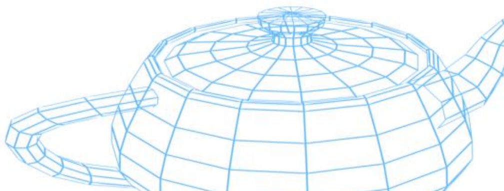
Scuola universitaria professionale della Svizzera italiana
Dipartimento tecnologie innovative

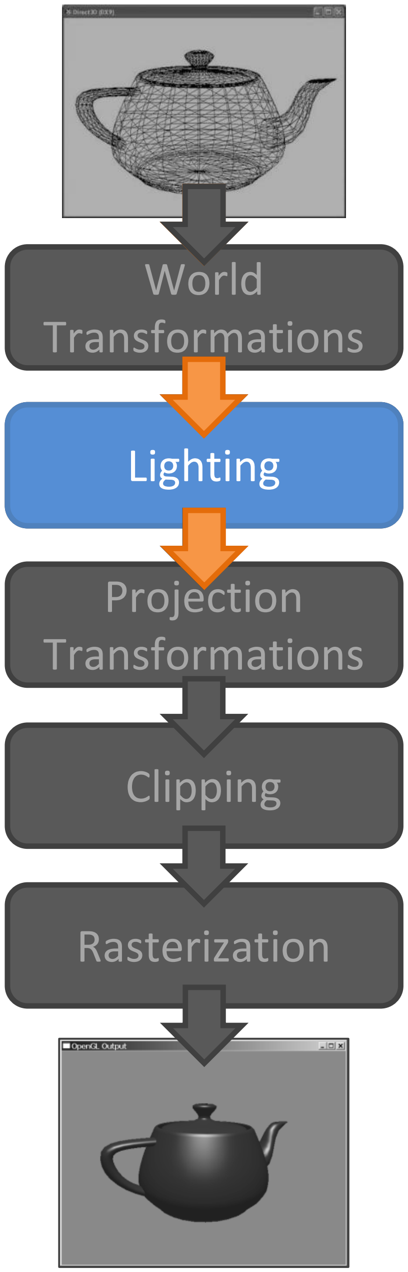
SUPSI

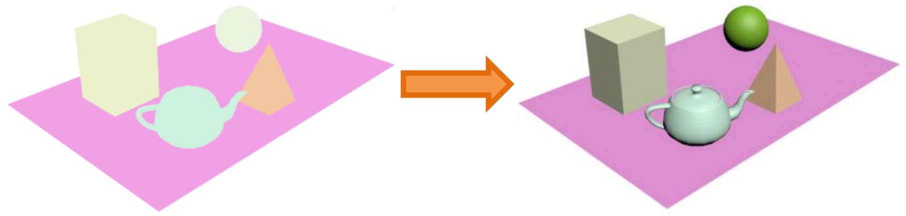
Computer Graphics

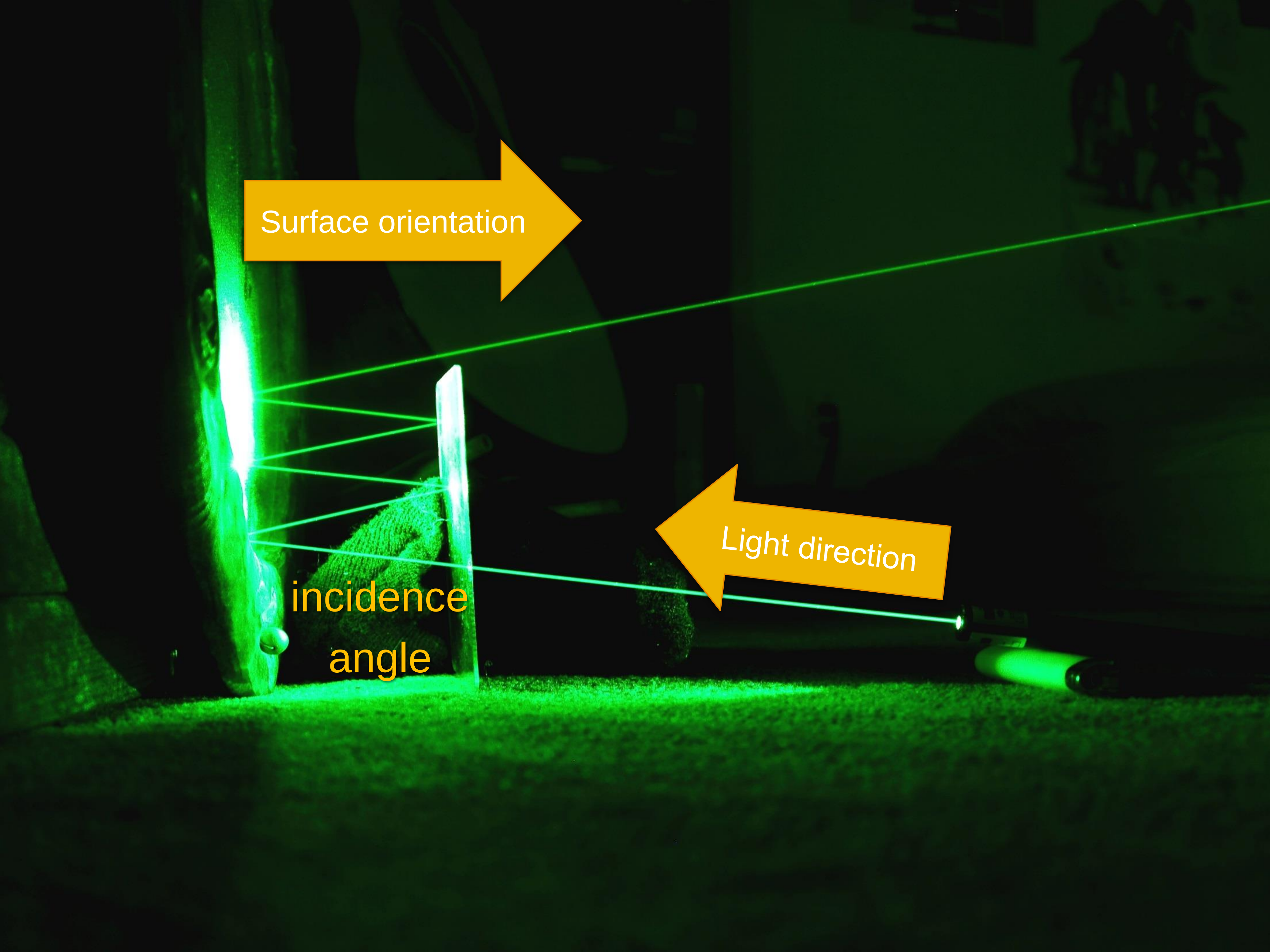
OpenGL (2): Lighting

Achille Peternier, lecturer

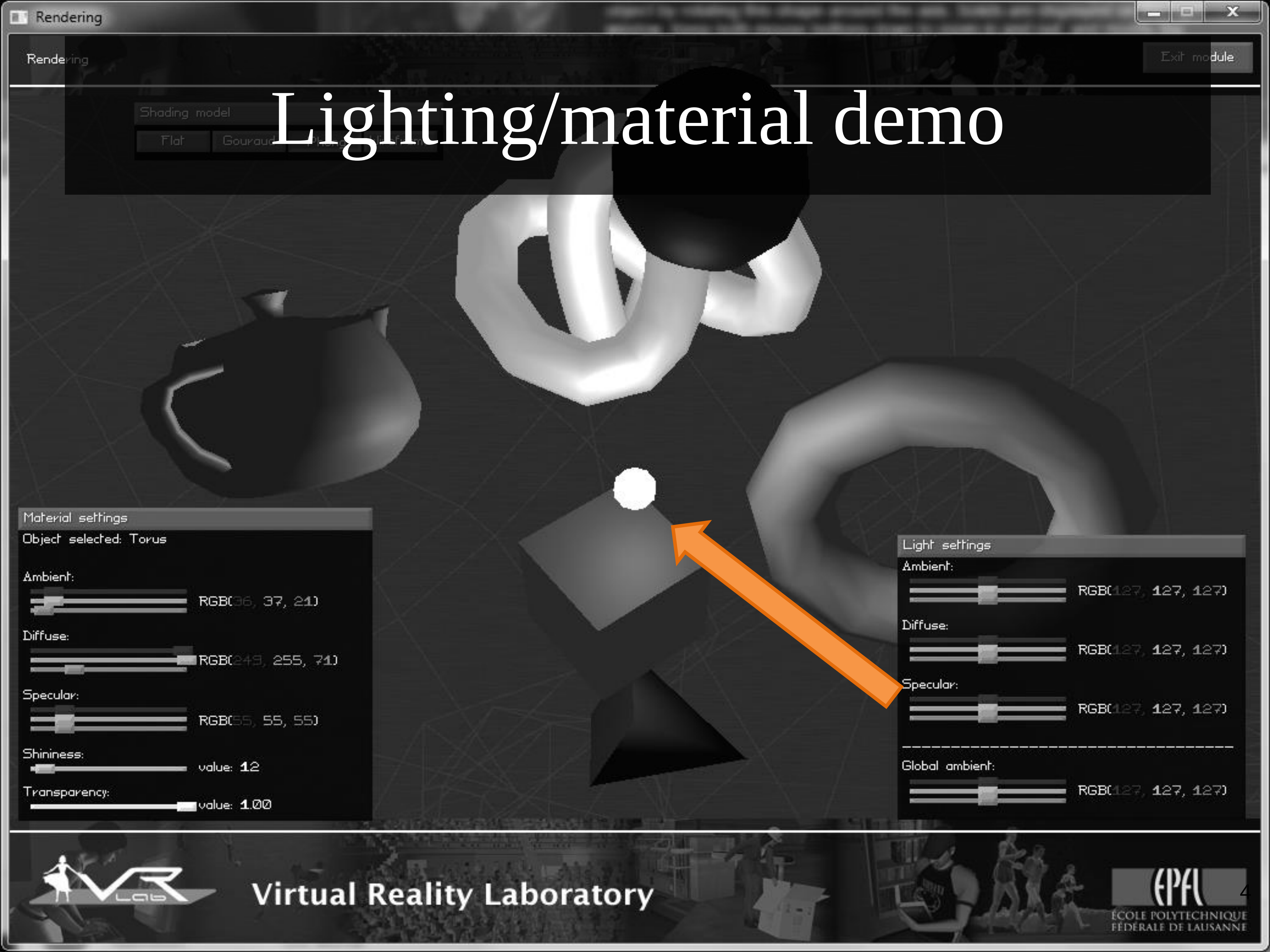



World Transformations
Lighting
Projection Transformations
Clipping
Rasterization




Surface orientation
incidence angle
Light direction

Lighting/material demo

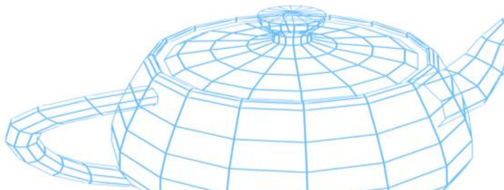


Material settings
Object selected: Torus
Ambient: RGB(36, 37, 21)
Diffuse: RGB(249, 255, 71)
Specular: RGB(55, 55, 55)
Shininess: value: 12
Transparency: value: 1.00

Light settings
Ambient: RGB(127, 127, 127)
Diffuse: RGB(127, 127, 127)
Specular: RGB(127, 127, 127)
Global ambient: RGB(127, 127, 127)

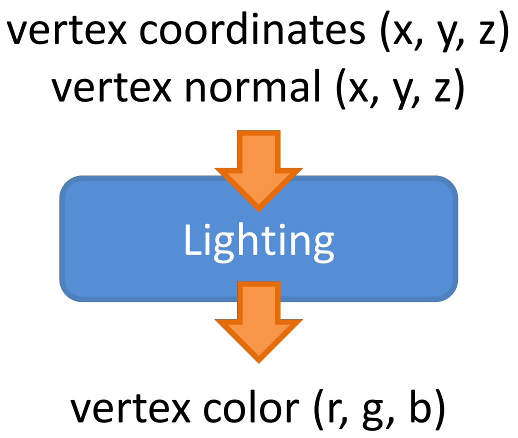
Lighting

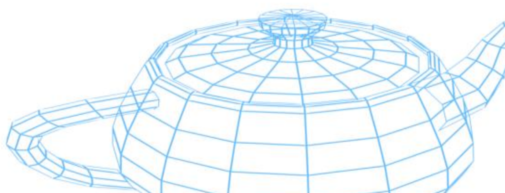
- So far, we specified vertex colors explicitly:
  - You can define vertex colors according to your own artistic taste or by using a custom lighting model.
  - …or you can use OpenGL fixed-pipeline lighting implementation and let it compute vertex colors for you.



Lighting

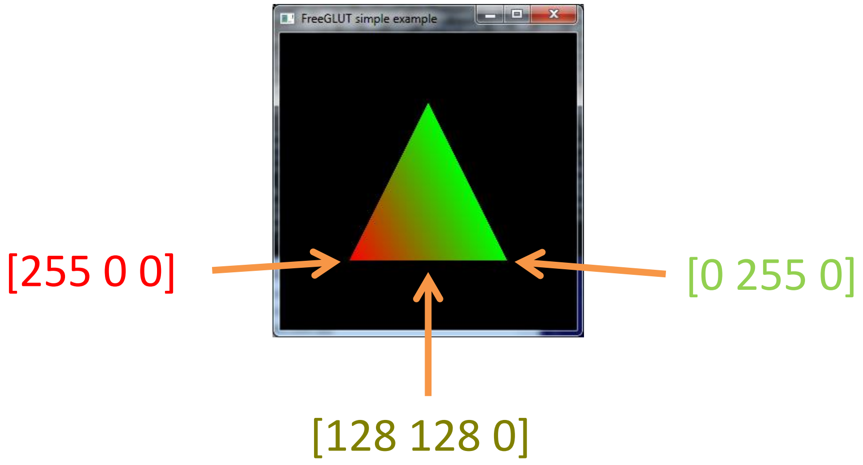
- For each vertex, you specify coordinates and the normal vector.
- OpenGL fills the vertex colors for you, according to the lighting settings you specified (e.g., light sources, material properties, etc.).

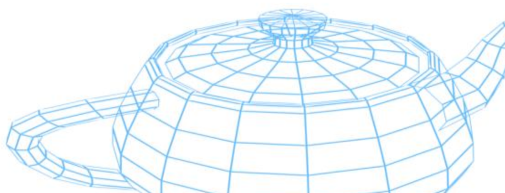




Lighting

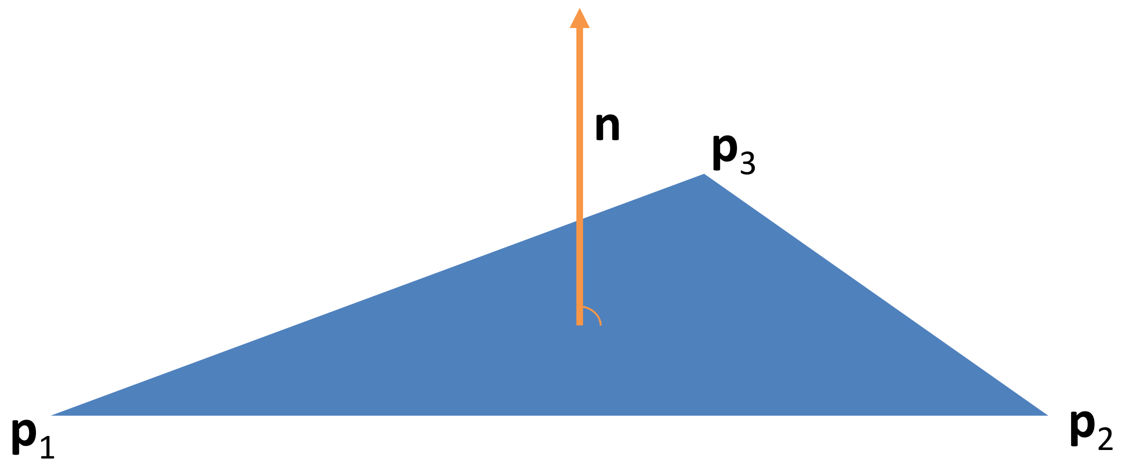
- The lighting contribution is computed for each vertex:
  - Each vertex will get a color:
    - OpenGL fixed-pipeline lighting works on **per-vertex** basis!
    - More advanced lighting implementations work on per-fragment basis.
  - Colors are interpolated during the rasterization step.

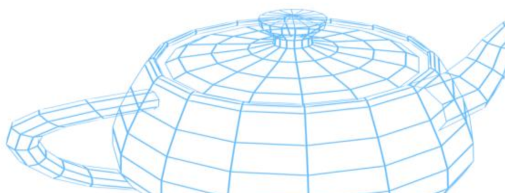




Normal

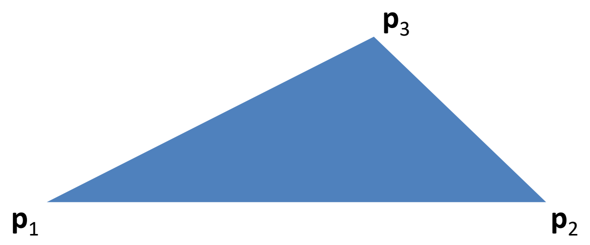
- A triangle’s normal is a vector perpendicular to the plane defined by its three vertices.





