



CSE251

Basics of Computer Graphics

Module: Lighting and Shading

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Lighting/Shading

- ▶ We know which pixels of the frame buffer belongs to which object after visibility and scan conversion.
- ▶ What colour to give to the pixel? “Current colour”??
- ▶ Depends on: the colour of the object, the material properties of the object, the colour of the light source, the angle of viewing with respect to object/lights, etc.
- ▶ **Lighting** and **shading**: Finding the colours for each pixel, perhaps after finding it on the extrema of the primitives.
- ▶ What is our guide? **Physics!**
- ▶ Computational Process:

Abstract – Represent – Process

Different Terms

- ▶ **Illumination Model:** How to “light” an object point given its material properties, the light sources, and the camera?
- ▶ **Shading Model:** How the illumination model applies to objects such as polygons and points.
- ▶ **Lighting:** Different types of lights.
- ▶ **Shadows:** How are shadows cast by objects.

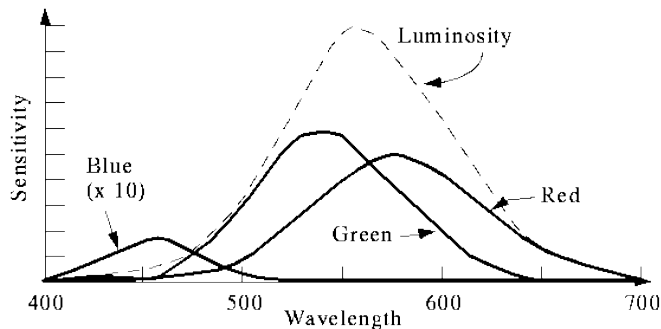
Colour Representation

- ▶ What do we write into the frame-buffer after identifying which pixels belong to a primitive?
- ▶ The **colour** and intensity!
- ▶ Colour represented using **Red**, **Green**, and **Blue**. Why?
- ▶ Visible portion of the electromagnetic spectrum:
From about 400nm (**Violet**) to 700nm (**Red**).
- ▶ A bulb appears **red** if it emits light of λ in the red range
- ▶ A flower appears **orange** because it absorbs light of all wavelengths **except** in the orange range.

Human Colour Perception

- ▶ **Rods** of our retina see gray levels
- ▶ **Cones** are of 3 types: **Red**, **Green**, and **Blue**.
- ▶ Their spectral responses respectively peak approximately at 575 nm, 535nm, and 445nm
- ▶ *Luminous efficiency*: human visual sensitivity to constant luminance light
- ▶ Bell-shaped curve with a peak around 550nm (**Green**).

Human Eye Response to colour



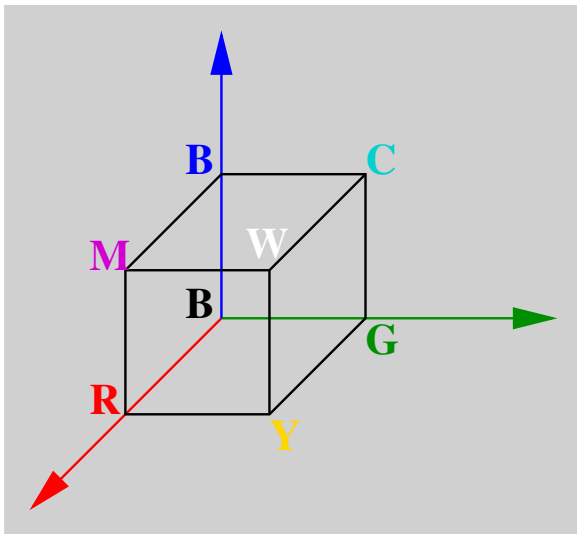
Tristimulus Theory

- ▶ All perceivable colours can be specified as weighted combination of primary colours R, G, and B.
- ▶ RGB define a set of basis vectors. Mix them in different measures to get any colour.
- ▶ Attractive, because a compact representation is possible.
- ▶ Problem reduces to: *Find RGB values to approximate a given perceptual colour*

RGB Colour Model

- ▶ Called the **Additive Primaries**.
- ▶ Colour Cube: $R+G = \text{Yellow}$, $R+B = \text{Magenta}$,
 $G+B = \text{Cyan}$, $R+G+B = \text{White}$, all zero gives **Black**.
- ▶ Popular in graphics, due to CRT/LCD Monitors
- ▶ Values commonly normalized to range $[0.0, 1.0]$. Externally 8-bits per colour channel
- ▶ Grays lie along the diagonal from $(0, 0, 0)$ to $(1, 1, 1)$.

