Lighting & Shading

From Physical Reality to Beautiful Renders

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Motivation

Why Lighting Matters

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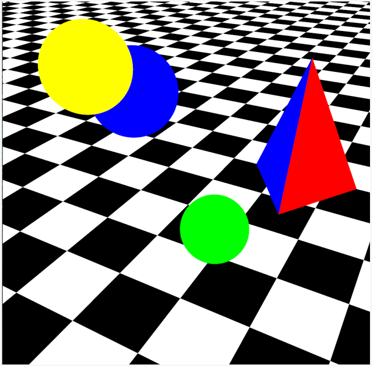

Without Lighting and Shading

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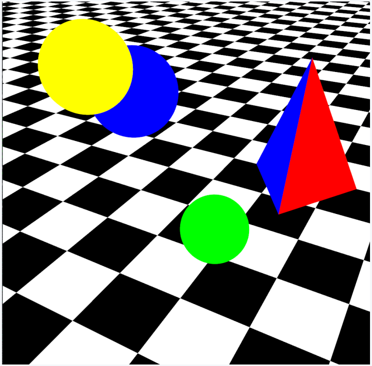

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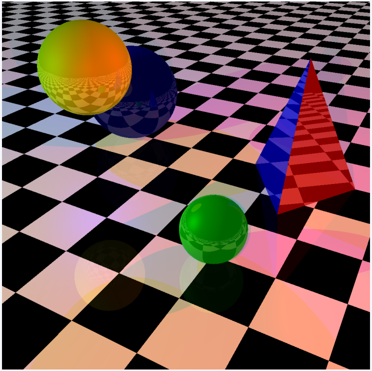
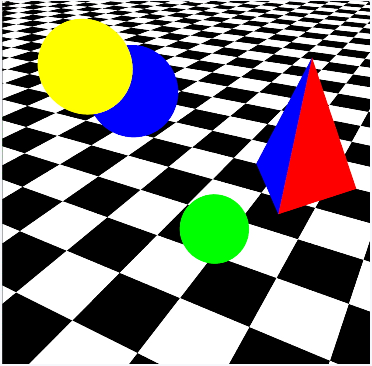


With Lighting and Shading

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

Why Lighting Matters



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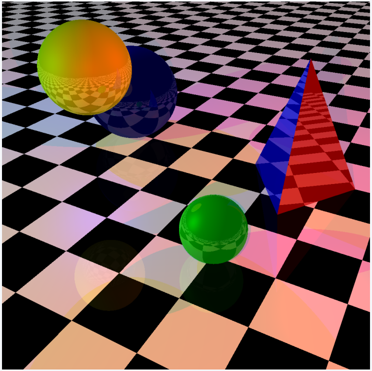

With Lighting and Shading

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

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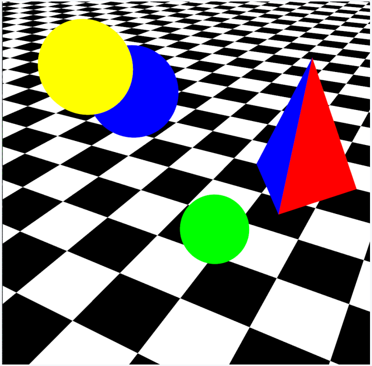

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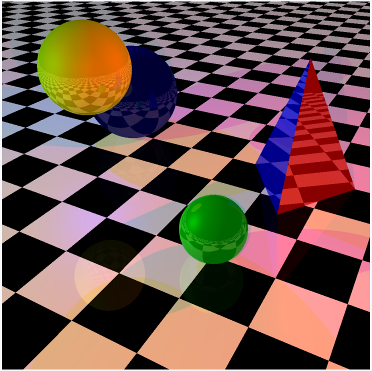
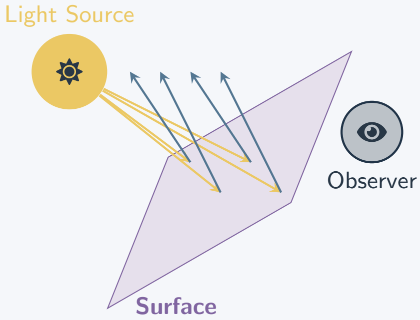


