The Graphics Pipeline and OpenGL II:
Lighting and Shading, Fragment Processing

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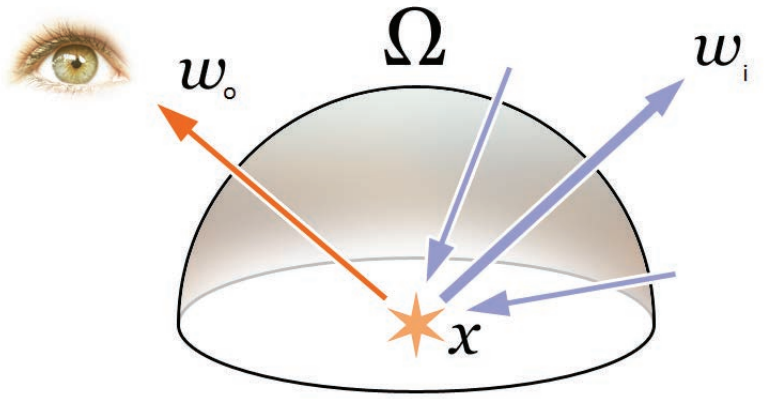
Stanford University

EE 267 Virtual Reality
Lecture 3
stanford.edu/class/ee267/

Lecture Overview

- the rendering equation, BRDFs
- lighting: computer interaction between vertex/fragment and lights
  - Phong lighting
- shading: how to assign color (i.e. based on lighting) to each fragment
  - Flat, Gouraud, Phong shading
- vertex and fragment shaders
- texture mapping

The Rendering Equation



- direct (local) illumination:
  light source → surface → eye
- indirect (global) illumination:
  light source → surface→ … → surface → eye

$$L_o(\mathbf{x}, \omega_o, \lambda, t) = L_e(\mathbf{x}, \omega_o, \lambda, t) + \int_\Omega f_r(\mathbf{x}, \omega_i, \omega_o, \lambda, t)\, L_i(\mathbf{x}, \omega_i, \lambda, t)\, (\omega_i \cdot \mathbf{n})\, \mathrm{d}\,\omega_i$$

Kajija “The Rendering Equation”, SIGGRAPH 1986

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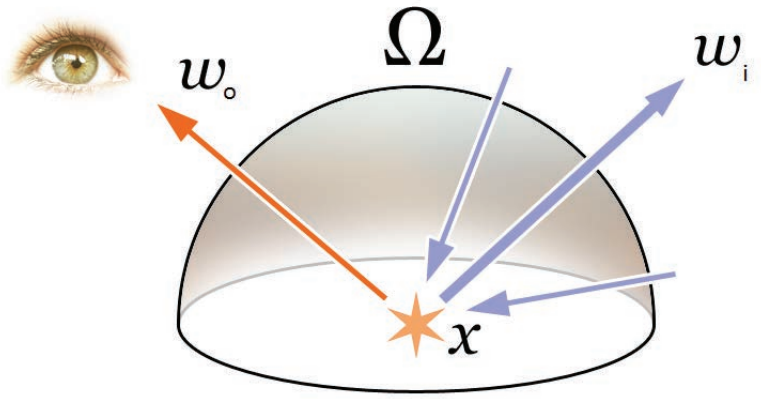

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radiance towards viewer — emitted radiance — BRDF — incident radiance from some direction

Kajija “The Rendering Equation”, SIGGRAPH 1986

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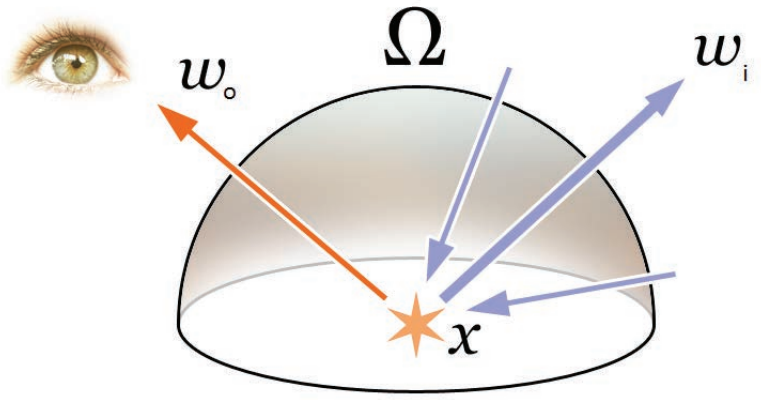

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3D location

$$L_o(\mathbf{x}, \omega_o, \lambda, t) = L_e(\mathbf{x}, \omega_o, \lambda, t) + \int_\Omega f_r(\mathbf{x}, \omega_i, \omega_o, \lambda, t)\, L_i(\mathbf{x}, \omega_i, \lambda, t)\, (\omega_i \cdot \mathbf{n})\, \mathrm{d}\,\omega_i$$

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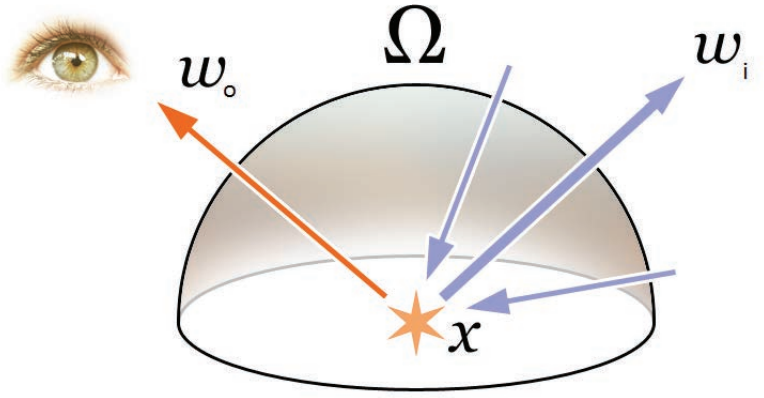

