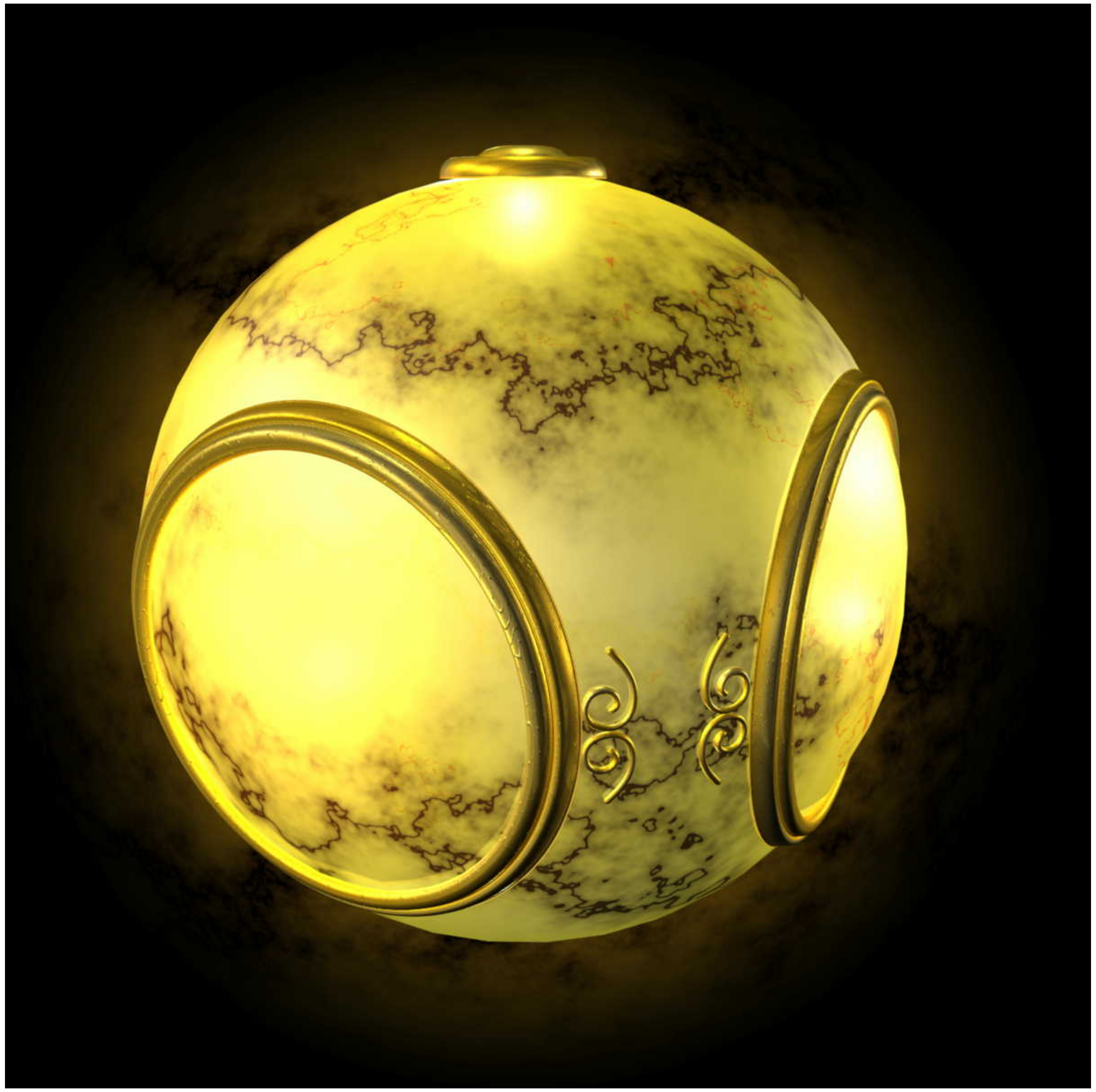
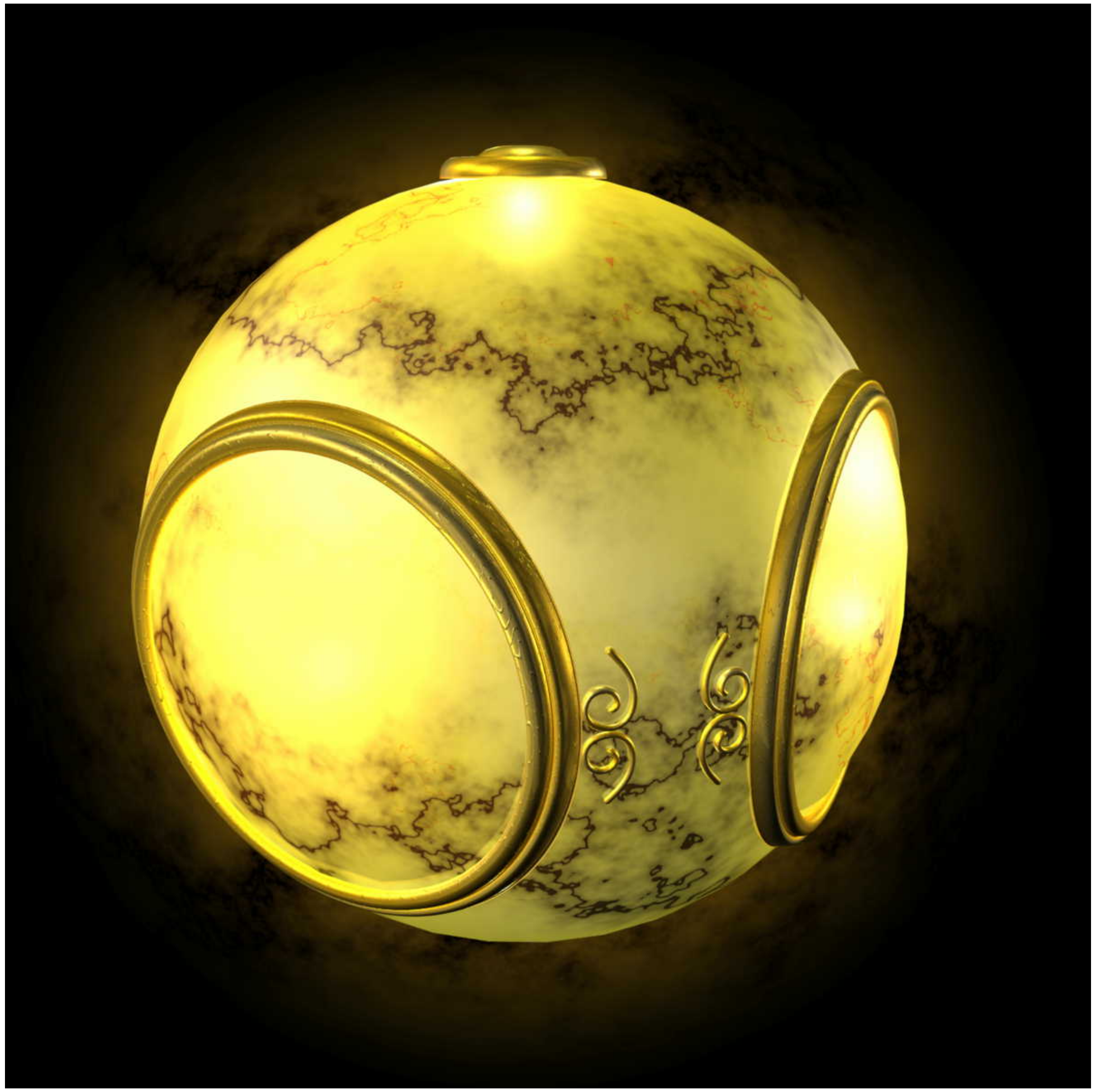
Lighting

CS452/CS552/EE465/EE505: Computer Graphics

Chapter 6 of Angel & Shreiner



When I think of computer graphics, I think of this.



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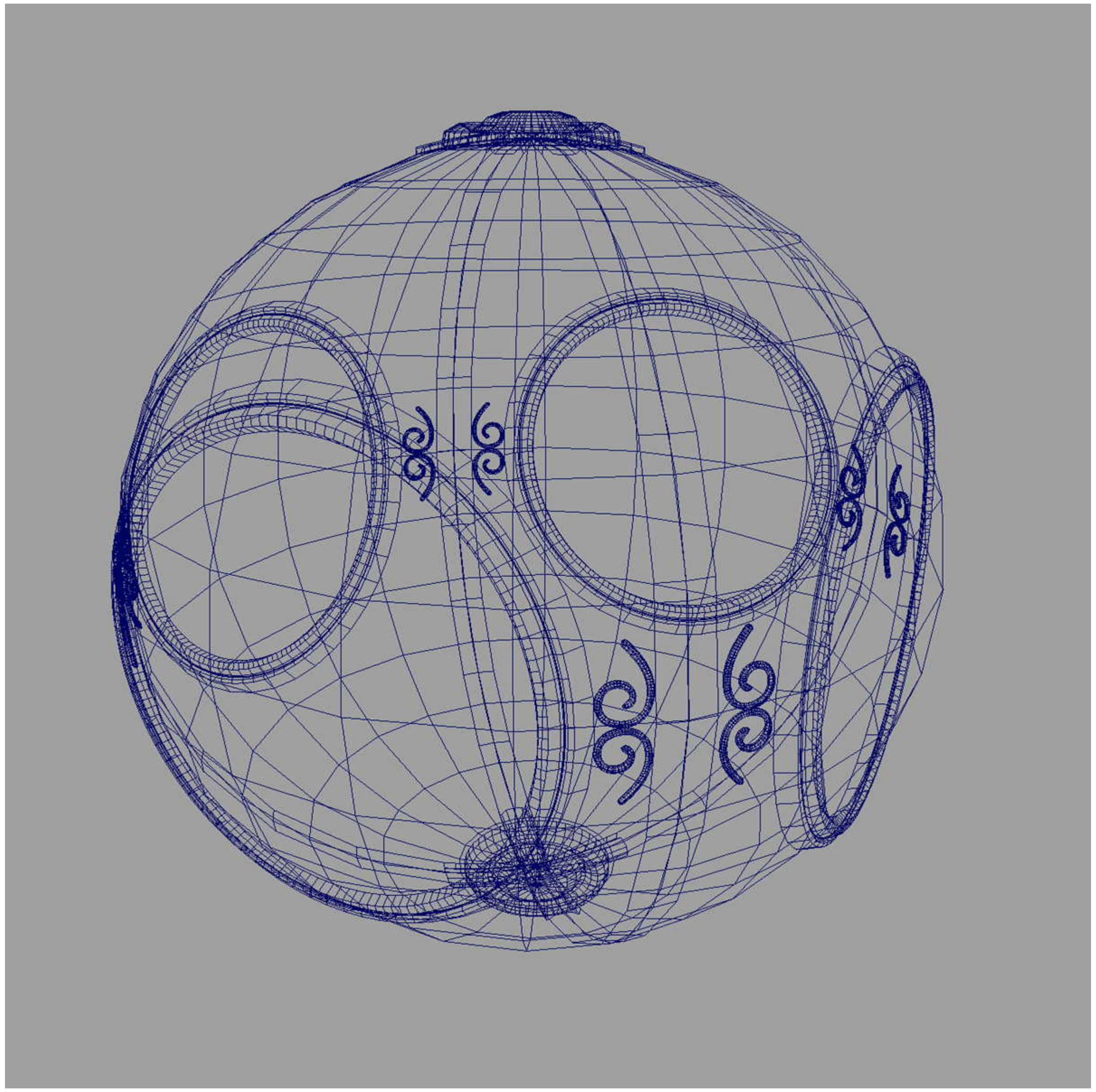
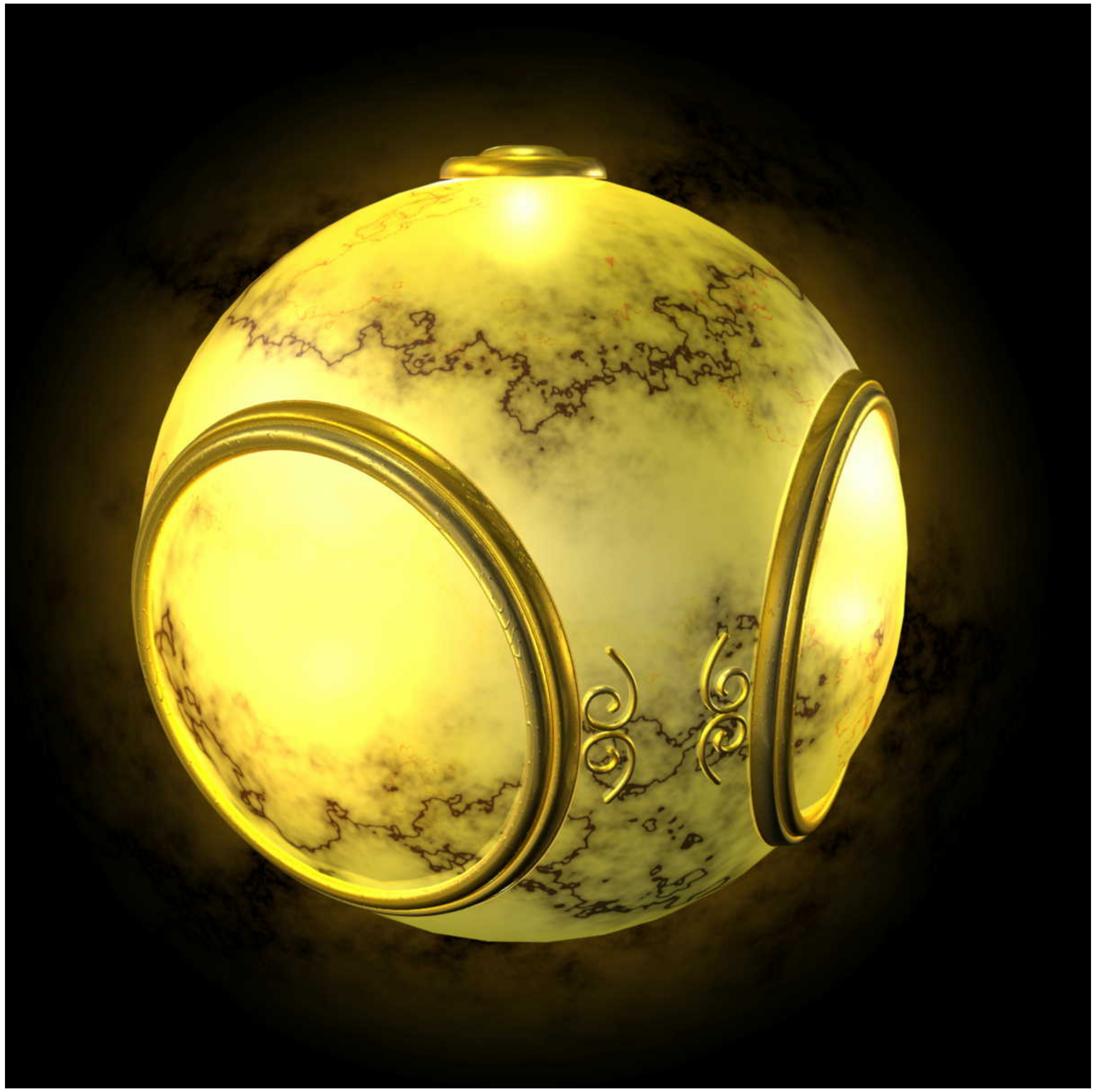
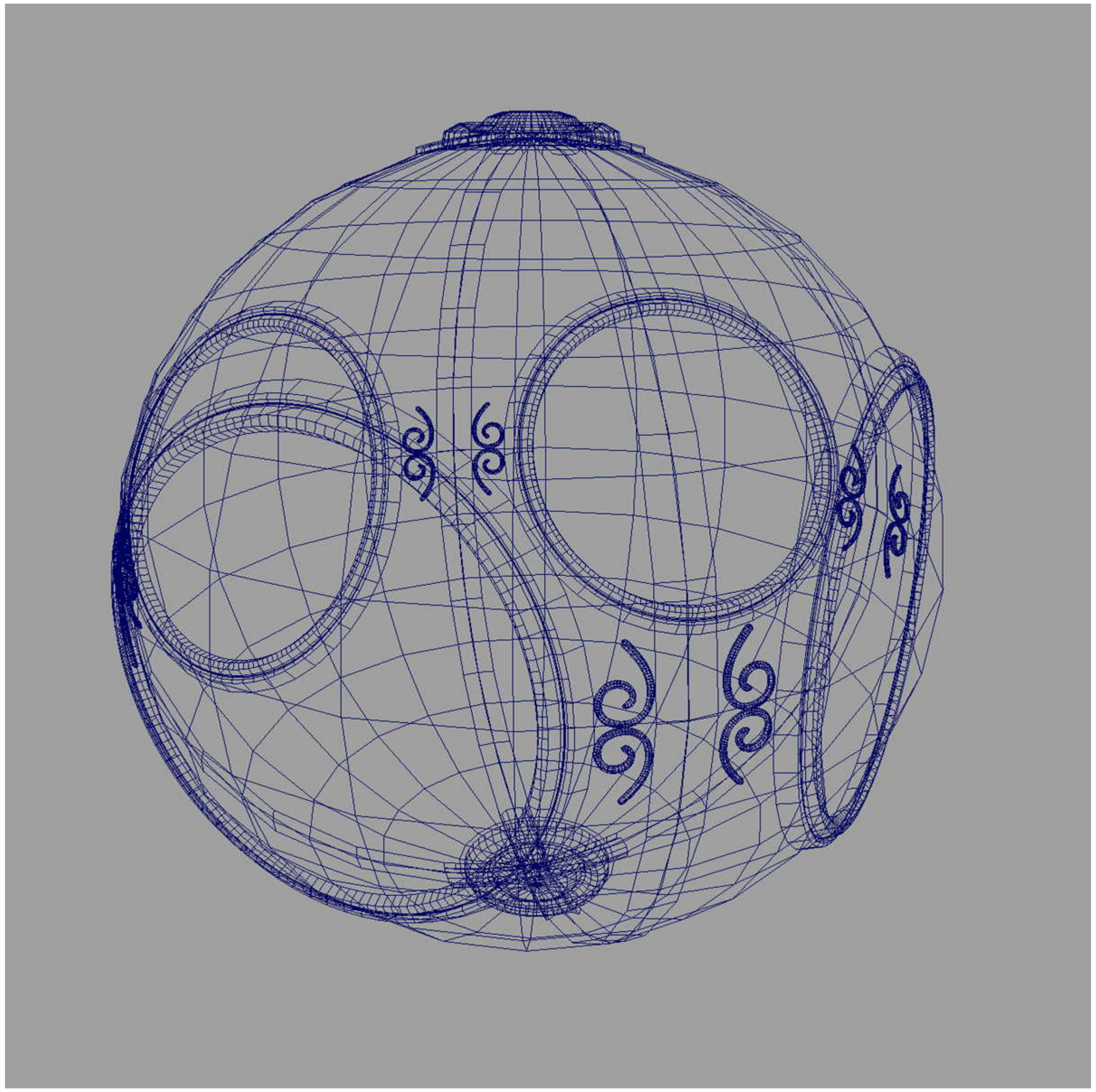


Up until now, here is where we have gotten to (3D shapes).



When I think of computer graphics, I think of this.

To make this, we need **lighting and texture**.



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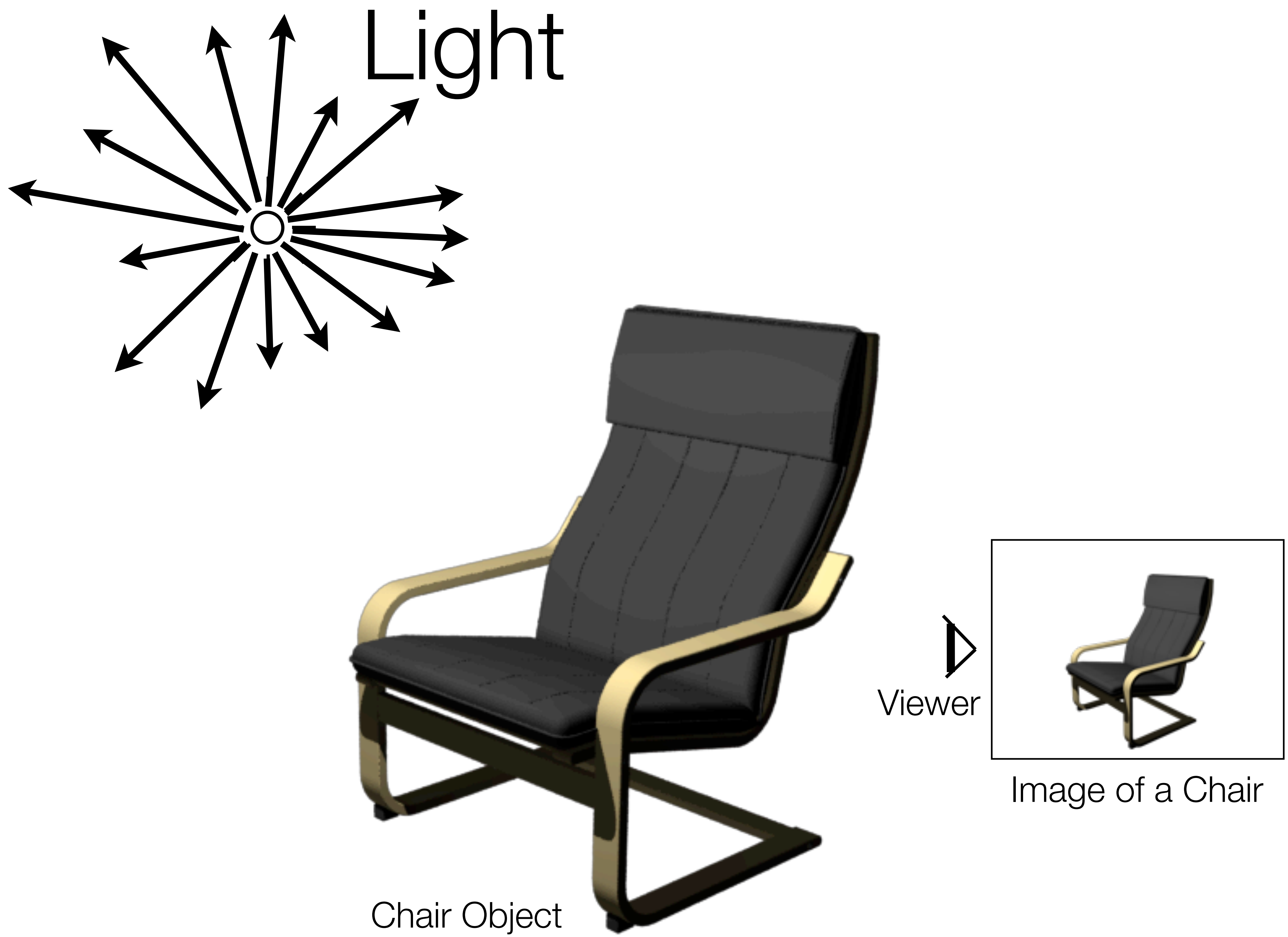
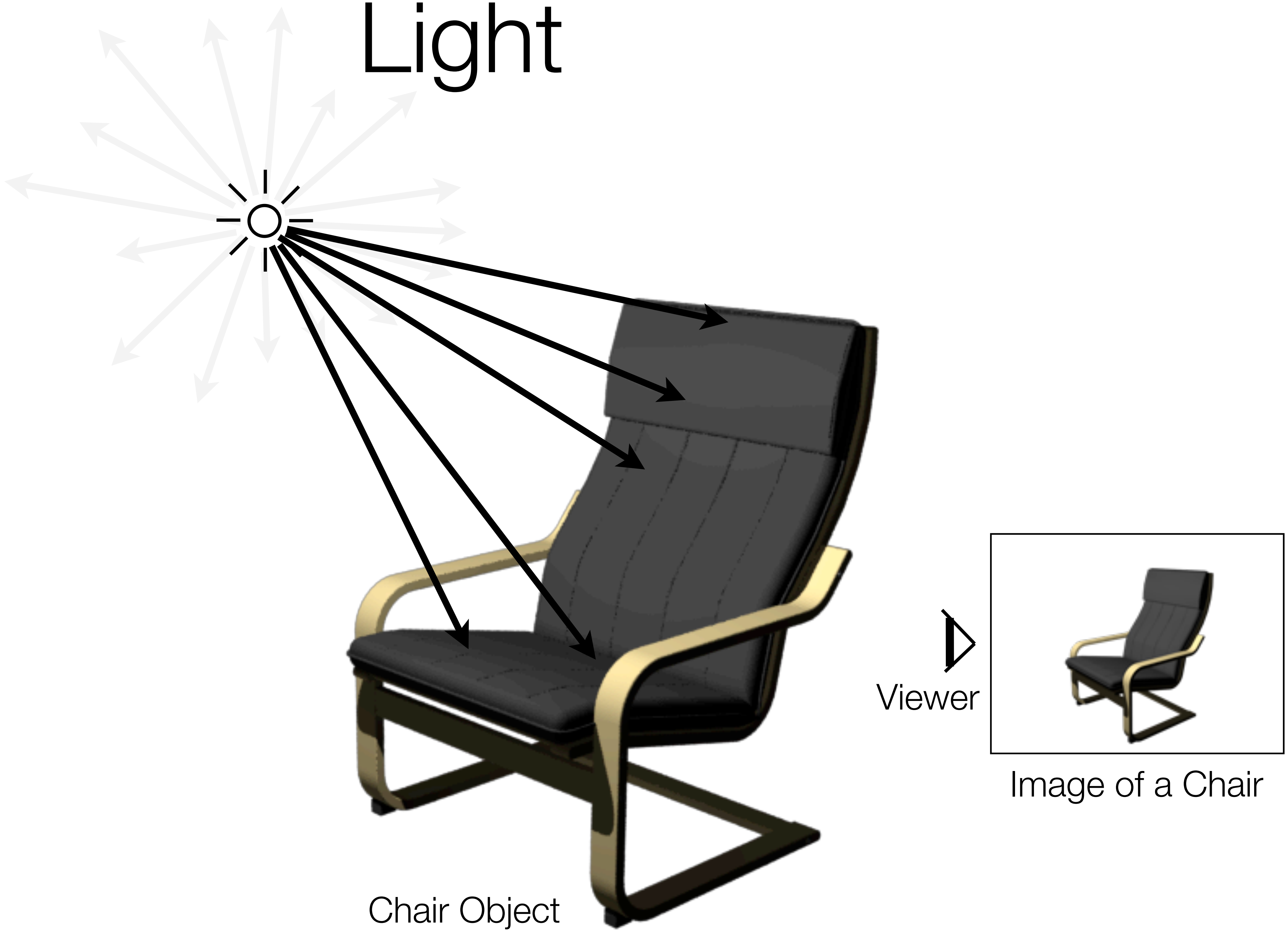


