Light
Shading

Shading = find color values at pixels of screen (when rendering a virtual 3D scene).

Same as finding color value for the closest triangle on the ray of the pixel (assuming this is an opaque object, and air is clear).

Core objective: Find color values for intersection of a ray with a triangle.
Shading = find color values at pixels of screen (when rendering a virtual 3D scene).
Shading

Shading = find color values at pixels of screen (when rendering a virtual 3D scene).

Same as finding color value for the closest triangle on the ray of the pixel (assuming this is an opaque object, and air is clear).
Shading

Shading = find color values at pixels of screen (when rendering a virtual 3D scene).

Same as finding color value for the closest triangle on the ray of the pixel (assuming this is an opaque object, and air is clear).

Core objective: Find color values for intersection of a ray with a triangle.
Shading

Core objective: Find color values for point at intersection of a ray with a triangle.
Core objective: Find color values for point at intersection of a ray with a triangle.

Recall:

- Rendering is triangle-driven (foreach triangle: render).
- Triangles are simply (triples of) vertices until rasterization phase, where pixels of the triangle are found from pixels of the vertices.

So the rays relevant for a given triangle are determined in the rasterization phase.
Modeling Light

Core objective: Find color values for intersection of a ray with a triangle.
Core objective: **Find color values for intersection of a ray with a triangle.**

Model physical light (photons)
Modeling Light

Core objective: Find color values for intersection of a ray with a triangle.

Model physical light (photons)

In real life, photons are

- Emitted from light sources.
- Reflected, absorbed, re-emitted, transmitted when hitting objects.
Modeling Light

Highly complex physical process, mainly at surfaces of materials. Zillions of photons involved.

Can only be modeled to a certain degree mathematically (ongoing research expands on the available models).
Modeling Light

Highly complex physical process, mainly at surfaces of materials. Zillions of photons involved.

Can only be modeled to a certain degree mathematically (ongoing research expands on the available models).

(Figure by Jason Jacobs)
Modeling Light

Realtime rendering additionally has severe time constraints.

Framerate \( \sim 30/\text{sec} \), screen size \( \sim 10^6 \) pixels \( \Rightarrow \) few GPU cycles available for calculation per ray.

For a 0.3 Teraflop CPU, this gives a maximum of \( 10^4 \) flops for all handling of all triangles pertaining to a given pixel/ray.
Realtime rendering additionally has severe time constraints.

Framerate $\sim 30$/sec, screen size $\sim 10^6$ pixels $\Rightarrow$ few GPU cycles available for calculation per ray.

For a 0.3 Teraflop CPU, this gives a maximum of $10^4$ flops for all handling of all triangles pertaining to a given pixel/ray.

Hence, realtime rendering uses rough models.
Realtime rendering additionally has severe time constraints.

Framerate $\sim 30$/sec, screen size $\sim 10^6$ pixels $\Rightarrow$ few GPU cycles available for calculation per ray.

For a 0.3 Teraflop CPU, this gives a maximum of $10^4$ flops for all handling of all triangles pertaining to a given pixel/ray.

Hence, realtime rendering uses rough models.

Today: the classic model (Phong’s lighting model, 1975) built into classic OpenGL under the name *the fixed-functionality pipeline*. The model is very heuristic (has skimpy physical backing). But gives an introduction to many main ingredients of lighting models.
Modeling Light

Realtime rendering additionally has severe time constraints.

Framerate $\sim 30$/sec, screen size $\sim 10^6$ pixels $\Rightarrow$ few GPU cycles available for calculation per ray.

For a 0.3 Teraflop CPU, this gives a maximum of $10^4$ flops for all handling of all triangles pertaining to a given pixel/ray.

Hence, realtime rendering uses rough models.

Today: the classic model (Phong’s lighting model, 1975) built into classic OpenGL under the name the fixed-functionality pipeline. The model is very heuristic (has skimpy physical backing). But gives an introduction to many main ingredients of lighting models.

More advanced models: use programmable GPU (shaders = programs for light calculations (and other vertex manipulation), see Chapters 20–21).
Modeling Light

Realtime rendering additionally has severe time constraints.

Framerate $\sim 30$/sec, screen size $\sim 10^6$ pixels $\Rightarrow$ few GPU cycles available for calculation per ray.

For a 0.3 Teraflop CPU, this gives a maximum of $10^4$ flops for all handling of all triangles pertaining to a given pixel/ray.

Hence, realtime rendering uses rough models.

Today: the classic model (Phong’s lighting model, 1975) built into classic OpenGL under the name *the fixed-functionality pipeline*. The model is very heuristic (has skimpy physical backing). But gives an introduction to many main ingredients of lighting models.