With Lighting and Shading

- **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



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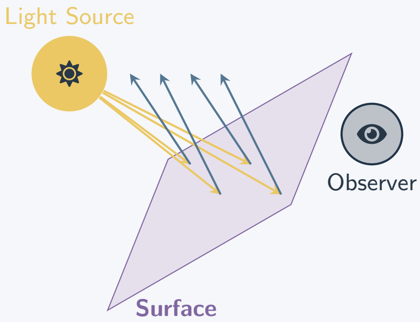

Reality vs Computation

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

Our Journey

Our Journey

Light Sources

- Point lights
- Directional
- Spotlights
- Attenuation

Our Journey

Light Sources → Surface Materials

- Point lights
- Directional
- Spotlights
- Attenuation

- Reflection types
- Surface normals
- Materials

Our Journey

Light Sources → Surface Materials → Phong Model

Light Sources

- Point lights
- Directional
- Spotlights
- Attenuation

Surface Materials

- Reflection types
- Surface normals
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Phong Model

- Ambient
- Diffuse
- Specular
- Mathematics

Our Journey

Light Sources → Surface Materials → Phong Model → Implementation

Light Sources

- Point lights
- Directional
- Spotlights
- Attenuation

Surface Materials

- Reflection types
- Surface normals
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Phong Model

- Ambient
- Diffuse
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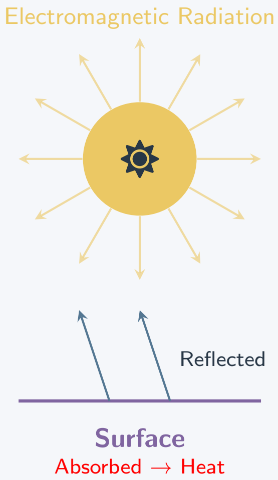
- Mathematics

Implementation

- Code structure
- Optimizations
- Edge cases

Light Sources

Light in Nature



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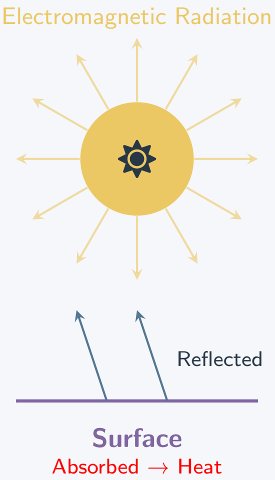


Physical Properties

Light is electromagnetic radiation:

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

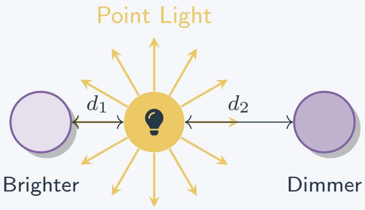
Surface interactions:

- **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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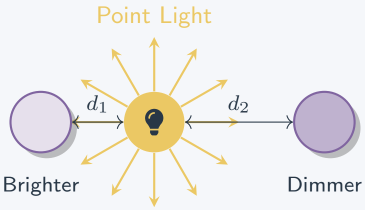
Real-world examples:

- Light bulbs, LEDs
- Candles



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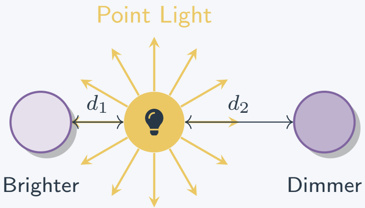


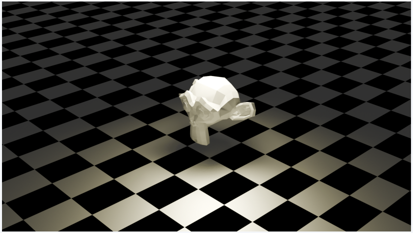
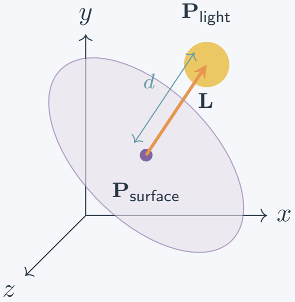


Figure 1: Point Light ft. Suzanne the monkey

Point Light Mathematics

Point Light Parameters

Position: $\mathbf{P}_{\text{light}} = (x_l, y_l, z_l)$
Intensity: I_{light} (brightness)
Color: $\mathbf{C}_{\text{light}} = (r, g, b)$