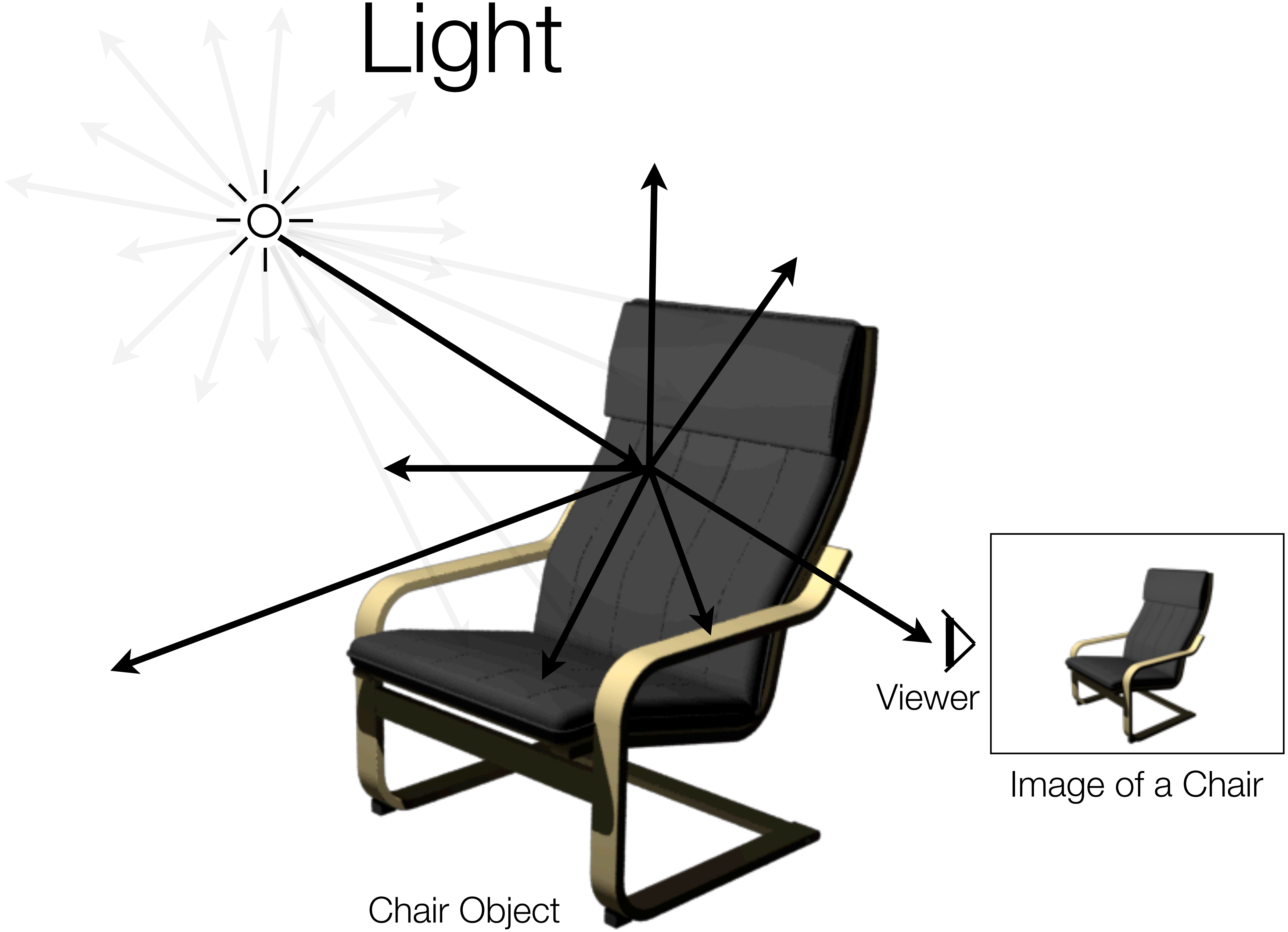
Source Emits Light Rays In Many Directions in 3D

Light

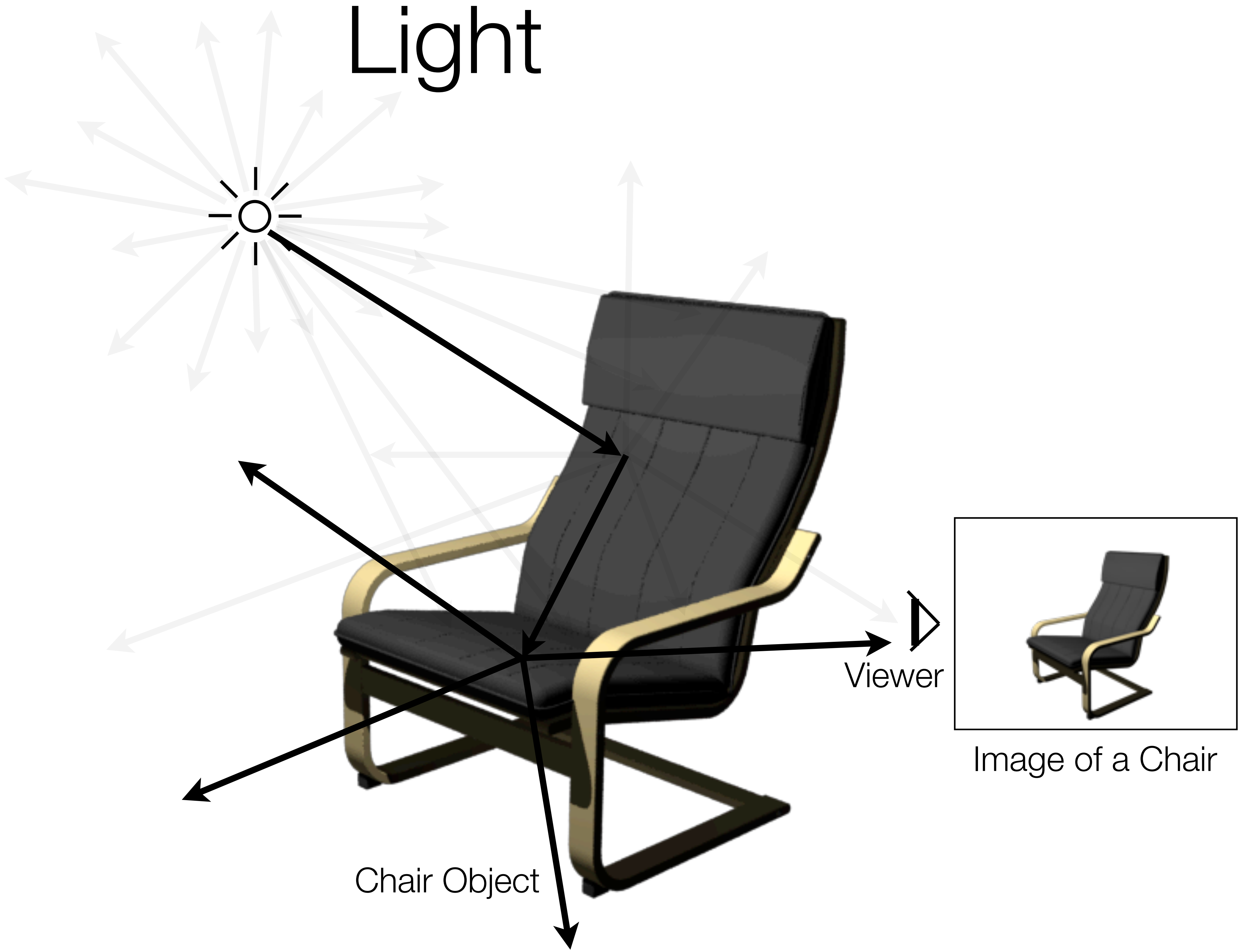


Many Rays From Source Hit Object in 3D

Light

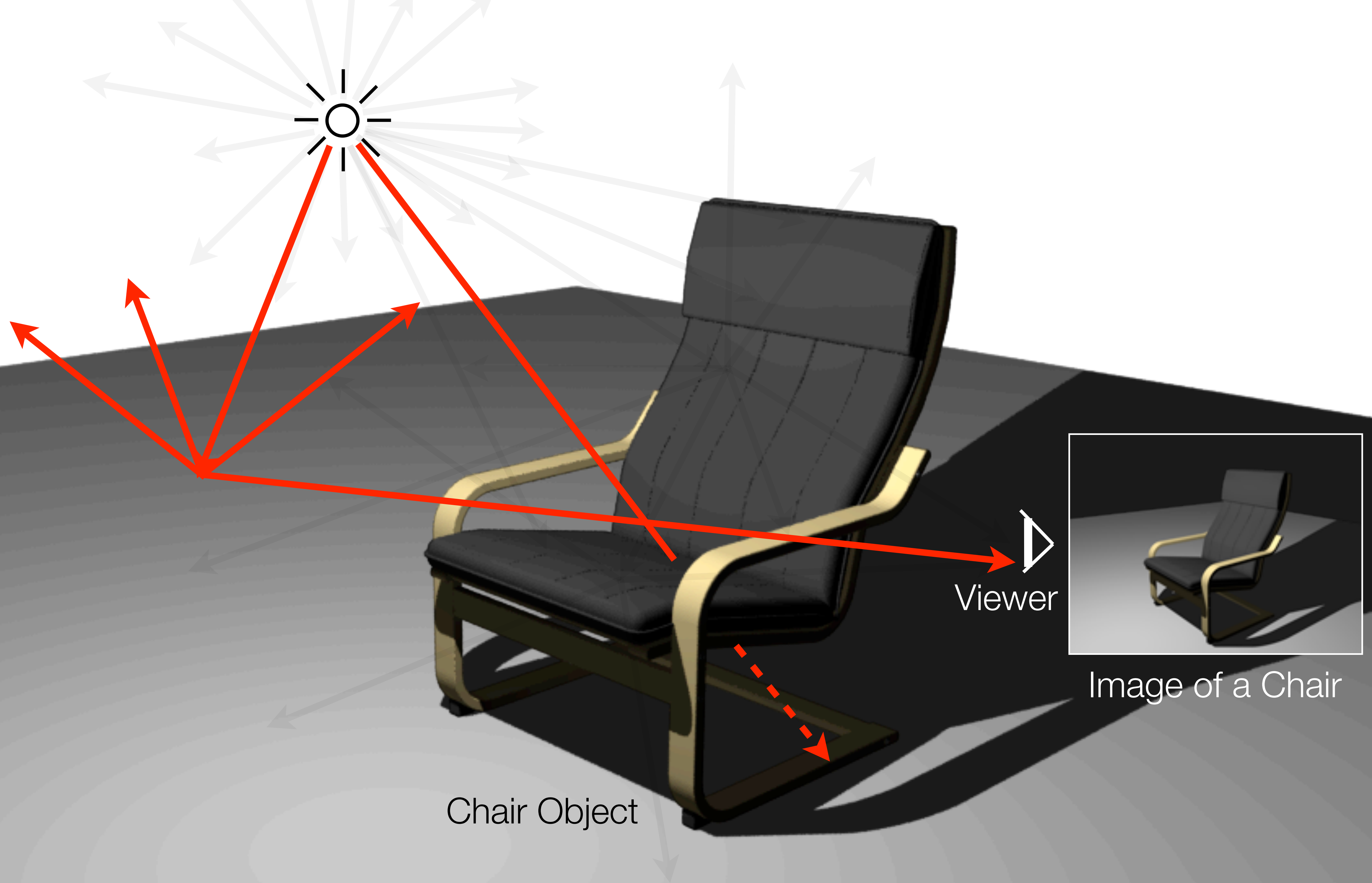


Incident Ray Reflects in Many Directions in 3D

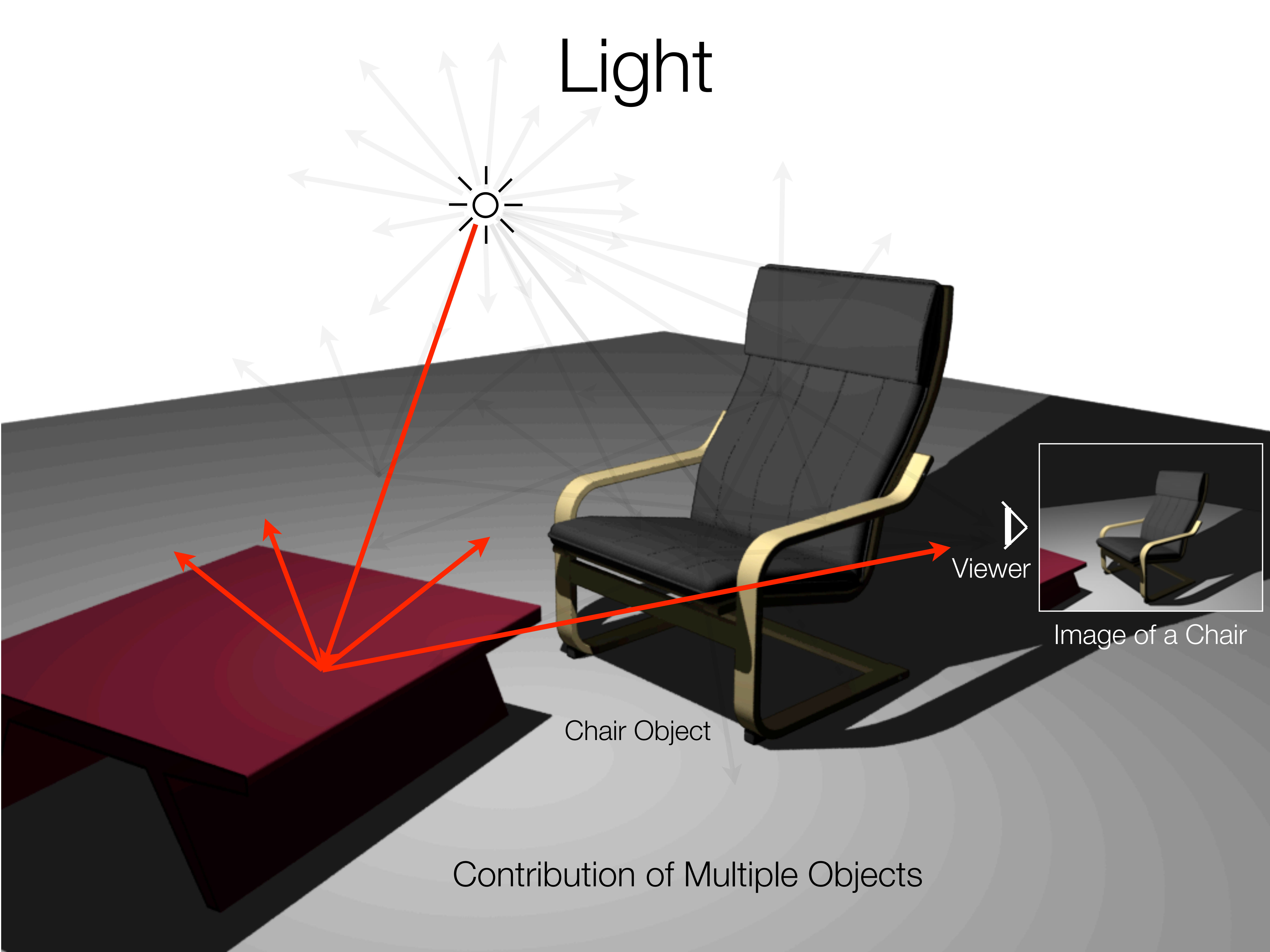


Secondary Reflections from The Same Object in 3D

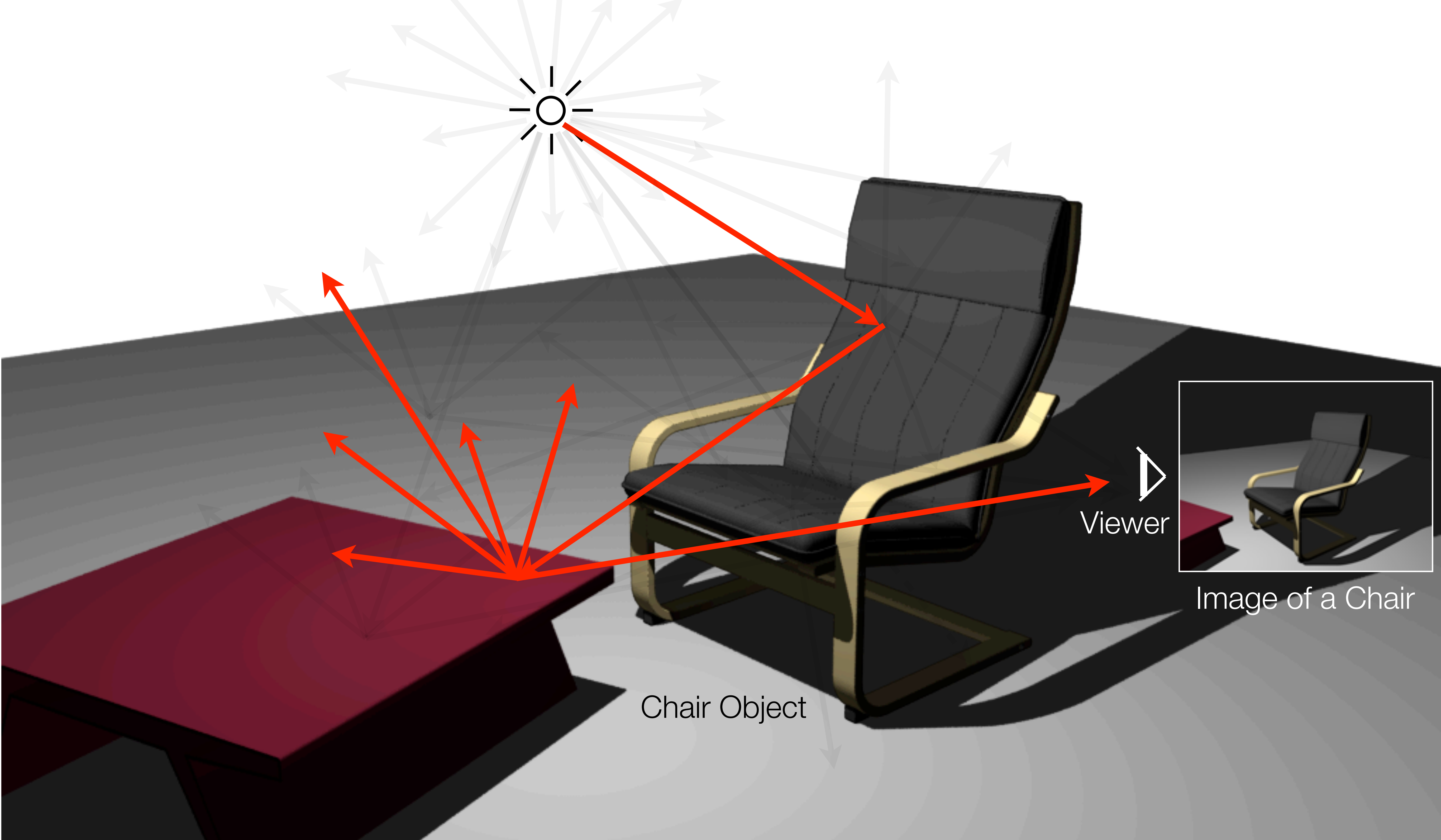
Light



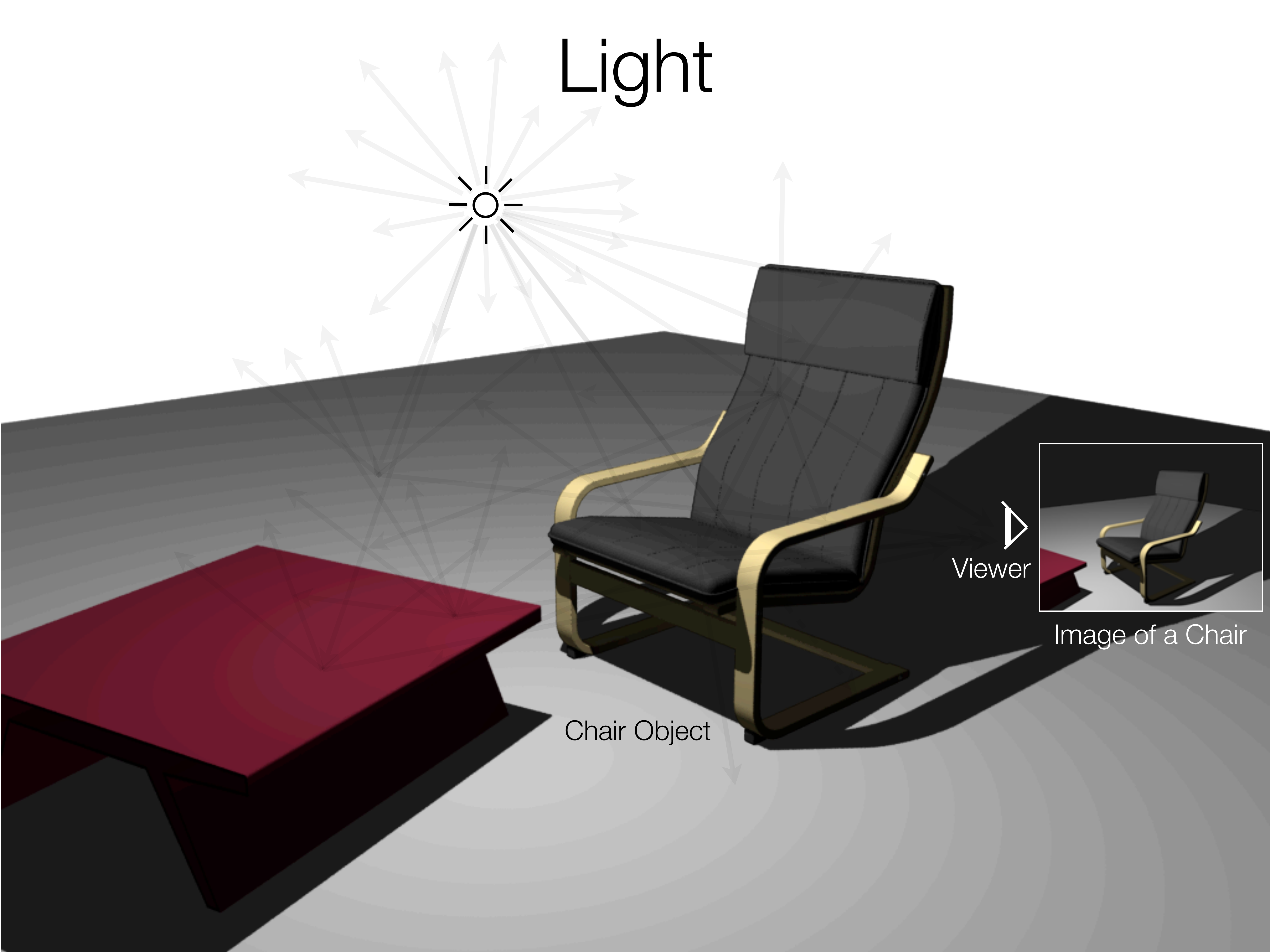
Light Rays Are Obstructed to Form Shadows