More advanced models: use programmable GPU (*shaders* = programs for light calculations (and other vertex manipulation), see Chapters 20–21).

Actually, on modern programmable GPUs, the fixed-functionality pipeline of classic mode OpenGL is just a default shader program. (Used to be hardwired into GPUs).
Color

Photons/light waves have frequencies:
Color

The lights following a ray has in real life a spectrum:
Color

The lights following a ray has in real life a spectrum:

The eye sees colors by light-sensitive cells called cones. Three types of cone cells, with different sensitivity to various wavelengths. Peaks of sensitivity in red, green, blue parts of spectrum, respectively.
Color

The lights following a ray has in real life a spectrum:

![Intensity vs Frequency Graphs](attachment://graphs.png)

The eye sees colors by light-sensitive cells called cones. Three types of cone cells, with different sensitivity to various wavelengths. Peaks of sensitivity in red, green, blue parts of spectrum, respectively.

So input spectrum in ray $\Rightarrow$ three-tuple output from each cone-triple to brain. Different spectra can give same output to brain.
Color

The lights following a ray has in real life a spectrum:

![Graphs showing intensity vs. frequency for different colors.]

The eye sees colors by light-sensitive cells called cones. Three types of cone cells, with different sensitivity to various wavelengths. Peaks of sensitivity in red, green, blue parts of spectrum, respectively.

So input spectrum in ray $\Rightarrow$ three-tuple output from each cone-triple to brain. Different spectra can give same output to brain.

On computer displays: use mix of (monocromatic) red, green, blue to stimulate cones and control the eye/brain’s color perception.
The eye sees colors by light-sensitive cells called cones. Three types of cone cells, with different sensitivity to various wavelengths. Peaks of sensitivity in red, green, blue parts of spectrum, respectively.

So input spectrum in ray $\Rightarrow$ three-tuple output from each cone-triple to brain. Different spectra can give same output to brain.

On computer displays: use mix of (monochromatic) red, green, blue to stimulate cones and control the eye/brain's color perception.

Hence, displays (and hence OpenGL) work with (R,G,B)-tuples as color values. [Or four-tuples, if alpha/transparency information is included.]
Lightning Models

- Define virtual lights.
- Define light/surface interactions.
Virtual Lights in OpenGL

- **Directional**: light direction same for all points in scene (light emits infinitely far from scene—think sun).

- **Positional**: light emits from a 3D point in the scene. Light direction varies for different points in the scene.

- **Spot**: like positional, but with cone restricting light emission.

Attenuation factor towards side of cone: \((\cos \alpha)\)

Attenuation factor for positional/spot lights (\(d\) = distance from surface point to light position):

\[
1 + a \cdot d + b \cdot d^2
\]
Virtual Lights in OpenGL

- **Directional**: light direction same for all points in scene (light emits infinitely far from scene—think sun).
- **Positional**: light emits from a 3D point in the scene. Light direction varies for different points in the scene.
Virtual Lights in OpenGL

- **Directional**: light direction same for all points in scene (light emits infinitely far from scene—think sun).
- **Positional**: light emits from a 3D point in the scene. Light direction varies for different points in the scene.
- **Spot**: like positional, but with cone restricting light emission. Attenuation factor towards side of cone: \((\cos \alpha)^h\)
Virtual Lights in OpenGL

- **Directional**: light direction same for all points in scene (light emits infinitely far from scene—think sun).
- **Positional**: light emits from a 3D point in the scene. Light direction varies for different points in the scene.
- **Spot**: like positional, but with cone restricting light emission. Attenuation factor towards side of cone: \((\cos \alpha)^h\)
Virtual Lights in OpenGL

- **Directional**: light direction same for all points in scene (light emits infinitely far from scene—think sun).
- **Positional**: light emits from a 3D point in the scene. Light direction varies for different points in the scene.
- **Spot**: like positional, but with cone restricting light emission. Attenuation factor towards side of cone: \((\cos \alpha)^h\)

**Attenuation** factor for positional/spot lights \((d = \text{distance from surface point to light position})\):

\[
\frac{1}{a + b \cdot d + c \cdot d^2}
\]
Phong's Lighting Model

- Models only opaque objects.
- Models generally only one level of light/surface interactions (except ambient term, see below).
- Light/surface interaction is modeled by two simple submodels, diffuse and specular term.
- Models indirect light effects very crudely (ambient term).
- Light actually generated at surface can be added (emissive term).
- Occlusion is not modeled (all objects see all lights).
Phong's Lightning Model

- Models only opaque objects.
- Models generally only one level of light/surface interactions (except ambient term, see below).
- Light/surface interaction is modeled by two simple submodels, diffuse and specular term.
- Models indirect light effects very crudely (ambient term).
- Light actually generated at surface can be added (emissive term).
- Occlusion is not modeled (all objects see all lights).
Generic Material and Light Interaction

Surfaces (materials) and light has color.
Generic Material and Light Interaction

Surfaces (materials) and light has color.