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Direction towards viewer

$$L_o(\mathbf{x}, \omega_o, \lambda, t) = L_e(\mathbf{x}, \omega_o, \lambda, t) + \int_\Omega f_r(\mathbf{x}, \omega_i, \omega_o, \lambda, t)\, L_i(\mathbf{x}, \omega_i, \lambda, t)\, (\omega_i \cdot \mathbf{n})\, \mathrm{d}\,\omega_i$$

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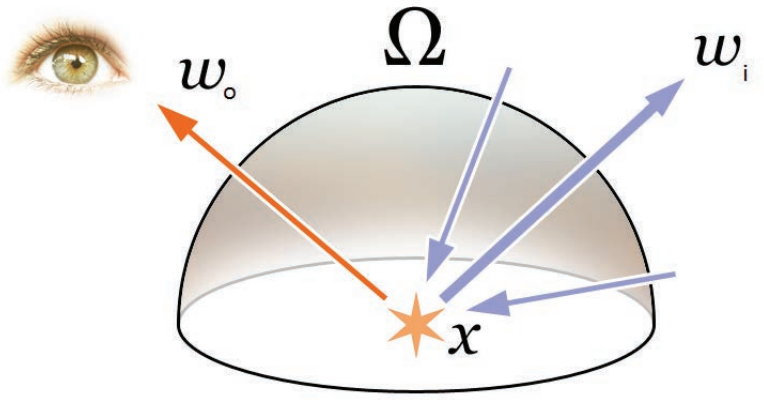

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wavelength

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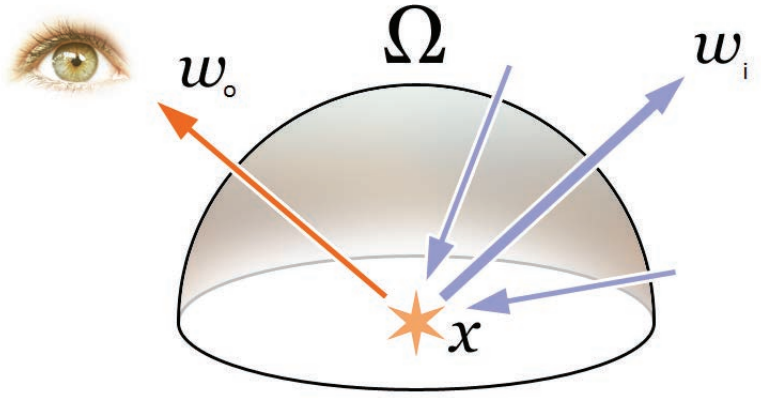

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time

$$L_o(\mathbf{x}, \omega_o, \lambda, t) = L_e(\mathbf{x}, \omega_o, \lambda, t) + \int_\Omega f_r(\mathbf{x}, \omega_i, \omega_o, \lambda, t)\, L_i(\mathbf{x}, \omega_i, \lambda, t)\, (\omega_i \cdot \mathbf{n})\, \mathrm{d}\,\omega_i$$

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The Rendering Equation

- drop time, wavelength (RGB) & global illumination to make it simple

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The Rendering Equation

- drop time, wavelength (RGB), emission & global illumination to make it simple

$$L_0(x,\omega_0) = \sum_{k=1}^{num\_lights} f_r\left(x,\omega_k,\omega_o\right) L_i(x,\omega_k)\left(\omega_k \cdot n\right)$$

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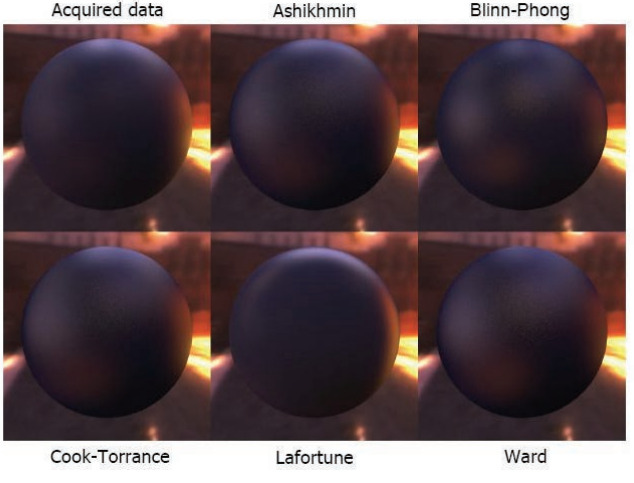
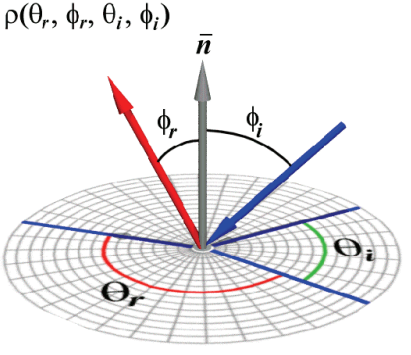
Bidirectional Reflectance Distribution Function (BRDF)

- many different BRDF models exist: analytic, data driven (i.e. captured)