RGB Colour Model (cont.)



CMY(K) Colour Model

- ▶ Called the **Subtractive Primaries**.
- ▶ Colour Cube: $C+M = \text{Blue}$, $C+Y = \text{Green}$,
 $M+Y = \text{Red}$, $C+M+Y = \text{Black}$, all zero gives **White**!
- ▶ Subtract RGB from 1.0, you get CMY, respectively.
- ▶ Since black is common, $\min(C, M, Y)$ is taken out as black or K component. Yields the **CMYK** colour model used in the 4-colour printing process.

Different Terms

- ▶ **Illumination Model:** How to “light” an object point given its material properties, the light sources, and the camera?
- ▶ **Shading Model:** How the illumination model applies to objects such as polygons and points.
- ▶ **Lighting:** Different types of lights.
- ▶ **Shadows:** How are shadows cast by objects.

Illumination Models

- ▶ Modelling of the interaction with light and an object point from the point of view of the camera image.
- ▶ Three factors come into play: light source properties, material properties, and atmospheric effects.
- ▶ Light sources emit light.
Properties: Colour and Directionality.
- ▶ Materials interact with light differently.
Properties: Reflectivity and Colour.
- ▶ Atmospheric effects: attenuation.

Material Properties

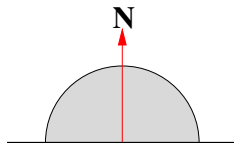
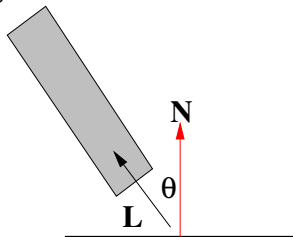
- ▶ **colour**: the paint used on the surface of the material with which the object is made.
- ▶ **Reflectivity**: how the material interacts with light.
Shiny, dull, grainy, etc.
- ▶ Hard to separate these effects in practice.
Combined impact is observed.
- ▶ **Diffuse reflection**: For dull, rough objects.
- ▶ **Specular reflection**: For smooth, shiny objects.

Diffuse or Lambertian Reflection

- ▶ Objects that obey Lambert's law of reflection: cloth, rough wall, etc.
- ▶ The normal component of light falling on it is absorbed by the object and is then reflected back equally in all directions.
- ▶ No preferred direction for reflecting light falling on it. Appearance of the point is independent of the view angle.
- ▶ Normal component of the light is proportional to $\cos \theta$.

Diffuse or Lambertian Reflection (cont.)

Light Source



Reflection in
all directions

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- ▶ Reflected light $I \propto I_L \cos \theta$ in all viewing directions.

Diffuse Illumination Equation

- ▶ The formula for computing the intensity at a point.
- ▶ For diffuse reflection, if I_p is the light falling at the surface,

$$I_d = I_p k_d \cos \theta = I_p k_d (\mathbf{N} \cdot \mathbf{L})$$

- ▶ k_d is the diffuse reflection coefficient.
- ▶ θ should be between 0 and 90. Otherwise, the light has no effect. (Object is self-occluding!)
- ▶ For correct effects, the real normal at the point is necessary. (Normals are coming of use!)

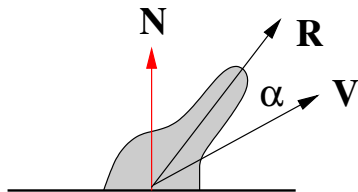
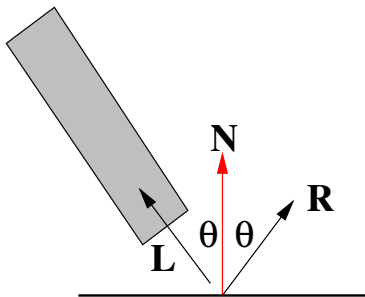
Material Colour

- ▶ What is the colour of an object?
The light it reflects. Rest is absorbed.
- ▶ A fully red object has colour (1, 0, 0). It reflects all of the red falling on it and none of the green or blue.
- ▶ How do we represent/simulate that?
- ▶ We also need to know the spectral composition of the light falling on the object.
- ▶ Illumination equation: $I_{d\lambda} = I_{p\lambda} k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L})$
- ▶ $k_d O_{d\lambda}$ can be called the **diffuse colour** of object.

