

Lighting & Shading

From Physical Reality to Beautiful Renders

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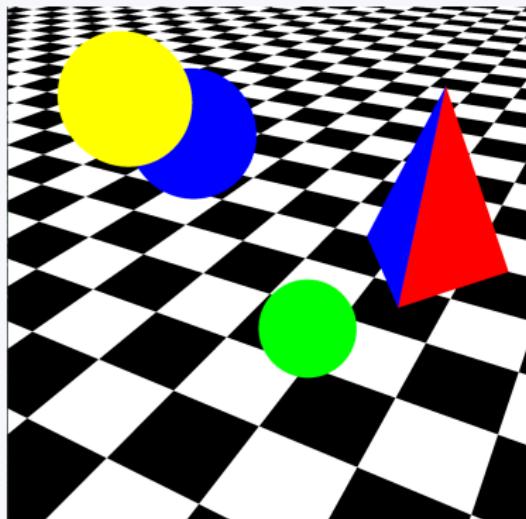
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Blinn-Phong Model

Motivation

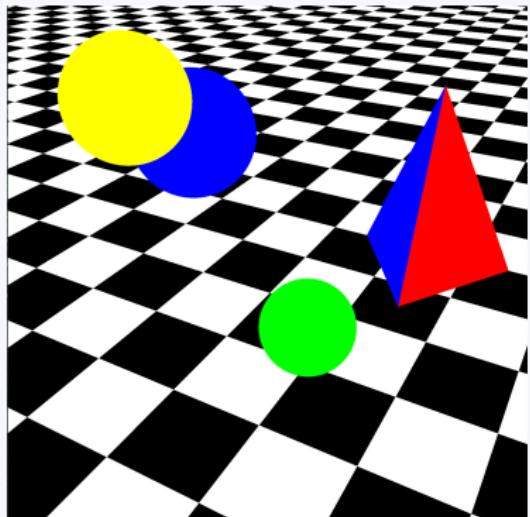
Why Lighting Matters

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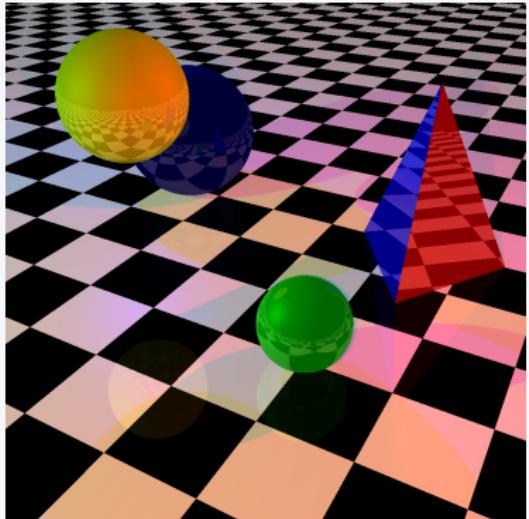


Without Lighting and Shading

Why Lighting Matters



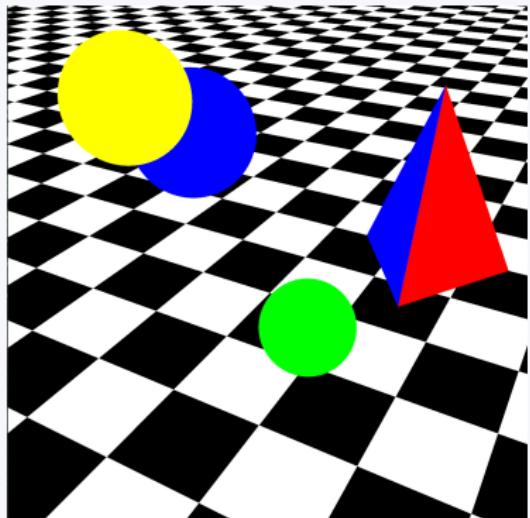
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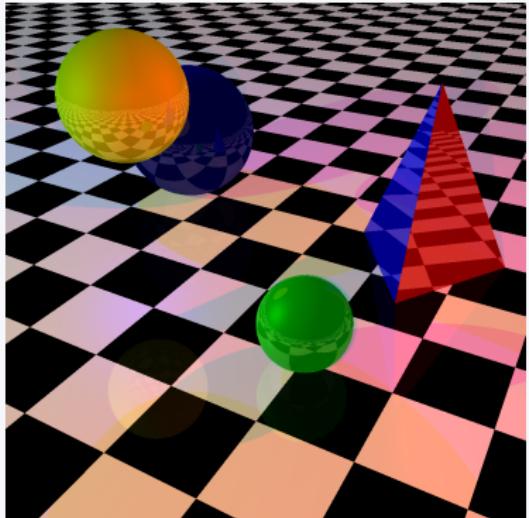
With Lighting and Shading

- **Depth perception** - Lighting reveals 3D shape and form

Why Lighting Matters



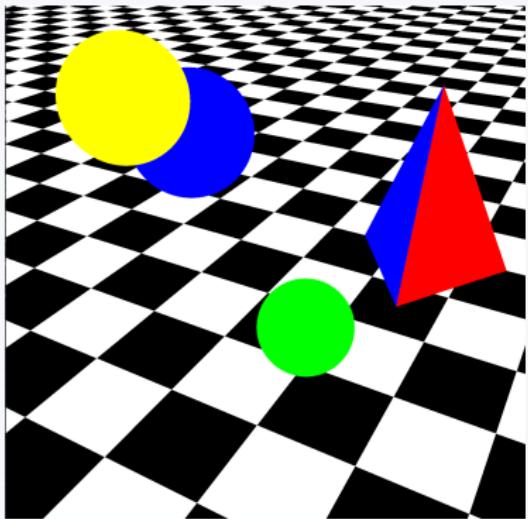
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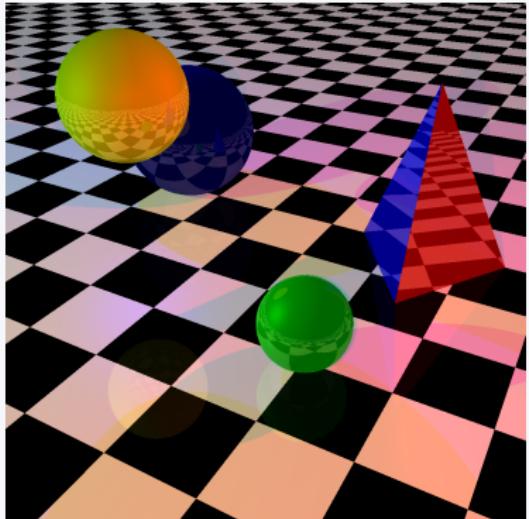
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- **Depth perception** - Lighting reveals 3D shape and form
- **Material properties** - Distinguishes between plastic, metal, wood

Why Lighting Matters



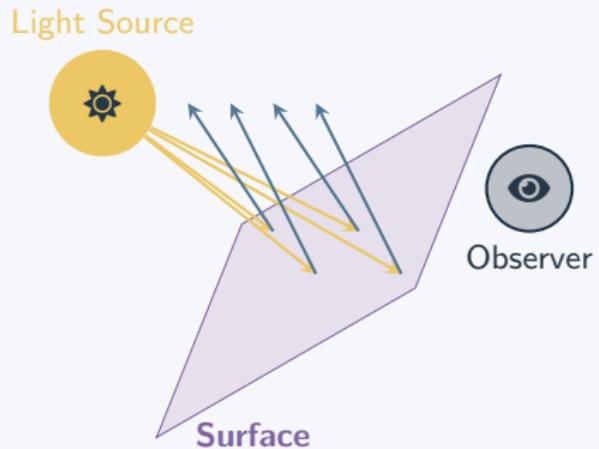
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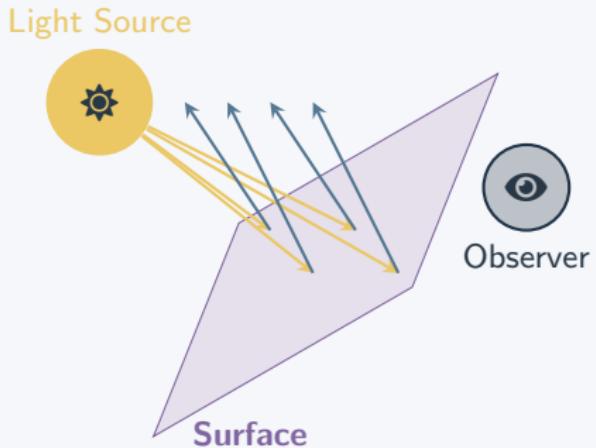
With Lighting and Shading