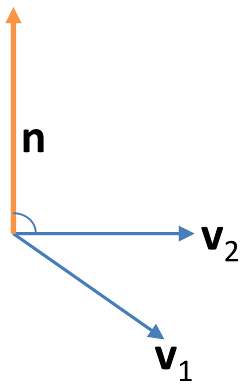
Normal

- A triangle’s normal is computed using the cross product between two vectors being part of the triangle’s plane:

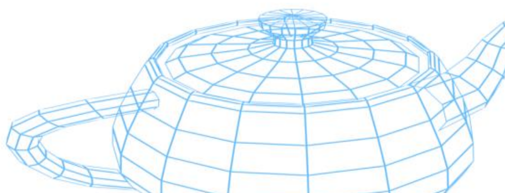


$$\mathbf{v}_1 = \mathbf{p}_2 - \mathbf{p}_1 \;, \quad \mathbf{v}_2 = \mathbf{p}_3 - \mathbf{p}_1$$

$$\mathbf{n} = \mathbf{v}_1 \times \mathbf{v}_2$$

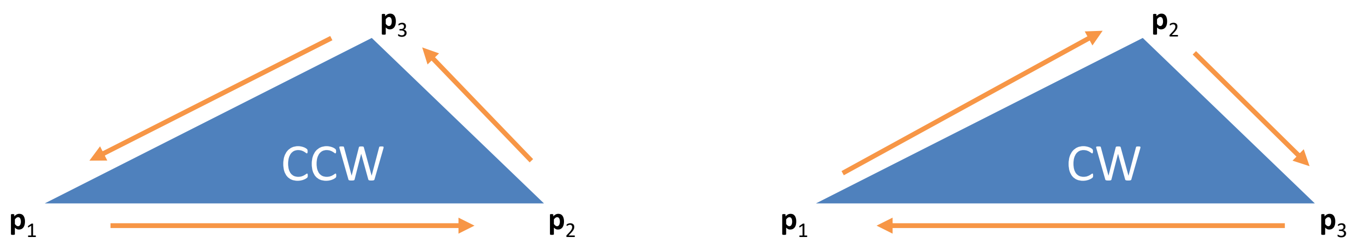


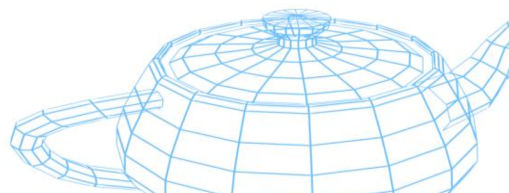
- The order used to specify vertices defines the direction of the normal (in/out).



Face orientation

- Triangles have two faces (front and back).
- Their orientation is defined by the order used to pass vertices (vertex winding order).
- The front face is defined (by default) by passing vertices in counterclockwise (CCW) direction.

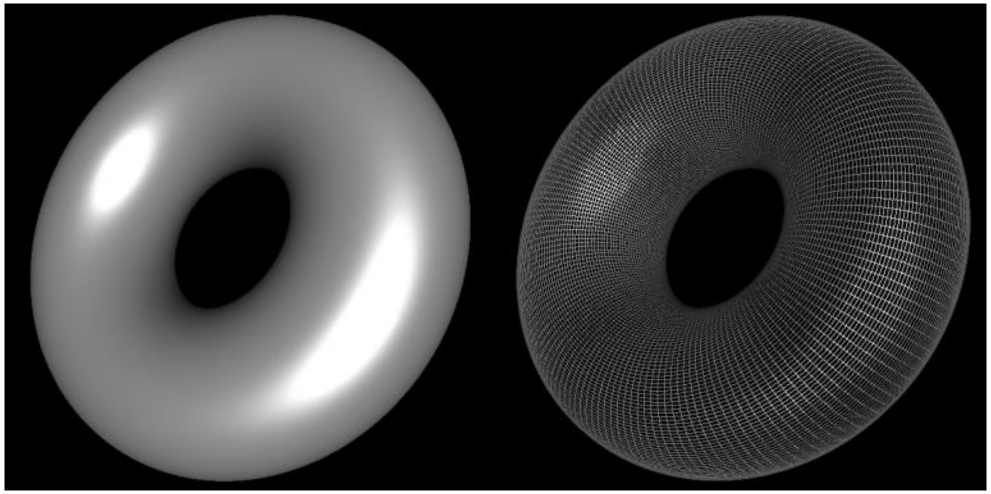


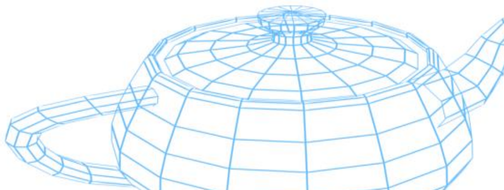


Face orientation

- The way front/back face orientation is determined can be changed from counter- to clockwise:
  - **`glFrontFace(GL_CW);`** // default is GL_CCW

- Use **`glPolygonMode()`** to change the way OpenGL renders front and back faces:
  - **`glPolygonMode(GL_FRONT_AND_BACK, GL_LINE);`** // Wireframe
  - **`glPolygonMode(GL_FRONT_AND_BACK, GL_FILL);`** // Solid





Face culling

- Only renders front faces by discarding (culling) back faces.

- Good performance optimization when closed meshes are used, e.g., most solid geometric objects (cubes, spheres, pyramids, etc.) and 3D models:
  - Avoid to waste rasterization resources by rendering triangles that are always hidden behind front faces.

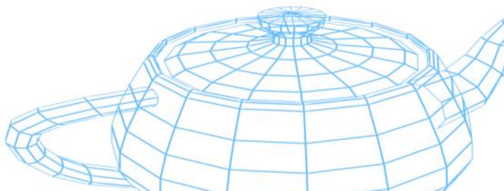
- Disabled by default, it is activated using:

  `glEnable(GL_CULL_FACE);`

- Culling mode is changed using:

  glCullFace(*flag*);

  where possible *flags* are **GL_BACK** (default), **GL_FRONT**, and **GL_FRONT_AND_BACK**

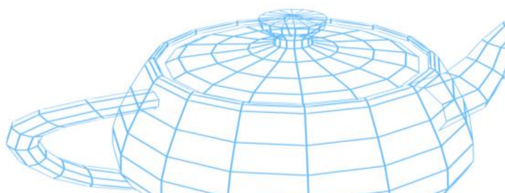


Tutorial

Face orientation

Per-vertex information

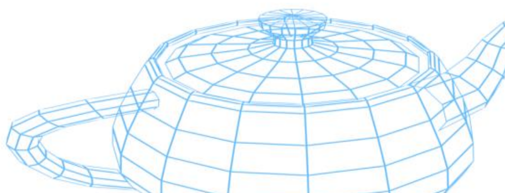
- Vertex position
  - x, y, z[, w] (usually as *float*)
- ~~Vertex color (RGB or RGBA)~~
  - ~~r, g, b[, a] (usually as *byte*)~~
- Vertex normal
  - x, y, z (usually as *float*)



Per-vertex information

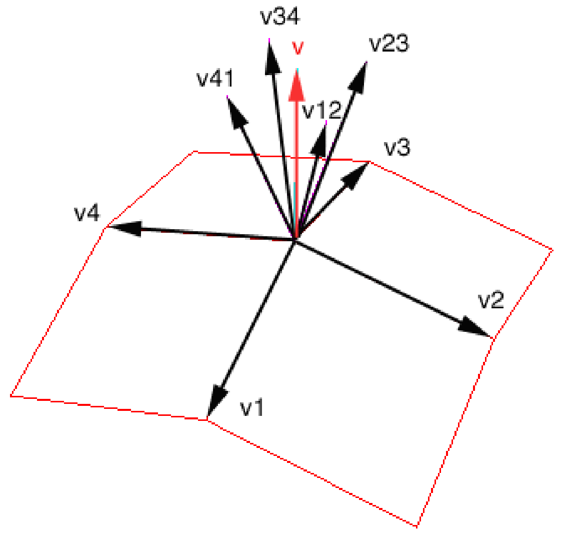
- The normal is specified through **`glNormal3*()`**.
- Normal vectors are defined per-vertex (each vertex has one normal).
- Normal vectors **must be normalized**!
  - Normal vectors are multiplied by the inverse transpose of the current matrix already loaded with **`glLoadMatrix()`**:
    - Scaling requires to re-normalize normal vectors!
    - Activate **`glEnable(GL_NORMALIZE)`** to deal with that.

```
glBegin(GL_TRIANGLES);
   glNormal3f(0.0f, 0.0f, 1.0f);
      glVertex3f(0.0f, 0.0f, 0.0f);
      glVertex3f(10.0f, 0.0f, 0.0f);
      glVertex3f(5.0f, 5.0f, 0.0f);
glEnd();
```