Light
Viewer
Image of a Chair
Chair Object
Contribution of Multiple Objects

Light



Contribution of Multiple Objects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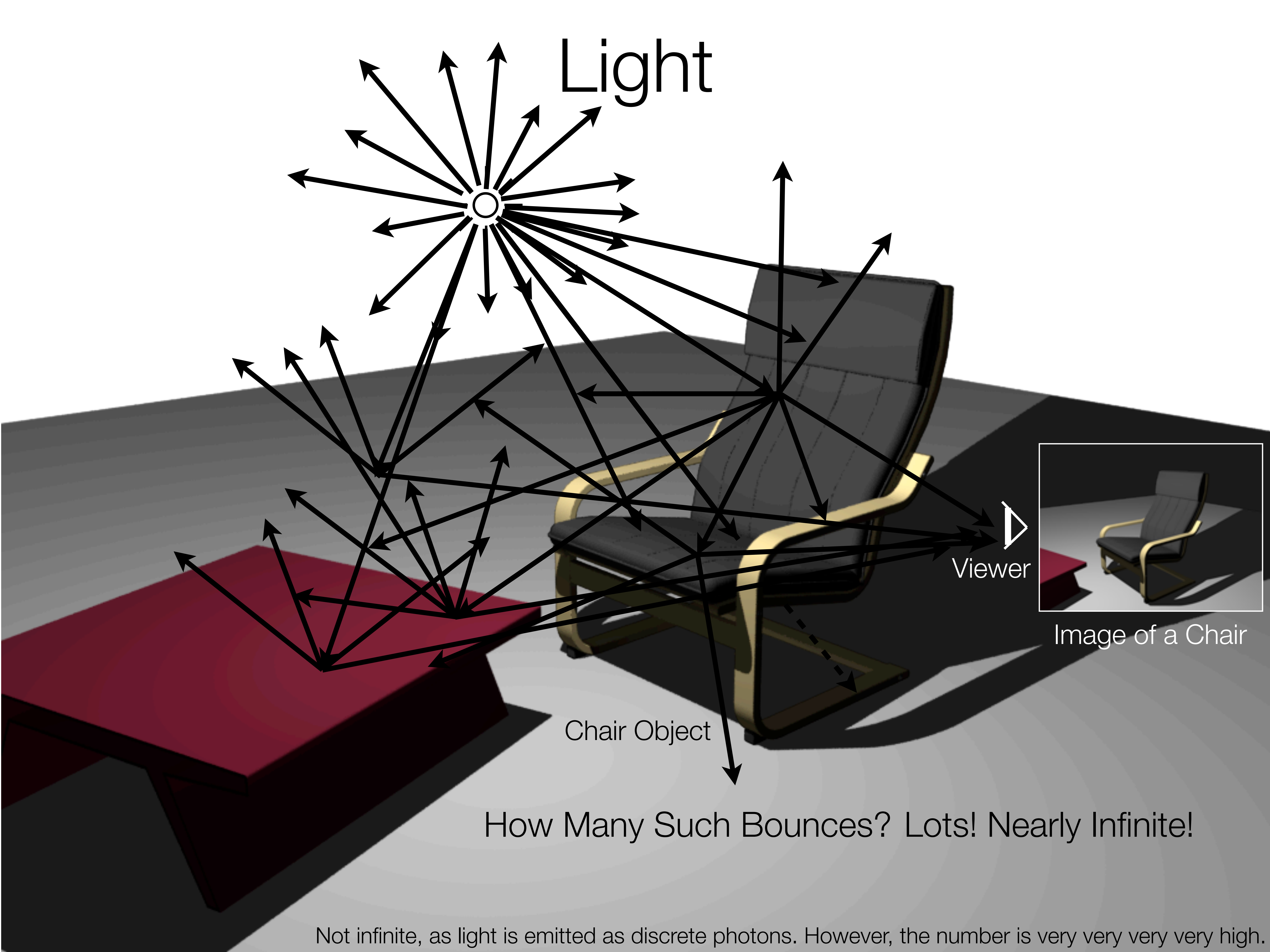
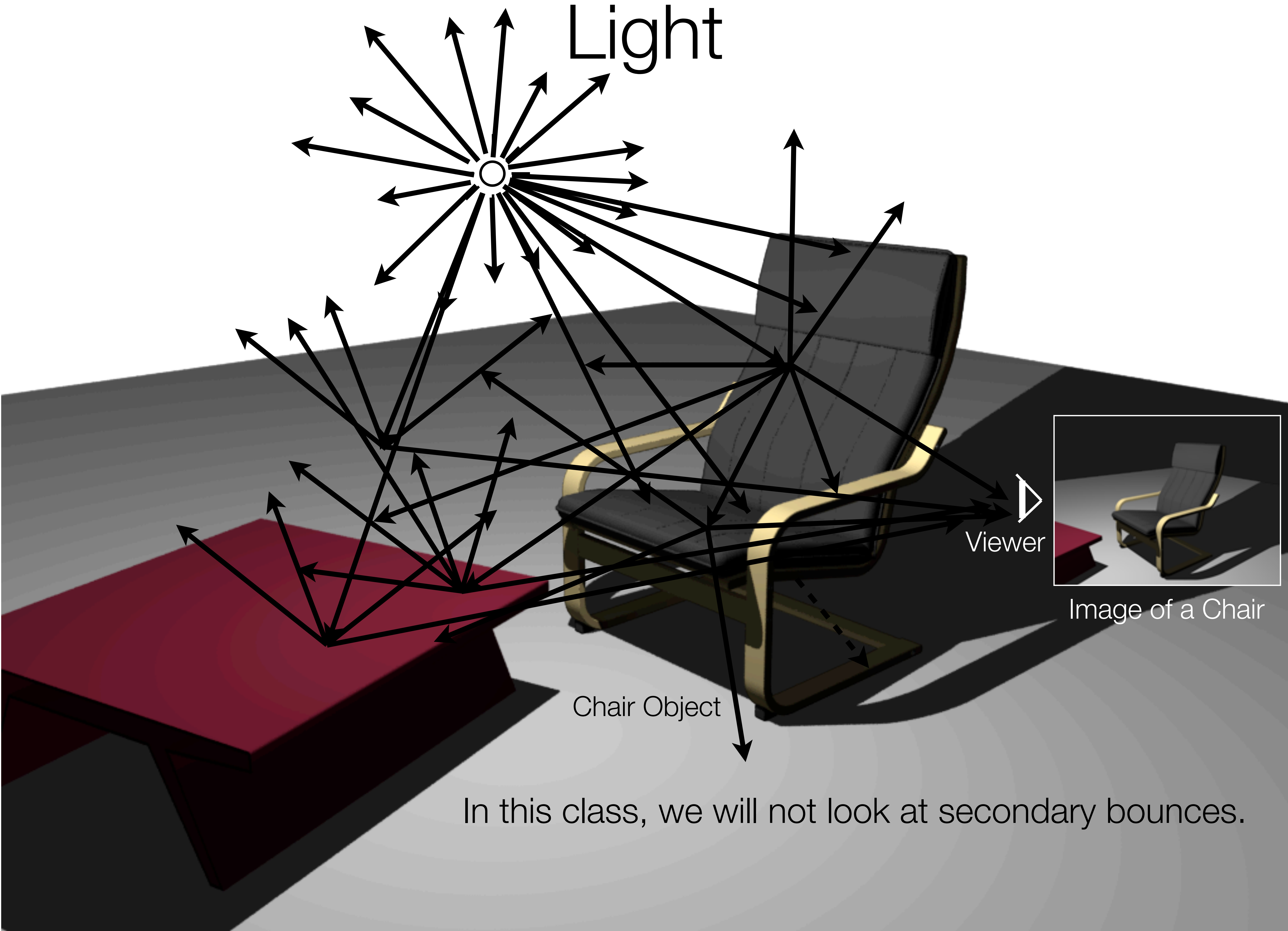
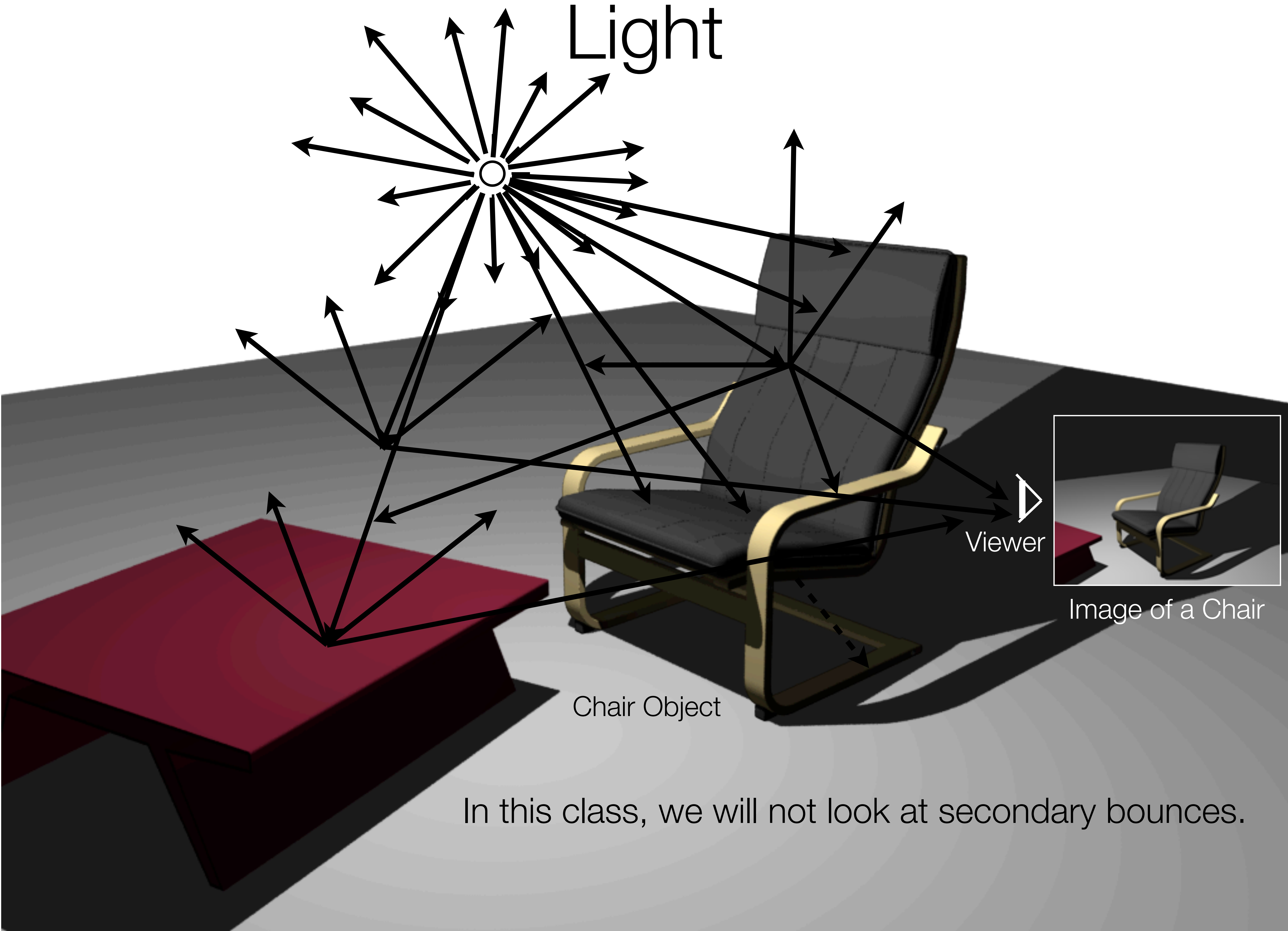

Light
Viewer
Image of a Chair
Chair Object
How Many Such Bounces? Lots! Nearly Infinite!
Not infinite, as light is emitted as discrete photons. However, the number is very very very very high.



In this class, we will not look at secondary bounces.



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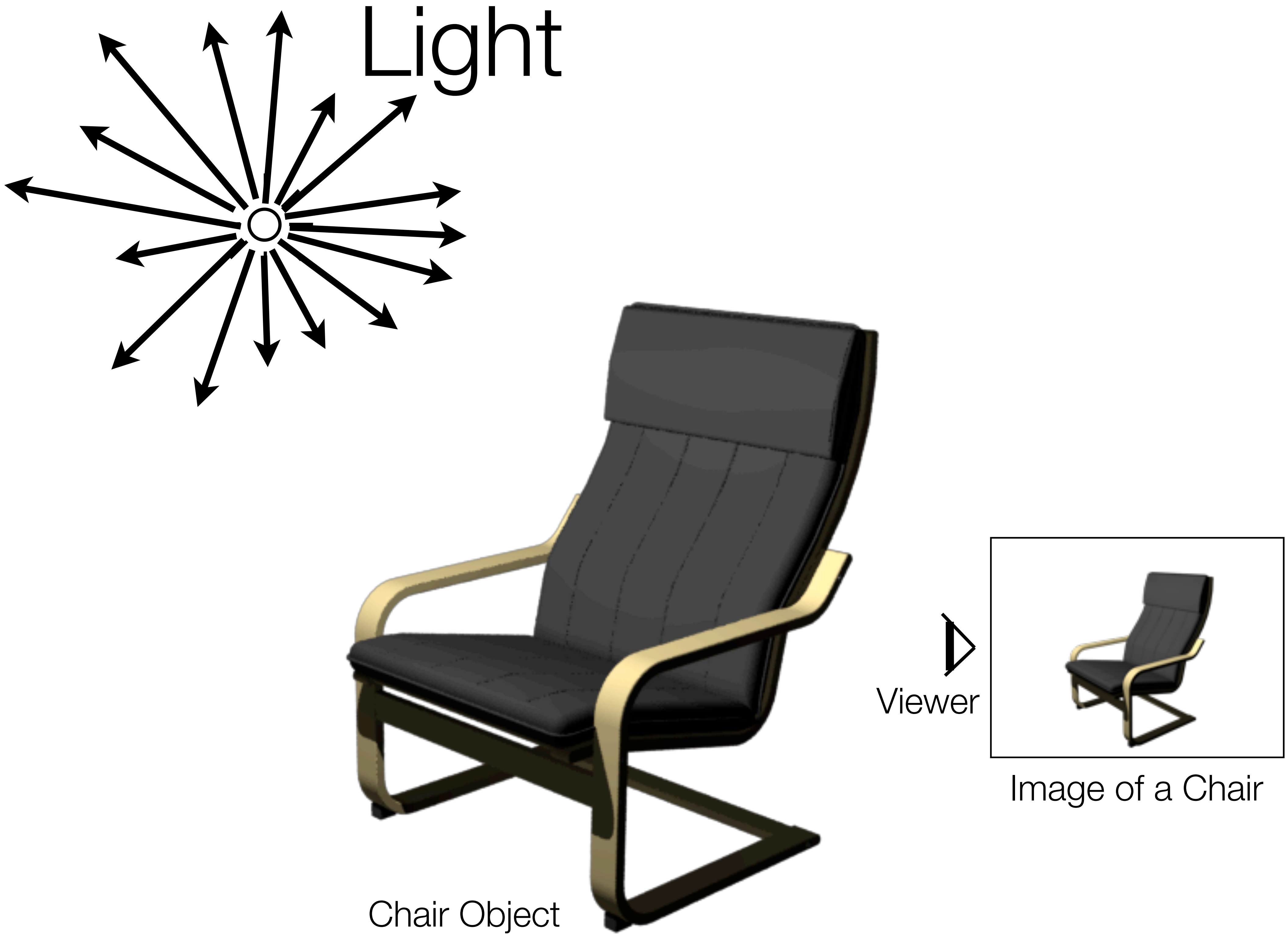

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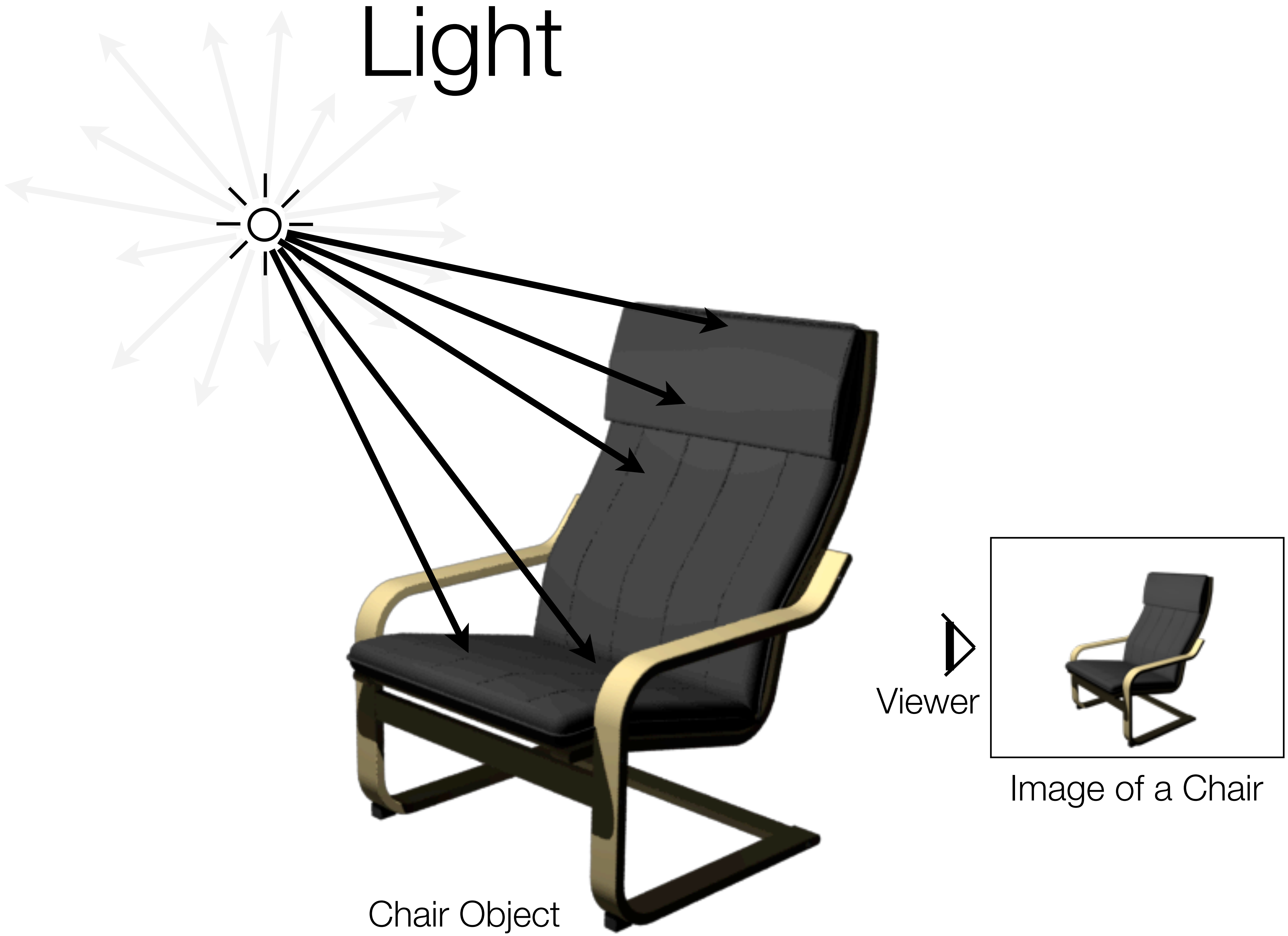

Many Rays From Source Hit Object in 3D

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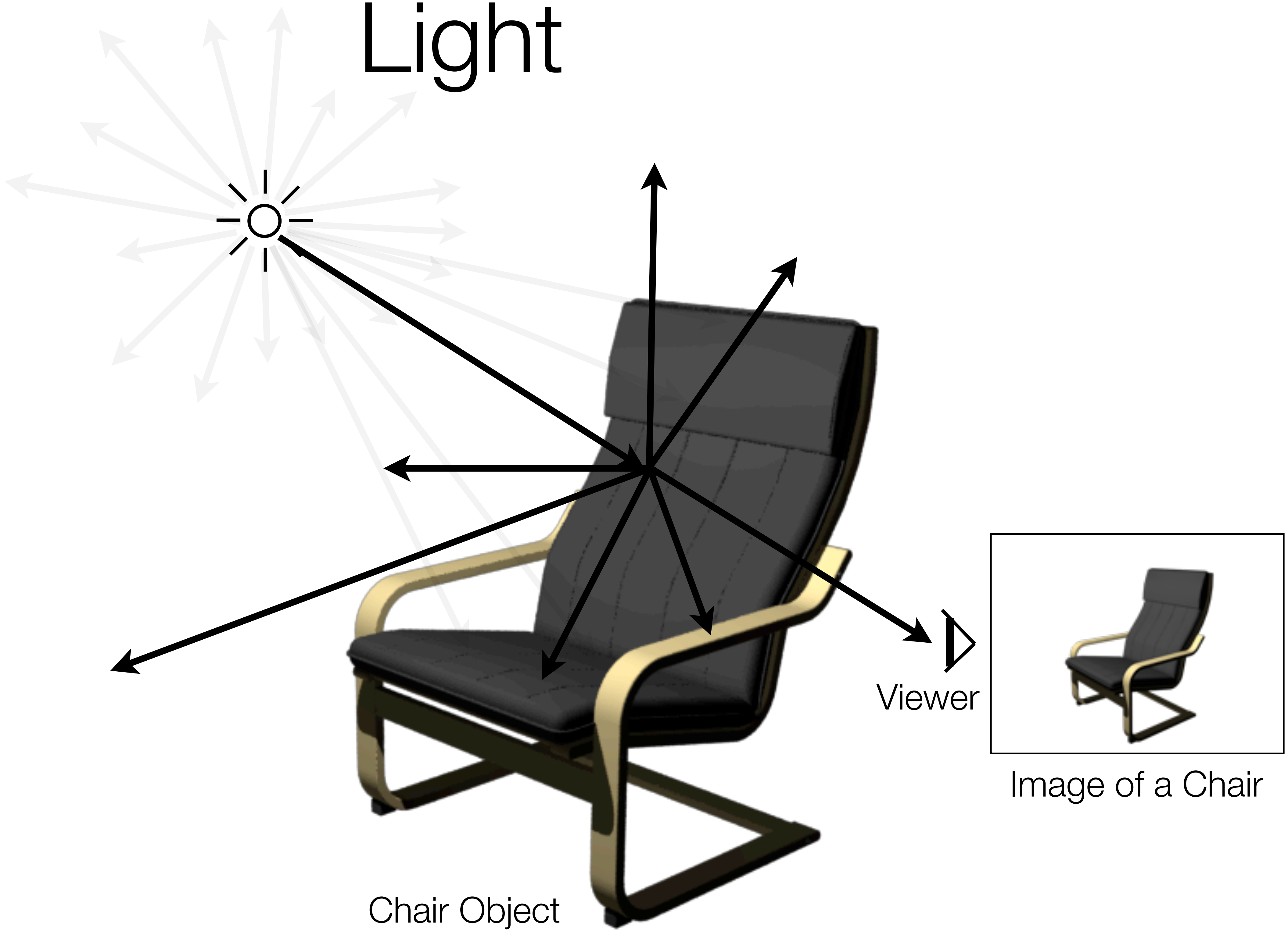