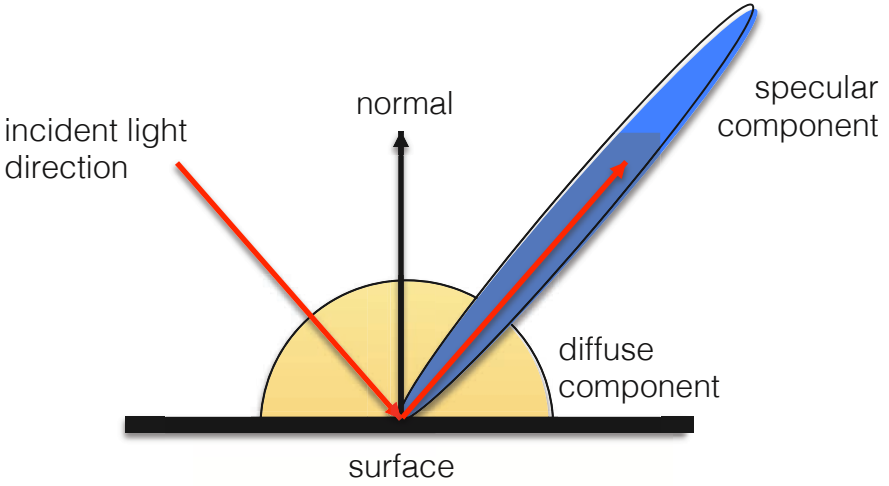
Ngan et al. 2004

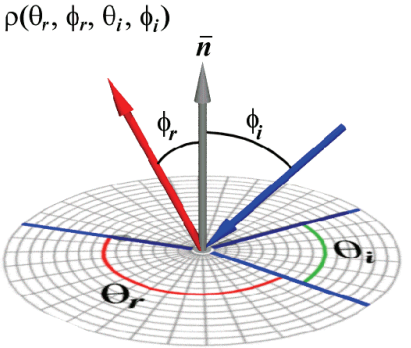


http://escience.anu.edu.au/lecture/cg/GlobalIllumination/BRDF.en.html

Bidirectional Reflectance Distribution Function (BRDF)

- can approximate BRDF with a few simple components





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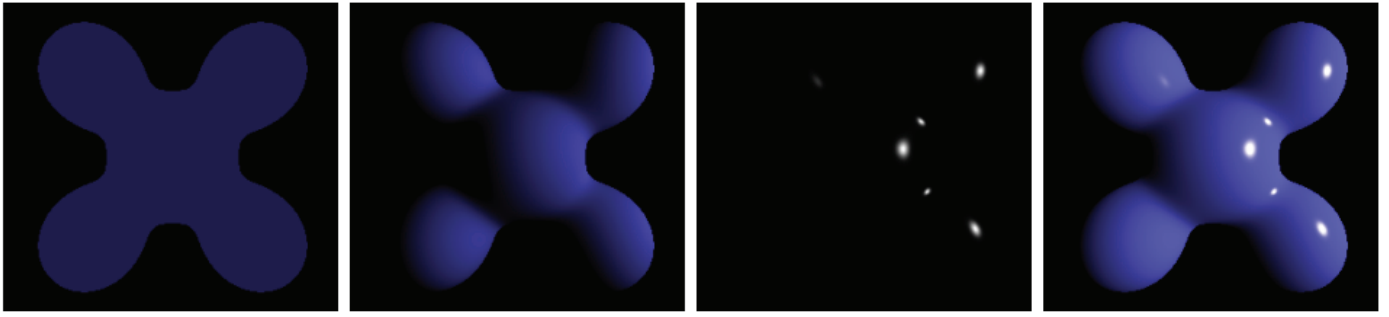
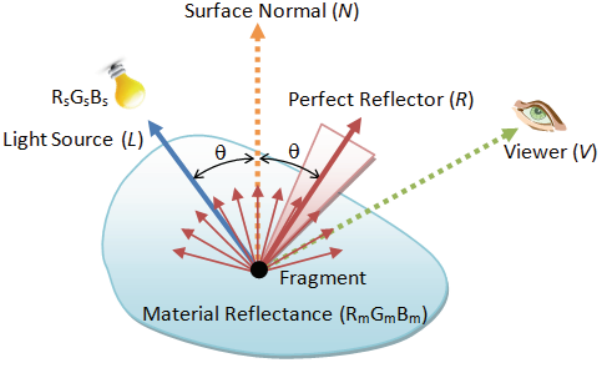
Phong Lighting

- emissive part can be added if desired
- calculate separately for each color channel: RGB



Phong Lighting

- simple model for direct lighting
- ambient, diffuse, and specular parts
- requires:
  - material color m_{RGB} (for each of ambient, diffuse, specular)
  - light color I_{RGB} (for each of ambient, diffuse, specular)



L normalized vector pointing towards light source

N normalized surface normal

V normalized vector pointing towards viewer

$$R = 2(N \bullet L)N - L$$

normalized reflection on surface normal

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Phong Lighting: Ambient

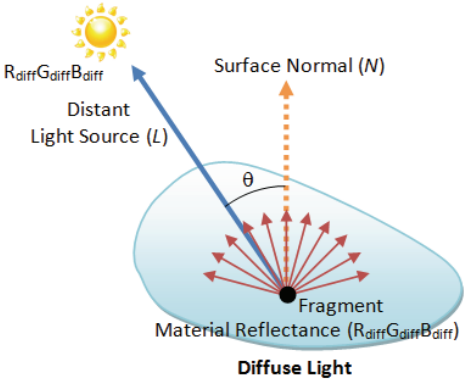
- independent of light/surface position, viewer, normal
- basically adds some background color

Ambient

$$m^{ambient}_{\{R,G,B\}} \cdot l^{ambient}_{\{R,G,B\}}$$

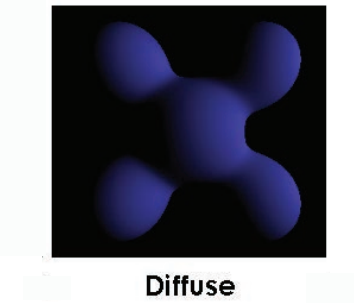
Phong Lighting: Diffuse

- needs normal and light source direction
- adds intensity cos-falloff with incident angle



$$m^{diffuse}_{\{R,G,B\}} \cdot l^{diffuse}_{\{R,G,B\}} \cdot \max(L \bullet N, 0)$$