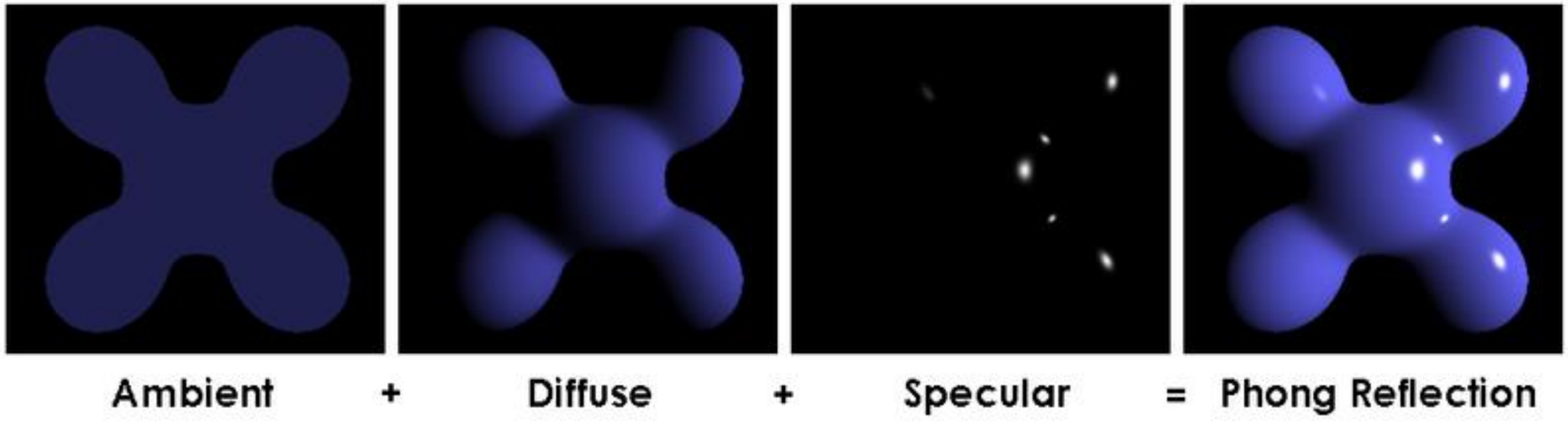


Shared normal vectors

- When one same vertex is shared by more than one single triangle, its normal can be computed as the **average** of the normal vectors of the faces that share it.
- It is common to define a threshold angle or normal group to prevent artifacts, e.g., when drawing a cube corner:
  - One different normal should be specified for each face, although some vertices are shared among neighbor faces.
- v = (v12 + v23 + v34 + n41)/|v12 + v23 + v34 + v41|



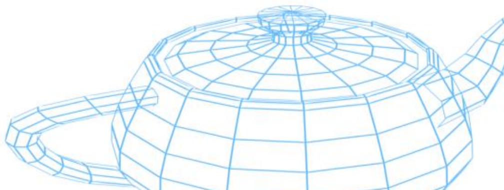
Lighting model



- Phong's reflection model, PhD thesis, Utah University, 1973
  - OpenGL uses a slightly different variant called Blinn-Phong reflection model.

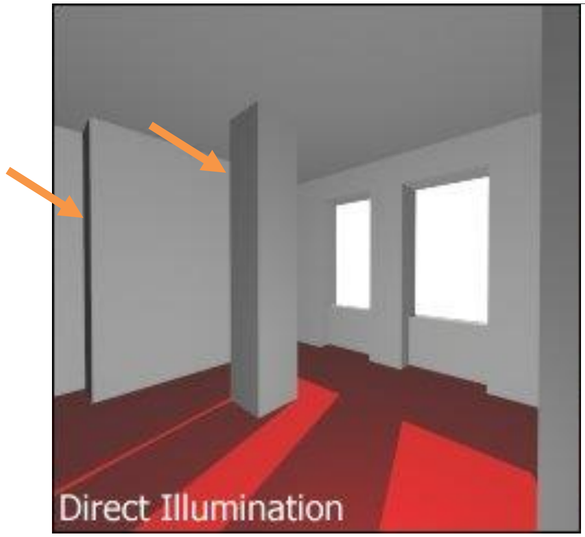
- Not to be confused with Phong shading.

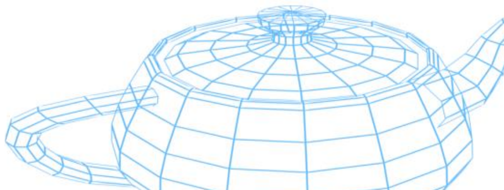
Bui Tuong Phong
1942 - 1975



Ambient term

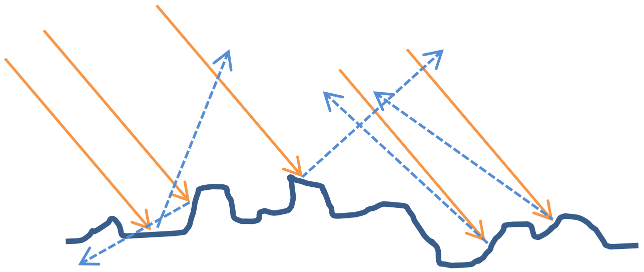
- Simulates indirect lighting:
  - When you switch a light on, some rays bounce on the wall one or more times and reach areas that are not directly facing the light source.
  - It is impossible to tell the original direction from scattered light that bounced several times.
  - If you switch the light off, the indirect light disappears.
  - Without ambient light, back faces would be always dark.



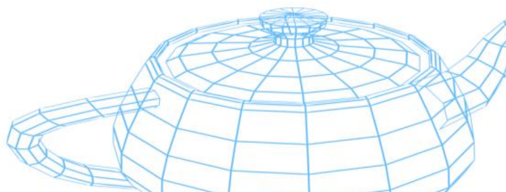


Diffuse term

- Is the light that comes from one direction:
  - It is brighter if it comes squarely down on a surface than if it barely glances off the surface.
  - Once it hits a surface, it is scattered equally in all directions, so it appears equally bright, no matter where the eye is located.
  - Based on the Lambert cosine law.

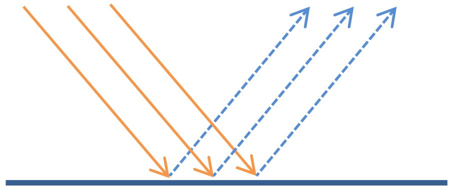
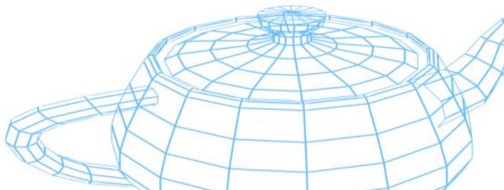


Johann Heinrich Lambert
1728 - 1777



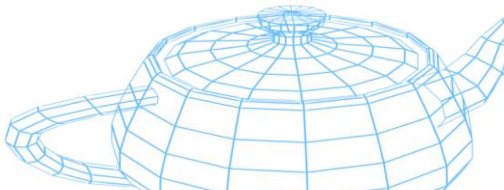
Specular term

- Is the light that comes from a particular direction, and it tends to bounce off the surface in a preferred direction:
  - A well-collimated laser beam bouncing off a high-quality mirror produces almost 100 percent specular reflection.
  - Shiny metal or plastic has a high specular component, and chalk or carpet has almost none.
  - You can think of specularity as shininess.

Emissive term

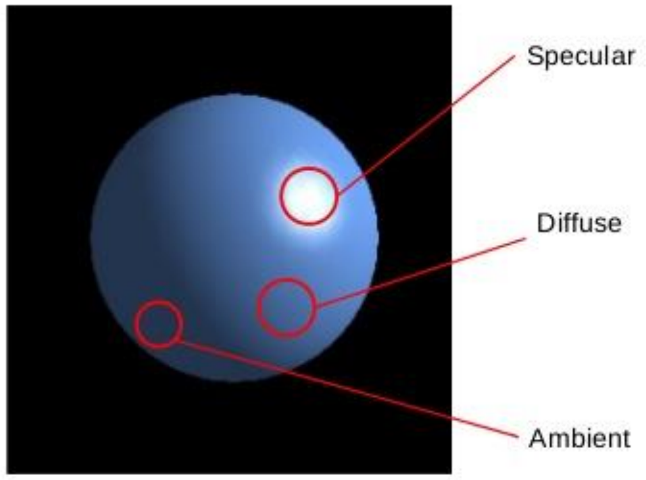
- Additional term used to simulate light originating from an object:
  - In the OpenGL lighting model, the emissive color of a surface adds intensity to the object, but is unaffected by any light sources (similarly to what we did with **`glColor*()`**).
  - The emissive color does not introduce any additional light into the overall scene.