- **Depth perception** - Lighting reveals 3D shape and form
- **Material properties** - Distinguishes between plastic, metal, wood
- **Realism** - Makes computer graphics believable and immersive

The Challenge: From Reality to Code



The Challenge: From Reality to Code



Reality vs Computation

Physical World:

- Millions of photons per surface point
- Complex wave interactions
- Multiple scattering events
- Continuous spectrum

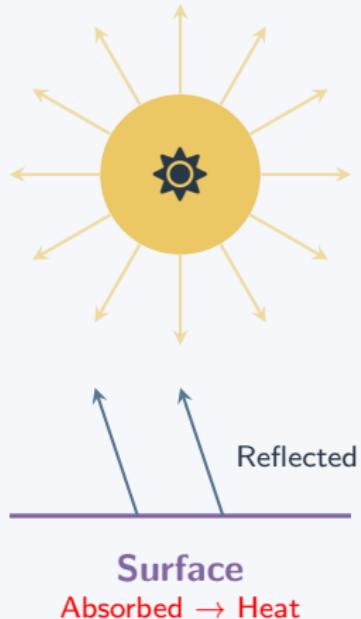
Computer Graphics:

- Discrete RGB values
- Simplified mathematical models
- Local illumination approximations
- Real-time constraints

Light Sources

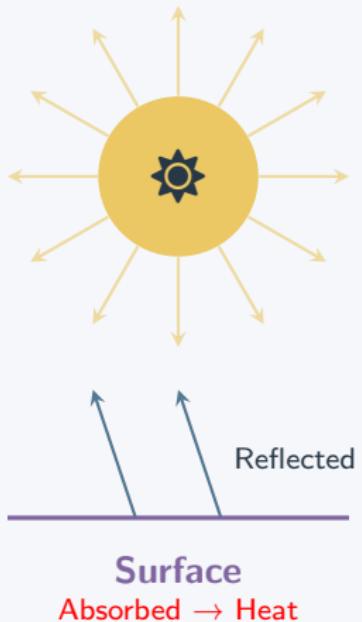
Light in Nature

Electromagnetic Radiation



Light in Nature

Electromagnetic Radiation



Physical Properties

Light is electromagnetic radiation:

- Wavelength determines color
- Intensity determines brightness
- Travels at speed of light (c)
- Behaves as waves and particles

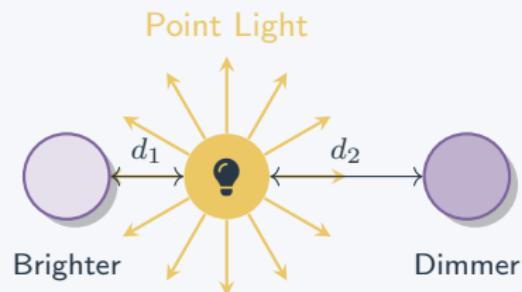
Surface interactions:

- **Reflection** (bounces off)
- **Absorption** (converts to heat)
- **Transmission** (passes through)

Point Light Sources - Introduction

Point Light Characteristics

Light emanating from a single point in all directions



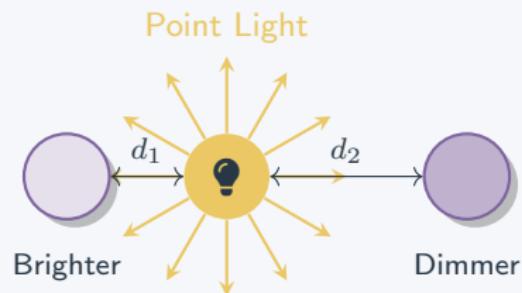
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Real-world examples:

- Light bulbs, LEDs
- Candles



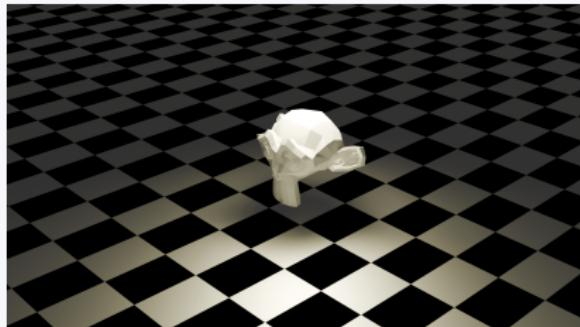
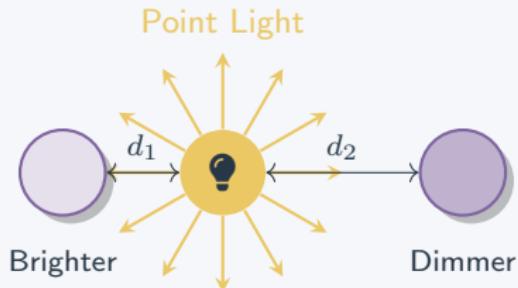
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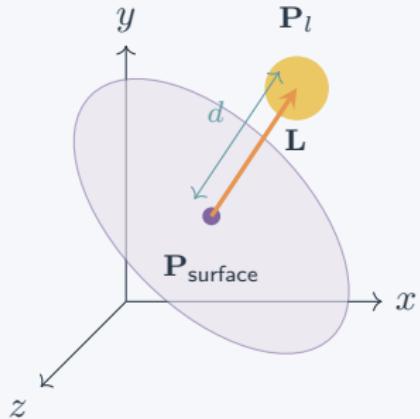
Point Light ft. Suzanne the monkey

Point Light Mathematics

Point Light Parameters

Position: $\mathbf{P}_l = (x_l, y_l, z_l)$

Intensity: \mathbf{I}_l (brightness; RGB channels)



Point Light Mathematics

Point Light Parameters

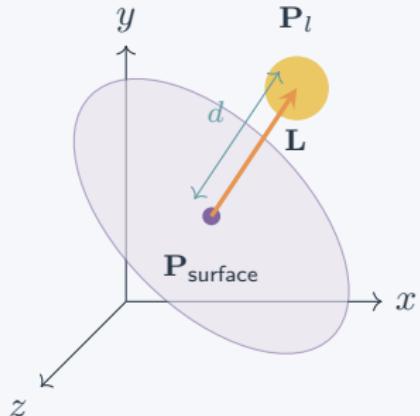
Position: $\mathbf{P}_l = (x_l, y_l, z_l)$

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Light direction to surface point:

$$\mathbf{L} = \mathbf{P}_l - \mathbf{P}_{\text{surface}}$$

$$\hat{\mathbf{L}} = \frac{\mathbf{L}}{|\mathbf{L}|} \quad (\text{normalized})$$



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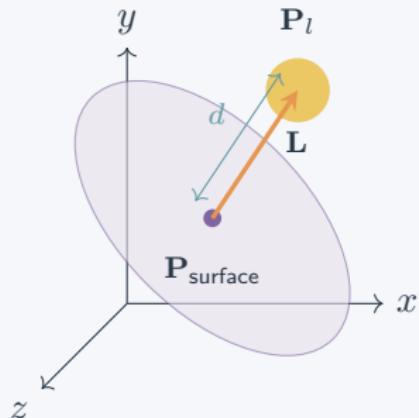
Light direction to surface point:

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Distance:

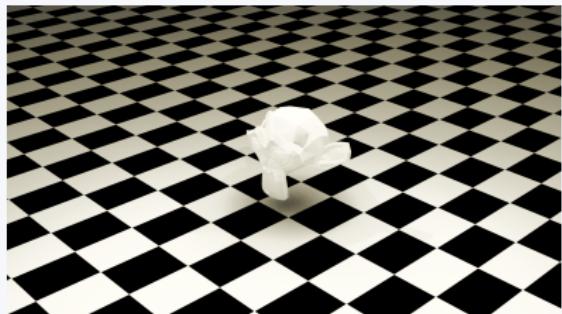
$$d = |\mathbf{P}_l - \mathbf{P}_{\text{surface}}|$$



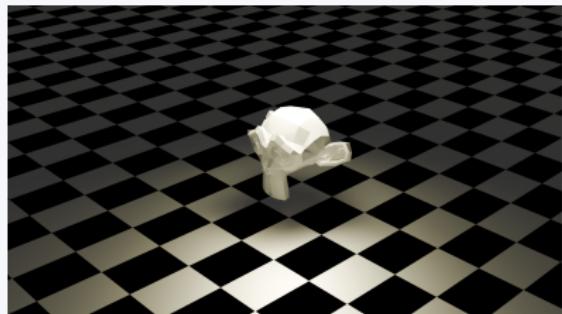
Attenuation

What is Attenuation?

Light becomes dimmer as distance increases due to the spreading of light energy over a larger area. Without this effect, distant objects would appear as bright as nearby ones, which is unrealistic.



No Attenuation

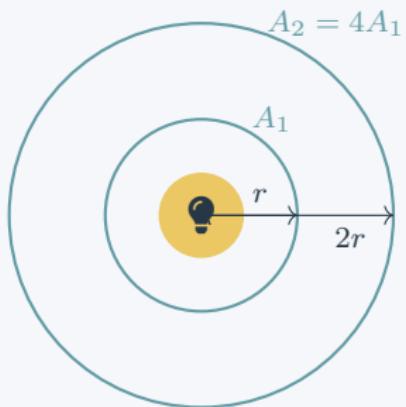


With Attenuation

Inverse Square Law - The Physics

$1/r^2$ Attenuation

- **Physical principle:** Light energy spreads over larger area as distance increases.

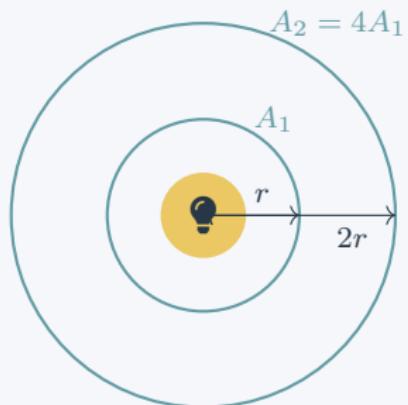


Same energy $\rightarrow 4 \times$ area $\rightarrow \frac{1}{4}$ intensity

Inverse Square Law - The Physics

$1/r^2$ Attenuation

- **Physical principle:** Light energy spreads over larger area as distance increases.
- **Sphere surface area:** $A = 4\pi r^2$

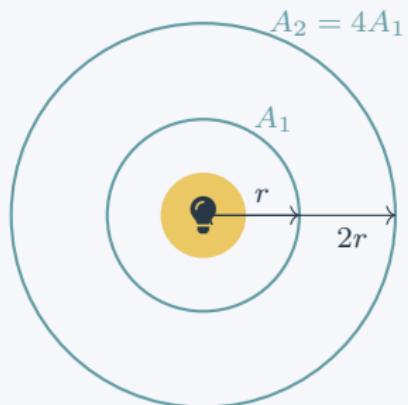


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Inverse Square Law - The Physics

$1/r^2$ Attenuation

- **Physical principle:** Light energy spreads over larger area as distance increases.
- **Sphere surface area:** $A = 4\pi r^2$
- **Energy conservation:** Same total energy spread over larger area.

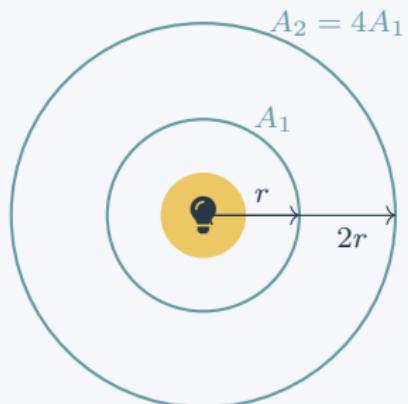


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- **Intensity per unit area:** $I \propto \frac{1}{r^2}$

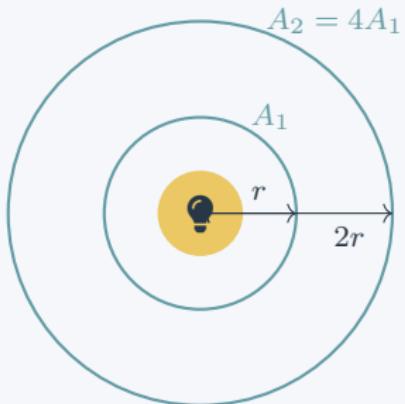


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Same energy $\rightarrow 4 \times$ area $\rightarrow \frac{1}{4}$ intensity

Attenuation Formula

$$I_{\text{received}} = \frac{\mathbf{I}_l}{d^2} \quad \text{where } d = \text{distance to light}$$

Point Light Implementation

Point Light Function Structure

Input parameters:

- Light position: \mathbf{P}_l
- Light intensity: \mathbf{I}_l
- Surface point: $\mathbf{P}_{\text{surface}}$

Point Light Implementation

Point Light Function Structure

Calculation steps:

$$\mathbf{L} = \mathbf{P}_l - \mathbf{P}_{\text{surface}}$$

$$d = |\mathbf{L}|$$

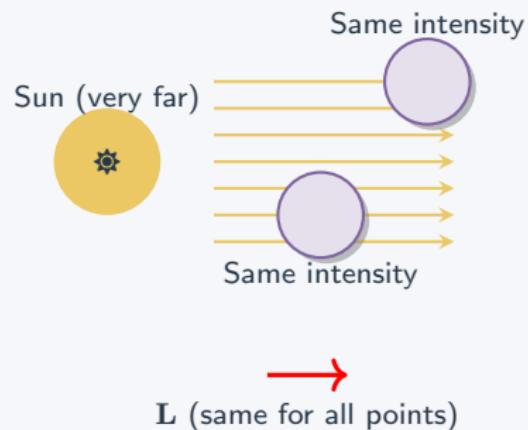
$$\hat{\mathbf{L}} = \mathbf{L}/d$$

$$I_{\text{final}} = \frac{\mathbf{I}_l}{\epsilon + d^2}$$

Directional Lights - The Sun Model

Directional Light Concept

Light source at infinite distance, so rays
are effectively parallel



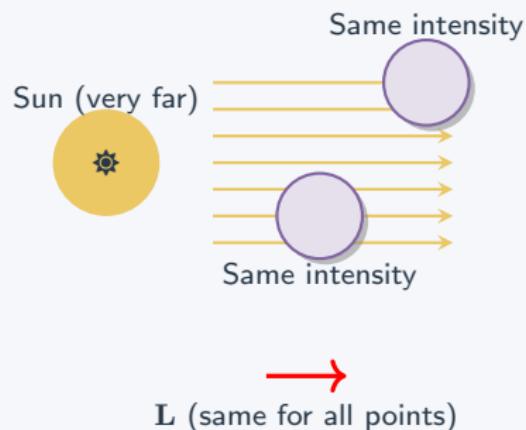
Directional Lights - The Sun Model

Directional Light Concept

Light source at infinite distance, so rays are effectively parallel

Characteristics:

- Parallel rays
- Same intensity everywhere
- No attenuation
- Defined by direction only

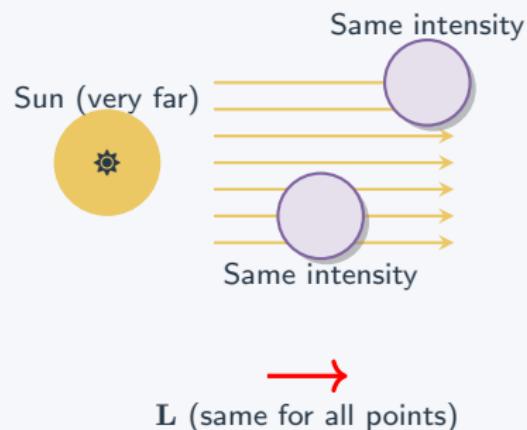


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Perfect for: Sun, moon, distant lights



Directional Lights - The Sun Model

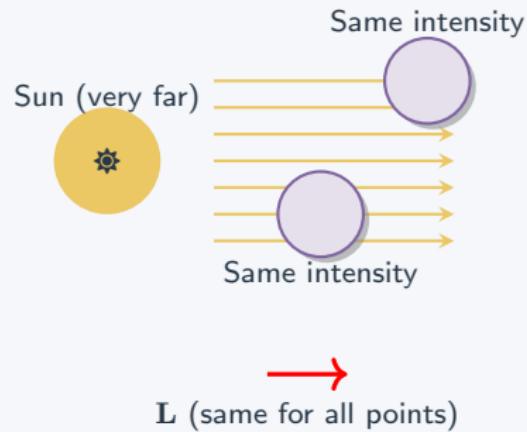
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Directional Light ft. Suzanne

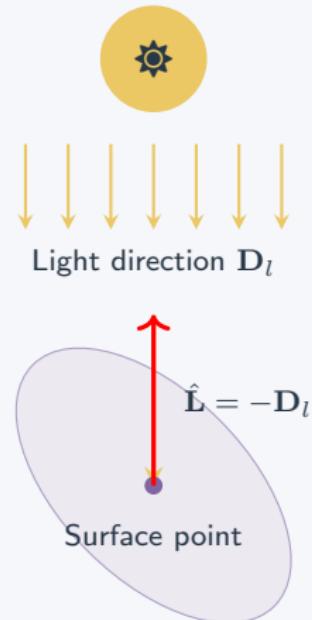


Directional Light Mathematics

Directional Light Parameters

Direction: $\mathbf{D}_l = (x, y, z)$

Intensity: I_l (constant)



Directional Light Mathematics

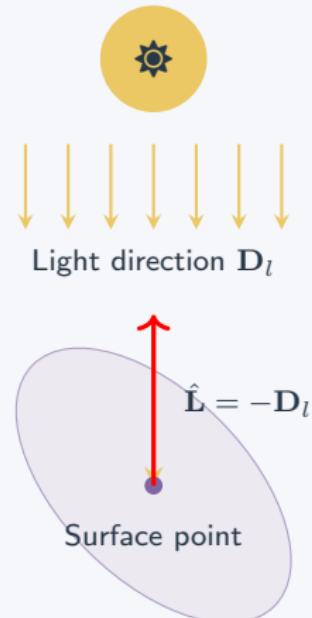
Directional Light Parameters

Direction: $\mathbf{D}_l = (x, y, z)$

Intensity: I_l (constant) **Light direction:**

$$\hat{\mathbf{L}} = -\mathbf{D}_l$$

Note: Assuming \mathbf{D}_l is normalized



Directional Light Mathematics

Directional Light Parameters

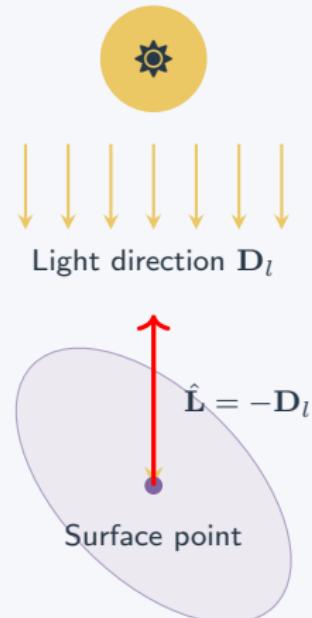
Direction: $D_l = (x, y, z)$

Intensity: I_l (constant) **Light direction:**

$$\hat{L} = -D_l$$

Intensity at any point:

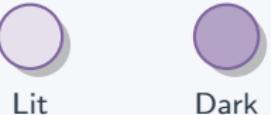
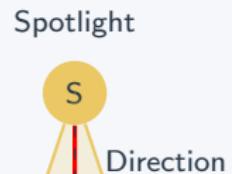
$$I_{\text{final}} = I_l \quad (\text{no attenuation})$$



Spot Lights - Introduction

Spot Light Characteristics

Light emanating from a point within a cone



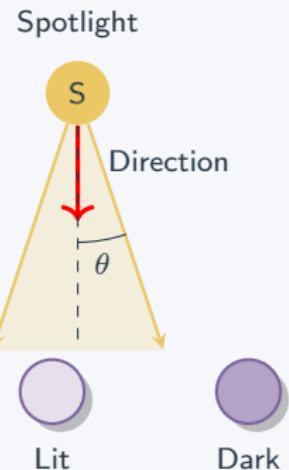
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Real-world examples:

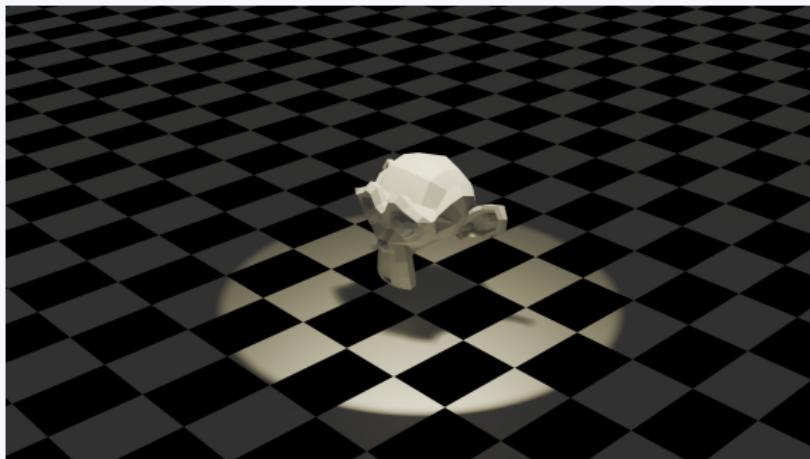
- Flashlights, headlights
- Stage spotlights
- Desk lamps



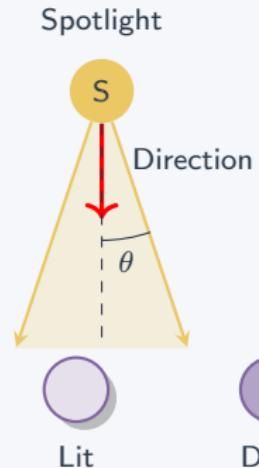
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Spot Light ft. Suzanne the monkey



Spot Light Mathematics - Cone Calculation

Spot Light Parameters

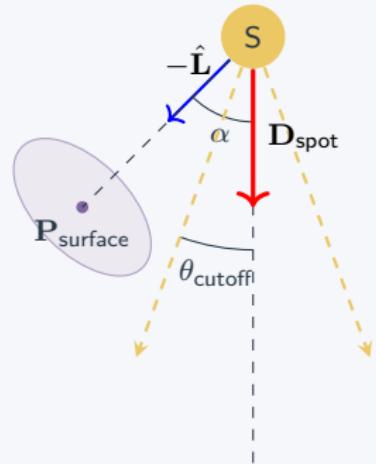
Position: P_l

Intensity: I_l

Direction: D_{spot}

Cone angle: θ_{cutoff}

Falloff exponent: e



Spot Light Mathematics - Cone Calculation

Spot Light Parameters

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Direction: \mathbf{D}_{spot}