Shiny Objects and Highlights

- ▶ Shiny objects (smooth metal, polished marble) behave differently.
- ▶ A **highlight** can be seen on them due to the light source. Highlight has the colour of the light source, irrespective of object colour.
- ▶ Highlight moves with the viewing angle. Appearance of the object point depends on the view angle.
- ▶ This is called **specular reflection**.
- ▶ A mirror is an ideal specular reflector.

Shiny Objects and Highlights (cont.)



**Maximum Reflection
along direction R**

Specular Reflections

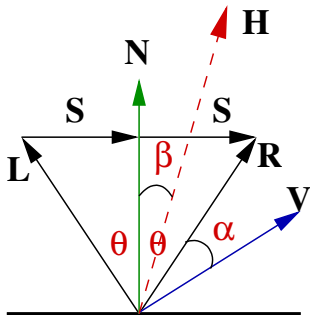
- ▶ A distinguished direction exists for reflection, depending on the incident light direction and normal direction.
- ▶ Reflection falls off quickly as view moves away from this angle.
- ▶ Reflect the light vector about the normal vector to get the specular reflection direction.

Specular Lighting: Phong Model

- ▶ α is the angle between the reflection direction R and the view direction V .
- ▶ Phong's model: $I_s = I_p k_s \cos^n \alpha = I_p k_s (\mathbf{V} \cdot \mathbf{R})^n$
- ▶ As n becomes larger, reflection becomes sharper. k_s is the specular reflection coefficient.
- ▶ Sometimes, specular colour $O_{s\lambda}$ is also given to the object!

Computing Reflection Vector R

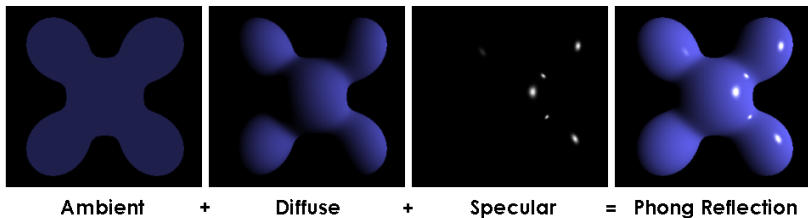
- ▶ $\mathbf{L} + \mathbf{S} = \mathbf{N} (\mathbf{N} \cdot \mathbf{L})$
- ▶ $\mathbf{R} = \mathbf{L} + 2\mathbf{S} = ??$
- ▶ Halfway vector \mathbf{H} may also be used: $\mathbf{H} = \frac{\mathbf{L} + \mathbf{V}}{|\mathbf{L} + \mathbf{V}|}$
- ▶ Maximum highlight when \mathbf{H} and \mathbf{N} coincide
- ▶ Deviation from it $\mathbf{N} \cdot \mathbf{H}$ can be used instead of $\mathbf{V} \cdot \mathbf{R}$



Ambient Light

- ▶ In graphics, some light is always present.
- ▶ This is called **ambient light** I_a , present everywhere.
- ▶ The net effect of all the light that reflects from the environment etc.
- ▶ This light helps see objects even when no explicit light source is present.
- ▶ Illumination equation: $I_\lambda = I_{a\lambda} k_a O_{a\lambda} + I_{p\lambda} k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L})$
- ▶ k_a is the ambient reflection coefficient.