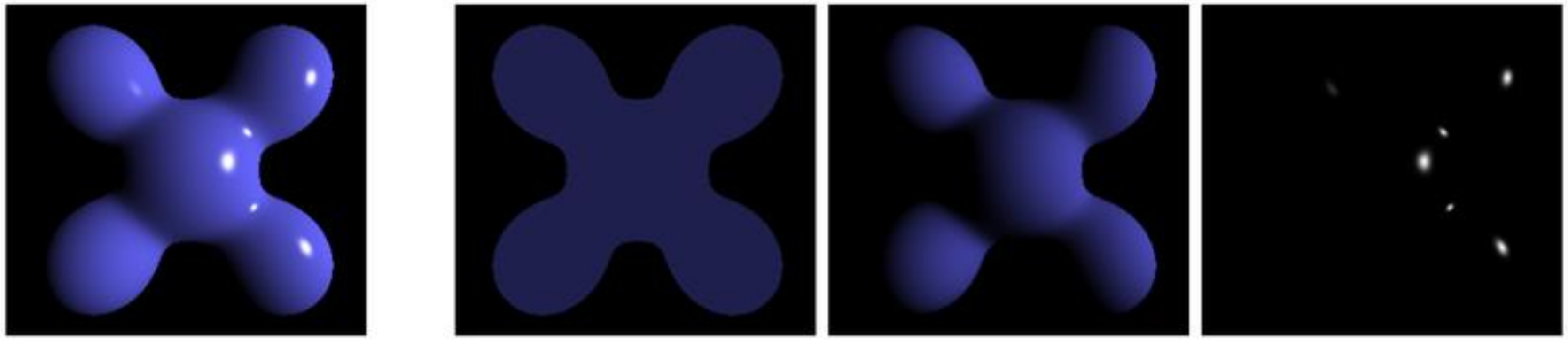
Lighting model

- Empirical model:
  - Combines diffuse reflection of rough surfaces with specular reflection of shiny surfaces.
  - An additional ambient component simulates indirect light scattering.

- Simple and computationally-light model:
  - Cannot simulate all existing materials.
  - No shadows, no global illumination.



Lighting model (Phong)

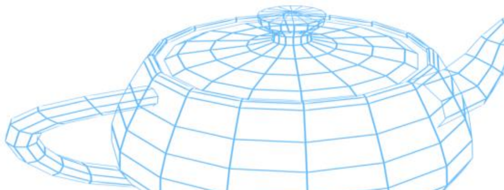


$$\overbrace{I_p} = \overbrace{k_a i_a} + \sum_{m \in lights} \left(\overbrace{k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d}} + \overbrace{k_s\left(\hat{R}_m \cdot \hat{V}\right)^{\alpha} i_{m,s}}\right)$$

Lighting model (Phong)

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d (\hat{L}_m \cdot \hat{N}) i_{m,d} + k_s (\hat{R}_m \cdot \hat{V})^{\alpha} i_{m,s}\right)$$

- I_p = surface point color
- k_* = material properties
- i_* = light properties
- a, d, s = ambient, diffuse, specular
- N = surface normal
- V = surface direction towards the viewer
- L_m = surface direction towards the light
- R_m = perfect reflection ray vector, defined as $\hat{R}_m = 2(\hat{L}_m \cdot \hat{N})\hat{N} - \hat{L}_m$
- α = shininess constant (larger for mirror-like surfaces)

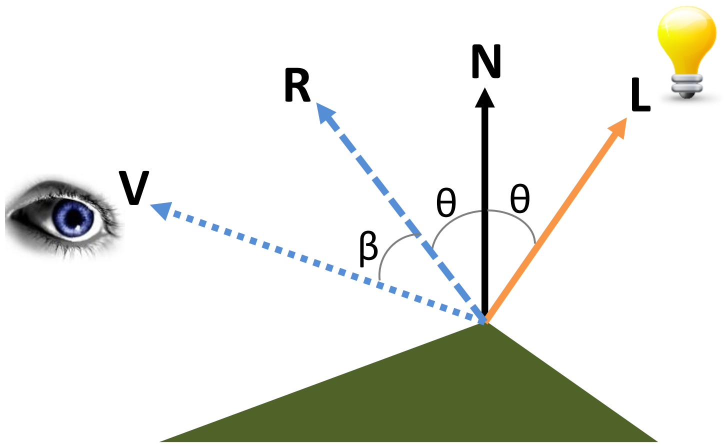


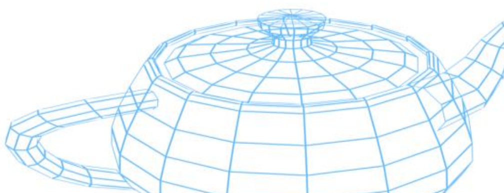
Lighting model (Phong)

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d(\hat{L}_m \cdot \hat{N}) i_{m,d} + k_s(\hat{R}_m \cdot \hat{V})^{\alpha} i_{m,s}\right)$$

$$\hat{R}_m = 2(\hat{L}_m \cdot \hat{N})\hat{N} - \hat{L}_m$$

- According to Phong's model, the specular component is proportional to the cosine of the angle β between the light reflection vector and the eye vector:
  - The specular effect is higher when R and V are closer.
  - The specular decay is determined by α (higher values mean faster decay).





Lighting model (Blinn-Phong)

(Phong, 1973)

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d} + k_s\left(\hat{R}_m \cdot \hat{V}\right)^{\alpha} i_{m,s}\right)$$

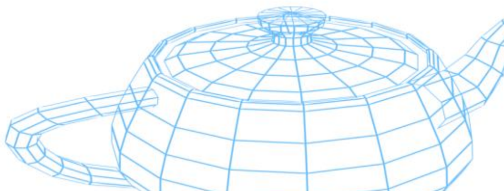
$$\xcancel{\hat{R}_m = 2\left(\hat{L}_m \cdot \hat{N}\right)\hat{N} - \hat{L}_m}$$

(Blinn, 1977)

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d} + k_s\left(\hat{N} \cdot \hat{H}_m\right)^{\alpha} i_{m,s}\right)$$

$$\hat{H}_m = \frac{\hat{L}_m + \hat{V}}{\left\| \hat{L}_m + \hat{V} \right\|}$$

- H = half-vector between the viewer and the light vector



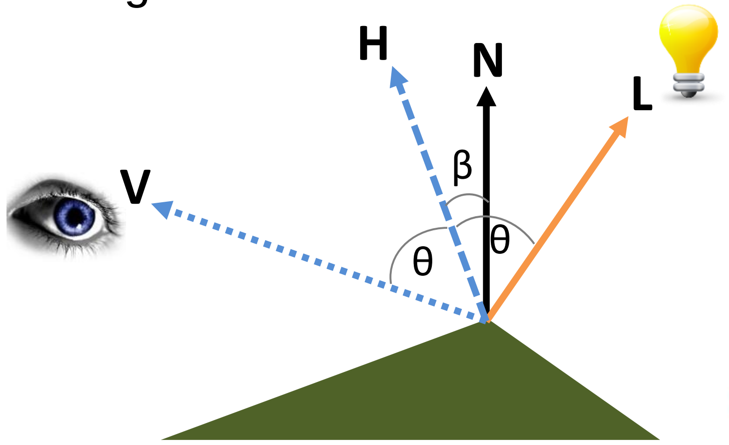
Lighting model (Blinn-Phong)

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d(\hat{L}_m \cdot \hat{N}) i_{m,d} + k_s(\hat{N} \cdot \hat{H}_m)^{\alpha} i_{m,s}\right)$$

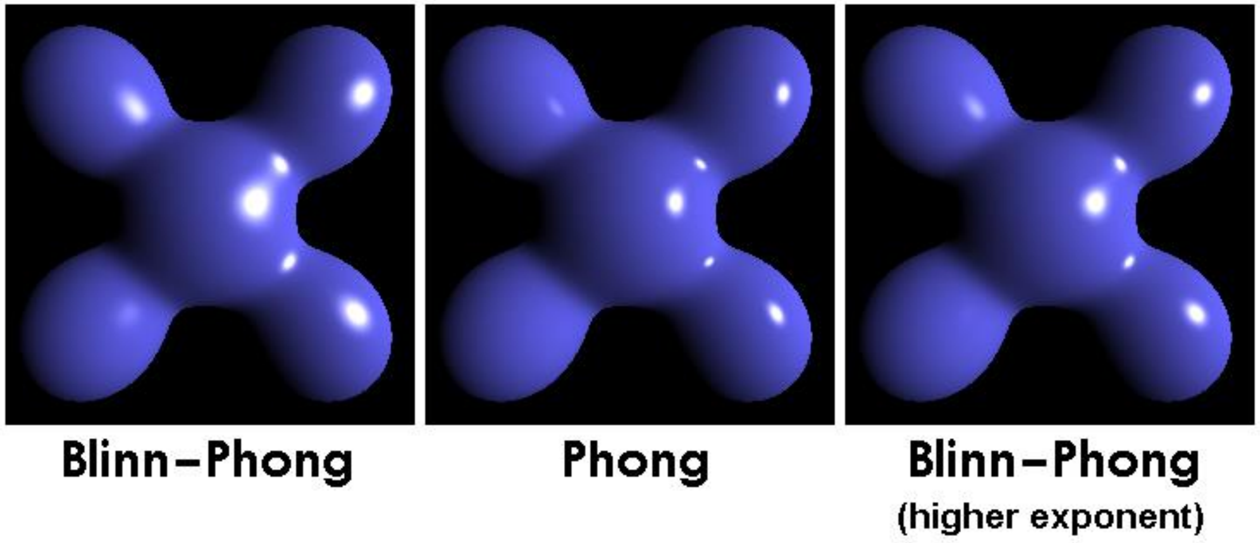
$$\hat{H}_m = \frac{\hat{L}_m + \hat{V}}{\| \hat{L}_m + \hat{V} \|}$$

- This variant is computationally slightly less expensive than the standard Phong's model.