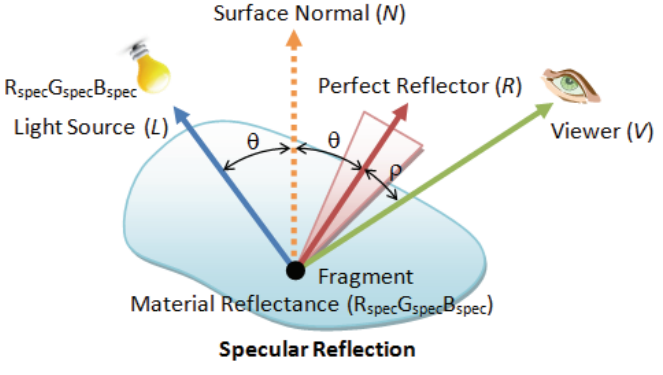
dot product



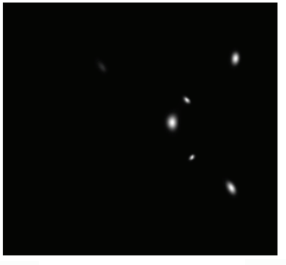
Phong Lighting: Specular

- needs normal, light & viewer direction

- models reflections = specular highlights
- shininess – exponent, larger for smaller highlights (more mirror-like surfaces)



$$m_{\{R,G,B\}}^{specular} \cdot l_{\{R,G,B\}}^{specular} \cdot \max(R \bullet V, 0)^{shininess}$$



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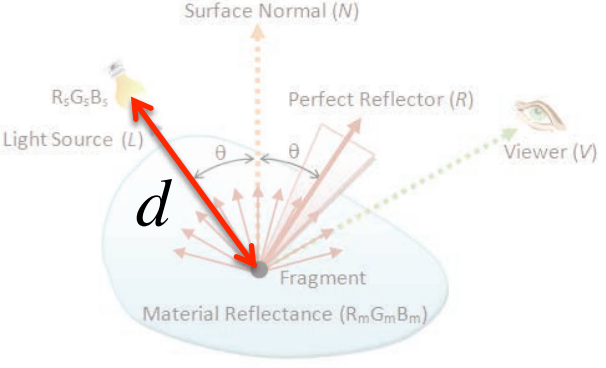
Phong Lighting: Attenuation

- models the intensity falloff of light w.r.t. distance
- The greater the distance, the lower the intensity



$$\frac{1}{k_c + k_l d + k_q d^2}$$

constant linear quadratic attenuation

Phong Lighting: Putting it all Together

- this is a simple, but efficient lighting model
- has been used by OpenGL for ~25 years
- absolutely NOT sufficient to generate photo-realistic renderings (take a computer graphics course for that)

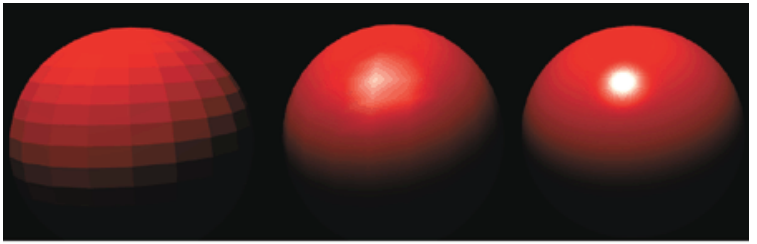
$$color_{\{R,G,B\}} = m^{ambient}_{\{R,G,B\}} \cdot l^{ambient}_{\{R,G,B\}} + \sum_{i=1}^{num\_lights} \frac{1}{k_c + k_l d_i + k_q d_i^2} \left(m^{diffuse}_{\{R,G,B\}} \cdot l^{diffuse}_{i,\{R,G,B\}} \cdot \max(L_i \bullet N, 0) + m^{specular}_{\{R,G,B\}} \cdot l^{specular}_{i\{R,G,B\}} \cdot \max(R_i \bullet V, 0)^{shininess} \right)$$

ambient attenuation diffuse specular

Lighting v Shading

- lighting: interaction between light and surface (e.g. using Phong lighting model)

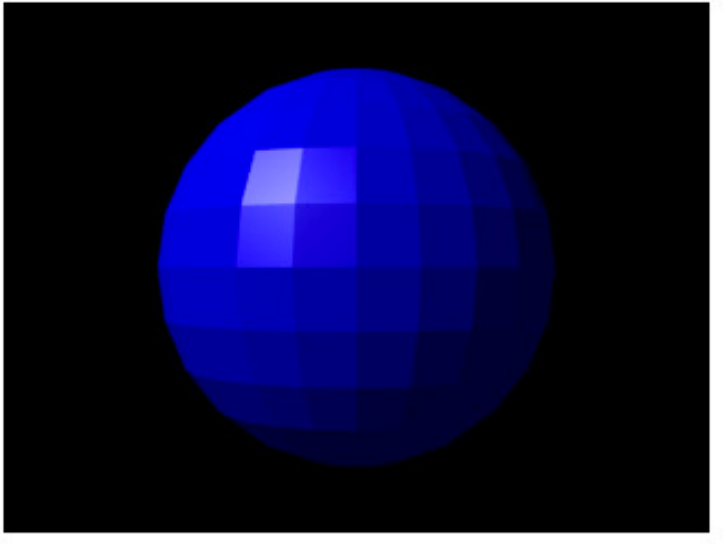
- shading: how to compute color of each fragment (e.g. interpolate colors)
  1. Flat shading
  2. Gouraud shading (per-vertex shading)
  3. Phong shading (per-fragment shading - different from Phong lighting)



courtesy: Intergraph Computer Systems

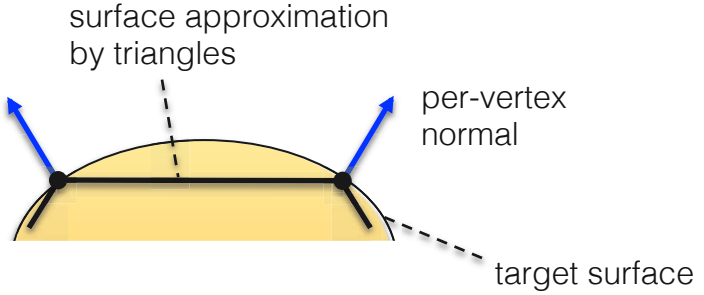
Flat Shading

- compute color only once per triangle (i.e. with Phong lighting)
- pro: usually fast to compute; con: fast creates a flat, unrealistic appearance
- we won't use it