Phong Reflection Example



Brad Smith

Atmospheric Effects

- ▶ Most straightforward is attenuation.
- ▶ The light that reaches the point $I = f_{\text{att}} I_p$.
- ▶ Physics says: $f_{\text{att}} = 1/d_L^2$ by inverse square law.
- ▶ In practice, it doesn't work well. Objects that are far become indistinguishable.
- ▶ In graphics, we use $f_{\text{att}} = 1/(c_1 + c_2 d_L + c_2 d_L^2)$
- ▶ Illum Equn: $I_\lambda = I_{a\lambda} k_a O_{a\lambda} + f_{\text{att}} I_\lambda k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L})$

One Light to More

- ▶ Total illumination equation for one light source:

$$I_{p\lambda} = I_{a\lambda} k_a O_{a\lambda} + f_{\text{att}} I_{\lambda} [k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L}) + k_s O_{s\lambda} (\mathbf{V} \cdot \mathbf{R})^n]$$

- ▶ When multiple light sources are involved?
- ▶ Simple model: Add up the individual contributions together!
- ▶ Question: Which terms depend on the light source?

Multiple Light Sources

- ▶ Contributions of diffuse, and specular reflections are added together.
- ▶ When multiple light sources are involved:

$$I_{p\lambda} = I_{a\lambda} k_a O_{a\lambda} + \sum_i f_{\text{att}_i} I_{\lambda i} [k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L}_i) + k_s O_{s\lambda} (\mathbf{V} \cdot \mathbf{R}_i)^n]$$

Emissive Colour

- ▶ Objects that emit colour such as a tubelight as an object.
- ▶ Material property can include emissive colours for such self luminous objects.
- ▶ The emissive colour is added to every point of the object.
- ▶ Only the appearance of the object is affected.
- ▶ Emissive objects do not work as light sources automatically.

Light Sources

- ▶ When the light source is infinitely far (like the Sun), only the direction matters. *Directional Light*
- ▶ When light has a position, \mathbf{L} vector can be computed from it. *Point Light Source*
- ▶ Point light sources illuminate in all directions.
- ▶ Alternately, light source can have a position, a direction, and a drop off formula. Lighting is maximum in the given direction and drops off as you move away from that direction. *Spot Light*
- ▶ Colour of the light is important to compute effects.

Light Sources in OpenGL

- ▶ Position: Set $(x, y, z, 0)$ for directional light sources, located at ∞ . Finite position for others. Default: point light source.
- ▶ Each has: Ambient, Diffuse, Specular colours. Spot direction, cut-off, exponent. Attenuation.
- ▶ Since each polygon is drawn independently, shadows do not appear automatically.
- ▶ Read about `glLight()`, `glLightModel()`.
And `glEnable()` for `GL_LIGHTi`, `GL_LIGHTING`.

Material in OpenGL

- ▶ **colours**: the material colour times the appropriate reflection coefficient.
- ▶ Ambient, Diffuse, Specular, Emissive colours.
- ▶ Shininess: like the n in the $\cos^n \alpha$ term.
- ▶ Produces good effects when combined with light sources.
- ▶ `glMaterial()` changes the current material properties. Read!

Lighting: Summary

- ▶ **Material:** Diffuse colour, specular colour, ambient colour.
- ▶ **Light Source:** Type, directionality and colour. Usually, diffuse, specular, and ambient colours could be attached to light sources.
- ▶ **Reflection:** Diffuse and Specular.
- ▶ Total illumination equation for multiple light sources:

$$I_{p\lambda} = I_{a\lambda} k_a O_{a\lambda} + \sum_i f_{att_i} I_{\lambda i} [k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L}_i) + k_s O_{s\lambda} (\mathbf{V} \cdot \mathbf{R}_i)^n]$$

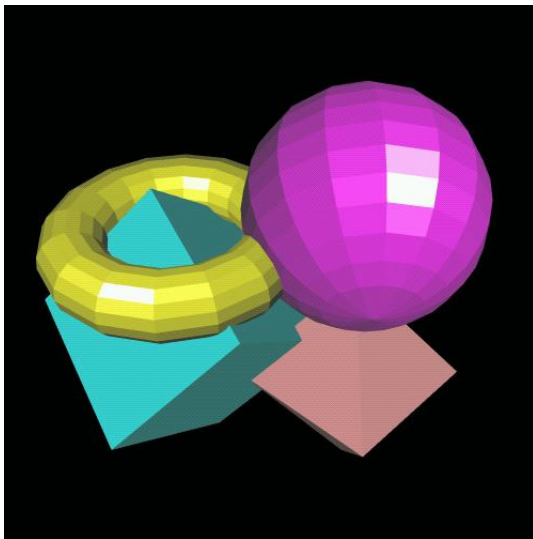
Shading Models for Polygons

- ▶ The illumination equation can be evaluated at every pixel to compute the colour/intensity there.
- ▶ This is expensive computationally.
(Does it give the correct results?)
- ▶ Can we take advantage of the coherence or the fact that we are computing for a planar polygon?
- ▶ A number of different options exist.