- The half-angle H is always below 90°
  - With standard Phong, the angle β could be larger than 90° under some circumstances, and give negative values.



Lighting model

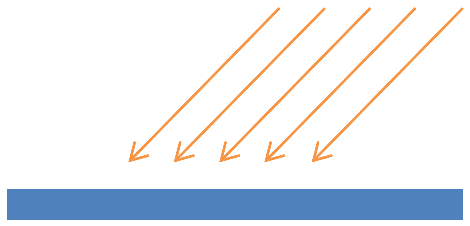


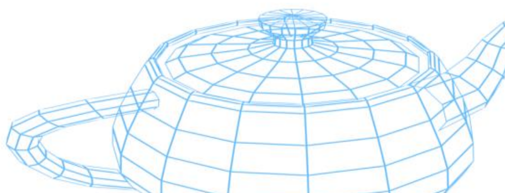
$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d} + k_s\left(\hat{N} \cdot \hat{H}_m\right)^{\alpha} i_{m,s}\right)$$

Similar models: just use a higher exponent (in Blinn-Phong) to make it looking more like Phong

Directional light

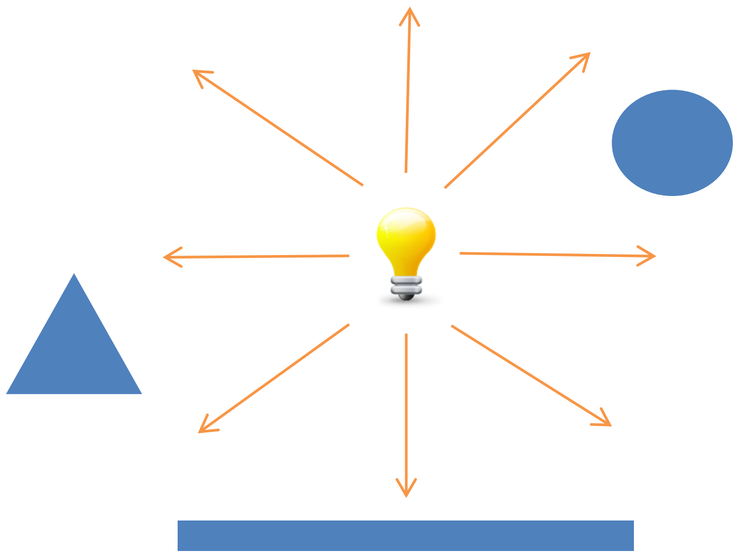
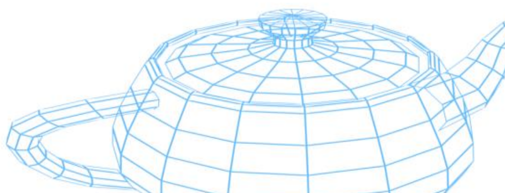
- Also called “infinite light”.
- Light is coming from an infinite distance, with all its rays perfectly parallel.
- E.g.: sun rays (on earth).
- Easiest and fastest light to simulate and compute:
  - ray vectors are all the same.





Omnidirectional light

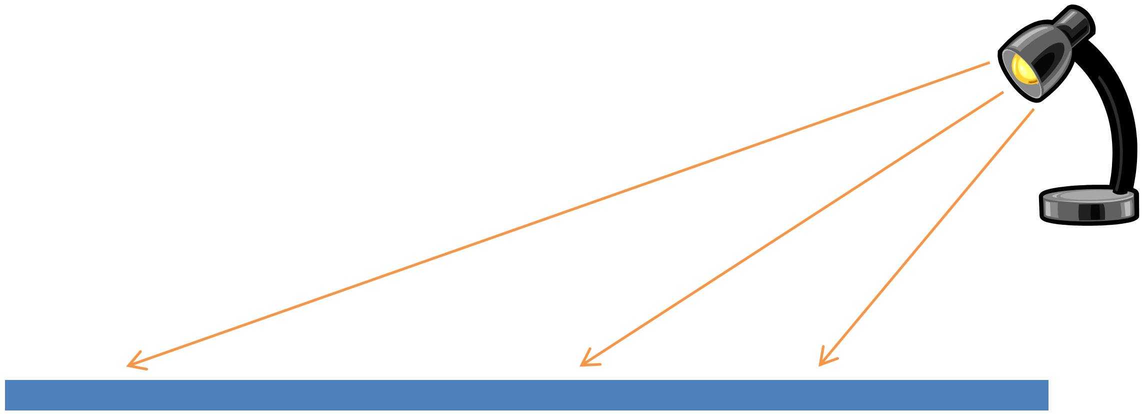
- Also called “point light”.
- Light irradiates equally in all directions, originating from a single point.
- E.g.: candle, emergency signal flare, sun rays (in space).

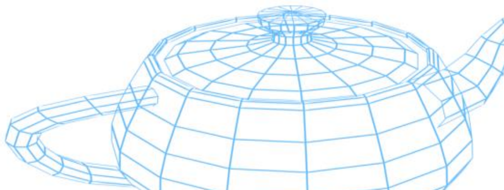



Spot light

- Light source with a cone of effect, optionally fading its intensity when closer to the border.

- E.g.: torch, desk lamp, stage light, projector.

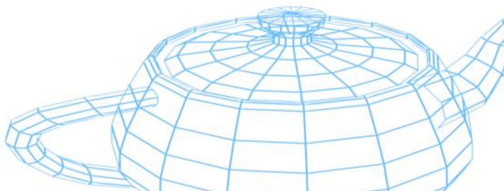




Attenuation

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

- I_f = final illumination after attenuation
- I_p = illumination computed through the lighting model
- d = distance of the light source
- k_c = constant factor
- k_l = linear factor
- k_q = quadratic factor

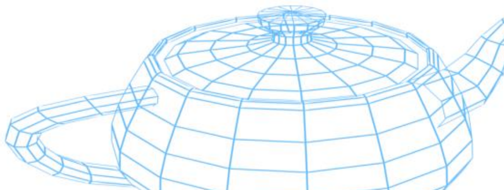


Lighting model

- Lighting is deactivated by default and must be enabled using:
  - **`glEnable(GL_LIGHTING);`**
- Each light source must be activated independently, using:
  - **`glEnable(GL_LIGHT#);`**

    Where # is in the range 0 to some maximum number of supported lights minus one.
  - You can query the maximum number of supported lights via see **`glGetIntegerv(GL_MAX_LIGHTS, &maxNrOfLights);`**

…I've never seen **`GL_MAX_LIGHTS`** returning more than 8 ☺

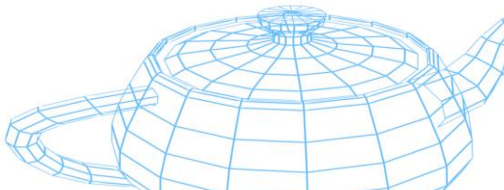


Lighting model

- **`GL_LIGHT0`** default parameters are different from **`GL_LIGHT1`** to **`GL_LIGHT_N`**.

- Usually, only the first 3-4 lights are hardware accelerated:
  - Use multipass rendering when many light sources are necessary.

- Do not activate more than the minimum number of lights required for rendering your object:
  - Visually useless.
  - Potential saturation, unless you use high dynamic range.
  - Unnecessarily slow.



Material properties

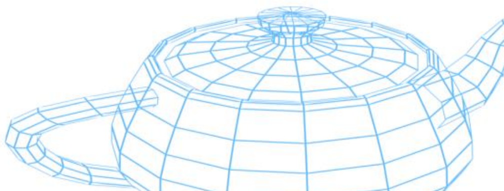
$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d} + k_s\left(\hat{N} \cdot \hat{H}_m\right)^{\alpha} i_{m,s}\right)$$

```
glm::vec4  ambient(0.2f, 0.2f, 0.2f, 1.0f);
glm::vec4  diffuse(0.8f, 0.8f, 0.8f, 1.0f);
glm::vec4  specular(0.5f, 0.5f, 0.5f, 1.0f);
int  shininess = 128;

glMaterialfv(GL_FRONT_AND_BACK, GL_AMBIENT,
             glm::value_ptr(ambient));

glMaterialfv(GL_FRONT_AND_BACK, GL_DIFFUSE,
             glm::value_ptr(diffuse));

glMaterialfv(GL_FRONT_AND_BACK, GL_SPECULAR,
             glm::value_ptr(specular));

glMaterialf(GL_FRONT_AND_BACK, GL_SHININESS, shininess);
```

