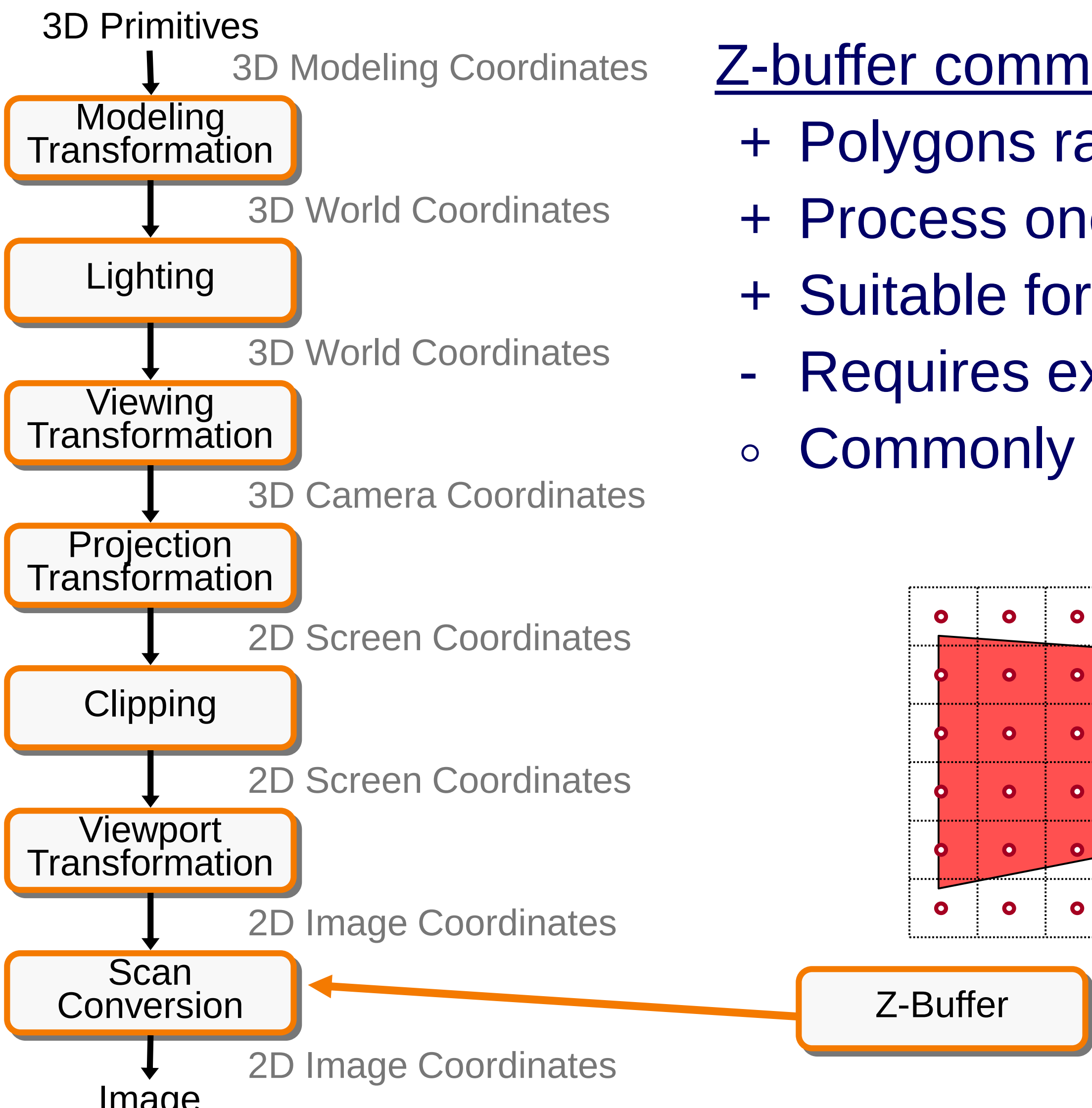
# Z-Buffer

Maintain **color & depth of closest** object per pixel

- Framebuffer now RGBAz – initialize z to far plane
- Update only pixels with depth closer than in z-buffer
- Depths are interpolated for in-primitive pixels from vertices, just like colors