Constant or Flat Shading

- ▶ Evaluate Illumination equation once per polygon
- ▶ Apply the intensity values to the whole polygon
- ▶ Each polygon gets a constant colour. They look flat
- ▶ Most easy computationally
- ▶ The results will be correct if:
 - $\mathbf{N} \cdot \mathbf{L}$ is constant across the polygon and
 - $\mathbf{N} \cdot \mathbf{V}$ is constant across the polygon and
 - Object is polyhedral, not an approximation
- ▶ Which point? Centre? First vertex? Results may vary.

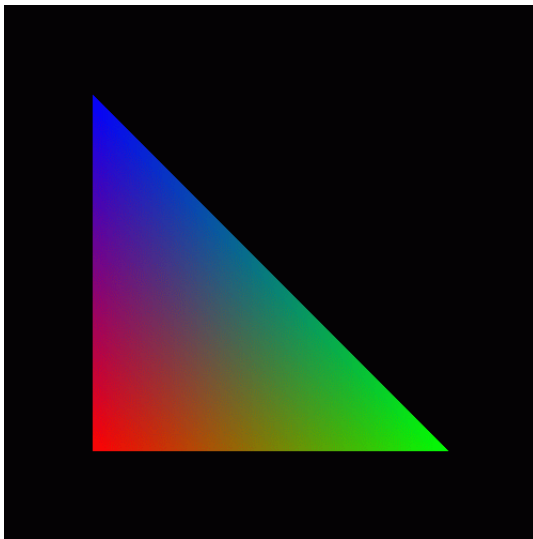
Constant or Flat Shading (cont.)



Interpolated Shading

- ▶ Results of flat shading are unsatisfactory.
- ▶ Interpolated shading assumes that properties can be calculated at the vertices and can be interpolated for the interior points.
- ▶ The interpolation can be done along with the interpolation of the Z values.
- ▶ Use the normal, light and view vectors for the vertices to compute the values.
- ▶ Since the polygon is planar, the normals should be the same!?!?

Interpolated Shading (cont.)

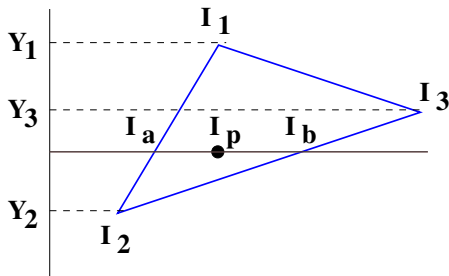


Gourard Shading

- ▶ Also called *colour interpolation shading*.
- ▶ Evaluate the illumination equation at each of the polygon vertices.
- ▶ Use exact normals – stored already or computed on the fly – if available.
- ▶ Otherwise, use the average of all polygons that meet at the vertex!
- ▶ Interpolate intensities along the edges that connect vertices.
- ▶ Interpolate along scan lines using intensities at the edges. This can be combined nicely with the computation we perform on spans of polygons nicely.

Gourard Shading (cont.)

- Produces good results, not correct according to Physics!

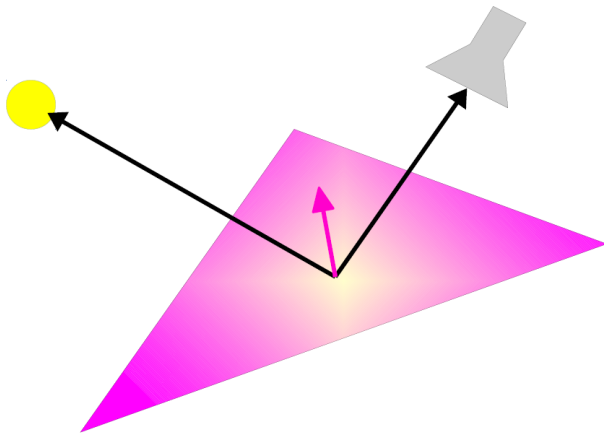


- Linear along edges for I_a, I_b and along scan line for I_p

Highlights under Interpolation

- ▶ Specular highlights are localized bright areas.
- ▶ If the highlight falls in the middle of a polygon, it will be completely missed as illumination equation is computed only for the vertices.
- ▶ If highlight falls on a vertex, it will be interpolated across, making it less local.
- ▶ These cannot be handled by interpolation of intensities.