Light properties

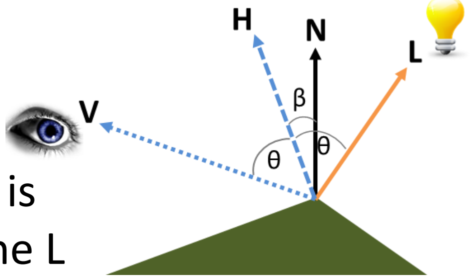
$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d\left(\hat{L}_m \cdot \hat{N}\right) i_{m,d} + k_s\left(\hat{N} \cdot \hat{H}_m\right)^{\alpha} i_{m,s}\right)$$

```
glm::vec4  ambient(1.0f, 1.0f, 1.0f, 1.0f);
glm::vec4  diffuse(1.0f, 1.0f, 1.0f, 1.0f);
glm::vec4  specular(1.0f, 1.0f, 1.0f, 1.0f);


glLightfv(GL_LIGHT#, GL_AMBIENT, glm::value_ptr(ambient));
glLightfv(GL_LIGHT#, GL_DIFFUSE, glm::value_ptr(diffuse));
glLightfv(GL_LIGHT#, GL_SPECULAR, glm::value_ptr(specular));
```



Light properties

Directional/infinite light settings

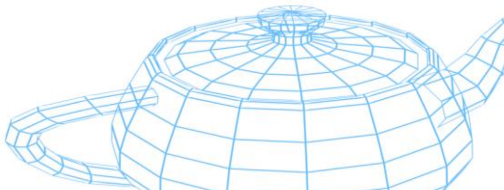


w is zero!

position is used as the L vector!

```
glm::vec4  position(x, y, z, 0.0f);

glLightfv(GL_LIGHT#, GL_POSITION, glm::value_ptr(position));
```

- Since the position is specified in homogeneous coordinates, it is computed as *x/w*, *y/w*, and *z/w.*
- When *w* approaches zero, *x*, *y*, and *z* approach infinity. You can verify it by dividing *x*, *y*, and *z* by a very small value.
- Diffuse and specular lighting calculations take the light's direction but not its actual position into account, and attenuation is disabled.



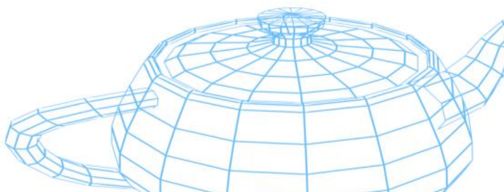
Light properties

Omnidirectional/point light settings

w is one!

```
glm::vec4  position(x, y, z, 1.0f);
float cutoff = 180.0f; // special value

glLightfv(GL_LIGHT#, GL_POSITION, glm::value_ptr(position));
glLightfv(GL_LIGHT#, GL_SPOT_CUTOFF, &cutoff);
```

- A special cutoff value of 180° is used to tell OpenGL that we want an omnidirectional light.



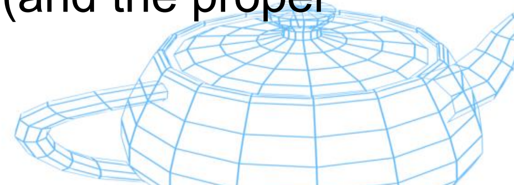
Light properties

Spot light settings

w is one!

```
glm::vec4  position(x, y, z, 1.0f);
float cutoff = 15.0f;    // Any angle between 0° and 90°
glm::vec3 direction(dx, dy, dz);

glLightfv(GL_LIGHT#, GL_POSITION, glm::value_ptr(position));
glLightfv(GL_LIGHT#, GL_SPOT_CUTOFF, &cutoff);
glLightfv(GL_LIGHT#, GL_SPOT_DIRECTION, glm::value_ptr(direction));
```

- Keep in mind that (any) light position and direction is multiplied by the current modelview matrix, like any other geometric primitive.
  - …you can then specify lights both in object coordinates (and the proper transformation matrices) or in world coordinates.



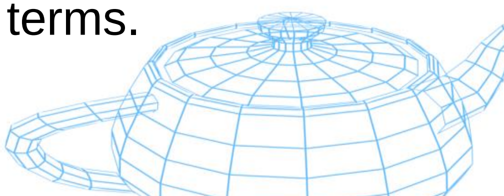
Light properties

Attenuation

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

```
glLightf(GL_LIGHT#, GL_CONSTANT_ATTENUATION, value);  // default 1.0
glLightf(GL_LIGHT#, GL_LINEAR_ATTENUATION, value);    // default 0.0
glLightf(GL_LIGHT#, GL_QUADRATIC_ATTENUATION, value); // default 0.0
```

- Attenuation works only for omnidirectional and spot lights.
- Attenuation does not affect the global ambient and emissive terms.

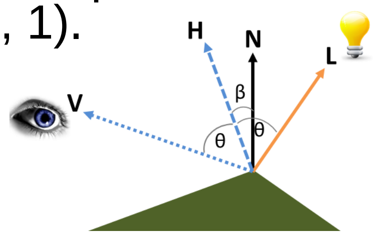


Light properties

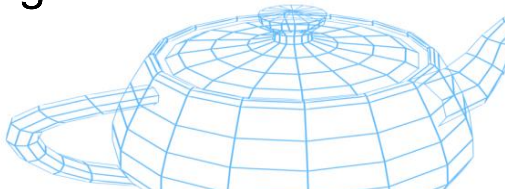
Global settings

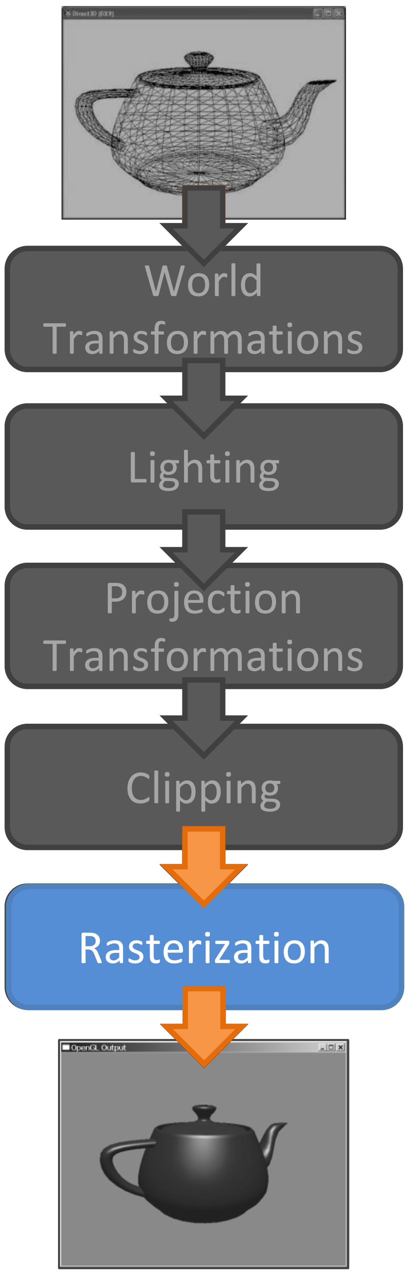
```
glm::vec4 gAmbient(0.2f, 0.2f, 0.2f, 1.0f);

glLightModelf(GL_LIGHT_MODEL_LOCAL_VIEWER, 1.0f); // default 0.0
glLightModelfv(GL_LIGHT_MODEL_AMBIENT, glm::value_ptr(gAmbient));
```

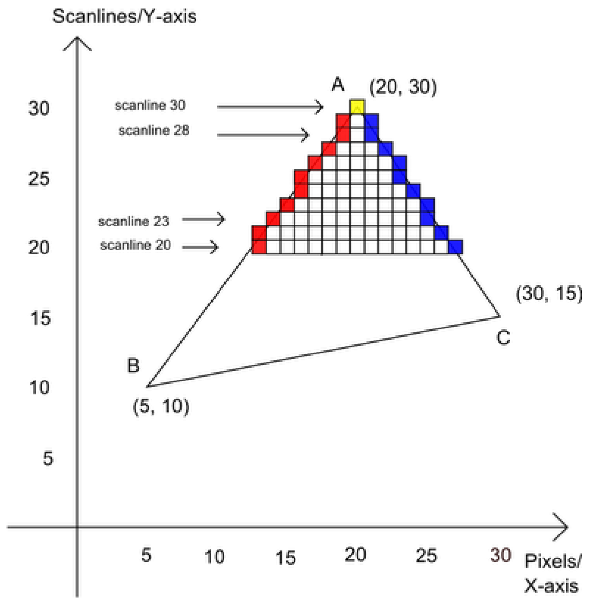
- Activate the local viewer position for a more accurate computation of specular highlights (recommended). Otherwise, the V vector is always (0, 0, 1).

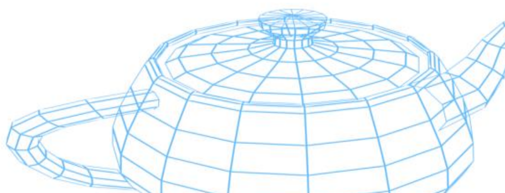


- The global ambient term is multiplied by each light ambient term:
  - Default is [0.2 0.2 0.2 1.0]: that's the reason why even bright ambient terms look so dark.