Gouraud or Per-vertex Shading

- compute color once per vertex (i.e. with Phong lighting)
- interpolate per-vertex colors to all fragments within the triangles!
- pro: usually fast-ish to compute; con: flat, unrealistic specular highlights



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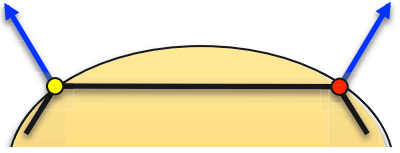

per-vertex lighting

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per-vertex lighting

shaded surface

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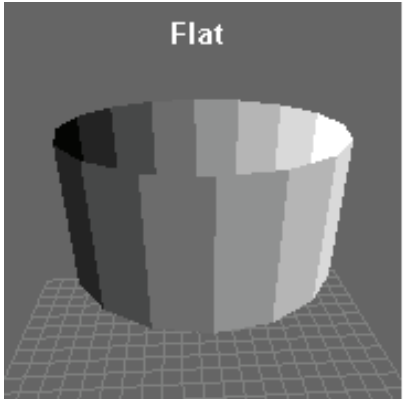
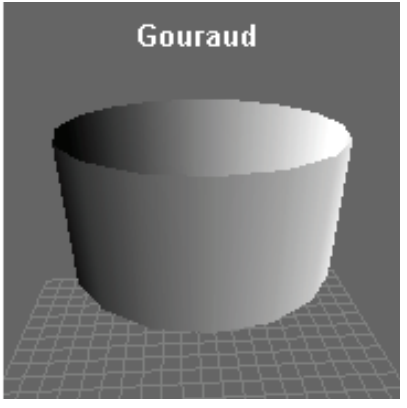
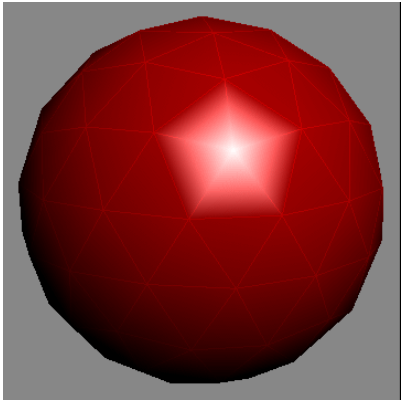


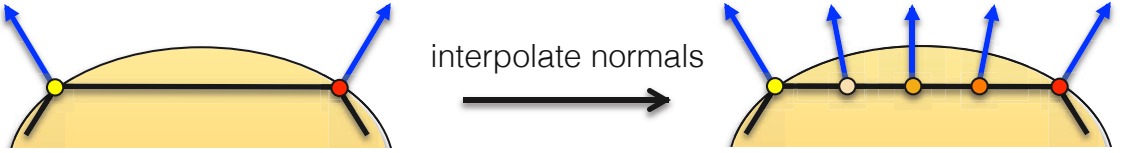




https://en.wikipedia.org/wiki/Gouraud_shading

Phong or Per-fragment Shading

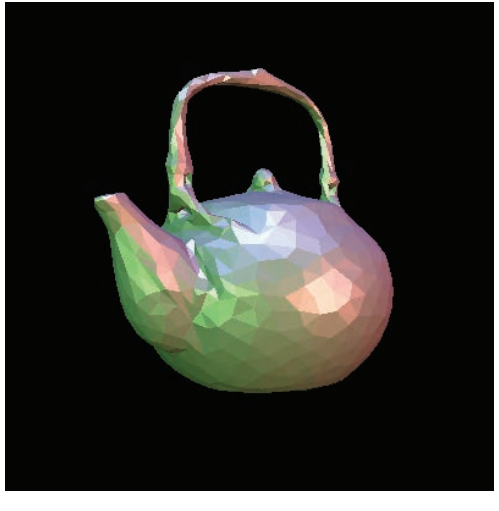
- compute color once per fragment (i.e. with Phong lighting)
- need to interpolate per-vertex normals to all fragments to do the lighting calculation!
- pro: better appearance of specular highlights; con: usually slower to compute