Light: intensity value in $[0, 1]$ for each of the three RGB-channels. One triple for each light.
Generic Material and Light Interaction

Surfaces (materials) and light has color.

Light: intensity value in $[0, 1]$ for each of the three RGB-channels. One triple for each light.

Material: scaling factor in $[0, 1]$ for each of the three RGB-channels. One triple for each vertex in each primitive.

Basic interaction: $(\text{light intensity value}) \times (\text{material attenuation factor})$.

(Note: multiplication performed separately on each of the three RGB-channels).

(Note: actually one light intensity triple (for lights) and one material attenuation factor (for vertices) for each of the terms ambient, diffuse, and specular (see later). But this flexibility often not used/needed.)
Generic Material and Light Interaction

Surfaces (materials) and light has color.

Light: intensity value in \([0, 1]\) for each of the three RGB-channels. One triple for each light.

Material: scaling factor in \([0, 1]\) for each of the three RGB-channels. One triple for each vertex in each primitive.

Basic interaction:

\[(\text{light intensity value}) \times (\text{material attenuation factor}).\]
Generic Material and Light Interaction

Surfaces (materials) and light has color.

Light: intensity value in $[0, 1]$ for each of the three RGB-channels. One triple for each light.

Material: scaling factor in $[0, 1]$ for each of the three RGB-channels. One triple for each vertex in each primitive.

Basic interaction:

$$\text{(light intensity value)} \times \text{(material attenuation factor)}.$$ 

(Note: multiplication performed separately on each of the three RGB-channels).
Generic Material and Light Interaction

Surfaces (materials) and light has color.

Light: intensity value in $[0, 1]$ for each of the three RGB-channels. One triple for each light.

Material: scaling factor in $[0, 1]$ for each of the three RGB-channels. One triple for each vertex in each primitive.

Basic interaction:

$$(\text{light intensity value}) \times (\text{material attenuation factor}).$$

(Note: multiplication performed separately on each of the three RGB-channels).

(Note: actually one light intensity triple (for lights) and one material attenuation factor (for vertices) for each of the terms ambient, diffuse, and specular (see later). But this flexibility often not used/needed.)
Diffuse Term in Phong

L’Amberts law [1760] for perfectly scattered light (100% matte surfaces).
L'Amberts law [1760] for perfectly scattered light (100% matte surfaces).

- Light influx per area on surface depends on angle $\theta$ between light vector (light direction) and surface normal at point. Dependency/attenuation is factor of $\cos \theta$.
- Light is scattered equally from point in all directions ($\Rightarrow$ eye ray vector does not matter).
Diffuse Term in Phong

L'Ambert's law [1760] for perfectly scattered light (100% matte surfaces).

- Light influx per area on surface depends on angle $\theta$ between *light vector* (light direction) and *surface normal* at point. Dependency/attenuation is factor of $\cos \theta$.
- Light is scattered equally from point in all directions ($\Rightarrow$ *eye ray vector* does not matter).
Specular Term in Phong

Models highlights/shininess using heuristic formula.

Let $\phi$ be the angle between the halfway vector $s = (l + e)$ and the normal vector $n$. The attenuation factor is $(\cos \phi)^f$. 
Specular Term in Phong

Models highlights/shininess using heuristic formula.

Depends on light vector (light direction), eye ray vector, and surface normal at point.
Specular Term in Phong

Models highlights/shininess using heuristic formula.

Depends on light vector (light direction), eye ray vector, and surface normal at point.

\[ \phi \] be angle between halfway vector \( s = (l + e) \) and the normal vector \( n \).

\[ \text{Attenuation factor: } (\cos \phi)^f \]
Specular Term in Phong

Models highlights/shininess using heuristic formula.

Depends on light vector (light direction), eye ray vector, and surface normal at point.

Let $\phi$ be angle between halfway vector $s = (l + e)$ and the normal vector $n$. 
Specular Term in Phong
Models highlights/shininess using heuristic formula.

Depends on light vector (light direction), eye ray vector, and surface normal at point.

Let $\phi$ be angle between halfway vector $s = (l + e)$ and the normal vector $n$.

Attenuation factor: $(\cos \phi)^f$
Specular Term in Phong

Models highlights/shininess using heuristic formula.

Depends on light vector (light direction), eye ray vector, and surface normal at point.