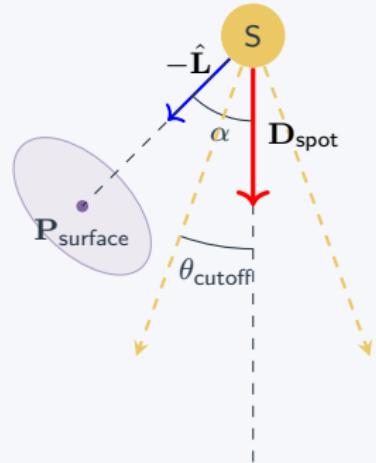
Cone angle: θ_{cutoff}

Falloff exponent: e

Step 1 - Calculate angle to surface:

$$\hat{\mathbf{L}} = \frac{\mathbf{P}_l - \mathbf{P}_{\text{surface}}}{|\mathbf{P}_l - \mathbf{P}_{\text{surface}}|}$$

$$\cos(\alpha) = \mathbf{D}_{\text{spot}} \cdot (-\hat{\mathbf{L}})$$



Spot Light Mathematics - Cone Calculation

Spot Light Parameters

Position: P_l

Intensity: I_l

Direction: D_{spot}

Cone angle: θ_{cutoff}

Falloff exponent: e

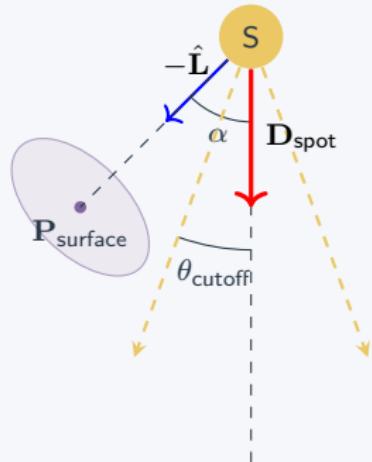
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$$\cos(\alpha) = \mathbf{D}_{\text{spot}} \cdot (-\hat{\mathbf{L}})$$

Step 2 - Check if inside cone:

if $\cos(\alpha) > \cos(\theta_{\text{cutoff}})$ then illuminate



Spot Light Attenuation

Complete Spot Light Formula

Angular attenuation:

$$\text{spot_factor} = \begin{cases} (\cos(\alpha))^e & \text{if } \cos(\alpha) > \cos(\theta_{\text{cutoff}}) \\ 0 & \text{otherwise} \end{cases}$$

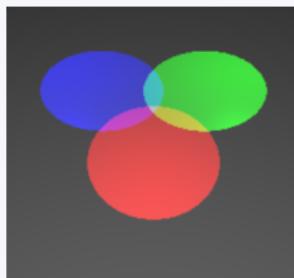
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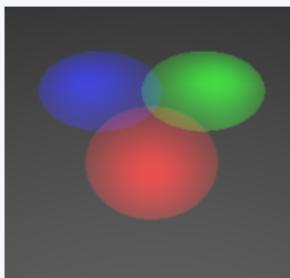
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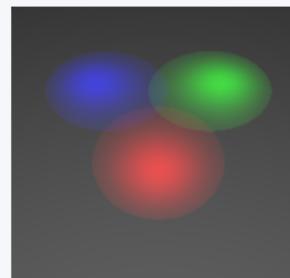
The e exponent controls how much brighter the light is at the center of the cone compared to the edges.



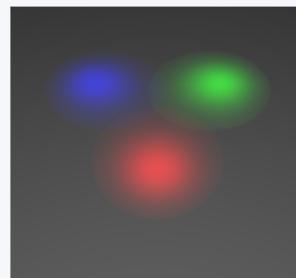
$e = 0$



$e = 10$



$e = 20$



$e = 30$

Spot lights for different values of e

Spot Light Attenuation

Complete Spot Light Formula

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Distance attenuation (same as point light):

$$\text{distance_attenuation} = \frac{1}{\epsilon + d^2}$$

Spot Light Attenuation

Complete Spot Light Formula

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Distance attenuation (same as point light):

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Final intensity:

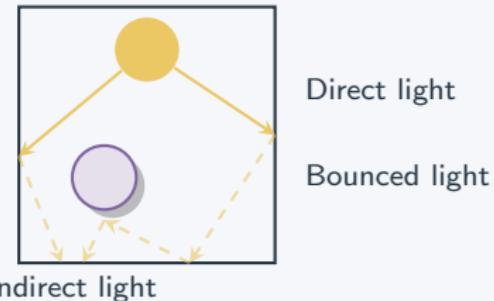
$$I_{\text{final}} = \begin{cases} \mathbf{I}_l \cdot (\cos(\alpha))^e \cdot \frac{1}{\epsilon + d^2} & \text{if } \cos(\alpha) > \cos(\theta_{\text{cutoff}}) \\ 0 & \text{otherwise} \end{cases}$$

Ambient Light - Global Illumination Approximation

Direct Lighting Problem

Real scenes have indirect lighting

- Light bounces off walls, ceiling
- Reflections illuminate shadows
- Even "dark" areas receive some light

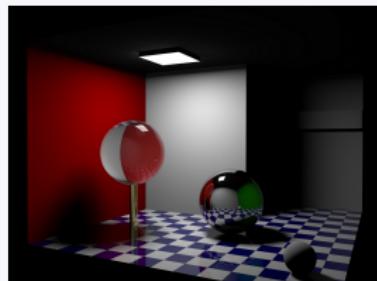


Ambient Light - Global Illumination Approximation

Direct Lighting Problem

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Only direct light



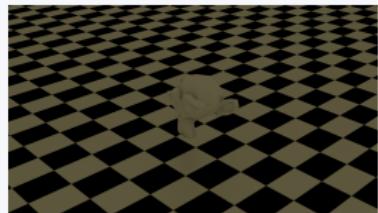
Global illumination

Ambient Light - Global Illumination Approximation

Solution: Ambient Light

Add constant ambient term

- Prevents completely black shadows
- Approximates global illumination
- Simple and fast to compute

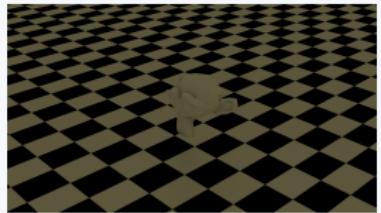


Ambient light ft. Suzanne the monkey

Ambient Light - Global Illumination Approximation

Ambient Light Parameters

Ambient intensity: I_l (constant)



Ambient light ft. Suzanne the monkey

Normal Vectors

Normal Vectors

Surface Normal Properties

Definition: Vector perpendicular to surface at a point

Normal Vectors

Surface Normal Properties

Definition: Vector perpendicular to surface at a point

Properties:

- Unit length: $|N| = 1$
- Points "outward" from surface
- Determines light interaction

Normal Vectors

Surface Normal Properties

Definition: Vector perpendicular to surface at a point

For triangles: Cross product of sides

$$\mathbf{N} = \frac{(\mathbf{b} - \mathbf{a}) \times (\mathbf{c} - \mathbf{a})}{|(\mathbf{b} - \mathbf{a}) \times (\mathbf{c} - \mathbf{a})|}$$

Normal Vectors

Surface Normal Properties

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For spheres: Normal at point \mathbf{P} is radial assuming center at origin

$$\mathbf{N} = \frac{\mathbf{P}}{|\mathbf{P}|}$$

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For spheres: Normal at point \mathbf{P} is radial assuming center at origin

$$\mathbf{N} = \frac{\mathbf{P}}{|\mathbf{P}|}$$

For planes: Normal defined by plane equation $Ax + By + Cz + D = 0$

$$\mathbf{N} = \frac{(A, B, C)}{\sqrt{A^2 + B^2 + C^2}}$$

Normal Vectors

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For planes: Normal defined by plane equation $Ax + By + Cz + D = 0$

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For arbitrary surfaces: Use gradient of implicit function

$$\mathbf{N} = \frac{\nabla f(x, y, z)}{|\nabla f(x, y, z)|}$$

The Phong Illumination Model

Phong Model: History

Historical Context

Developed by **Bui Tuong Phong** as his PhD dissertation at the University of Utah in 1973.