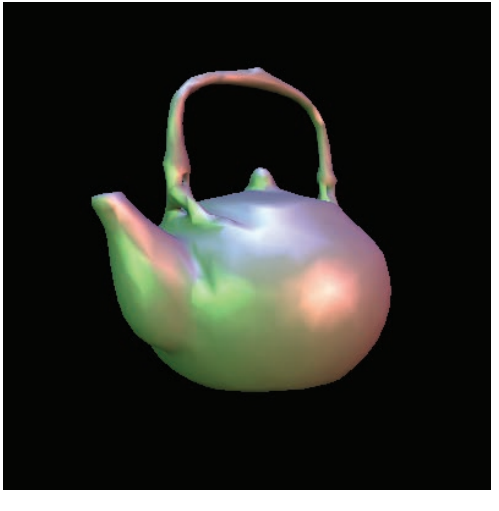
per-fragment lighting

Shading

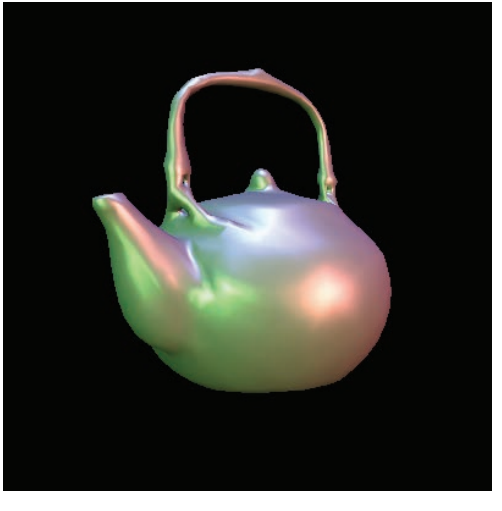
Flat Shading



Gouraud Shading

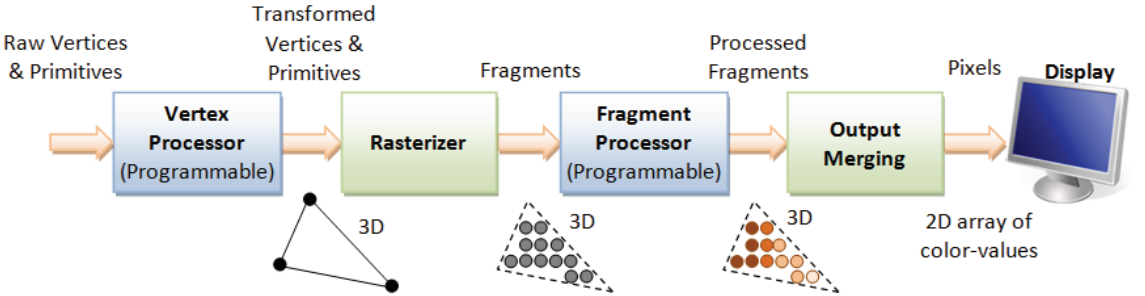


Phong Shading



http://www.decew.net/OSS/timeline.php

Back to the Graphics Pipeline



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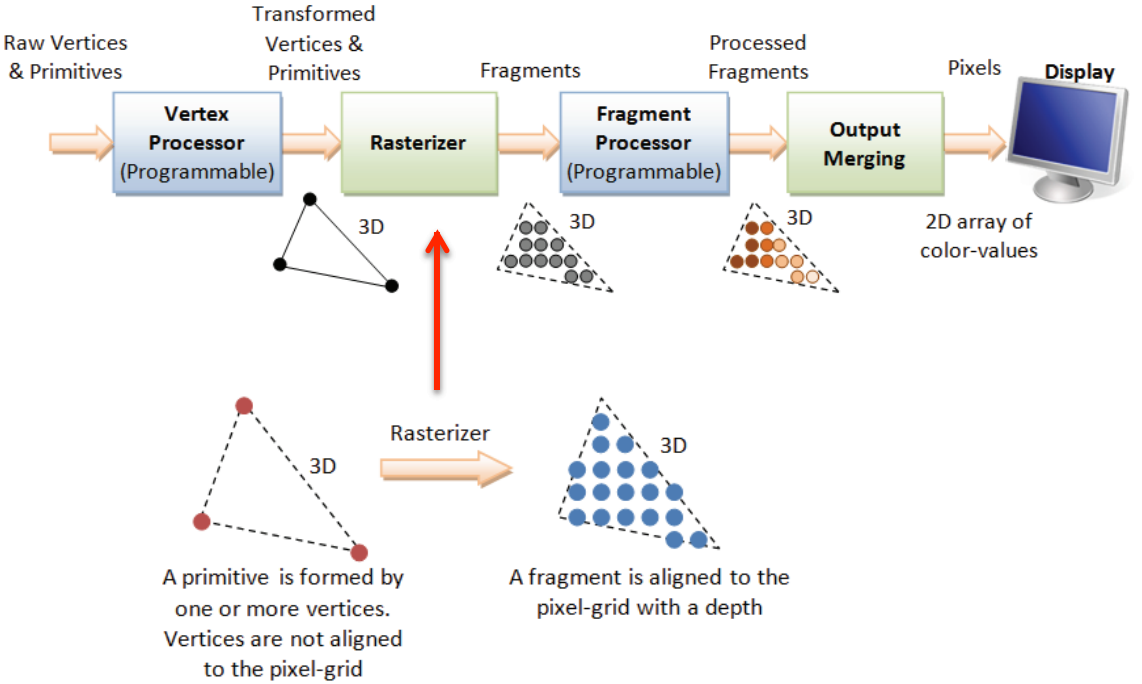
Rasterization



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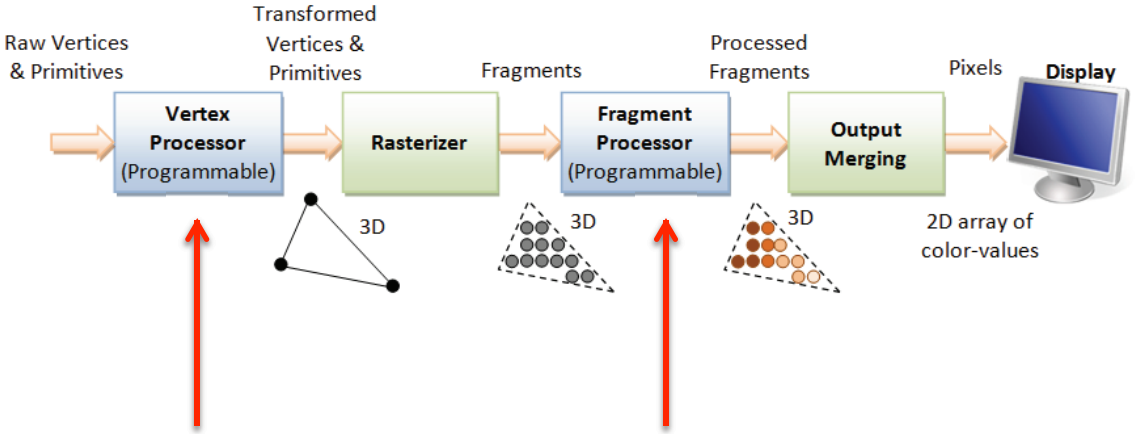
Per-vertex Lighting v Per-fragment Lighting



vertex shader

- lighting calculations done for each vertex

fragment shader

- lighting calculations done for each fragment

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Vertex and Fragment Shaders

- shaders are small programs that are executed in parallel on the GPU for each vertex (vertex shader) or each fragment (fragment shader)