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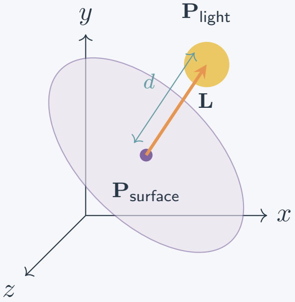
Light direction to surface point:

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

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



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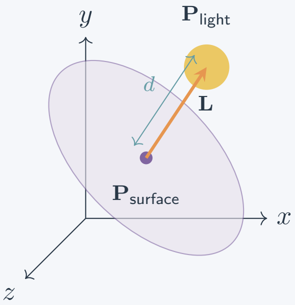
Distance:

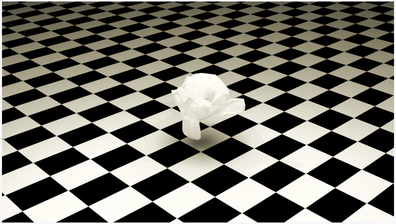
$$d = |\mathbf{P}_{\text{light}} - \mathbf{P}_{\text{surface}}|$$



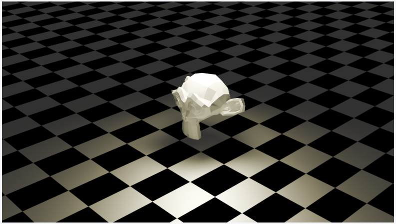
Attenuation

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

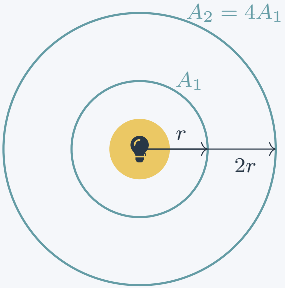


With Attenuation

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

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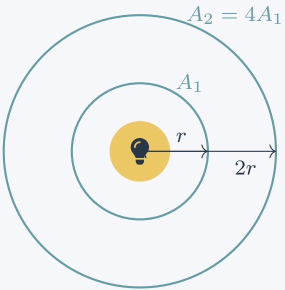
- **Sphere surface area:** $A = 4\pi r^2$



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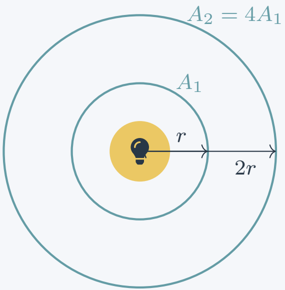
Inverse Square Law - The Physics

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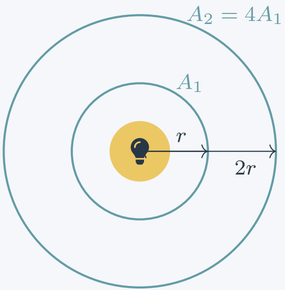
- **Intensity per unit area:** $I \propto \frac{1}{r^2}$



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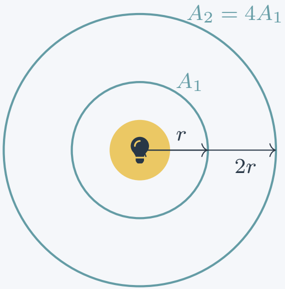


Same energy $\rightarrow$ 4$\times$ area $\rightarrow$ $\frac{1}{4}$ intensity

Attenuation Formula

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

Point Light Implementation

Point Light Function Structure

Input parameters:

- Light position: $\mathbf{P}_{\text{light}}$
- Light intensity: I_{light}
- Light color: $\mathbf{C}_{\text{light}} = (r, g, b)$
- Surface point: $\mathbf{P}_{\text{surface}}$

Point Light Implementation

Point Light Function Structure

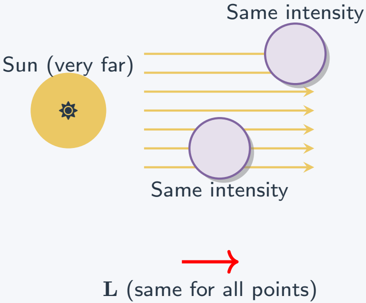
Calculation steps:

$$\begin{aligned}
\mathbf{L} &= \mathbf{P}_{\text{light}} - \mathbf{P}_{\text{surface}} \\
d &= |\mathbf{L}| \\
\hat{\mathbf{L}} &= \mathbf{L}/d \\
I_{\text{final}} &= \frac{I_{\text{light}}}{\epsilon + d^2}
\end{aligned}$$