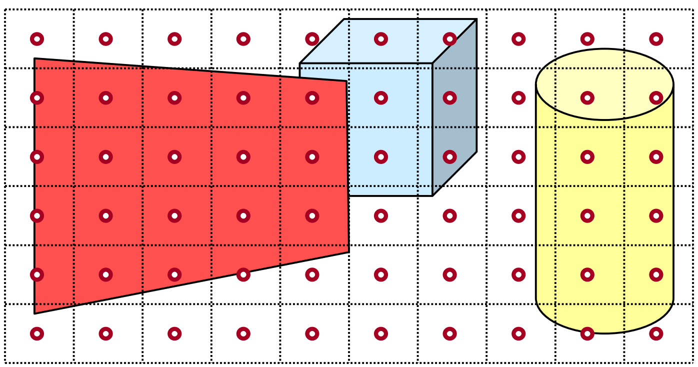


# Z-Buffer

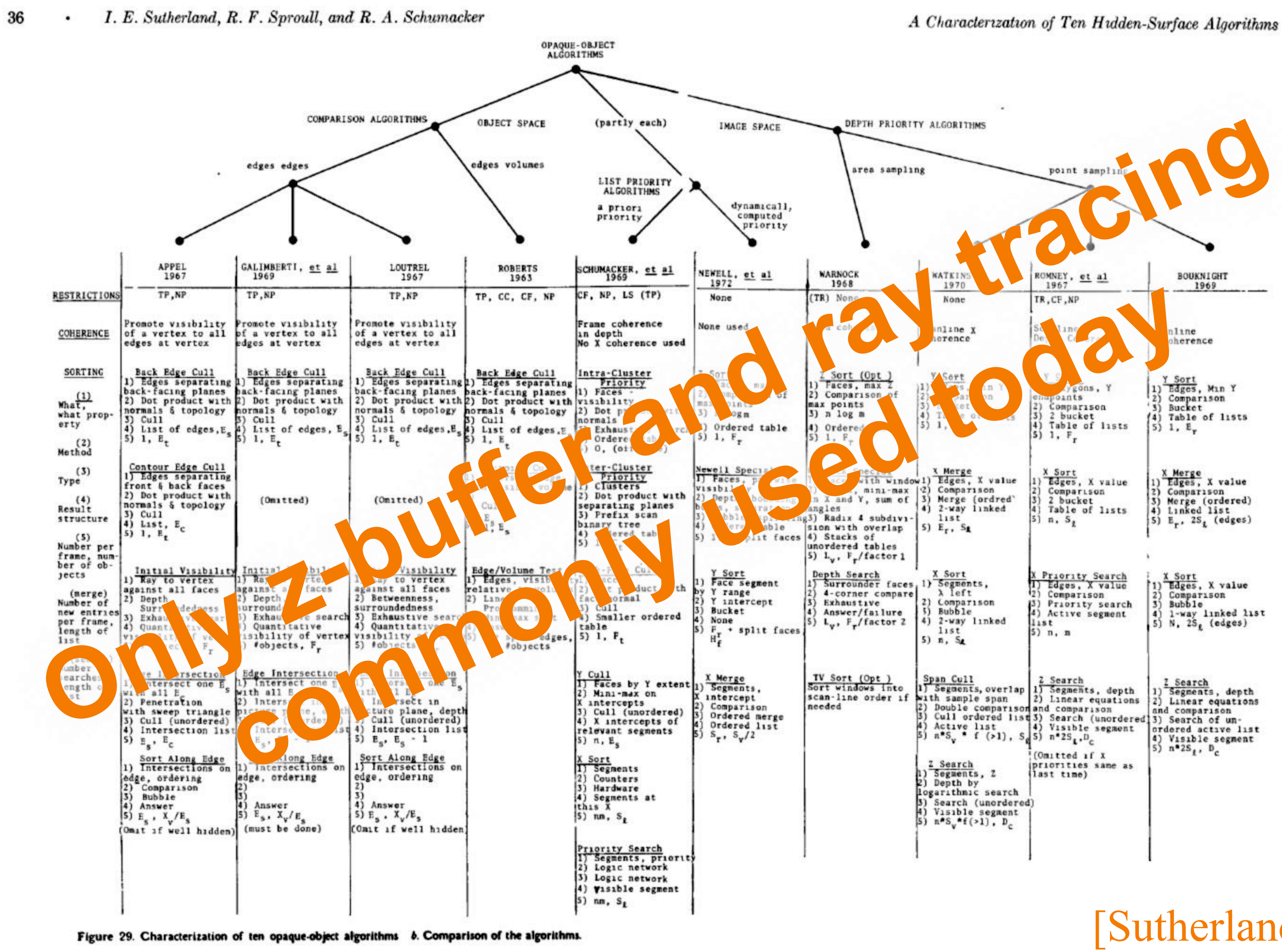



## Z-buffer comments

- \+ Polygons rasterized in any order
- \+ Process one polygon at a time
- \+ Suitable for hardware pipeline
- \- Requires extra memory for z-buffer
- ∘ Commonly in hardware