Incident Ray Reflects in Many Directions in 3D

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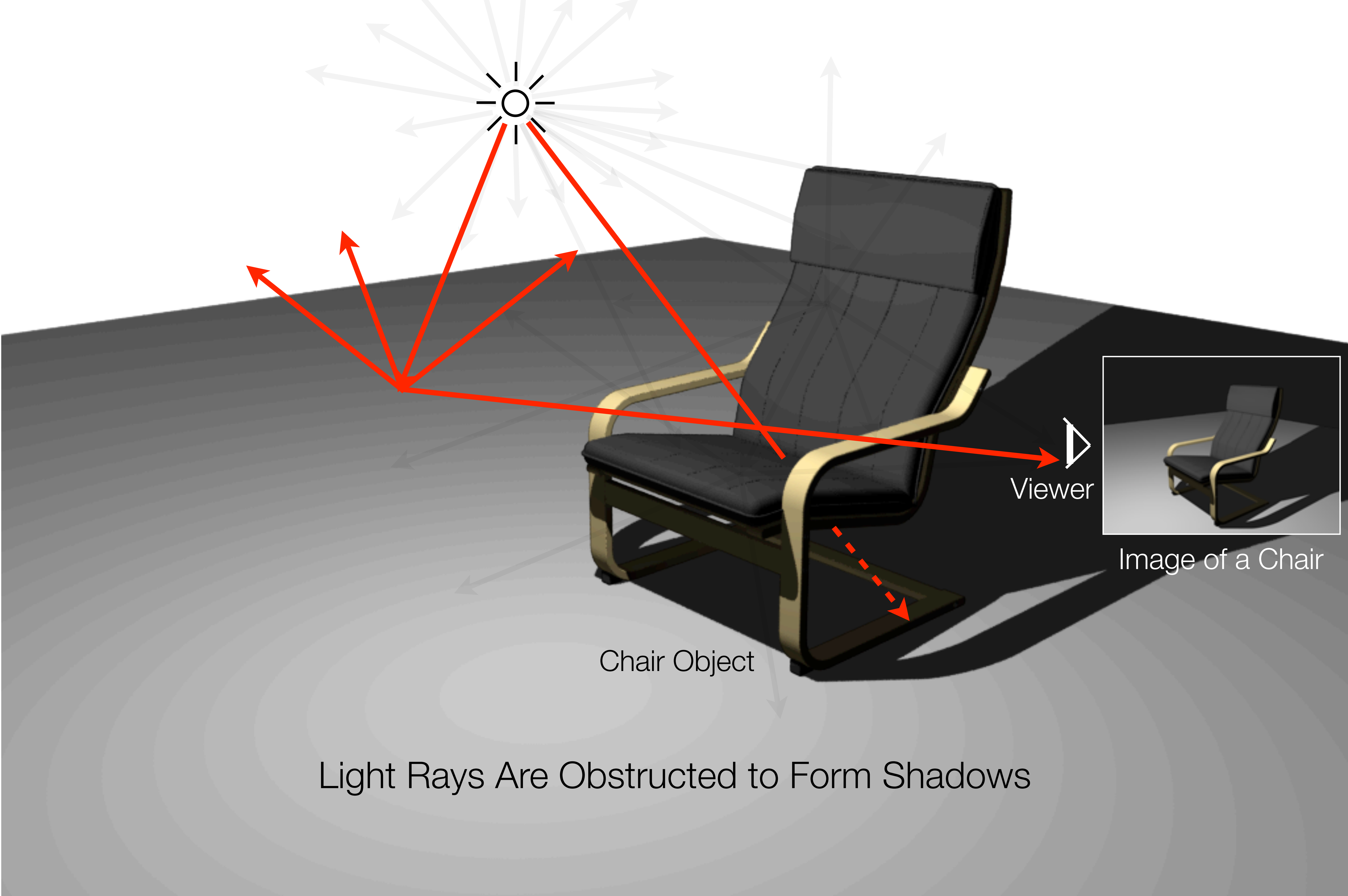
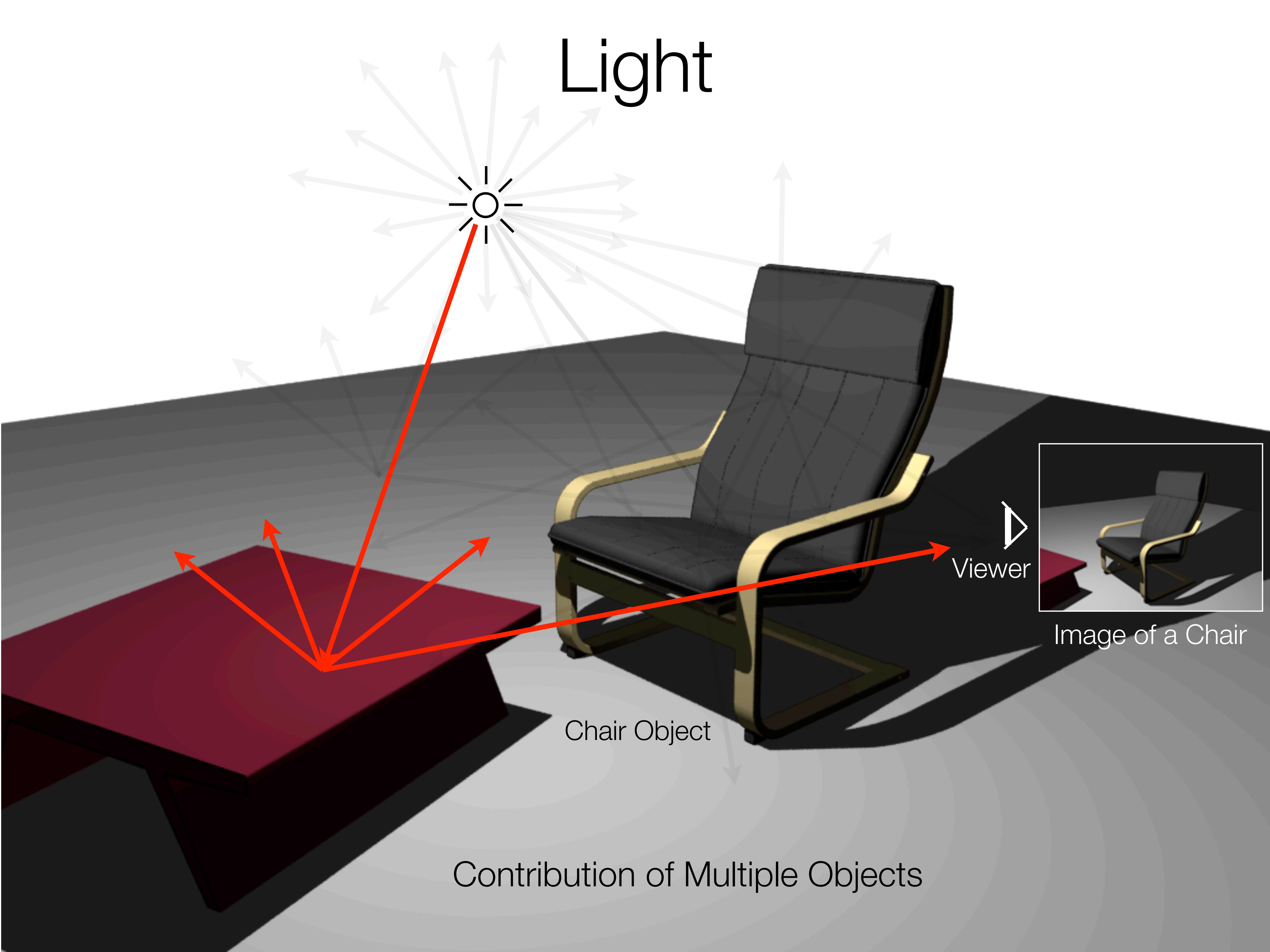
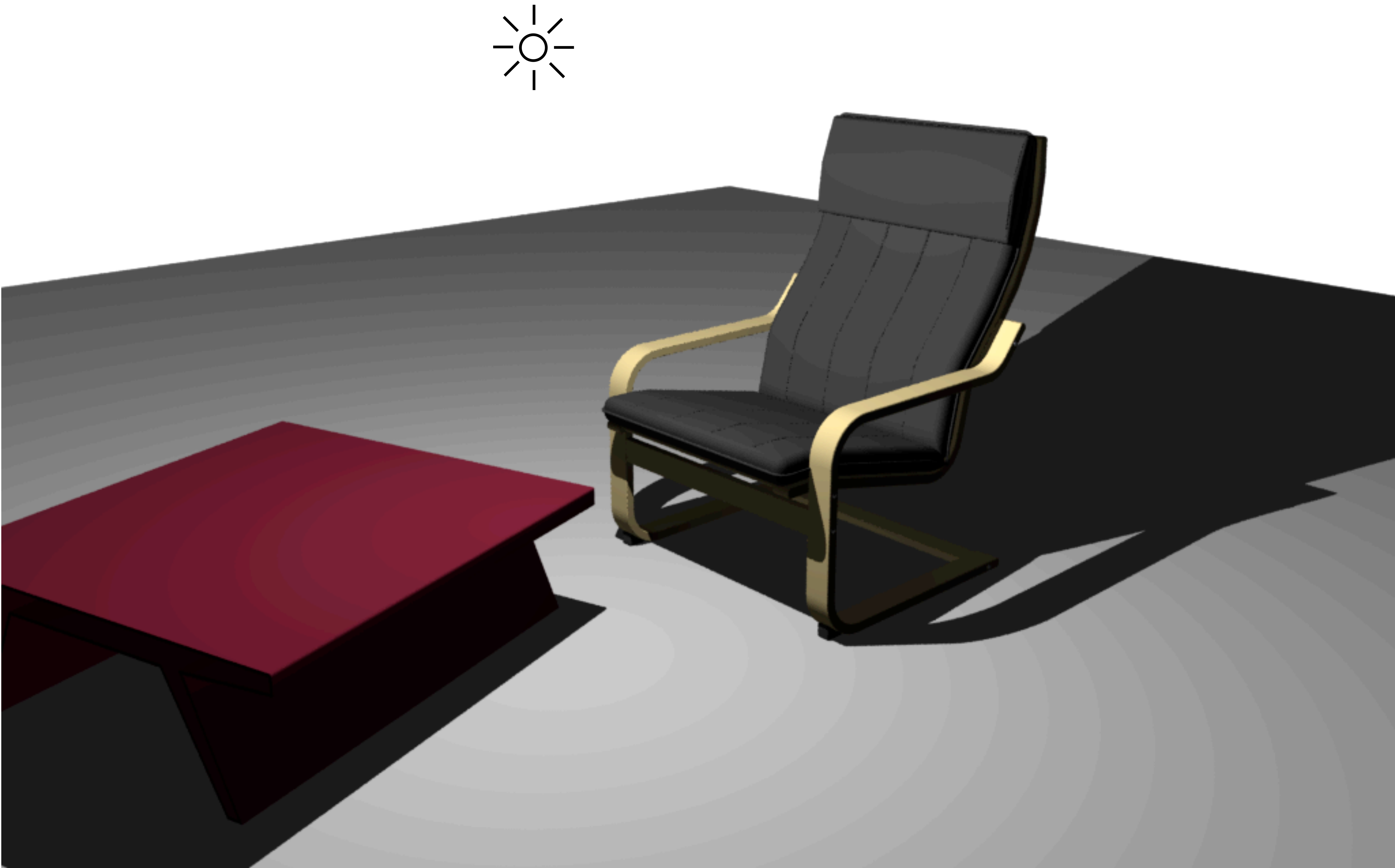


Light Rays Are Obstructed to Form Shadows


Light
Viewer
Image of a Chair
Chair Object
Contribution of Multiple Objects

To light an object,



To light an object,

☼ We need **light sources**,

To light an object,

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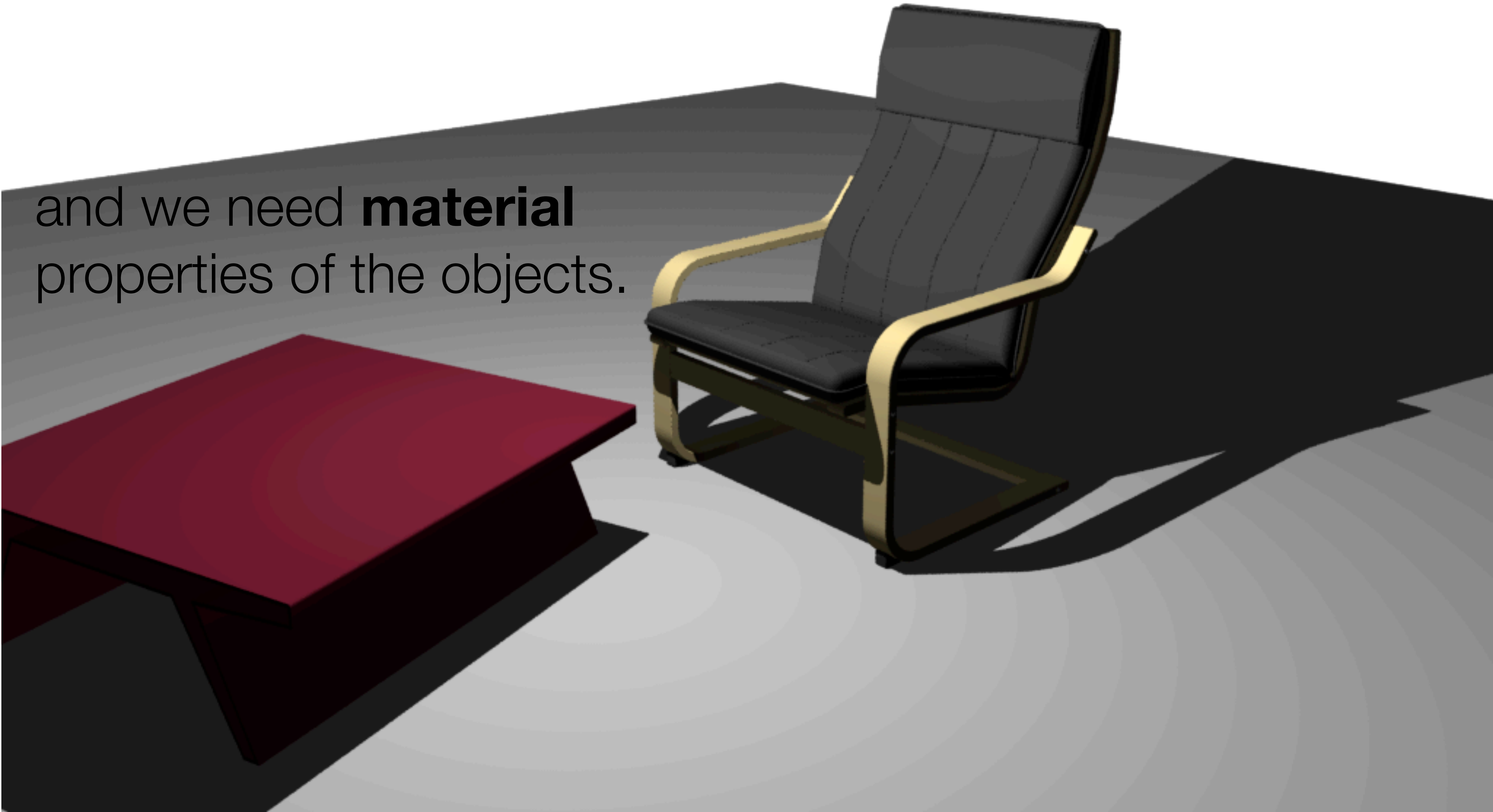

and we need **material** properties of the objects.

Types of Light Sources

Ambient Light

Point Light Sources

Spotlight

Directional (Distant) Light Sources

Types of Light Sources

Ambient Light: Uniform Light Present 'Everywhere'

Most of this room has yellow lighting everywhere.

If you are ambitious, you could either model the yellow lighting from each light source and each wall and ceiling location...

Types of Light Sources

Ambient Light: Uniform Light Present ‘Everywhere’

Most of this room has yellow lighting everywhere.

Or you could just have a single light quantity that represents ambient yellow light everywhere.

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Ambient light has three values: I_{ar}, I_{ag}, I_{ab}

Types of Light Sources

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ambient

Ambient light has three values: I_{ar}, I_{ag}, I_{ab}

red green blue

Types of Light Sources

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Most of this room has yellow lighting everywhere.

Or you could just have a single light quantity that represents ambient yellow light everywhere.

Ambient light has three values: I_{ar}, I_{ag}, I_{ab}

Example: $I_{ar} = 150$, $I_{ag} = 150$, $I_{ab} = 20$.

Types of Light Sources

Ambient Light: Uniform Light Present ‘Everywhere’

Usually, we put all values together as a single vector.

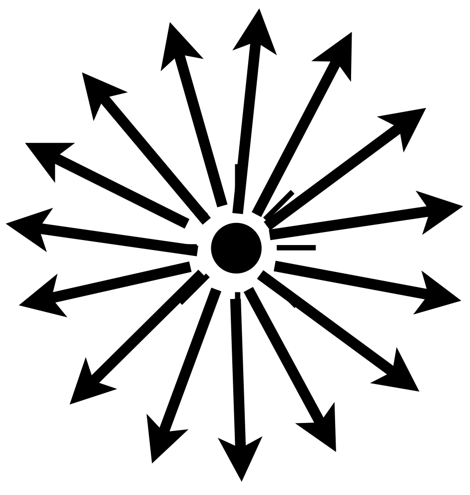
$$\mathbf{I}_a = \begin{bmatrix} I_{ar} \\ I_{ag} \\ I_{ab} \end{bmatrix}$$

Ambient light has three values: I_{ar}, I_{ag}, I_{ab}

Example: $I_{ar} = 150$, $I_{ag} = 150$, $I_{ab} = 20$.

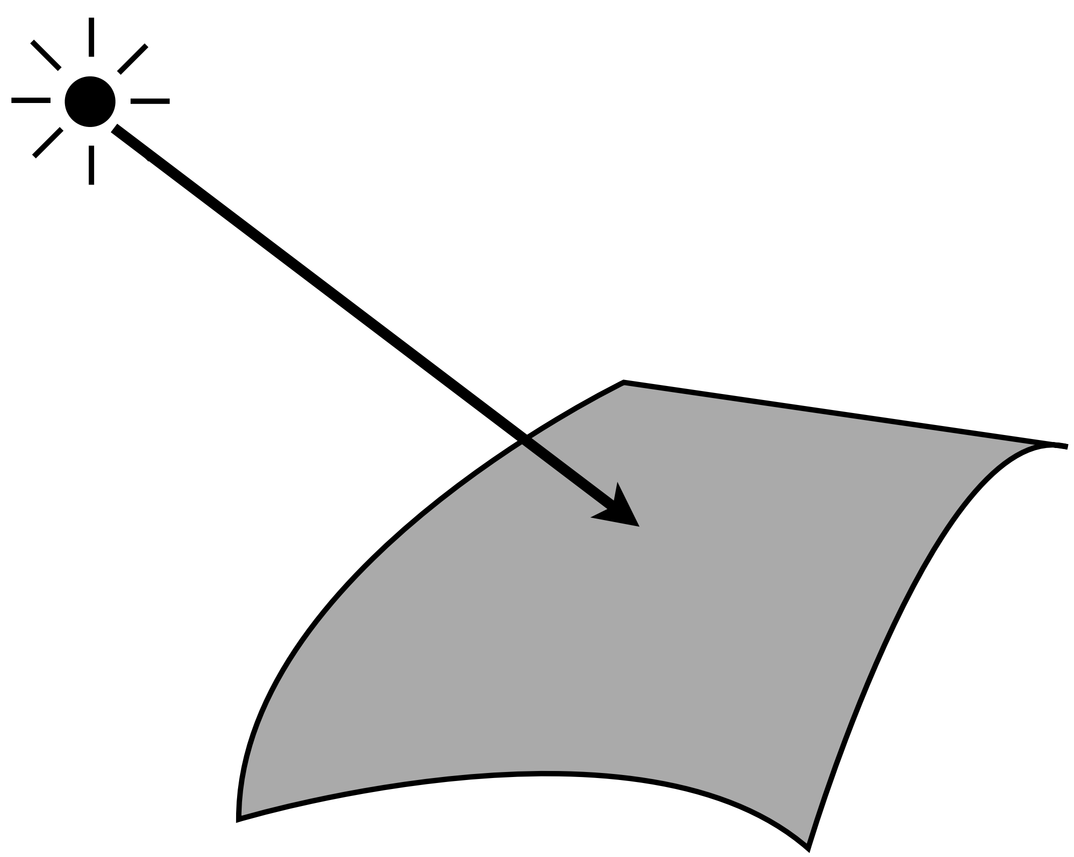
Types of Light Sources

Point Light Source



Types of Light Sources

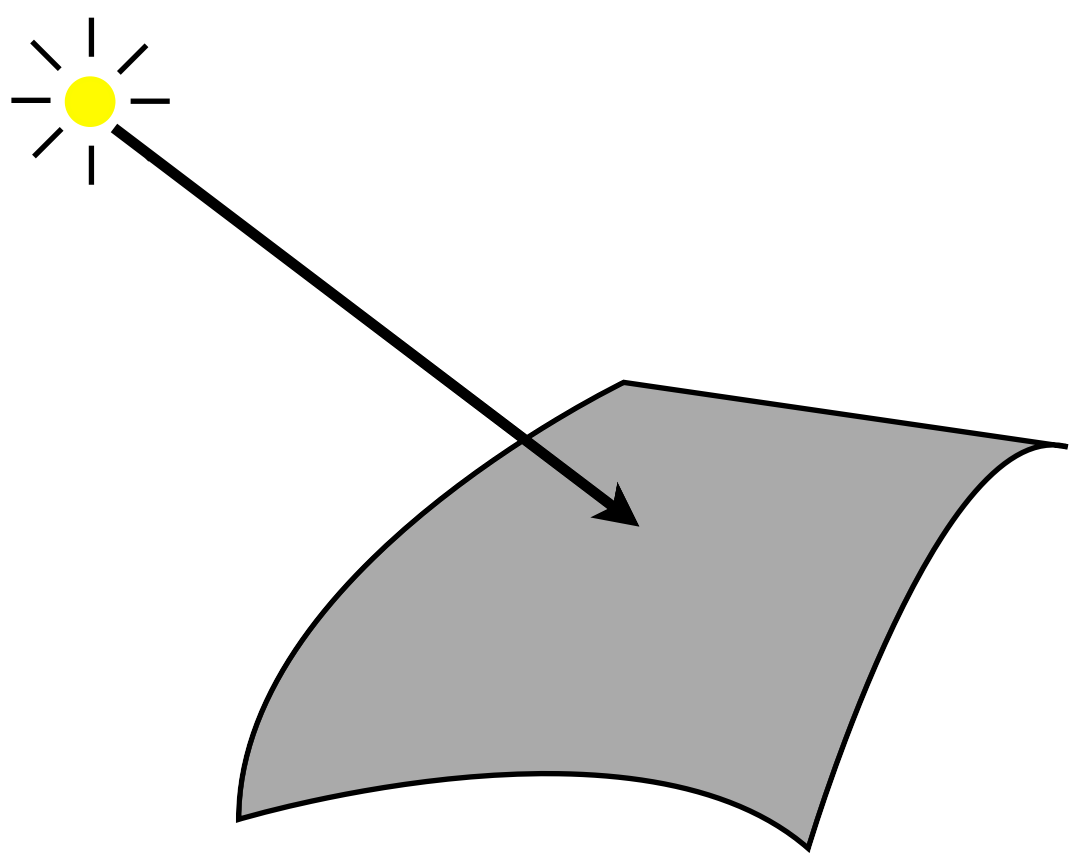
Point Light Source: Brightness falls off with distance