Highlights under Interpolation



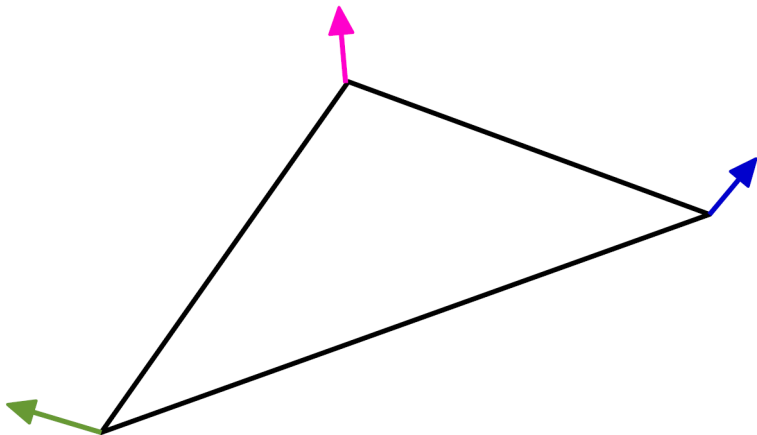
Polygon Approximation

- ▶ When a curved object is approximated using a polygon, adjacent polygons could have different intensity values.
- ▶ Flat shading will bring it out sharply; object will appear *faceted*.
- ▶ Interpolated shading may not help much if neighbouring polygons have different normals.
- ▶ Will it help to evaluate the illumination equation at each pixel?

Normals at Points

- ▶ If a parametric or analytic representation of the object that is approximated is available, exact normals can be computed at each point.
- ▶ Keep the equations along with the objects so that exact normals can be computed.
- ▶ Alternately, compute the normals for each vertex when converting the smooth object to a polygon mesh.
- ▶ Keeping the normal vector at each vertex along with the 3D coordinates is quite popular.

Normals at Points (cont.)

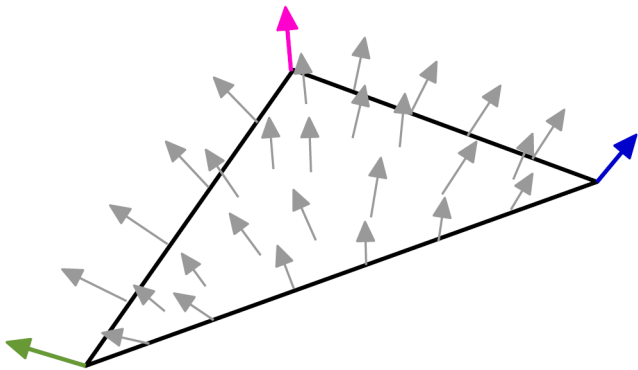


- Normals could be from the underlying exact surface.

Phong Shading

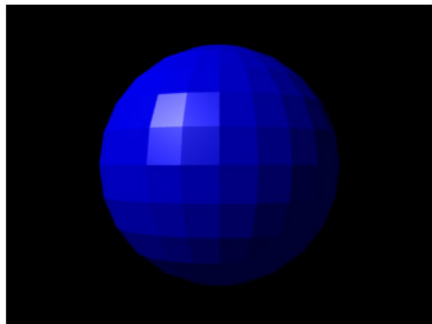
- ▶ Interpolate surface normals across the polygon, given the normals at the vertices.
- ▶ Compute illumination equation with these interpolated normals for each pixel.
- ▶ Computes highlights very well.
- ▶ Computation time is more as the equation is evaluated at every pixel.
- ▶ Interpolation of normals is not physically based!
- ▶ Also called *normal vector interpolation shading*

Phong Shading (cont.)