# Hidden Surface Removal Algorithms




Only z-buffer and ray tracing commonly used today

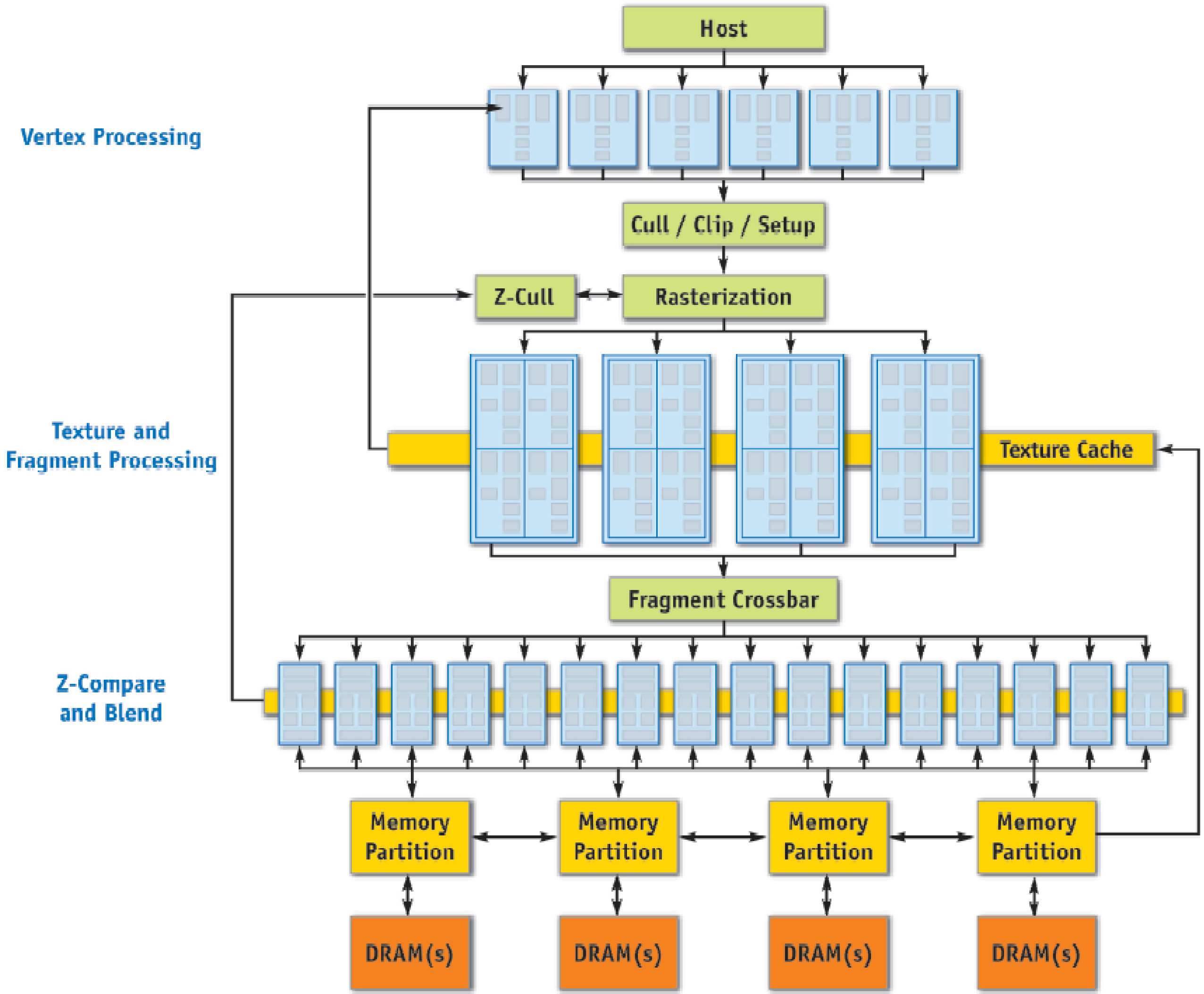
[Sutherland '74]