Types of Light Sources

Point Light Source: Brightness falls off with distance

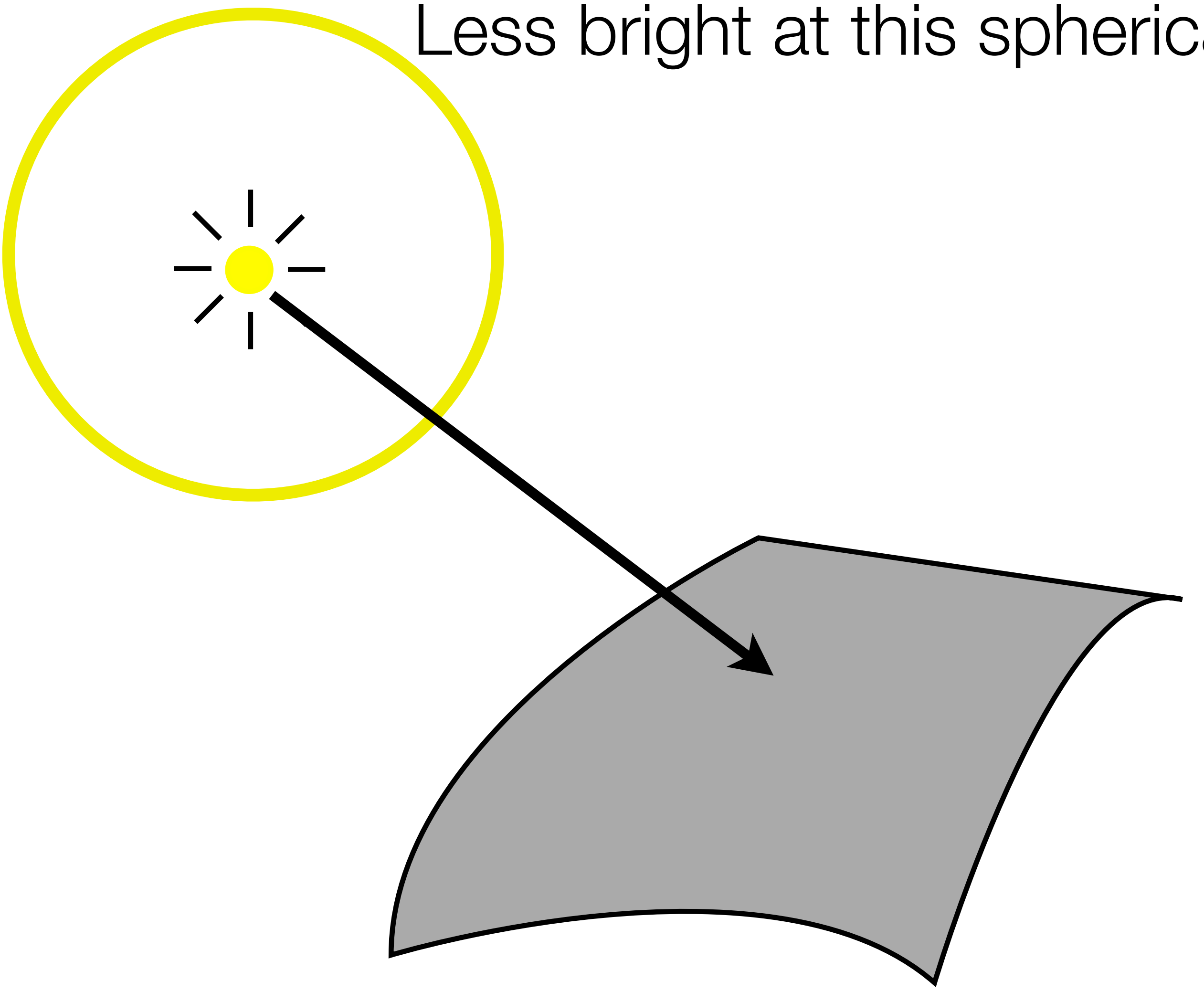
Brightest in the center.



Types of Light Sources

Point Light Source: Brightness falls off with distance

Less bright at this spherical envelope.



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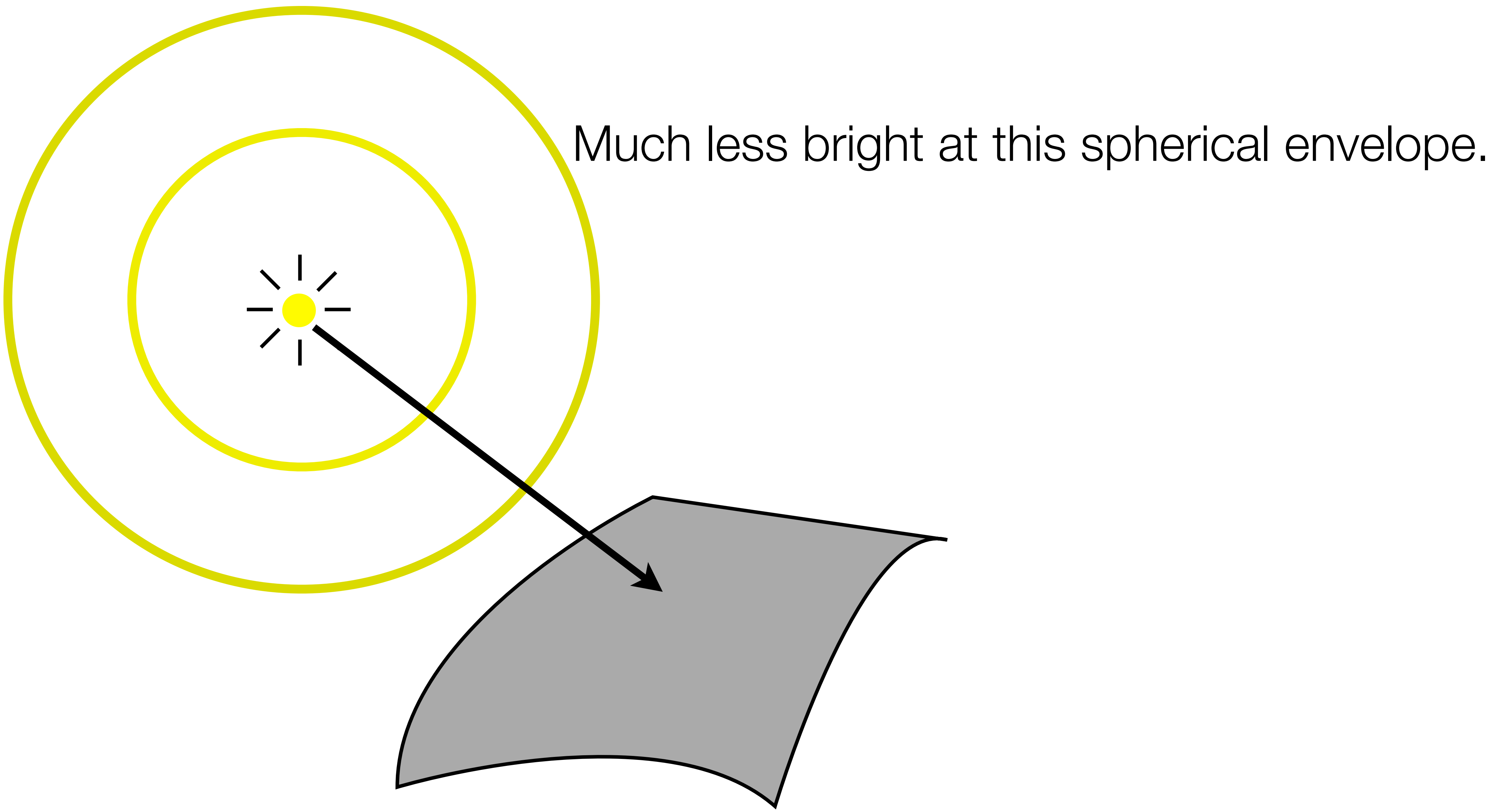

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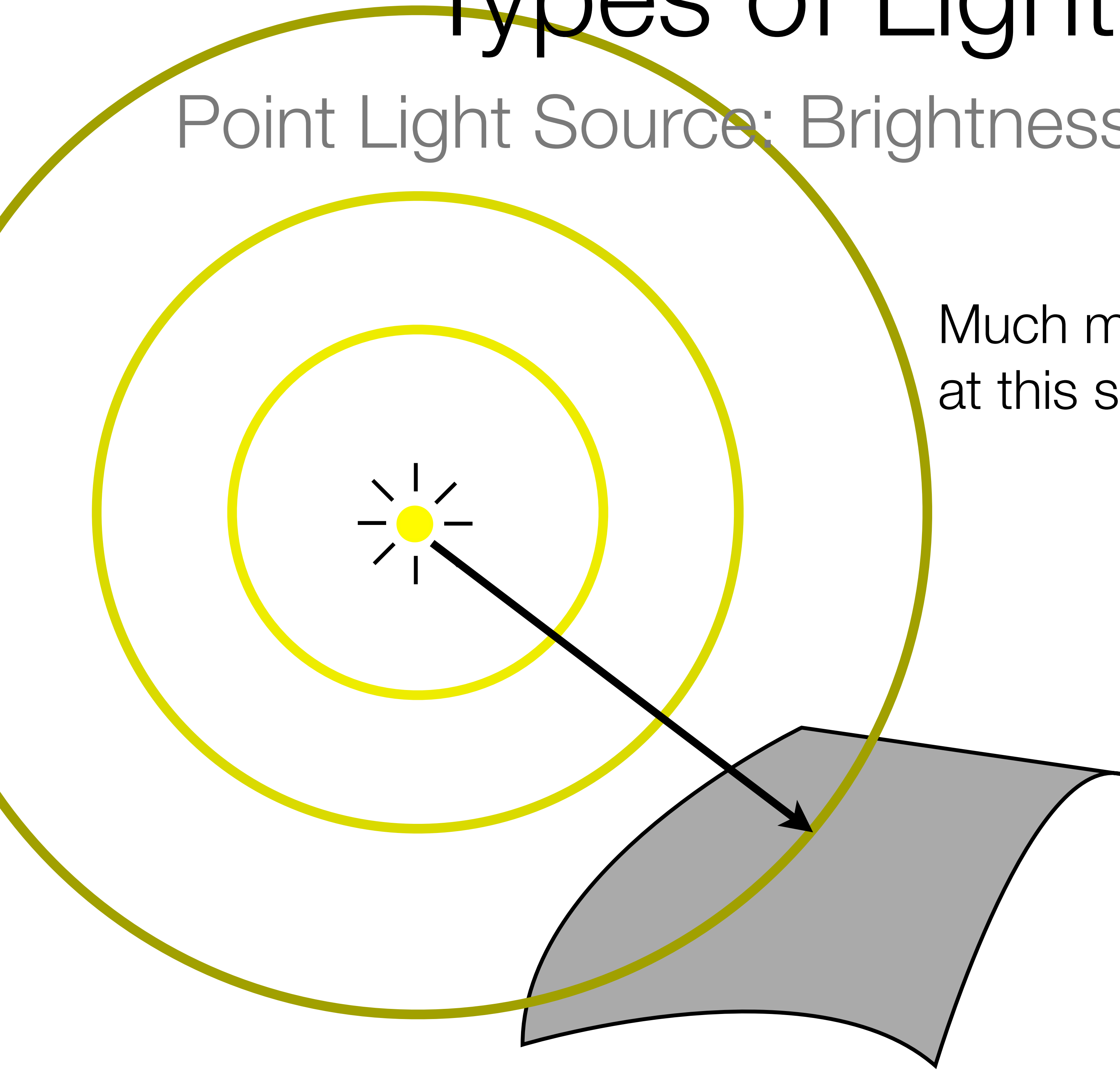
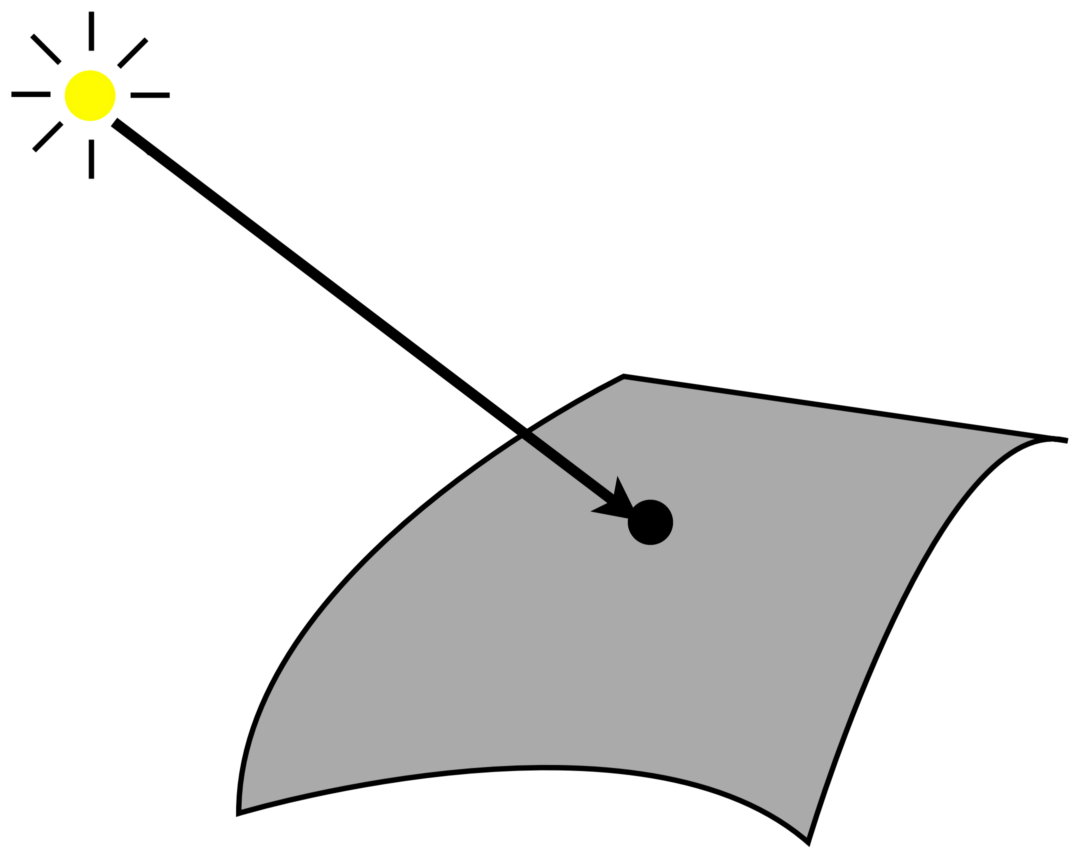


Much much less bright
at this spherical envelope.

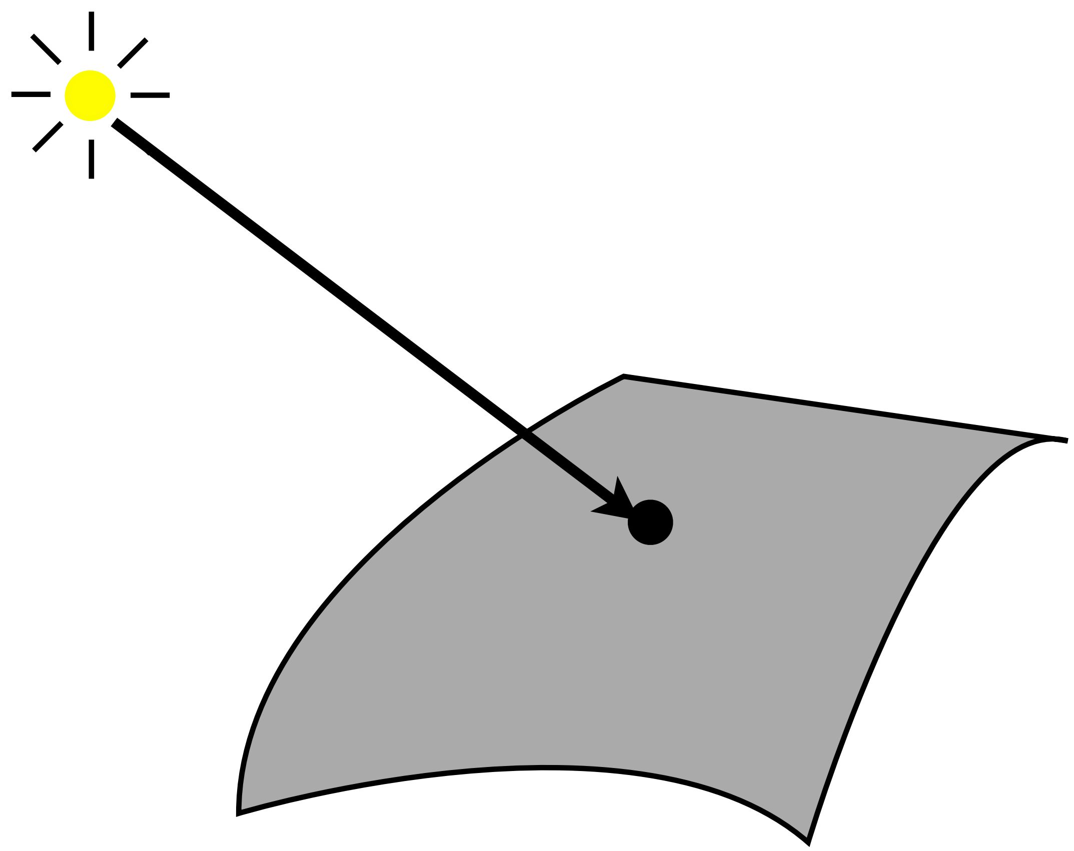
Types of Light Sources

Point Light Source: Brightness falls off with distance



Types of Light Sources

Point Light Source: Brightness falls off as **square** of distance

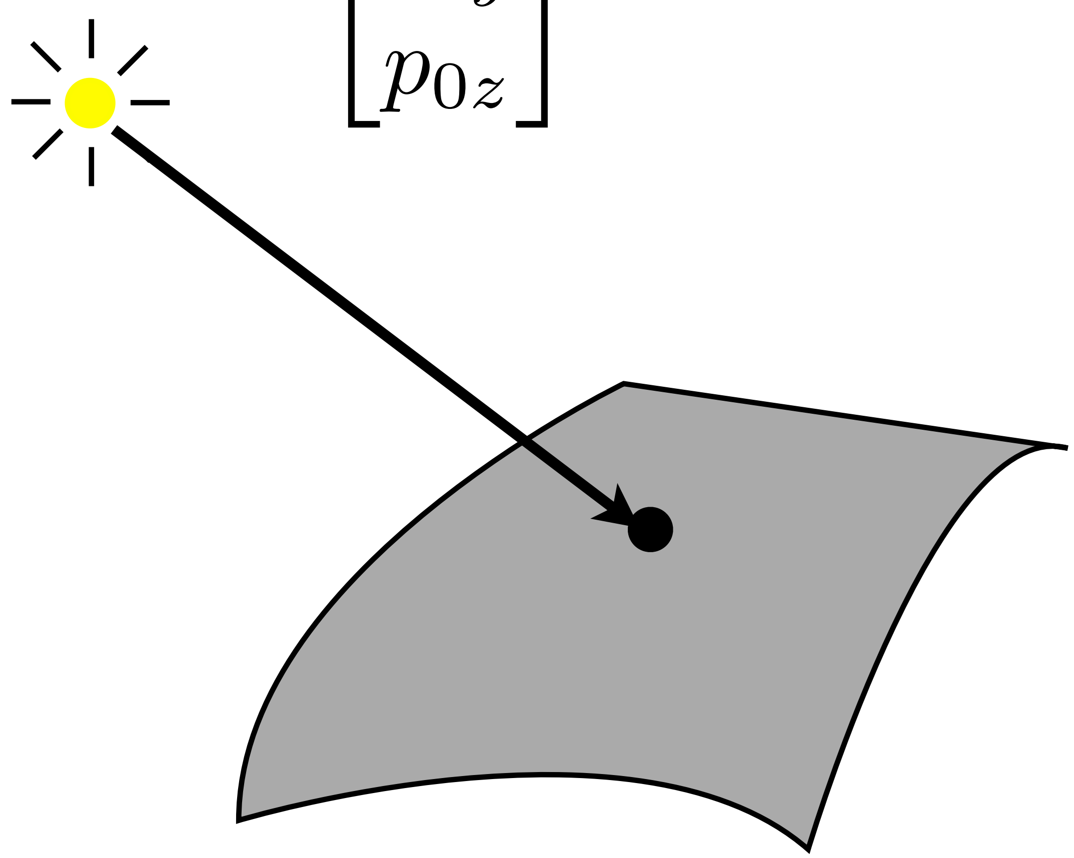


Types of Light Sources

Point Light Source: Brightness falls off as **square** of distance

Source location

$$\mathbf{p}_0 = \begin{bmatrix} p_{0x} \\ p_{0y} \\ p_{0z} \end{bmatrix}$$



Brightness at source location $\mathbf{p}_0$:

$$\mathbf{I}(\mathbf{p}_0) = \begin{bmatrix} I_r(\mathbf{p}_0) \\ I_g(\mathbf{p}_0) \\ I_b(\mathbf{p}_0) \end{bmatrix}$$