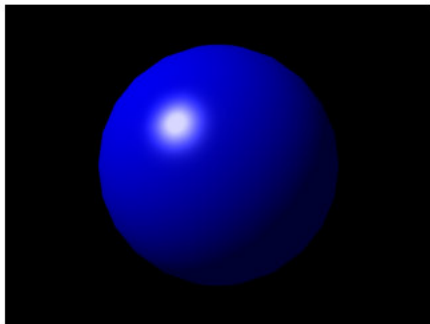


- ▶ Exact normals (not interpolated) can be evaluated at each pixel in the fragment shader for exact lighting.

Phong Shading



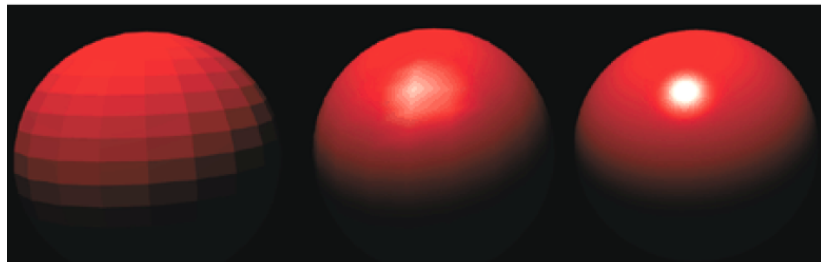
FLAT SHADING



PHONG SHADING

Flat vs Gouraud vs Phong Shading

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Flat

Gouraud

Phong

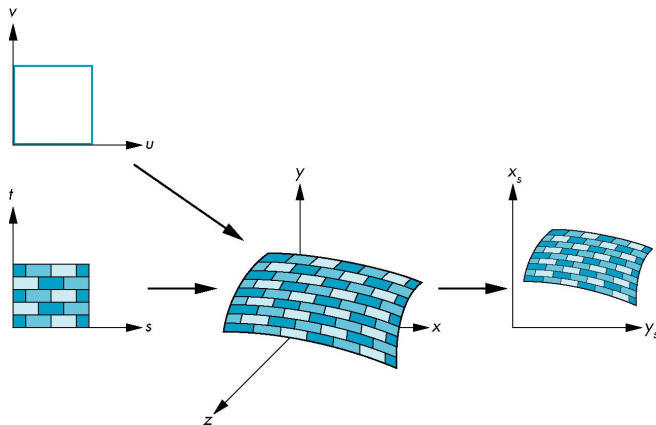
Texture Mapping

- ▶ Shading can produce only uniform or smooth surfaces. They look plastic and artificial.
- ▶ Map a real or synthetic image onto a polygon surface.
- ▶ Each 3D point is also associated with a 2D texture coordinate pair.
- ▶ These refer to points in the image to associate with the points.
- ▶ While scan converting the polygon, the pixel coordinates are mapped to the texture image coordinates.
- ▶ The texture colour for the pixel is obtained by interpolating the texture image using these coordinates.
- ▶ Finally, a texture colour is obtained for the pixel.

Texture Mapping (cont.)



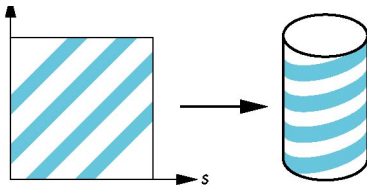
Texture Mapping



Source: Interactive Computer Graphics 4E Addison-Wesley 2005

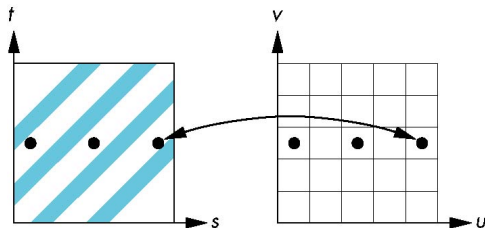
Texture Mapping

- ▶ *Backward Mapping*: Given a 3D point, find mapping to a 2D coordinate in texture image. Generally hard to find.
- ▶ *Two-part Mapping*: First map texture to a regular 3D model (e.g., Sphere or Cylinder) and then eventually map from 3D model to actual object.