Directional Lights - The Sun Model

Directional Light Concept

Light source at infinite distance, so rays are effectively parallel



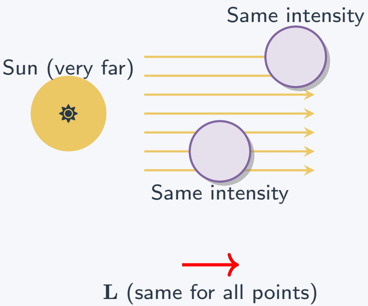
Directional Lights - The Sun Model

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

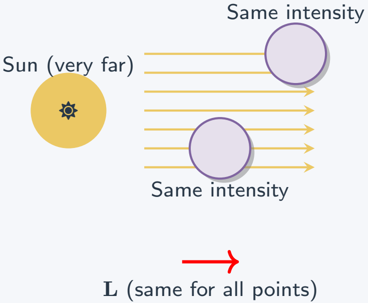

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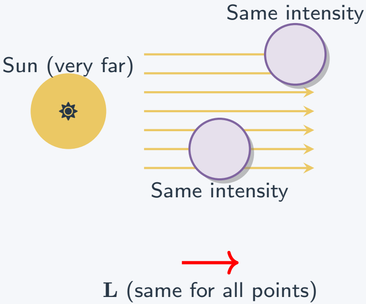
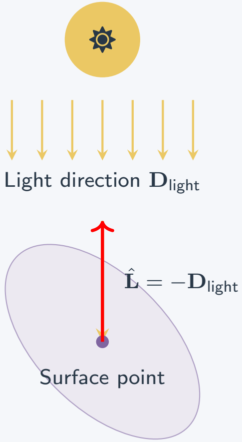
Figure 2: Directional Light ft. Suzanne



Directional Light Mathematics

Directional Light Parameters

Direction: $\mathbf{D}_{\text{light}} = (x, y, z)$
Intensity: I_{light} (constant)
Color: $\mathbf{C}_{\text{light}} = (r, g, b)$



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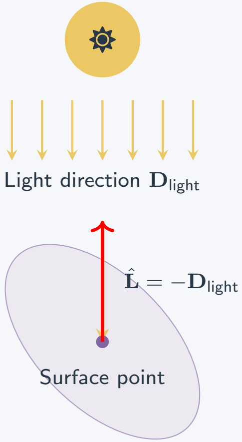
Light direction:

$$\hat{\mathbf{L}} = -\mathbf{D}_{\text{light}}$$

Note: Assuming $\mathbf{D}_{\text{light}}$ is normalized



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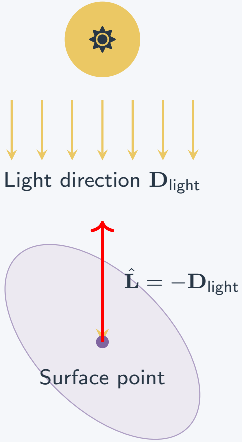
Intensity at any point:

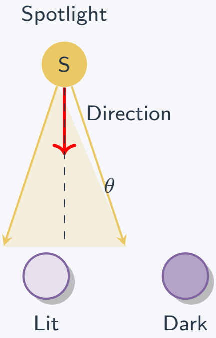
$$I_{\text{final}} = I_{\text{light}} \quad \text{(no attenuation)}$$



Spot Lights - Introduction

Spot Light Characteristics

Light emanating from a point within a cone



Spot Lights - Introduction

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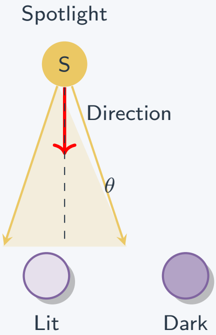
Light emanating from a point within a cone

Real-world examples:

- Flashlights, headlights
- Stage spotlights
- Desk lamps



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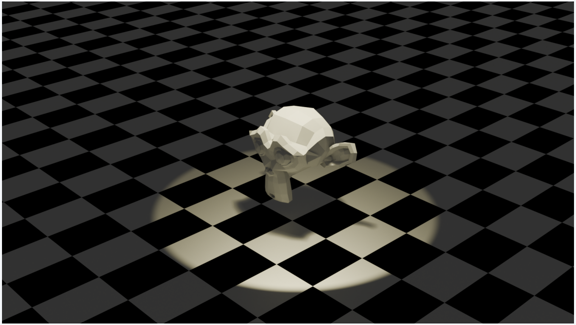
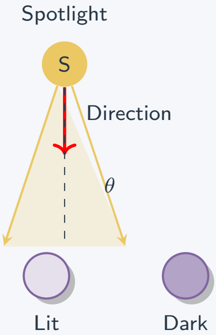


Figure 3: Spot Light ft. Suzanne the monkey



Spot Light Mathematics - Cone Calculation

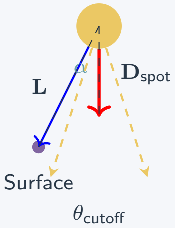
Spot Light Parameters

Position: $\mathbf{P}_{\text{light}}$

Direction: $\mathbf{D}_{\text{spot}}$ (where spotlight points)

Cone angle: θ_{cutoff} (half-angle of cone)

Falloff exponent: e (controls edge softness)



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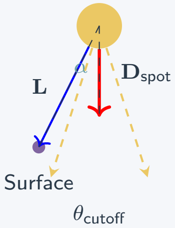
Step 1 - Calculate angle to surface:

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

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



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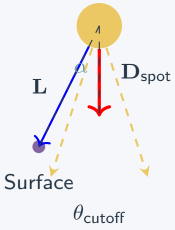
$$\cos(\alpha) = \mathbf{D}_{\text{spot}} \cdot (-\hat{\mathbf{L}})$$

Step 2 - Check if inside cone:

$$\text{if } \cos(\alpha) > \cos(\theta_{\text{cutoff}}) \text{ then illuminate} \tag{1}$$



Spot Light Attenuation

Complete Spot Light Formula

Angular attenuation:

$$\text{spot\_factor} = \begin{cases} (\cos(\alpha))^e & \text{if } \cos(\alpha) > \cos(\theta_{\text{cutoff}}) \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

[Spotlight falloff with different exponents]

Spot Light Attenuation

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Distance attenuation (same as point light):

$$\text{distance\_attenuation} = \frac{1}{a + b \cdot d + c \cdot d^2} \tag{3}$$

[Spotlight falloff with different exponents]

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Final intensity:

$$I_{\text{final}} = I_{\text{light}} \cdot \text{spot\_factor} \cdot \text{distance\_attenuation} \tag{4}$$

Spot Light Attenuation

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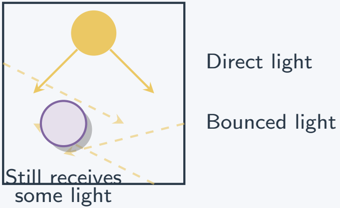
[Spotlight falloff with different exponents]

Ambient Light - Global Illumination Approximation

Ambient Light Purpose

Problem: Real scenes have indirect lighting

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



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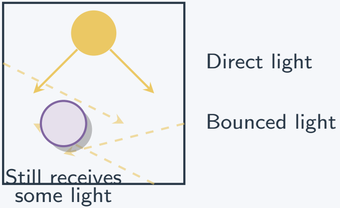
Solution: Add constant ambient term

- Prevents completely black shadows
- Approximates global illumination



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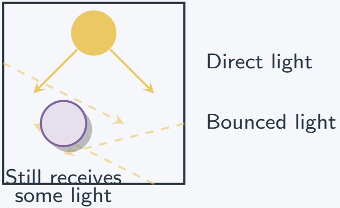

Light Attenuation Models Summary

Light Type	Attenuation	Use Cases
Point	$\frac{1}{a+bd+cd^2}$	Bulbs, candles
Directional	None ($I =$ constant)	Sun, moon
Spotlight	Distance $\times$ angular	Flashlights, lamps
Area	Complex (sampling)	Panels, windows
Ambient	None (constant)	Global approximation

[Comparison of all light types on same scene]