Types of Light Sources

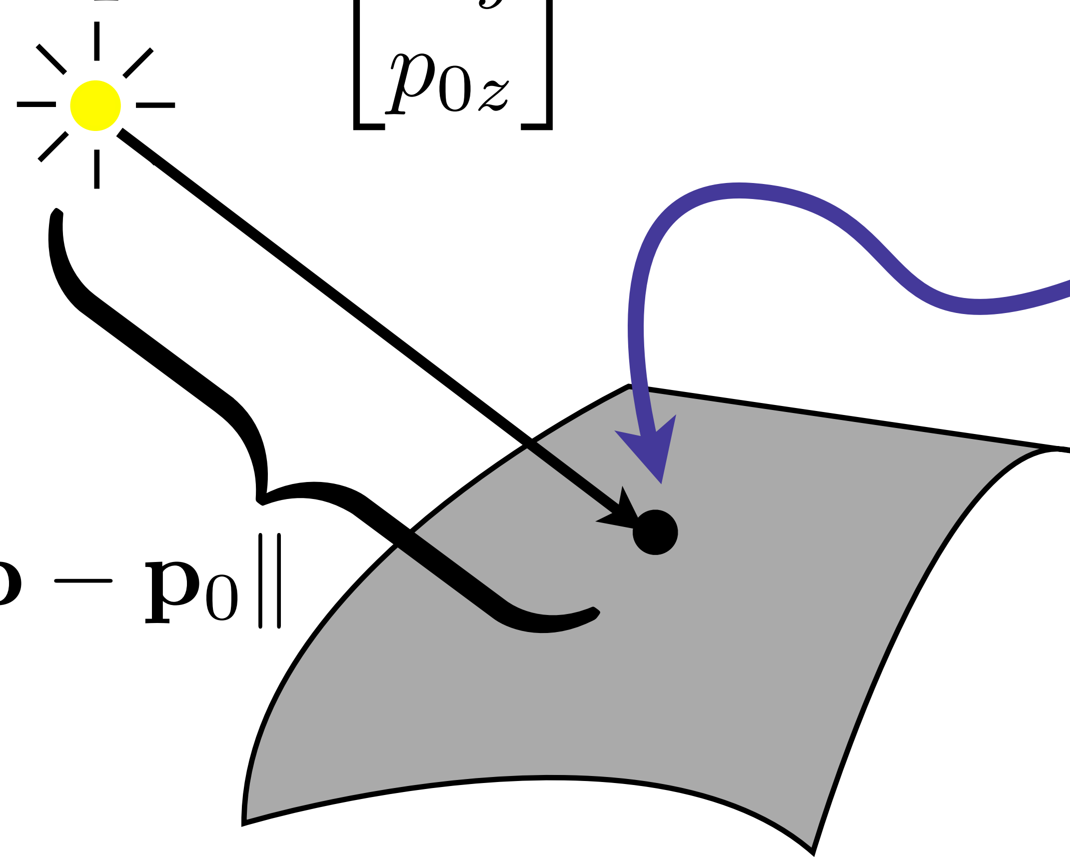
Point Light Source: Brightness falls off as **square** of distance

Source location

$$\mathbf{p}_0 = \begin{bmatrix} p_{0x} \\ p_{0y} \\ p_{0z} \end{bmatrix}$$

Location of point on surface

$$\mathbf{p} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}$$



Distance: $\|\mathbf{p} - \mathbf{p}_0\|$

Brightness at source location **p**$_0$:

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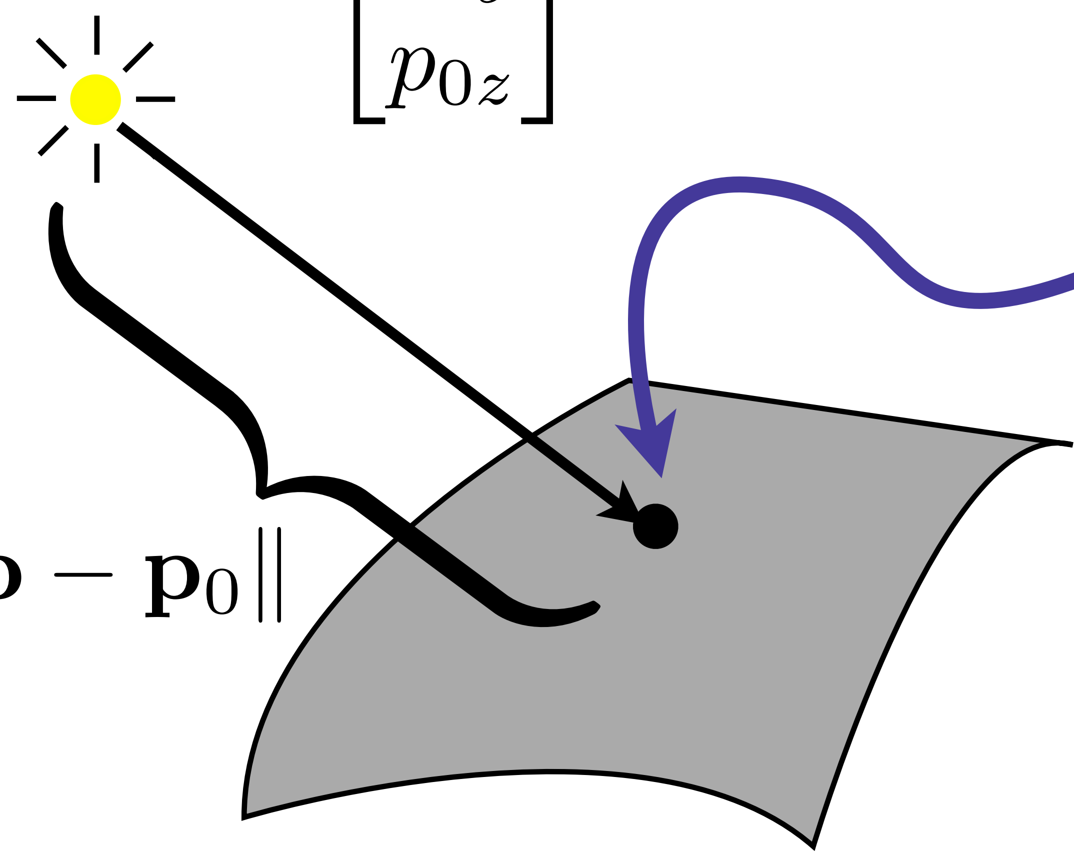

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Brightness at point $\mathbf{p}$:

$$\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0)$$

Types of Light Sources

Point Light Source: Brightness falls off as **square** of distance

Source location

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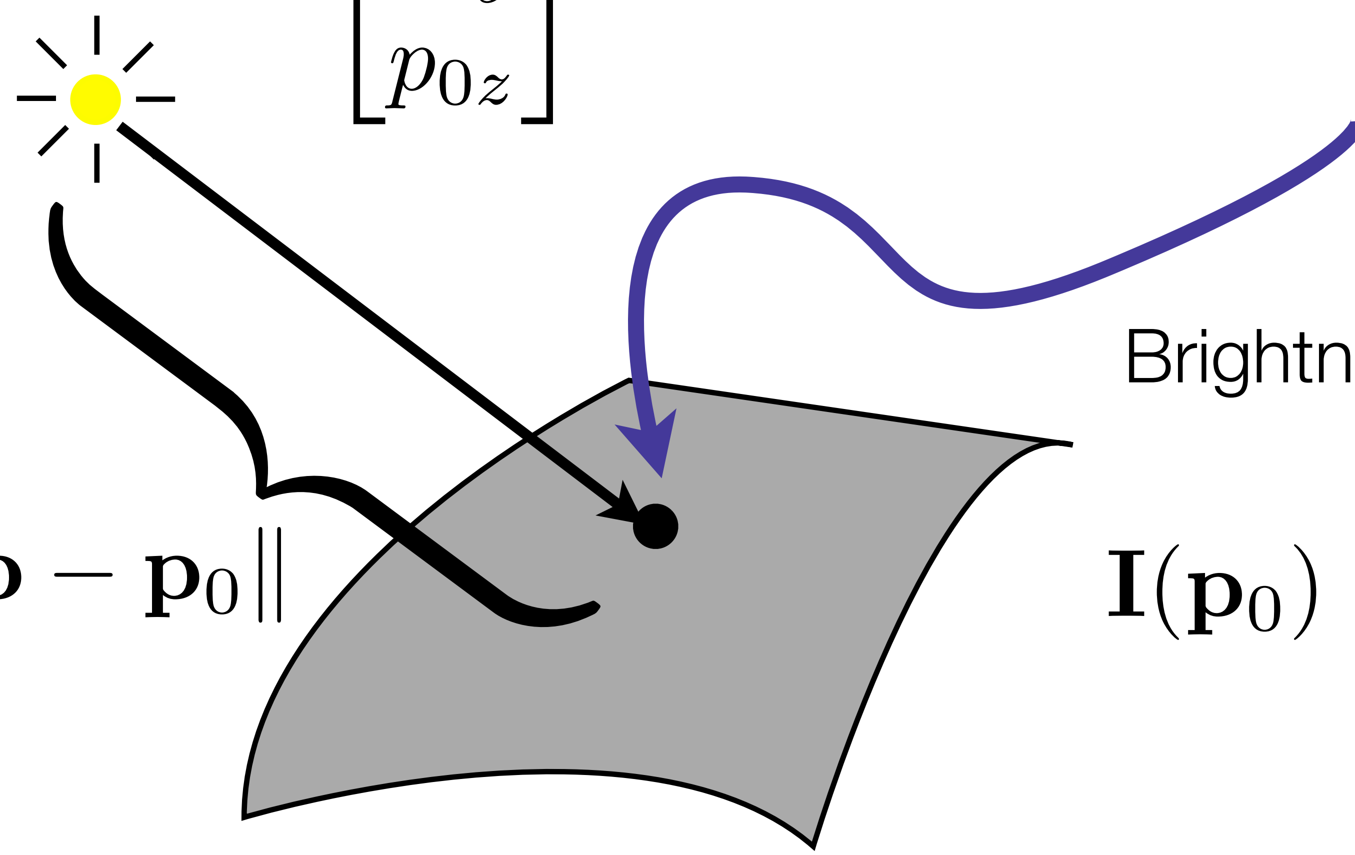

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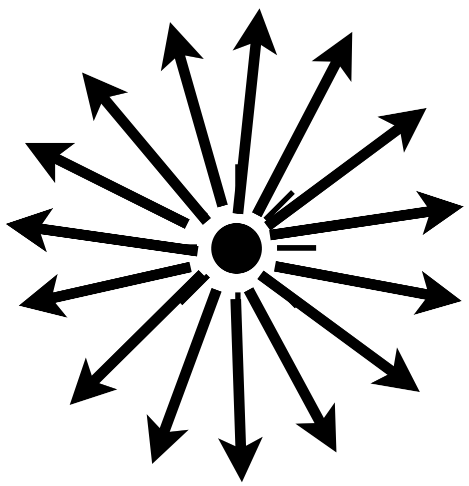
Brightness at point **p**:

$$\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0)$$

Dependence on square of distance

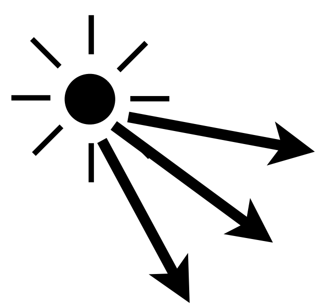
Types of Light Sources

Point Light Source



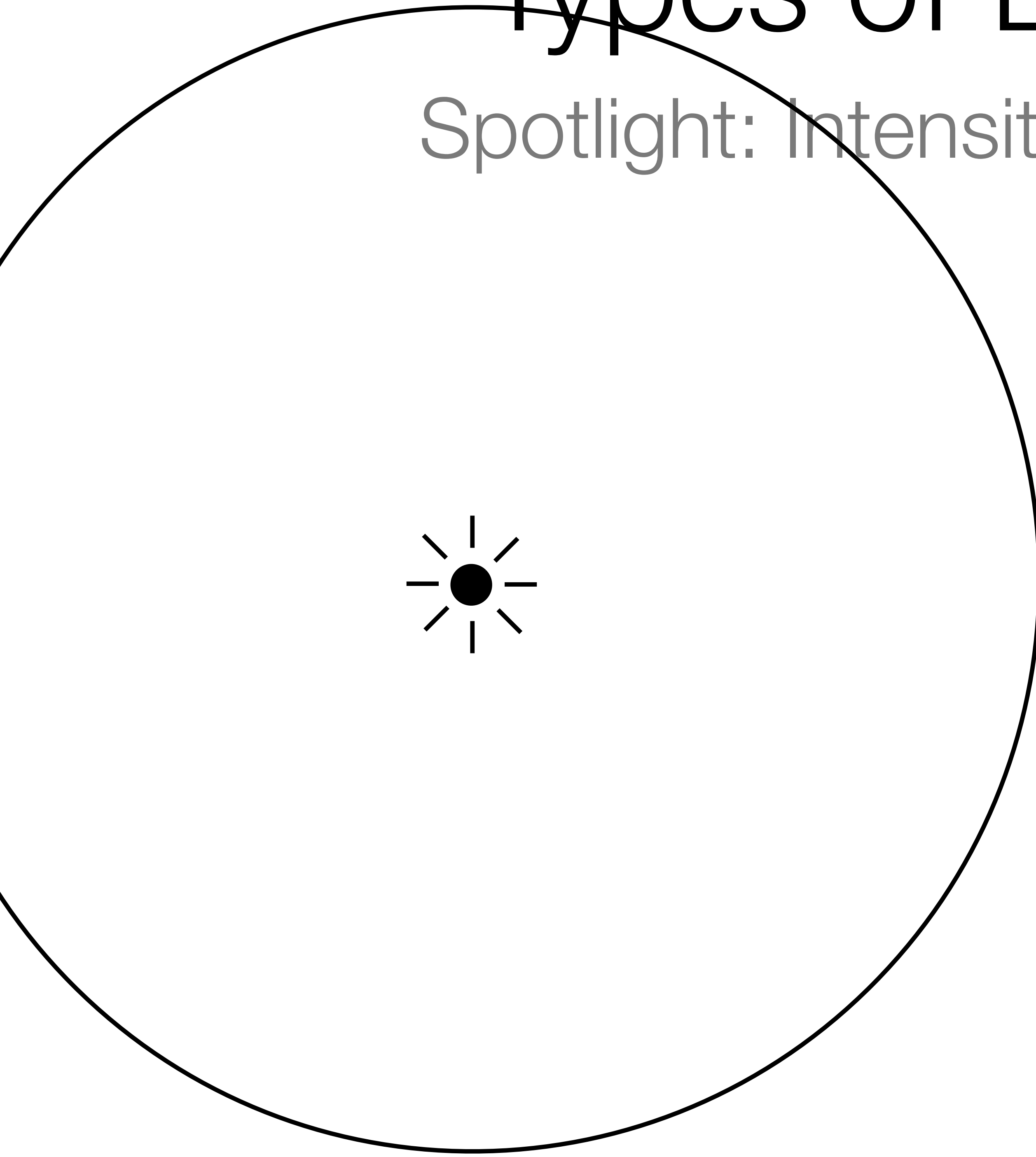
Types of Light Sources

Spotlight: Rays are emitted over a narrow angle



Types of Light Sources

Spotlight: Intensity falls away with angle



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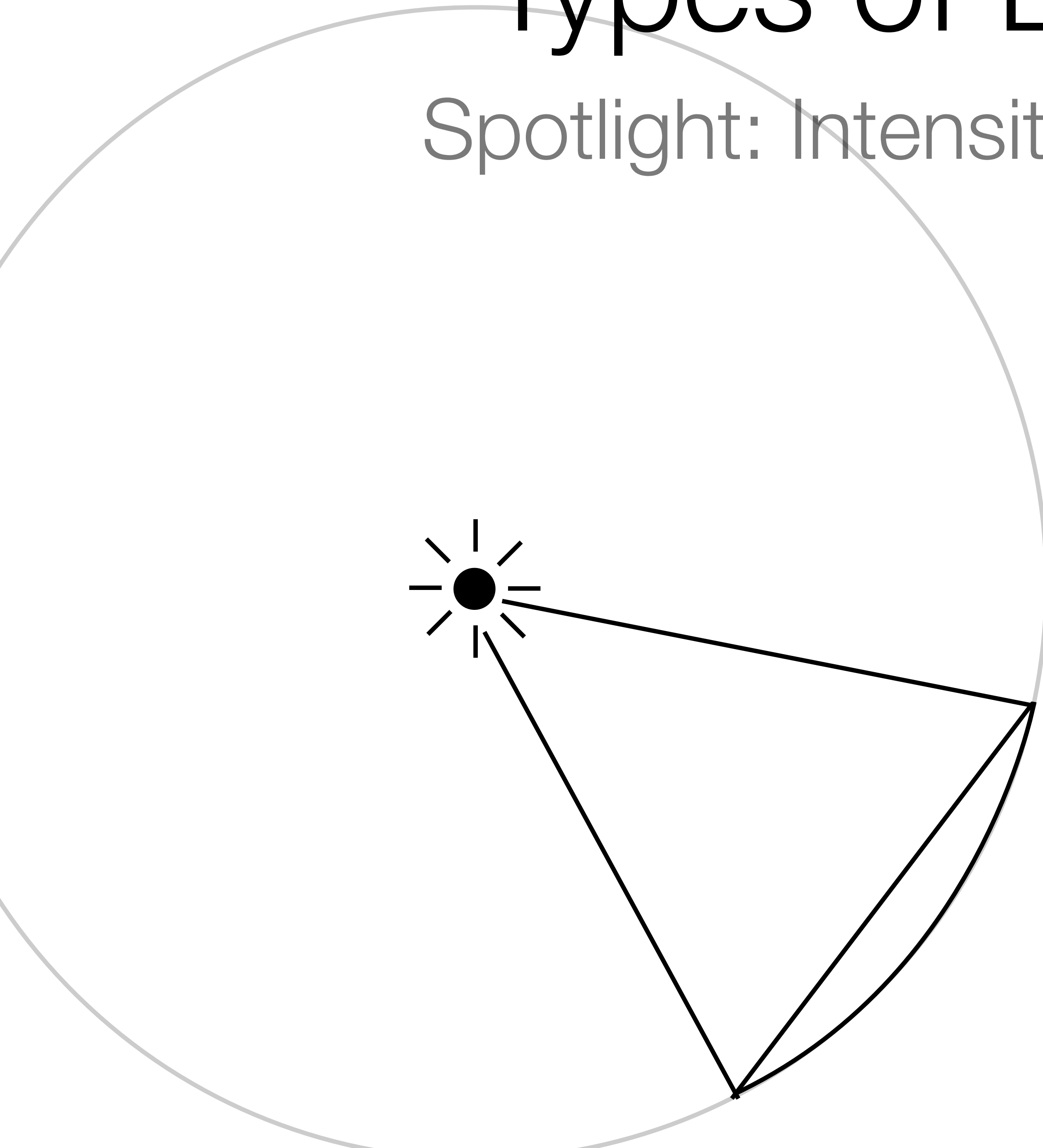

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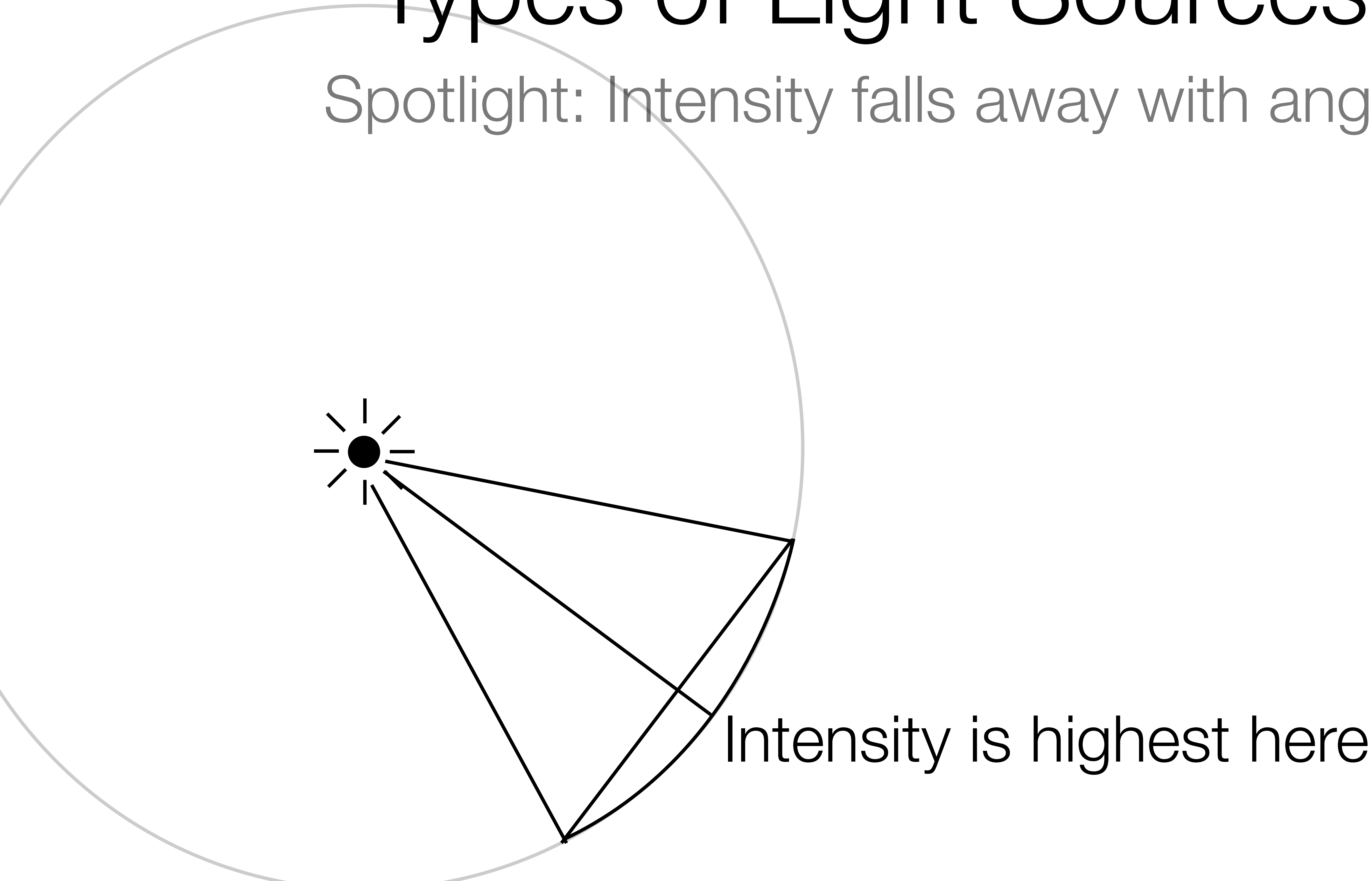