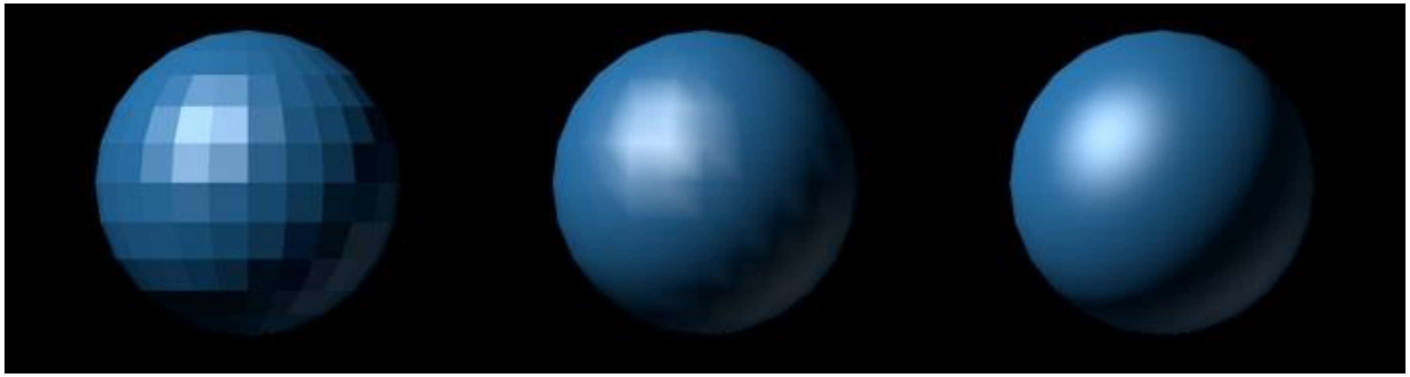

World Transformations
Lighting
Projection Transformations
Clipping
Rasterization


Scanlines/Y-axis
30
25
20
15
10
5
scanline 30
scanline 28
scanline 23
scanline 20
A
(20, 30)
(30, 15)
C
B
(5, 10)
5
10
15
20
25
30
Pixels/
X-axis



Shading

- Shading is decoupled from the lighting model.
- Three main shading options:



Flat shading
`glShadeModel(GL_FLAT);`

Gouraud shading
`glShadeModel(GL_SMOOTH);`

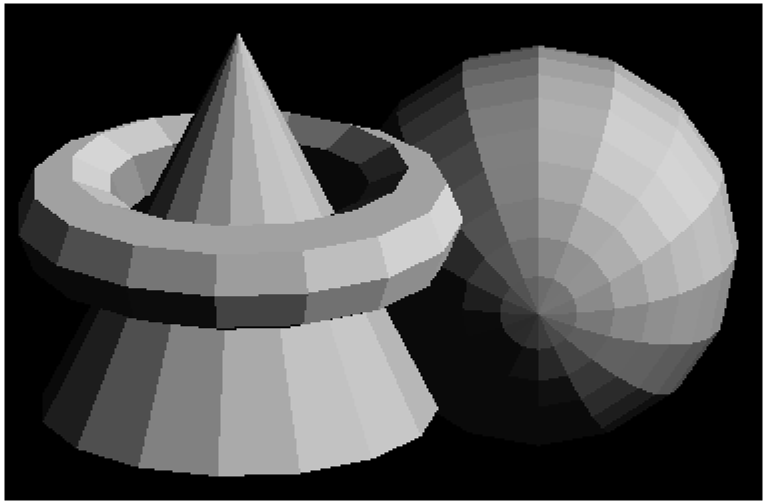
Phong shading
(use shaders)

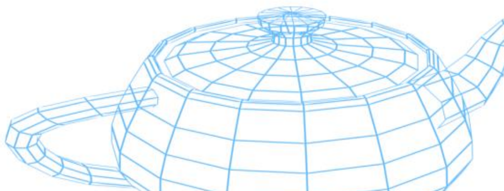
Flat shading

- Also called “constant shading”.

- One single color is used for drawing all the pixels of the primitive.
- Very fast, poor quality:
  - Activated using **`glShadeModel(GL_FLAT);`**

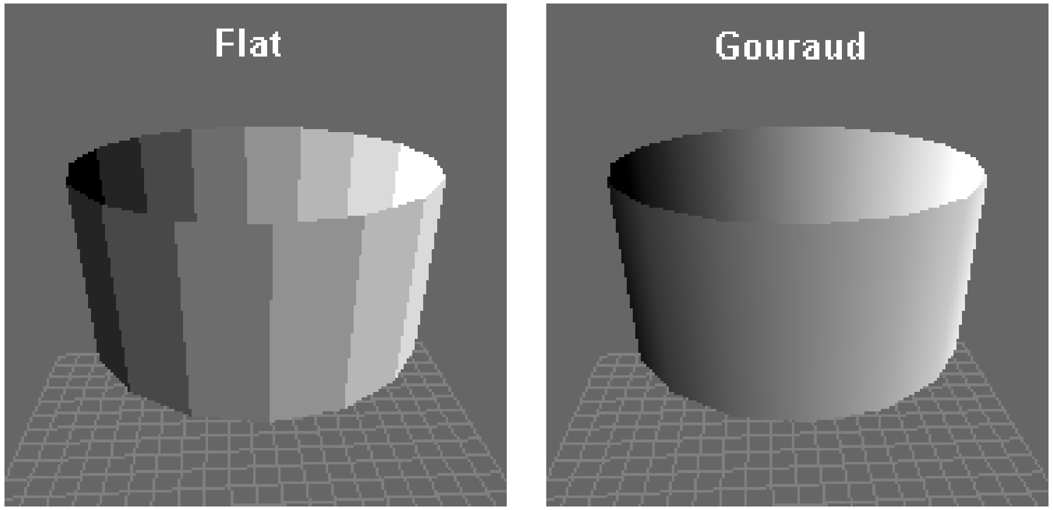
- Last vertex color is used for the whole surface.


[source: John T. Bell]



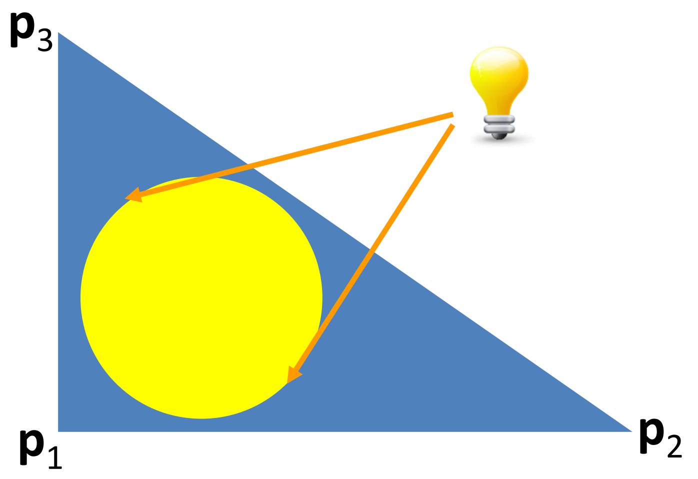
Gouraud shading

- Vertex colors are linearly interpolated over the surface.
- Still very fast and with better quality than flat shading:
  - When normal vectors are properly set, edges disappear.
- Default shading used by the OpenGL fixed pipeline:
  - Activated using **`glShadeModel(GL_SMOOTH)`**.



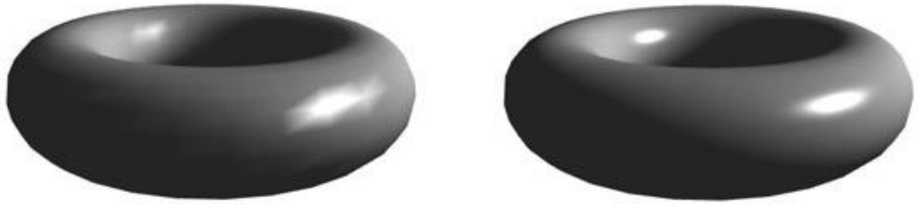
Missed highlights

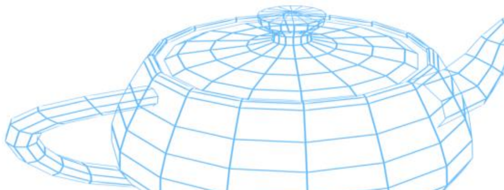
- Since the lighting model is computed at each vertex, a large triangle may completely miss one light’s contribution:
  - Use a higher level of tessellation.
  - Use shaders to compute the lighting model on per-pixel basis.



Phong shading

- Also referred to as “per-pixel lighting”.
- The normal is interpolated over the surface and the lighting equation is computed locally within each fragment:
  - Requires much more computational power:
    - Normalization occurring at each fragment.
- When high tessellation is used, Gouraud shading looks like Phong shading:
  - One triangle per pixel $\rightarrow$ Gouraud = Phong
- Phong shading can only be implemented using programmable shaders (OpenGL 2.0+).


[source: www.lighthouse3d.com]



Tutorial

Lighting example