Goal: Fast, realistic-looking lighting

In Phong's words:

"We do not expect to be able to display the object exactly as it would appear in reality, with texture, overcast shadows, etc. We hope only to display an image that approximates the real object closely enough to provide a certain degree of realism."

Phong completed his PhD in only **two years**, a record at the time. Yet tragically, he died of cancer only two years later.



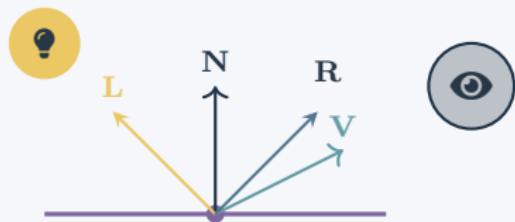
Bui Tuong Phong
(1942-1975)

Phong Model Overview

Phong Formula

Break lighting into three components that can be computed independently

$$\begin{aligned}I &= I_{\text{ambient}} + I_{\text{diffuse}} + I_{\text{specular}} \\&= k_a I_a + k_d \mathbf{I}_l (\mathbf{N} \cdot \mathbf{L}) + k_s \mathbf{I}_l (\mathbf{R} \cdot \mathbf{V})^n\end{aligned}$$

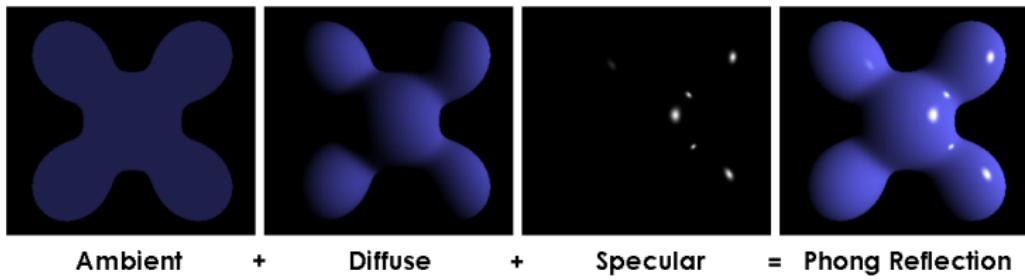
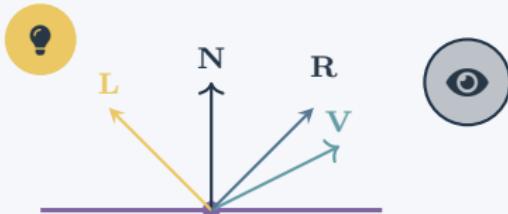


Phong Model Overview

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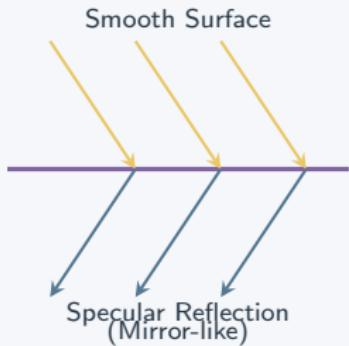
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Phong model components

Types of Reflection

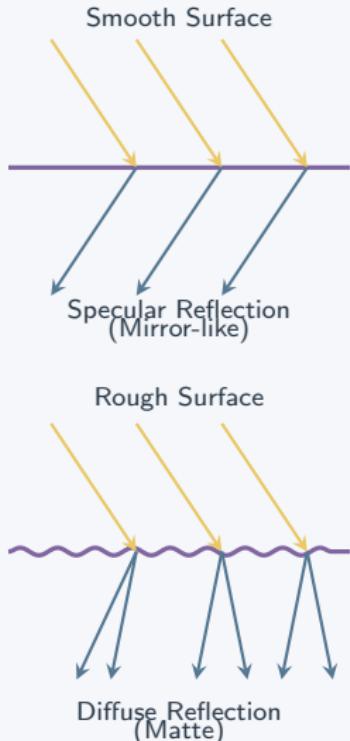


Reflection Types

Specular Reflection:

- Smooth surfaces (mirrors, metals)
- Preserves light direction
- Creates sharp highlights
- View-dependent

Types of Reflection



Reflection Types

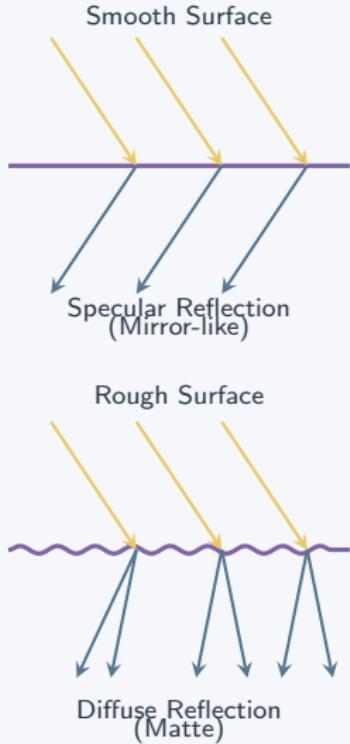
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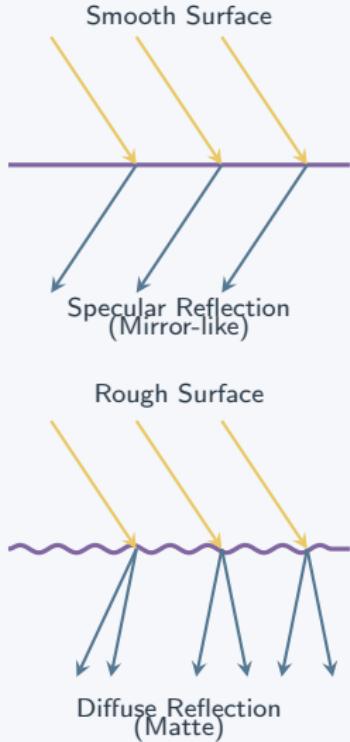
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- View-independent

Types of Reflection



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Real surfaces: Combination of three types

Ambient Reflection - Mathematics

Ambient Component Formula

Simplest lighting component:

$$I_{\text{ambient}} = \mathbf{k}_a \odot \mathbf{I}_a$$

- \mathbf{k}_a = ambient reflection coefficient of the material
- \mathbf{I}_a = intensity of ambient light in the scene

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Ambient Reflection - Mathematics

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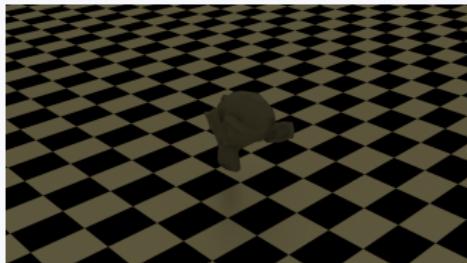
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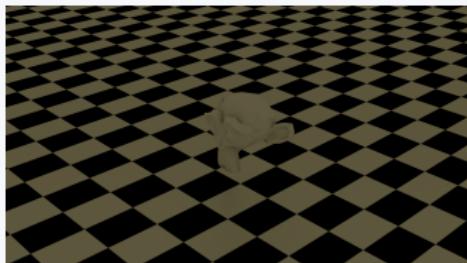
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Low \mathbf{k}_a