# Rasterization Summary

- Scan conversion
  - Sweep-line algorithm
- Shading algorithms
  - Flat, Gouraud
- Texture mapping
  - Mipmaps
- Visibiliity determination
  - Z-buffer

This is all in hardware

# GPU Architecture

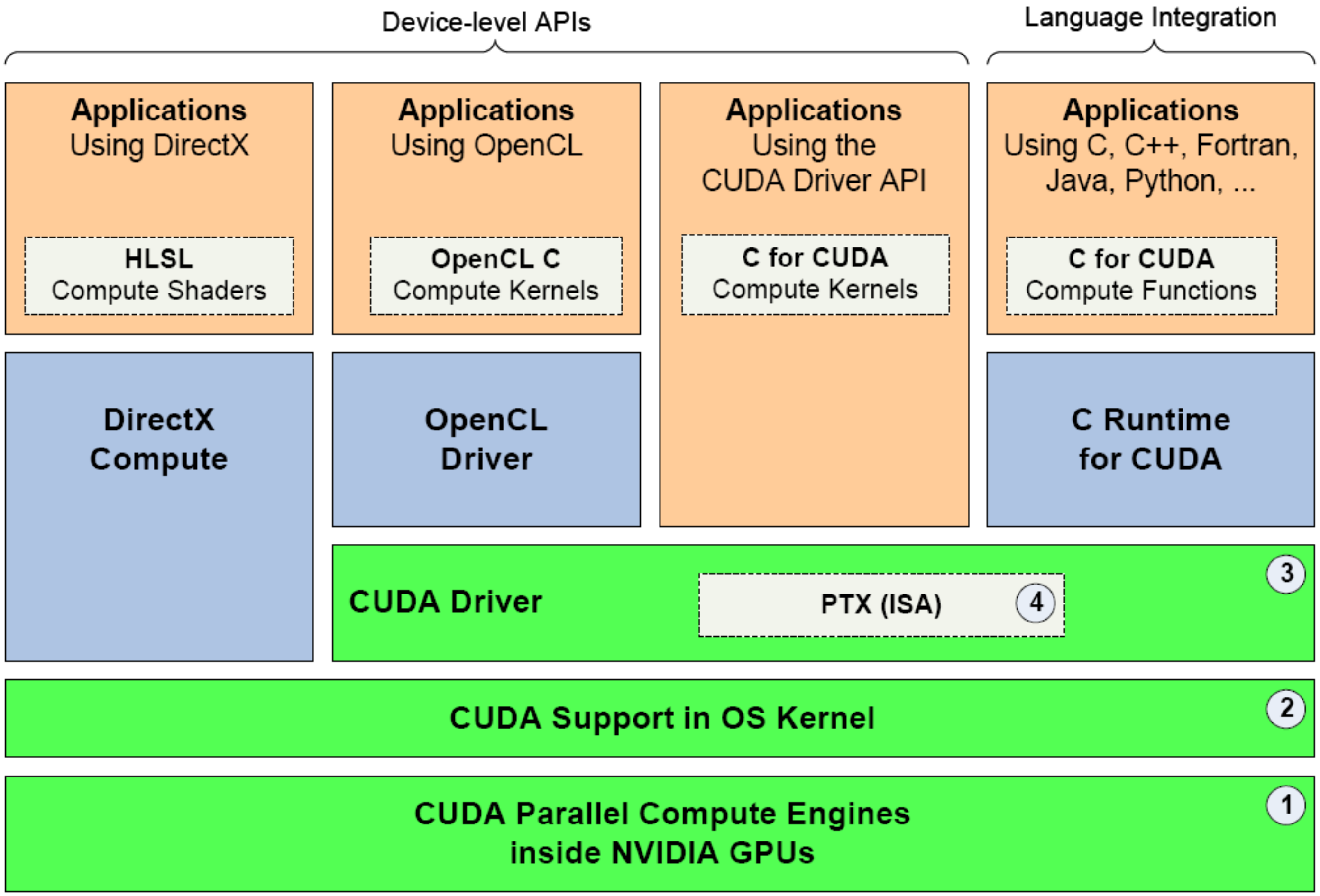



GeForce 6 Series Architecture

GPU Gems 2, NVIDIA

# Actually …

- Modern graphics hardware is programmable




www.nvidia.com/cuda

# Trend …

- GPU is general-purpose parallel computer



www.nvidia.com/cuda