- vertex shader:
  - modelview projection transform of vertex & normal (see last lecture)
  - if per-vertex lighting: do lighting calculations here (otherwise omit)

- fragment shader:
  - assign final color to each fragment
  - if per-fragment lighting: do all lighting calculations here (otherwise omit)

Fragment Processing

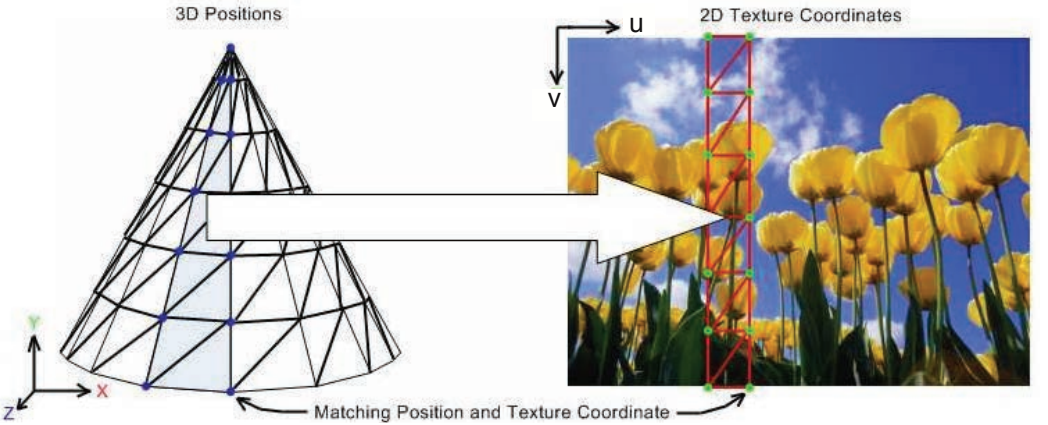
- lighting and shading (per-fragment) – we already discussed this
- texture mapping

these also happen, but don't worry about them (we wont touch these):

- fog calculations
- alpha blending
- hidden surface removal (using depth buffer)
- scissor test, stencil test, dithering, bitmasking, …

Texture Mapping

- texture = 2D image (e.g. RGBA)
- we want to use it as a “sticker” on our 3D surfaces
- mapping from vertex to position on texture (texture coordinates u,v)



https://blogs.msdn.microsoft.com/danlehen/2005/11/06/3d-for-the-rest-of-us-texture-coordinates/

Texture Mapping

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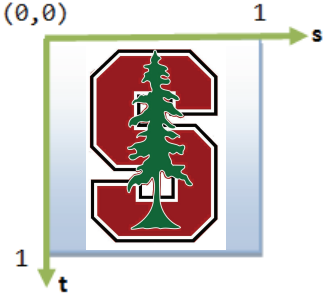
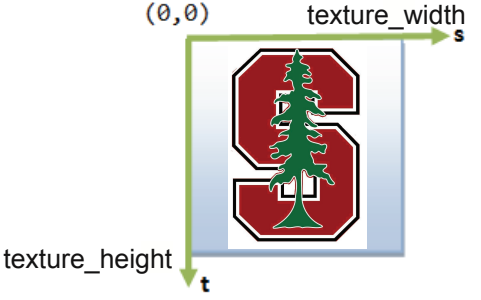