High \mathbf{k}_a

Diffuse Reflection - Introduction

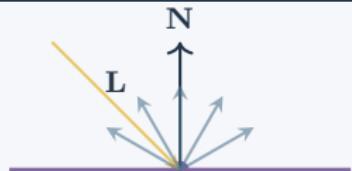
Lambertian Surfaces

Examples:

Paper, wood, fabric

Characteristics:

- Surface appears equally bright from all viewing angles
- Light scattered uniformly in all directions
- Brightness depends only on angle of incident light



Equal brightness
all directions

Diffuse Reflection - Introduction

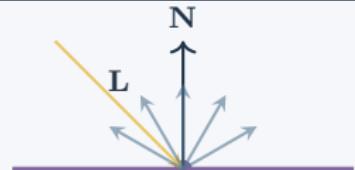
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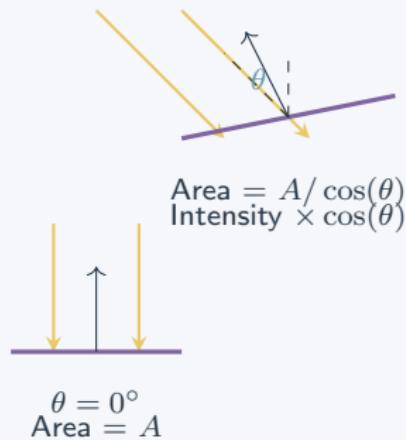


Examples of diffuse surfaces:
wood and fabric

Lambert's Cosine Law - Intuition

Why Cosine?

Consider light hitting a surface:



Lambert's Cosine Law - Intuition

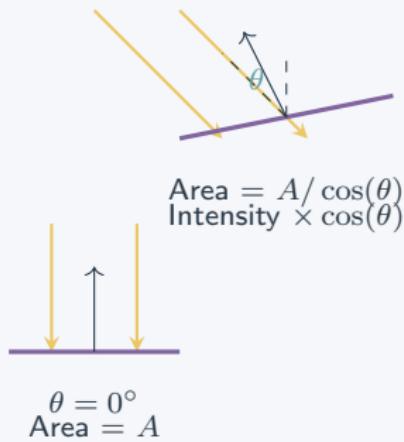
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Energy per unit area depends on angle

When light hits at angle θ :

- Same light beam covers larger area
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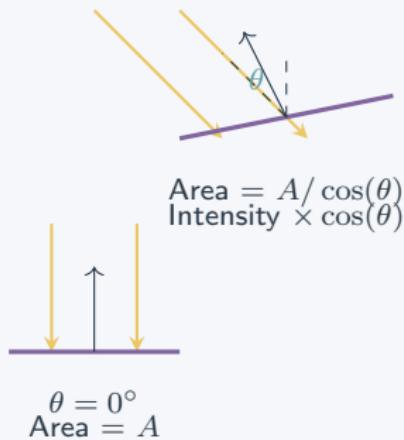
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- Area increases by factor $1/\cos(\theta)$
- Energy density decreases by factor $\cos(\theta)$

Mathematical relationship:

$$\text{Effective intensity} \propto \cos(\theta) = \mathbf{N} \cdot \mathbf{L}$$



Diffuse Reflection - Mathematics

Lambert's Law Implementation

Diffuse component formula:

$$I_{\text{diffuse}} = \mathbf{k}_d \odot \mathbf{I}_l (\mathbf{N} \cdot \mathbf{L})$$

where:

- \mathbf{k}_d = diffuse reflection coefficient (material color)
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With Clamping:

$$I_{\text{diffuse}} = \mathbf{k}_d \odot \mathbf{I}_l \max(0, \mathbf{N} \cdot \mathbf{L})$$

To avoid negative lighting.

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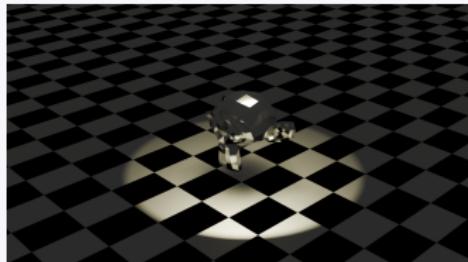
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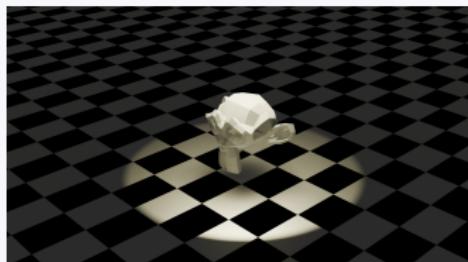
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Low diffuse



High diffuse

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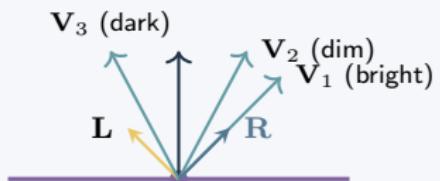
Shiny Surfaces

Examples:

Mirrors, metals, plastic

Characteristics:

- View-dependent brightness
- Creates highlights
- Follows law of reflection
- Intensity depends on viewing angle



Specular Reflection - Introduction

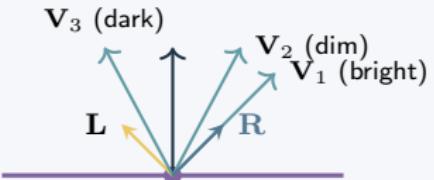
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Examples of diffuse surfaces: metal and glass

Perfect Reflection Theory

Law of Reflection

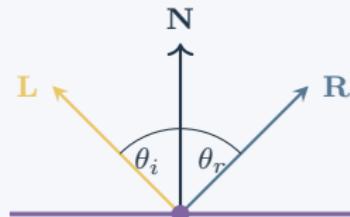
Physical principle: Angle of incidence equals angle of reflection

Vector formulation:

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

where:

- \mathbf{R} = reflection direction
- \mathbf{N} = surface normal
- \mathbf{L} = direction to light source



$$\theta_i = \theta_r$$

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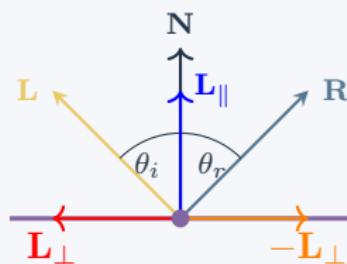
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Derivation: Decompose \mathbf{L} into normal and tangential components

$$\mathbf{L}_{\parallel} = (\mathbf{N} \cdot \mathbf{L})\mathbf{N}$$

$$\mathbf{L}_{\perp} = \mathbf{L} - \mathbf{L}_{\parallel}$$

$$\mathbf{R} = \mathbf{L}_{\parallel} - \mathbf{L}_{\perp} = 2\mathbf{L}_{\parallel} - \mathbf{L}$$

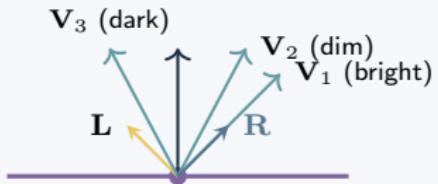


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Phong Specular Model - Insight

Phong's Insight

Perfect mirrors are rare in computer graphics. Most surfaces have some roughness that spreads the reflection.

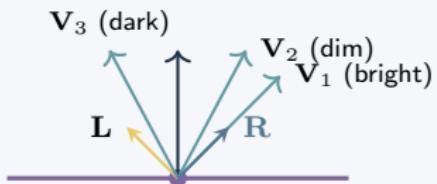


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Solution: Model the spread using a power function. Brightness decreases as viewing direction deviates from perfect reflection.