Let $\phi$ be angle between halfway vector $s = (l + e)$ and the normal vector $n$.

Attenuation factor: $(\cos \phi)^f$
Ambient Term(s) in Phong

Models indirect light (crudely).
Ambient Term(s) in Phong

Models indirect light (crudely).

“Everywhere is some light”.
Ambient Term(s) in Phong

Models indirect light (crudely).

“Everywhere is some light”.

Light calculation does not depend points normal vector, direction of eye ray, direction of light (except for spot attenuation).
Ambient Term(s) in Phong

Models indirect light (crudely).

“Everywhere is some light”.

Light calculation does not depend points normal vector, direction of eye ray, direction of light (except for spot attenuation).

More precisely: there is one global ambient term, plus one ambient term for each light. The latter allows for individually colored light, and distance and spot attenuation. Besides distance and spot attenuation, the calculation is just the basic multiplication of material and light.
Emissive Term in Phong

This is another material value signifying if light is actually created at the point.

This is just an RGB-triple added to the result of the rest of the calculations for the point.
Emissive Term in Phong

This is another material value signifying if light is actually created at the point.

This is just an RGB-triple added to the result of the rest of the calculations for the point.

Note: the “emitted light” is only used for the color value of the pixel (of the ray hitting the point). It is not taken into consideration when calculating color values at other points.
Emissive Term in Phong

This is another material value signifying if light is actually created at the point.

This is just an RGB-triple added to the result of the rest of the calculations for the point.

Note: the “emitted light” is only used for the color value of the pixel (of the ray hitting the point). It is not taken into consideration when calculating color values at other points.

Thus, having a bulb both visible and giving light in a scene will involve:

- Creating polygons for the bulb and setting their emissive properties to non-zero (probably close to (1,1,1)).
- Creating a virtual light at the center of the bulb.
Lighting Equation

Add basic interactions between material and light as follows:

- One term for object light emission (usually zero).
- One term for global ambient light.
- For each light defined: add terms for per-light ambient term, diffuse term, and specular term (with distance and spot attenuation where appropriate).

This is done once for each RGB-channel. A resulting value above 1.0 is just truncated to 1.0.
Lighting Equation in Math

\[
\text{channel value} = \text{emissive_term} \\
+ \text{amb}_\text{material} \times \text{amb}_\text{global} \\
+ \sum_{\text{all lights}} \text{dist}_\text{attenuation} \times \text{spot}_\text{attenuation} \times \\
(\text{amb}_\text{material} \times \text{amb}_\text{light} + \\
\max\{\vec{l} \cdot \vec{n}, 0\} \times \text{diff}_\text{material} \times \text{diff}_\text{light} + \\
(\max\{\vec{s} \cdot \vec{n}, 0\})^f \times \text{spec}_\text{material} \times \text{spec}_\text{light})
\]
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

- Flat shading: Color calculated for one point is used for entire triangle.
- Smooth shading (aka. Gouraud shading): Colors calculated for three vertices are interpolated across the entire triangle (individually for each RGB-channel).
- Phong shading: Color calculation done for all points of pixels. Calculation time increases down the list. Phong shading needs programmable shaders (not part of OpenGL fixed-functionality pipeline).
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

- **Flat shading**: Color calculated for one point is used for entire triangle.

Calculation time increases down the list. Phong shading needs programmable shaders (not part of OpenGL fixed-functionality pipeline).
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

- **Flat shading**: Color calculated for one point is used for entire triangle.
- **Smooth shading** (aka. Gouraud shading): Colors calculated for three vertices are interpolated across the entire triangle (individually for each RGB-channel).
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

- **Flat shading**: Color calculated for one point is used for entire triangle.
- **Smooth shading** (aka. Gouraud shading): Colors calculated for three vertices are interpolated across the entire triangle (individually for each RGB-channel).
- **Phong shading**: Color calculation done for all points of pixels.
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

▶ **Flat shading**: Color calculated for one point is used for entire triangle.

▶ **Smooth shading** (aka. Gouraud shading): Colors calculated for three vertices are interpolated across the entire triangle (individually for each RGB-channel).

▶ **Phong shading**: Color calculation done for all points of pixels.
Shading models

So we now have information in each vertex. How spread color calculation over entire triangle pixels?

- **Flat shading**: Color calculated for one point is used for entire triangle.
- **Smooth shading** (aka. Gouraud shading): Colors calculated for three vertices are interpolated across the entire triangle (individually for each RGB-channel).
- **Phong shading**: Color calculation done for all points of pixels.

Calculation time increases down the list. Phong shading needs programmable shaders (not part of OpenGL fixed-functionality pipeline).