Source: Interactive Computer Graphics 4E Addison-Wesley 2005

Texture Mapping: Aliasing



Source: Interactive Computer Graphics 4E Addison-Wesley 2005

Transparency

- ▶ How do we deal with transparent objects?
- ▶ Need to model Refraction.
- ▶ **Ignore them!** Leads to non-refractive transparency, which is still OK.
- ▶ Refraction takes considerable effort to handle. We will see it later.
- ▶ Other tricks: Interpolated transparency

Interpolated Transparency

- ▶ When two objects overlap at a pixel, use a weighted average of the two colours at the pixel.
- ▶ $I_{\lambda} = (1 - k_{t1}) I_{\lambda1} + k_{t1} I_{\lambda2}$
- ▶ k gives the transmission coefficient or the transparency of each polygon.
If $k_{t1} = 0$, polygon 1 is totally opaque.
- ▶ $(1 - k)$ is opacity.

RGBA Colours

- ▶ Graphics systems (OpenGL, for example) use 4-component colours, with A being the α channel.
- ▶ Alpha measures the opacity of the colour. Equals 1 for completely opaque objects and 0 for totally transparent ones.
- ▶ A similar interpolation formula is used when an object with alpha is drawn on top of another object.
- ▶ If the Z-buffer test succeeds, the colours of the new polygon are blended into the frame buffer using α instead of replacing it entirely.

Shadows

- ▶ Shadows are the results of light **not** reaching some part of the scene.
- ▶ Surfaces that are not visible from the light sources are in shadow. VSD algorithms can be used to determine this.
- ▶ **Shadow Map:** A bitmap in image space containing projections of shadowed regions.
- ▶ Modify the illumination equation to:

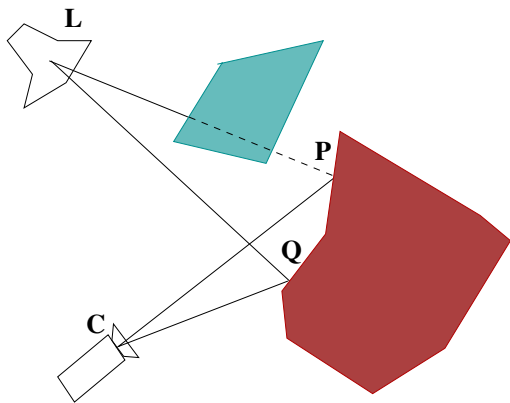
$$I_{p\lambda} = I_{a\lambda} k_a O_{a\lambda} + \sum_{1 \leq i \leq m} S_i f_{\text{att}_i} I_{\lambda i} \{k_d O_{d\lambda} (\mathbf{N} \cdot \mathbf{L}_i) + k_s O_{s\lambda} (\mathbf{V} \cdot \mathbf{R}_i)^n\}$$

- ▶ Shadow map S_i indicates if the pixel is under the shadow for the light source i . $S_i = 0$ if under shadow, $S_i = 1$ otherwise.

2-Pass Z-buffer Shadow Algorithm

- ▶ Draw the scene with light source as the camera using Z-buffering.
- ▶ Read the depth values from the Z-buffer into a z_l buffer. This is the *Shadow Map*.
- ▶ Draw scene from camera's viewpoint with Z-buffering.
- ▶ Transform each visible point (x_o, y_o, z_o) to (x'_o, y'_o, z'_o) in the light source's coordinates.
- ▶ If $z'_o > z_l(x'_o, y'_o)$, there is another point that is closer to the light source. Do not light the pixel.

2-Pass Z-buffer Shadow Algorithm (cont.)

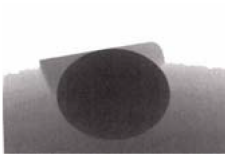


- Point P will be shadowed and Q will not be.

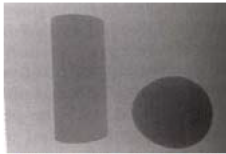
2-Pass Z-buffer Shadow Algorithm (cont.)



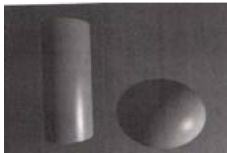
Overview



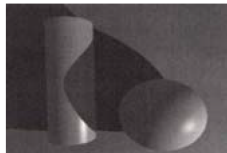
Light's Z-buffer



Observer's Z-buffer



Observer's Image



With shadows

Source: Foley & Van Dam