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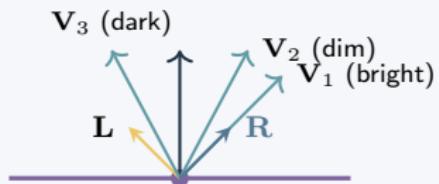
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Key assumption:

- Perfect reflection at $\mathbf{V} = \mathbf{R}$
- Intensity decreases with angle between \mathbf{V} and \mathbf{R}
- Use cosine raised to a power for smooth falloff



Specular Mathematics: Intensity Calculation

Phong Specular Formula

Specular intensity:

$$I_{\text{specular}} = \mathbf{k}_s \odot \mathbf{I}_l (\mathbf{R} \cdot \mathbf{V})^n \quad (1)$$

where:

- \mathbf{k}_s = specular reflection coefficient
- \mathbf{I}_l = light intensity
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- n = shininess exponent (controls highlight size)

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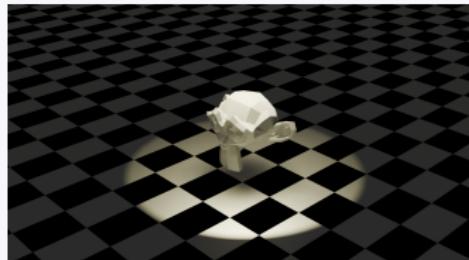
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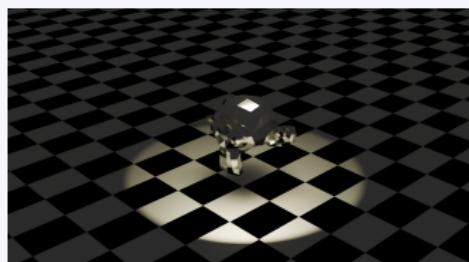
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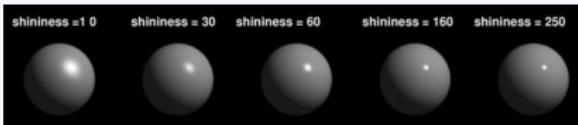


Low specular



High specular

Shininess Parameter (n) - Effect on Highlights



Shininess Exponent

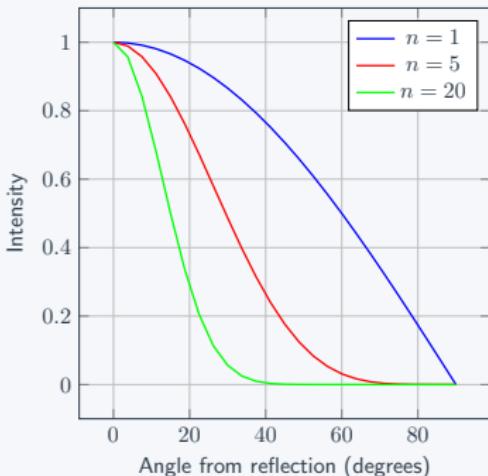
Mathematical effect:

$$(\cos(\alpha))^n$$

As n increases:

- Highlight becomes smaller
- Highlight becomes sharper
- Material appears shinier

Spheres with different shininess parameters



Complete Phong Equation Assembly

Putting It All Together

Complete Phong illumination model:

$$I = I_{\text{ambient}} + I_{\text{diffuse}} + I_{\text{specular}}$$

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$$\mathbf{I} = \mathbf{k}_a \odot \mathbf{I}_a + \sum_{i=1}^n \mathbf{I}_{l_i} \odot [\mathbf{k}_d \max(0, \mathbf{N} \cdot \mathbf{L}_i) + \mathbf{k}_s \max(0, \mathbf{R}_i \cdot \mathbf{V})^n]$$

Blinn-Phong: A More Efficient Alternative

Motivation for Blinn-Phong

Problem with Phong: Computing the reflection vector \mathbf{R} is expensive

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



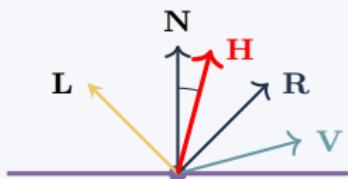
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Halfway vector bisects
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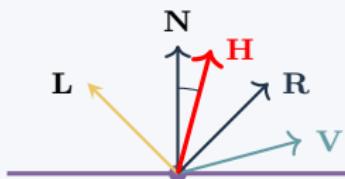
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Key insight:

- When $\mathbf{V} = \mathbf{R}$, the halfway vector \mathbf{H} equals the normal \mathbf{N}
- We can measure the angle between \mathbf{H} and \mathbf{N} instead
- Much cheaper to compute!



Halfway vector bisects
 \mathbf{L} and \mathbf{V}

Blinn-Phong Mathematics and Comparison

Blinn-Phong Formula

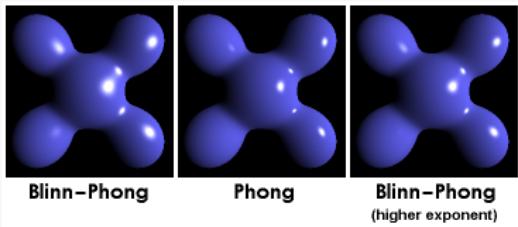
Halfway vector calculation:

$$\mathbf{H} = \frac{\mathbf{L} + \mathbf{V}}{|\mathbf{L} + \mathbf{V}|} \quad (3)$$

Specular term:

$$I_{\text{spec}} = \mathbf{k}_s \odot \mathbf{I}_l \max(0, \mathbf{N} \cdot \mathbf{H})^{n'} \quad (4)$$

where n' is typically 2-4 times larger than Phong's n



Blinn-Phong vs Phong

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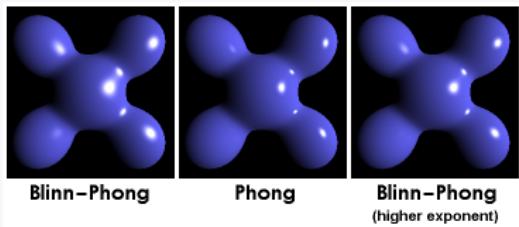
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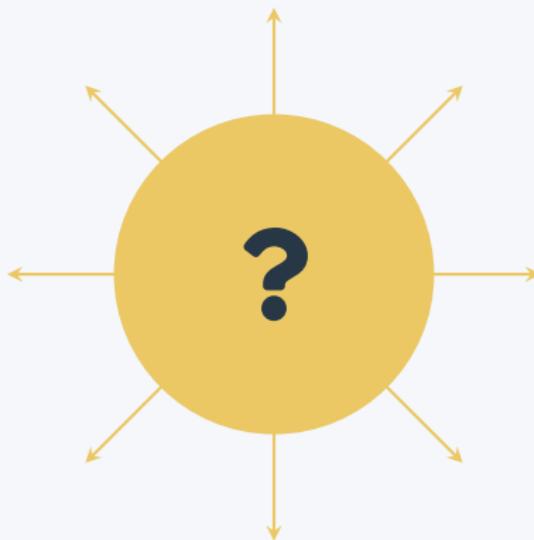
Performance comparison:

- **Phong:** 5 operations (2 dot products, 1 scalar multiply, 2 vector ops)
- **Blinn-Phong:** 4 operations (1 vector add, 1 normalize, 1 dot product)



Blinn-Phong vs Phong

Questions?



References & Further Reading

-  Peter Shirley and Steve Marschner et al. *Fundamentals of Computer Graphics (4th Edition)*. CRC Press, 2016.
Available as PDF
-  Matt Pharr, Wenzel Jakob, and Greg Humphreys. *Physically Based Rendering: From Theory to Implementation (4th Edition)*. Morgan Kaufmann, 2023.
Available online
-  Peter Shirley. *Ray Tracing in One Weekend*. Self-published, 2016–2020.
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-  MIT OpenCourseWare: 6.837 Computer Graphics.
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-  Scratchapixel: Learn Computer Graphics Programming.
scratchapixel.com