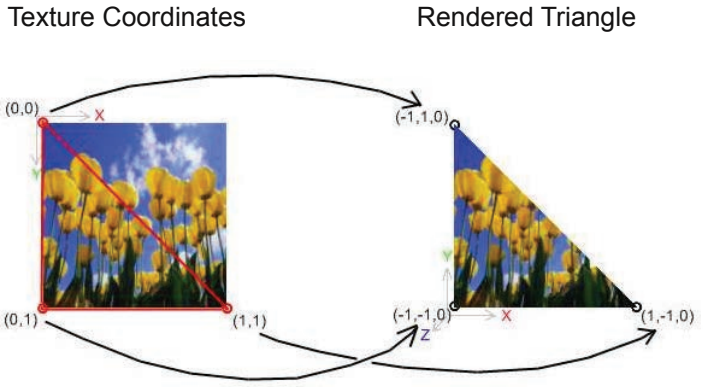
Normalized Texture Coordinates

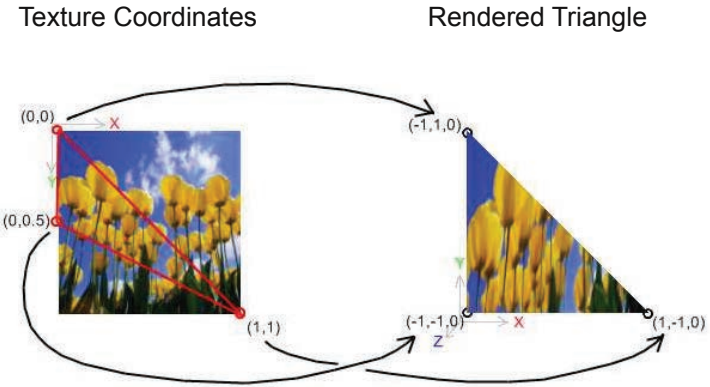


Non-normalized Texture Coordinates

Texture Mapping

- same texture, different texture coordinates



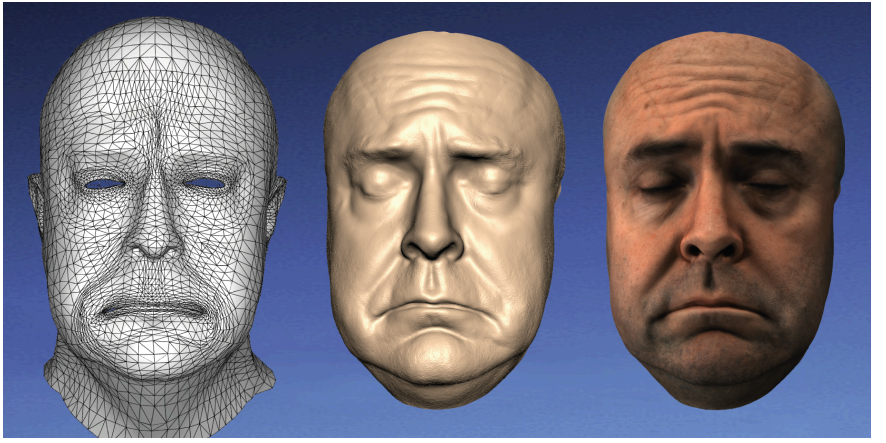


https://blogs.msdn.microsoft.com/danlehen/2005/11/06/3d-for-the-rest-of-us-texture-coordinates/

Texture Mapping

- texture mapping faces

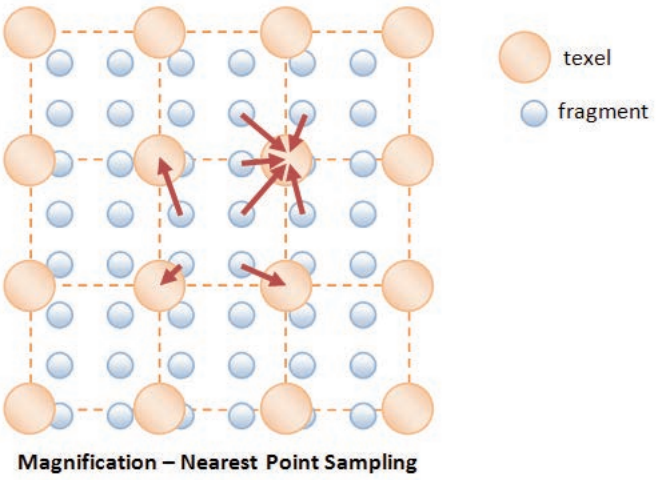
turbosquid.com

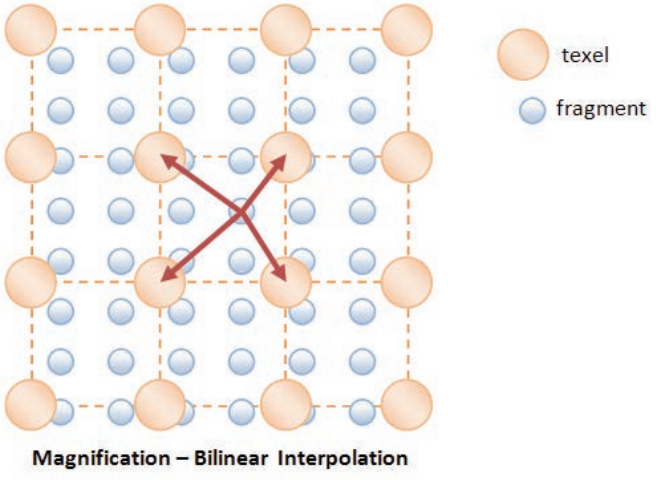


Bermano et al. 2013

Texture Mapping

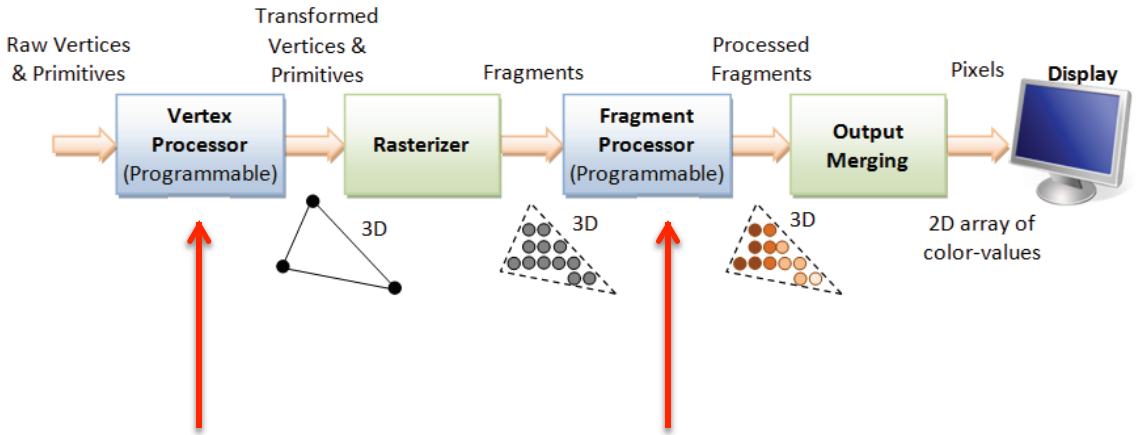
- texture filtering: fragments don't align with texture pixels (texels) → interpolate





https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Next Lecture: Vertex & Fragment Shaders, GLSL



vertex shader

- transforms & (per-vertex) lighting

fragment shader

- texturing
- (per-fragment) lighting

https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

Summary

- the rendering equation, BRDFs
- lighting: computer interaction between vertex/fragment and lights
  - Phong lighting
- shading: how to assign color (i.e. based on lighting) to each fragment
  - Flat, Gouraud, Phong shading
- vertex and fragment shaders
- texture mapping

Further Reading

- good overview of OpenGL (deprecated version) and graphics pipeline (missing a few things) :

  https://www.ntu.edu.sg/home/ehchua/programming/opengl/CG_BasicsTheory.html

- textbook: Shirley and Marschner “Fundamentals of Computer Graphics”, AK Peters, 2009

- definite reference: “OpenGL Programming Guide” aka “OpenGL Red Book”

- WebGL / three.js tutorials: https://threejs.org/