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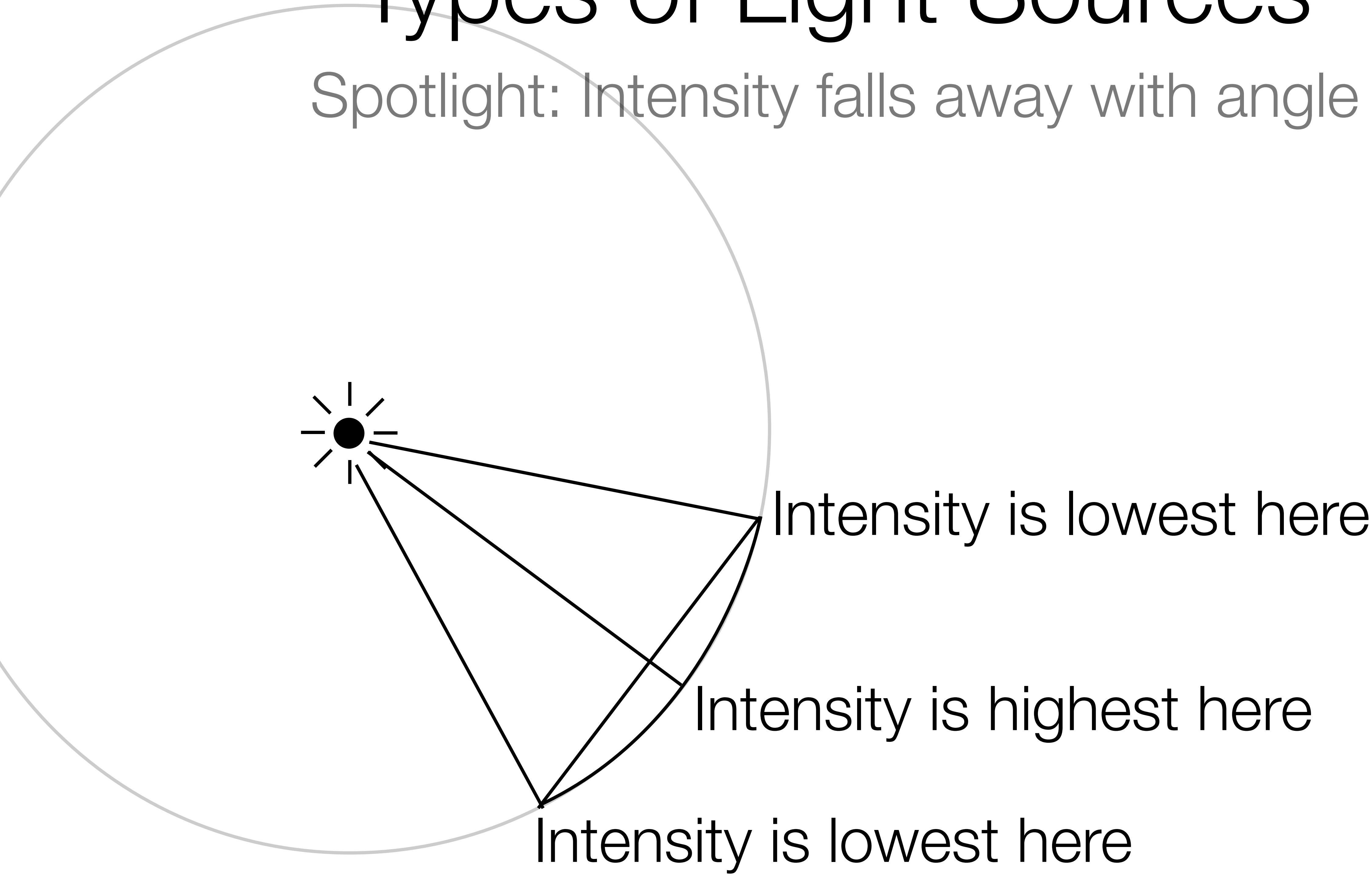

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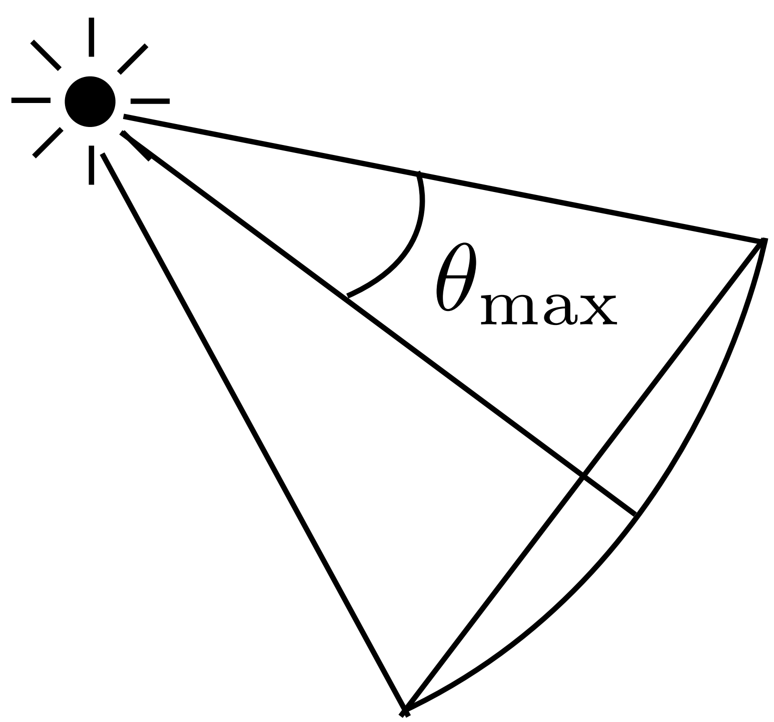

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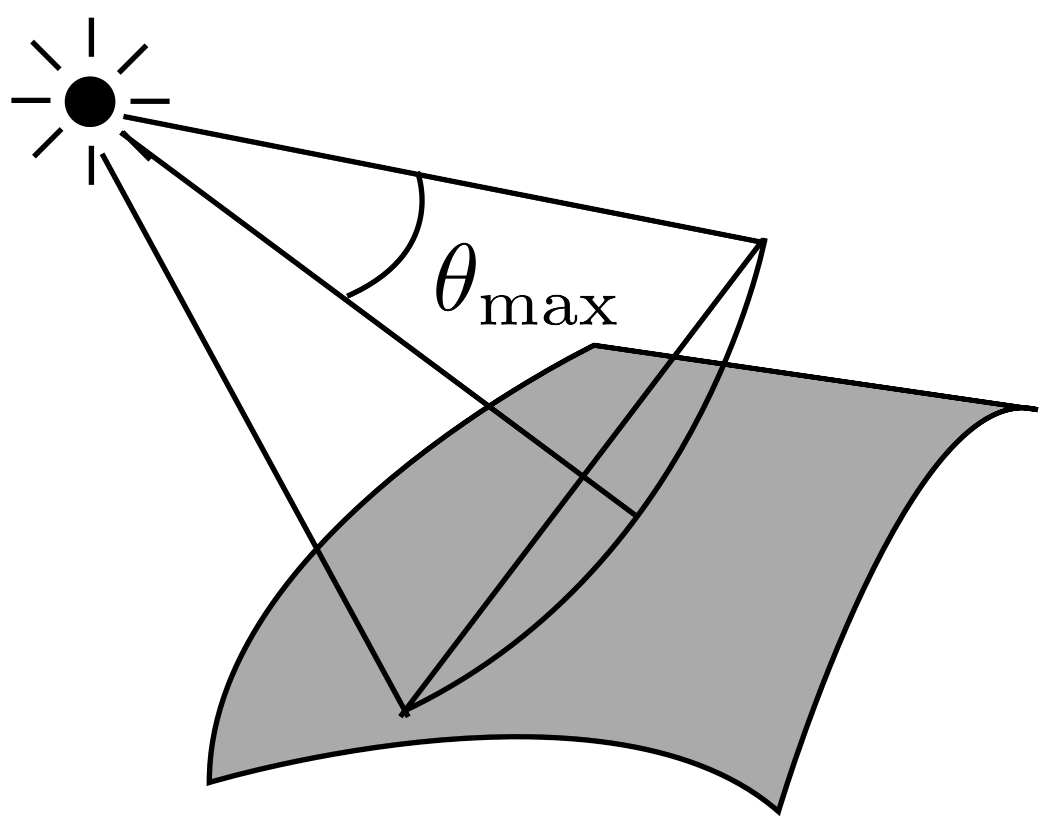
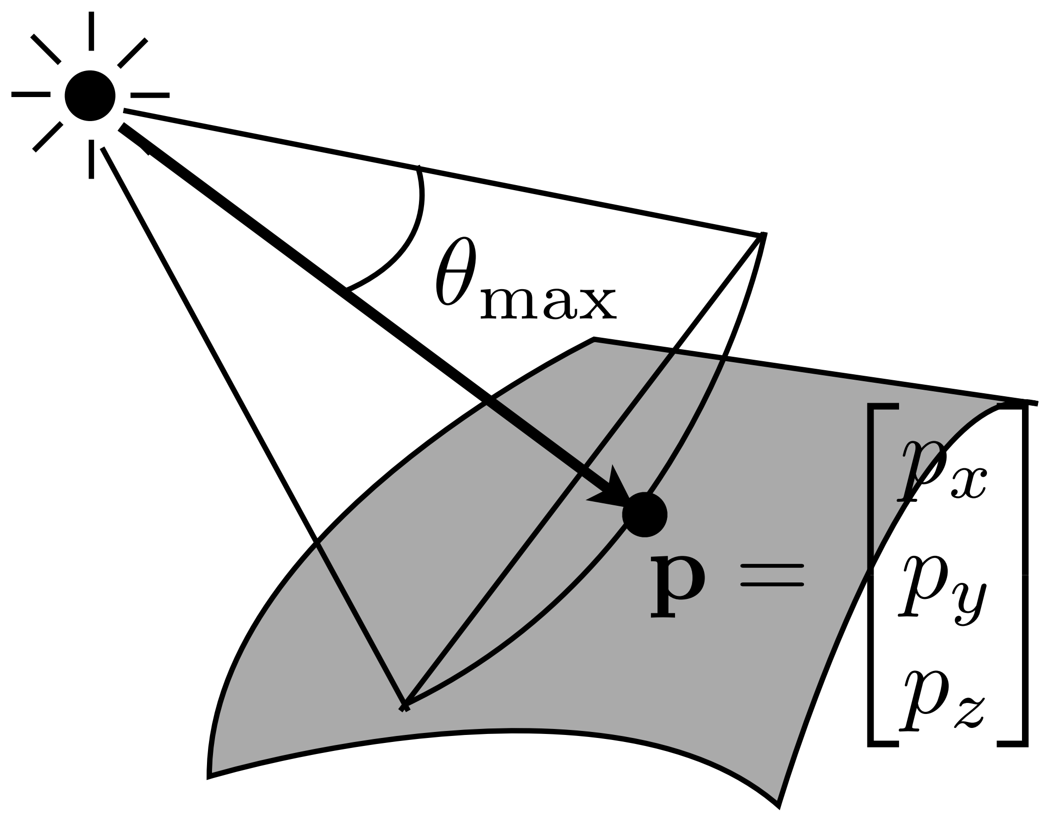


Types of Light Sources

Spotlight: Intensity is proportional to cosine of angle

p lies along direction of **maximum** intensity.

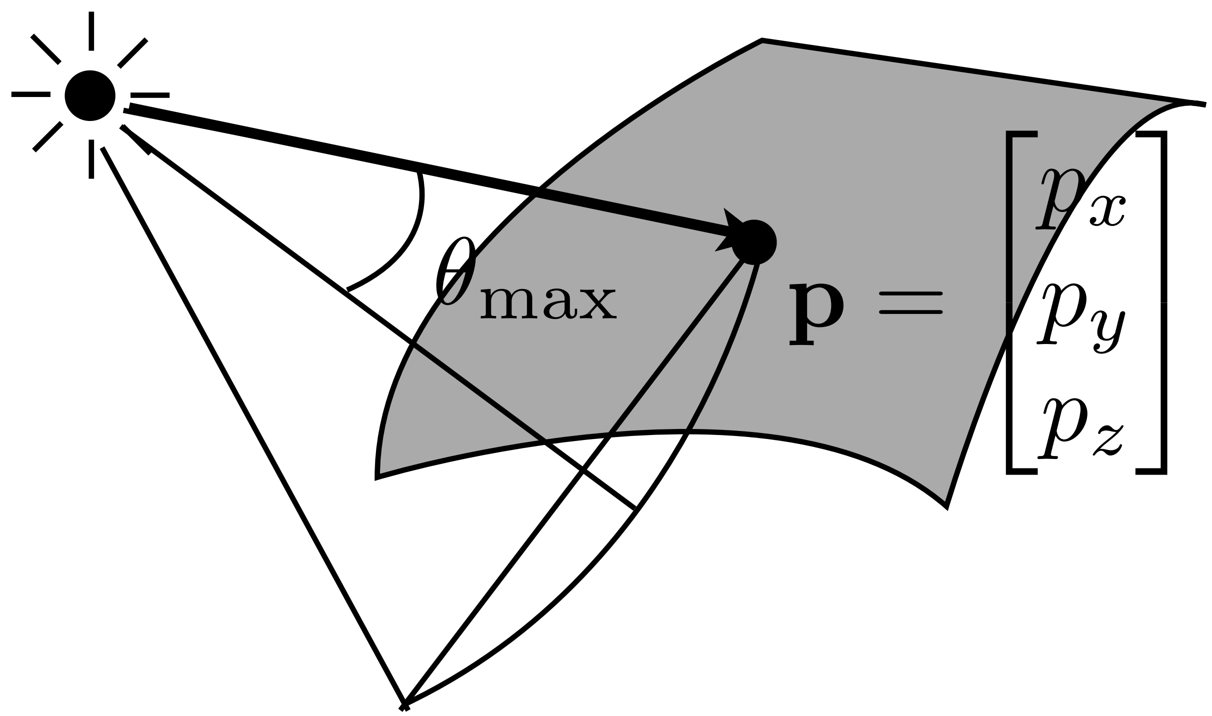


Brightness at point **p**: $$\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)$$

Types of Light Sources

Spotlight: Intensity is proportional to cosine of angle

p lies along direction of **minimum** intensity.

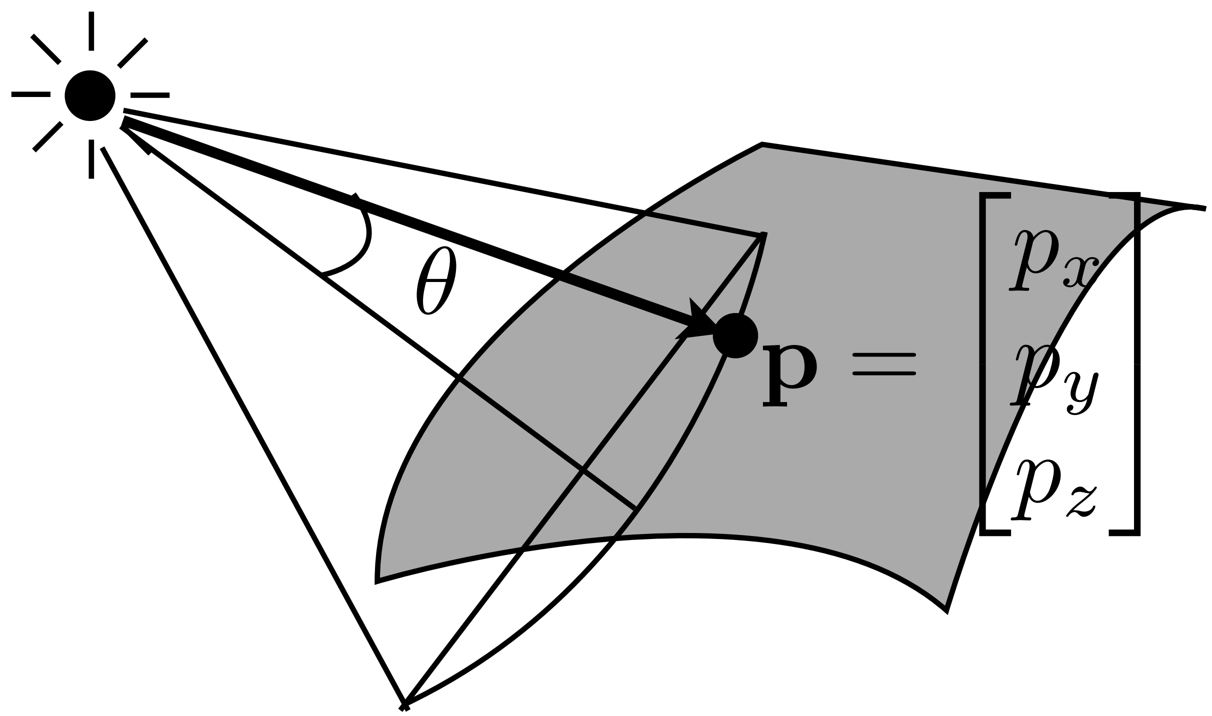


Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \dfrac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos \theta_{\max}$

Types of Light Sources

Spotlight: Intensity is proportional to cosine of angle

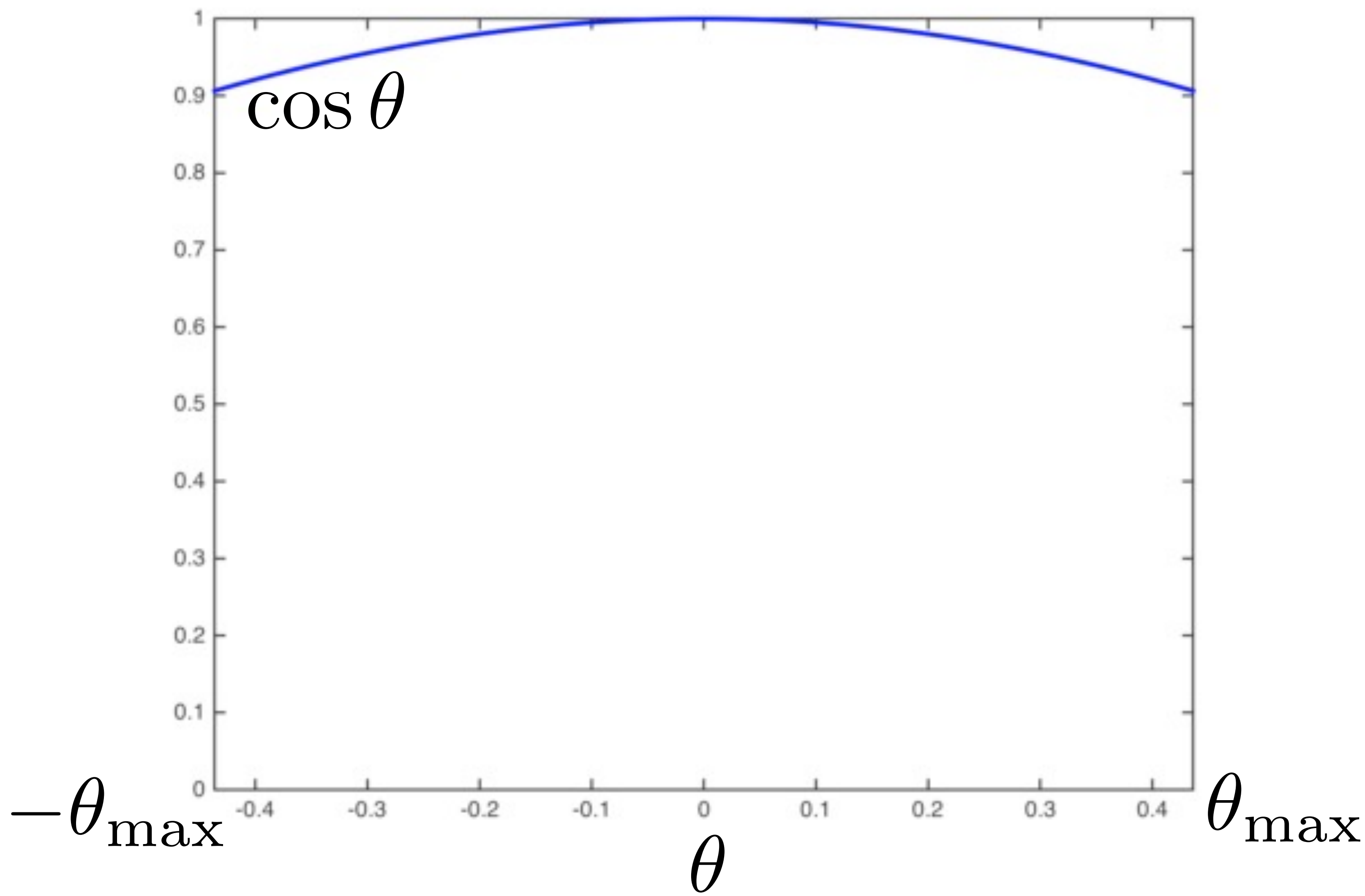
p lies along direction between maximum and minimum intensities.



Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \dfrac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos\theta$

Types of Light Sources

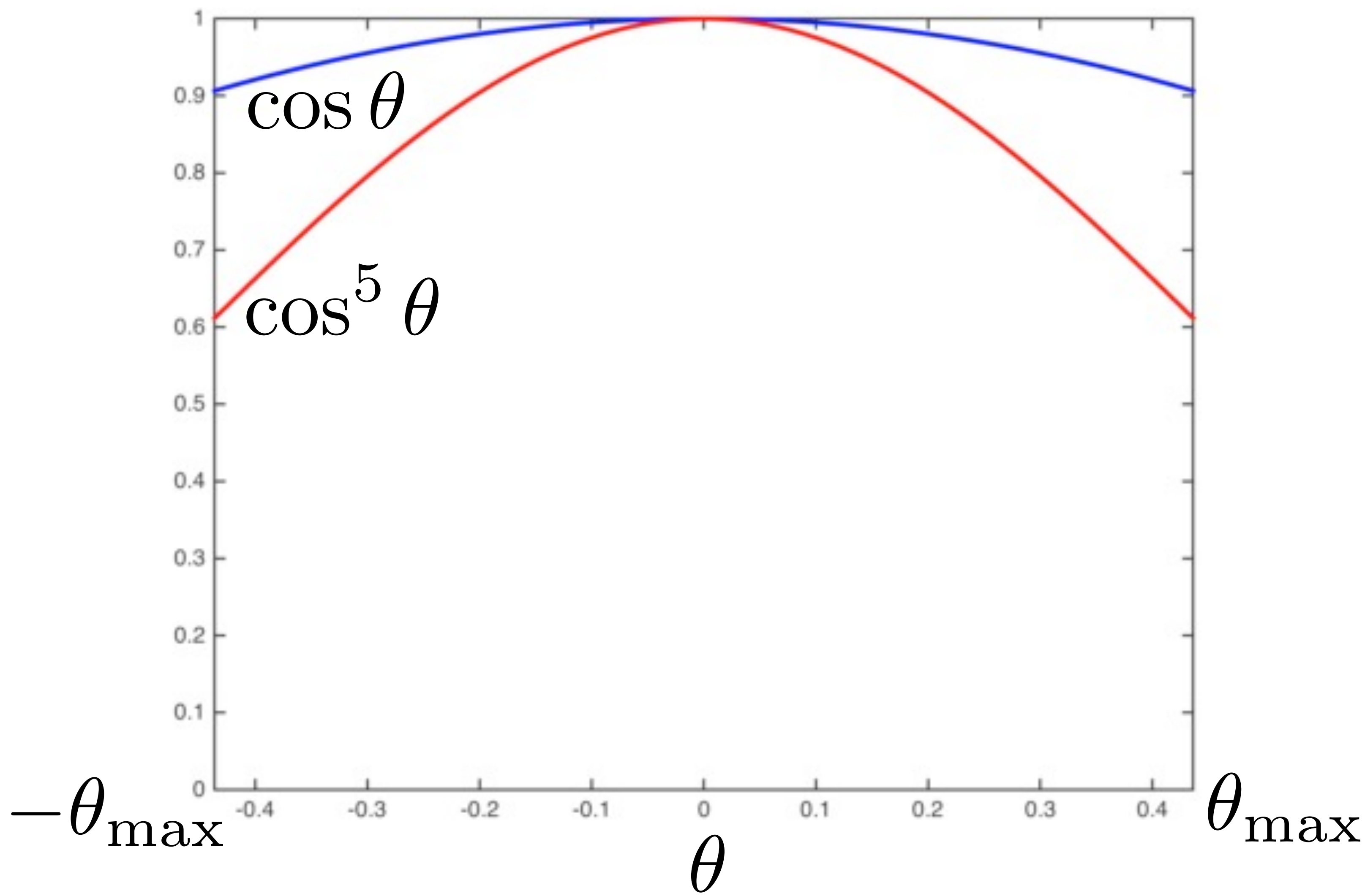
Oftentimes, dependence on cos θ
does not introduce a significant drop-off.



Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos\theta$

Types of Light Sources

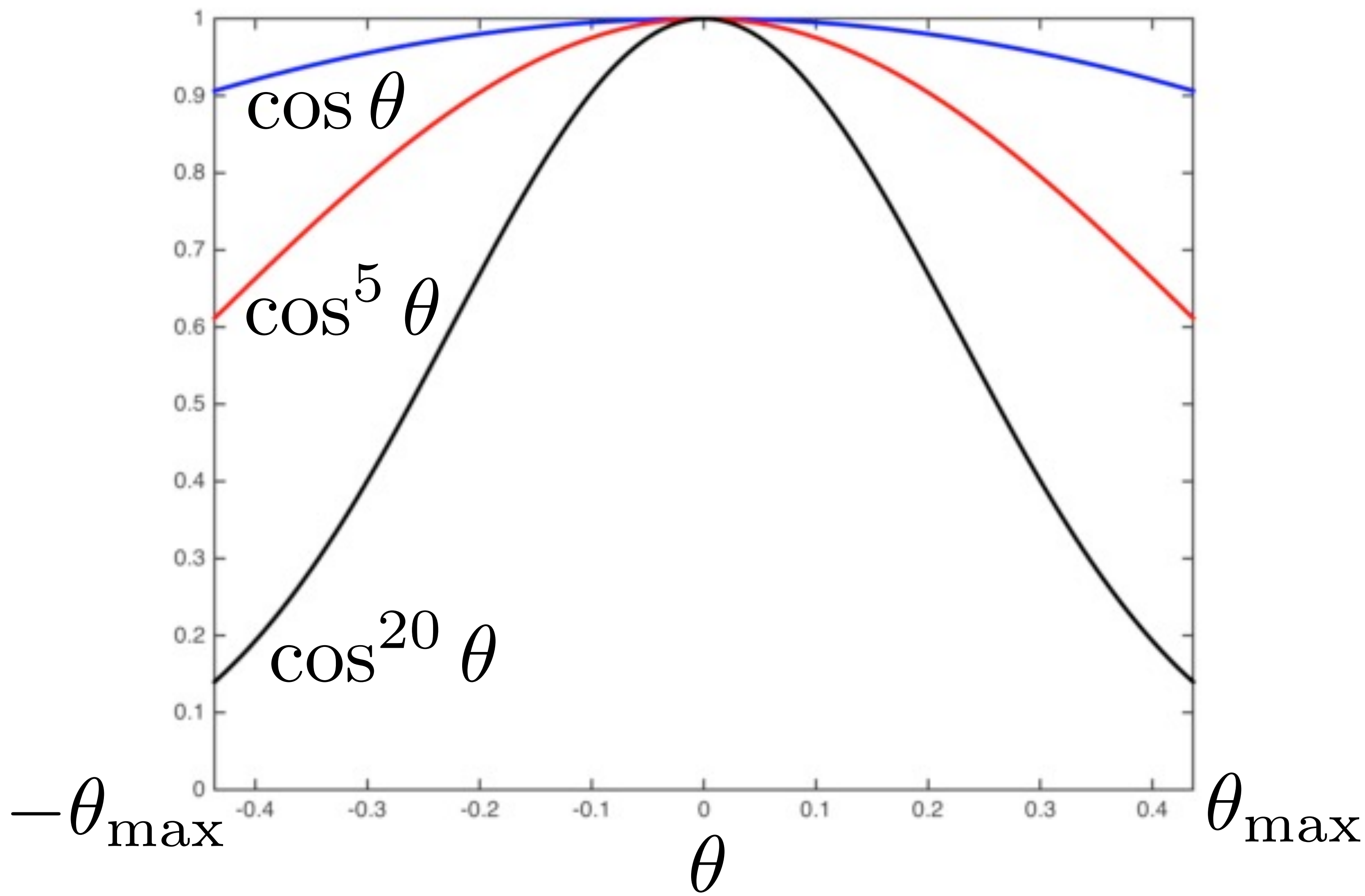
So we introduce an exponent, $\cos^e \theta$,
to introduce a drastic drop-off.



Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \dfrac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos^e \theta$

Types of Light Sources

The bigger the value of e in $\cos^e \theta$,
the more drastic is the drop-off.

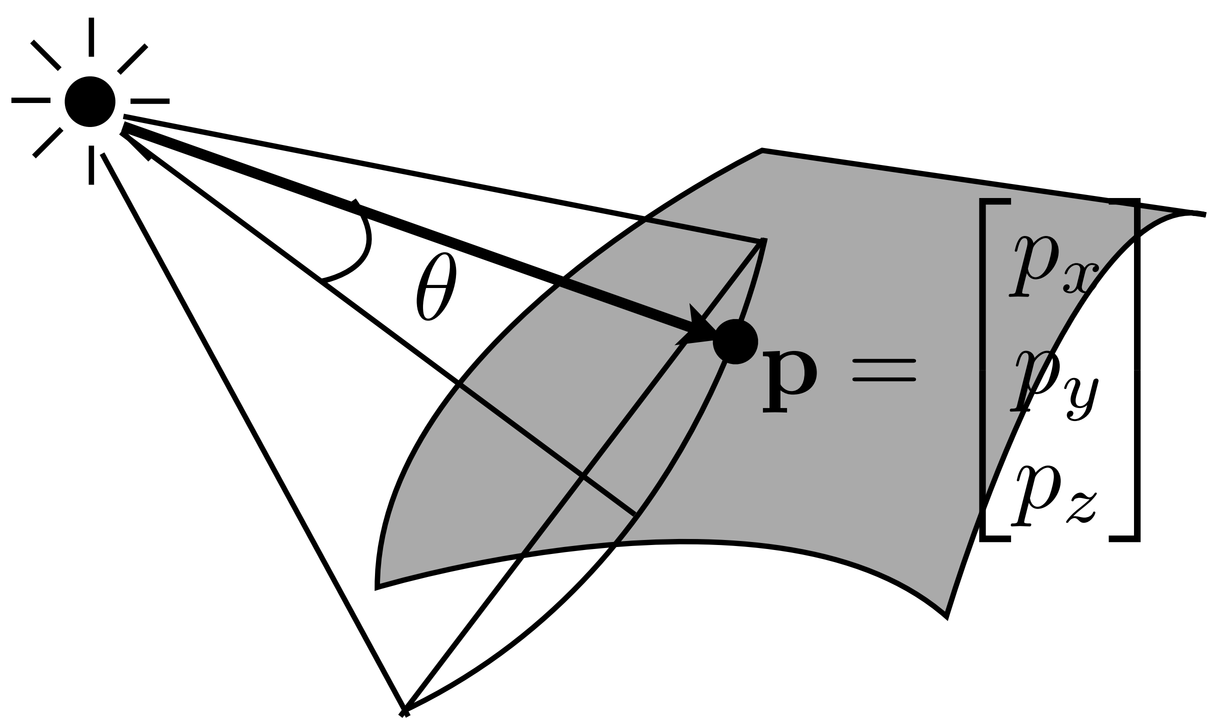


Brightness at point **p**: $\mathbf{I}(\mathbf{p},\mathbf{p}_0) = \dfrac{1}{\|\mathbf{p}-\mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)\cos^e\theta$

Types of Light Sources

Spotlight: Intensity is proportional to cosine of angle exponentiated

p lies along direction between maximum and minimum intensities.

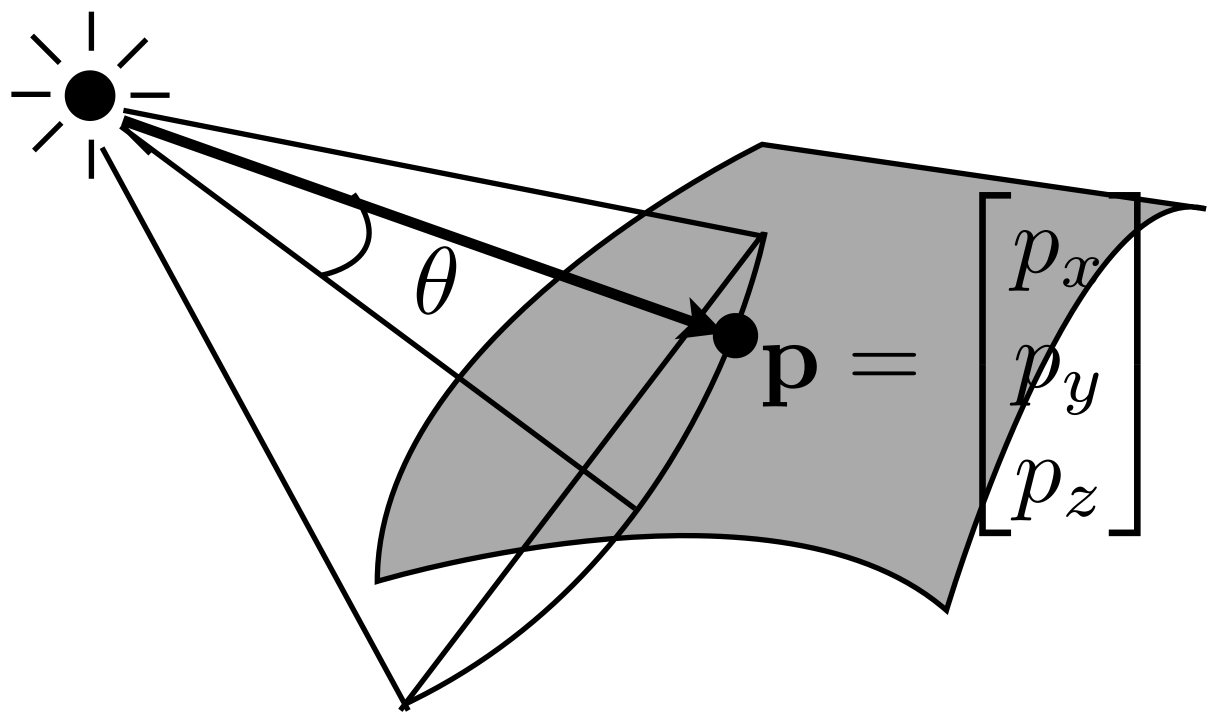


Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos^e \theta$

Types of Light Sources

How to calculate cos θ?

p lies along direction between maximum and minimum intensities.



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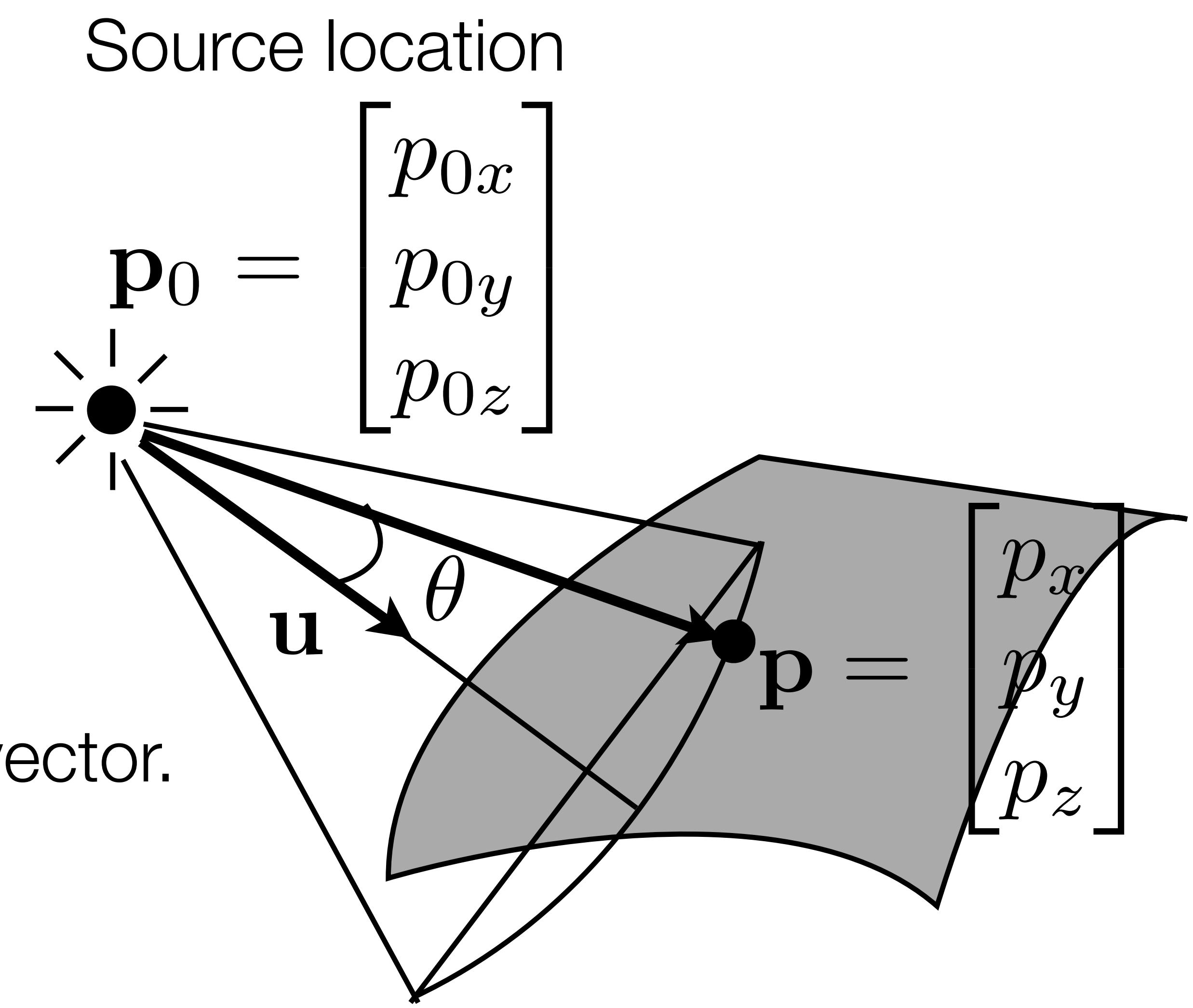
Types of Light Sources

Need source location $\mathbf{p}_0$ and direction of maximum intensity $\mathbf{u}$



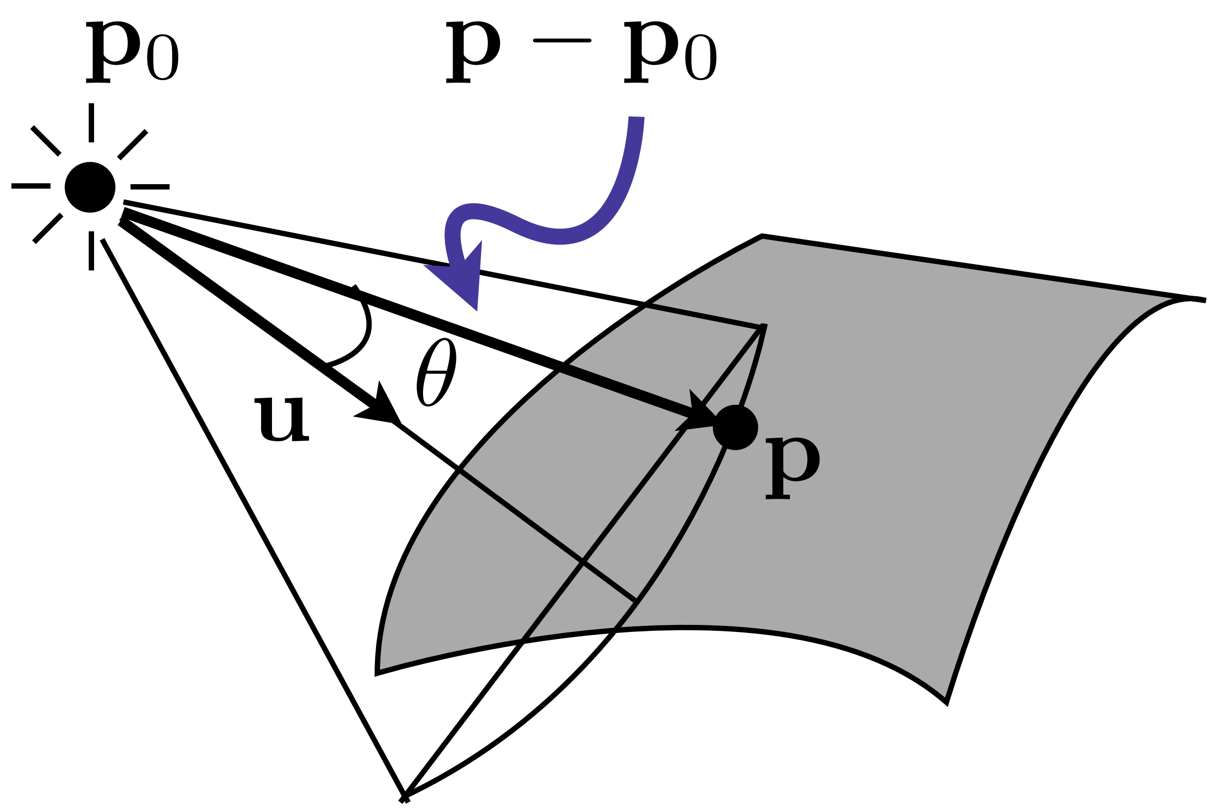
u is a unit vector.

Brightness at point **p**: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos^e \theta$

Types of Light Sources

Need source location $\mathbf{p}_0$ and direction of maximum intensity $\mathbf{u}$

Vector from $\mathbf{p}_0$ to $\mathbf{p}$: $\mathbf{p} - \mathbf{p}_0$

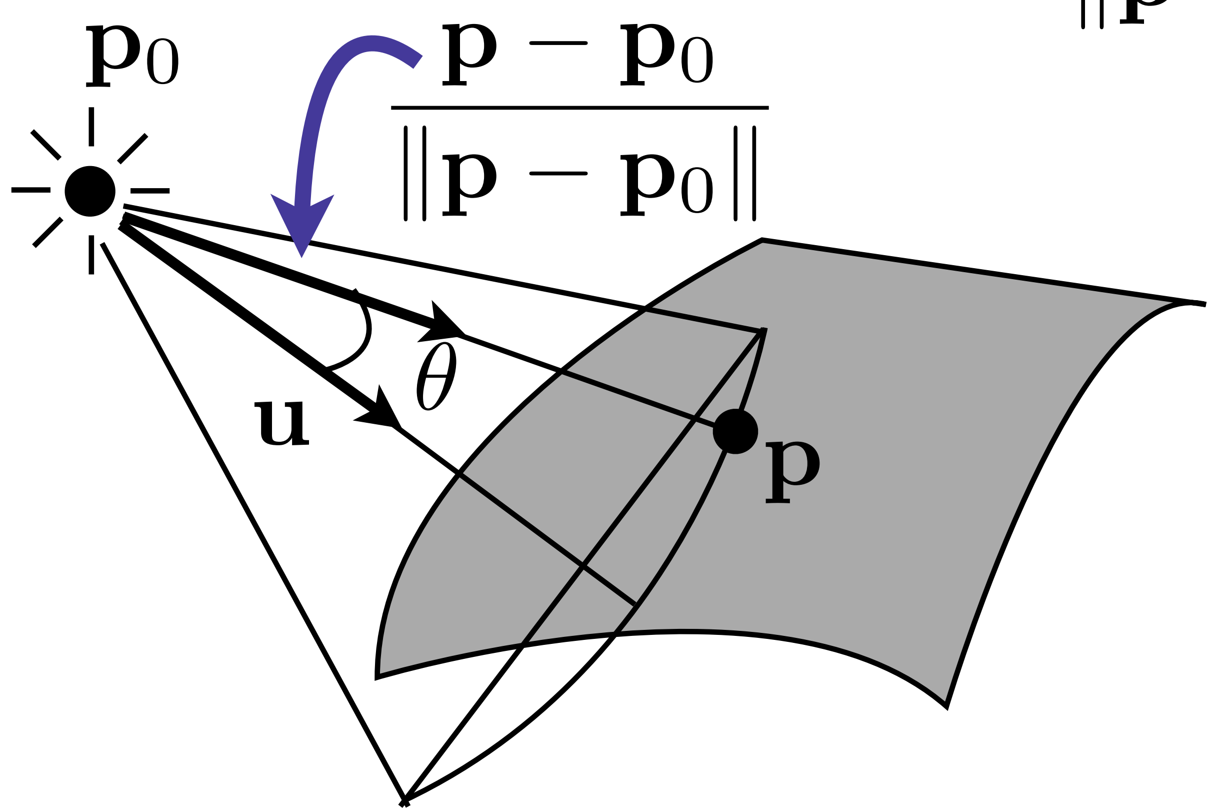


Brightness at point $\mathbf{p}$: $\mathbf{I}(\mathbf{p}, \mathbf{p}_0) = \frac{1}{\|\mathbf{p} - \mathbf{p}_0\|^2} \mathbf{I}(\mathbf{p}_0) \cos^e \theta$

Types of Light Sources

Need source location $\mathbf{p}_0$ and direction of maximum intensity $\mathbf{u}$

Unit vector along direction from $\mathbf{p}_0$ to $\mathbf{p}$: $\dfrac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}$



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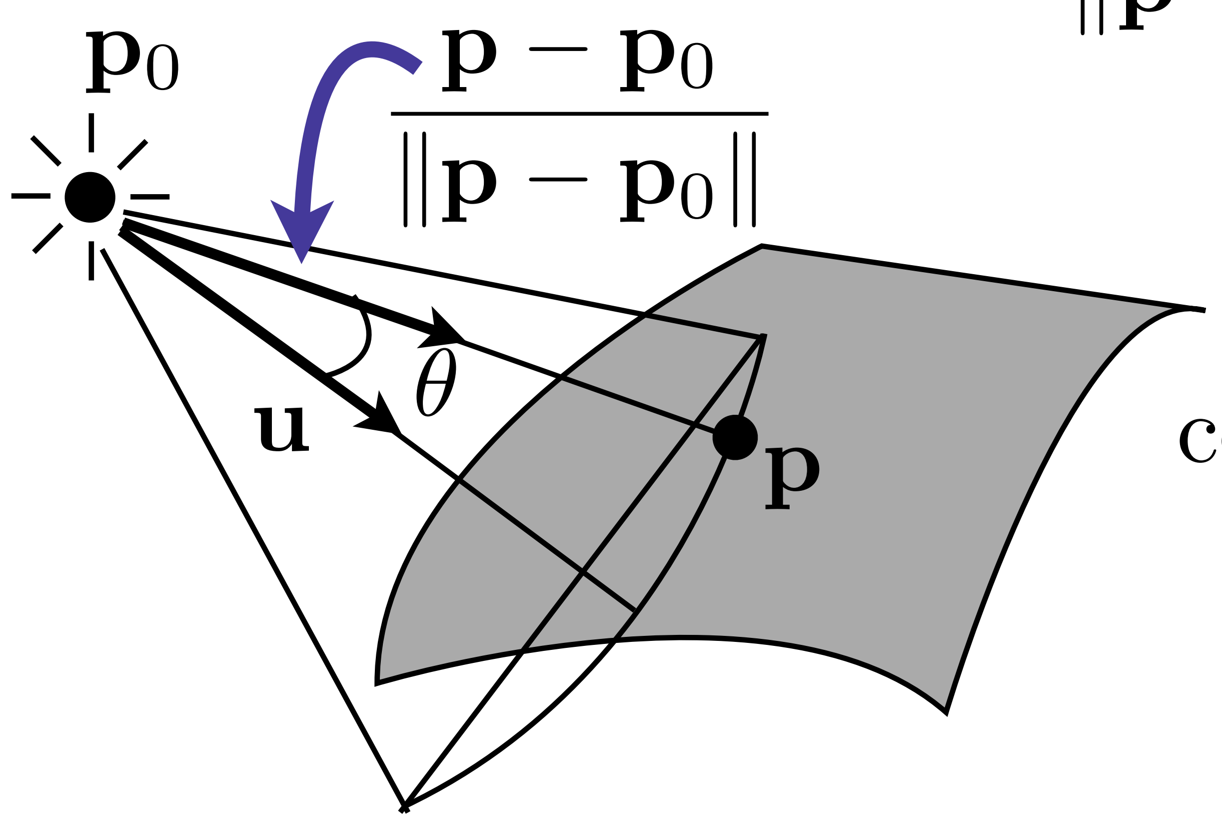

$$\cos\theta = \mathbf{u}\cdot\left(\frac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}\right)$$

Brightness at point $\mathbf{p}$: $\mathbf{I}(\mathbf{p},\mathbf{p}_0) = \dfrac{1}{\|\mathbf{p}-\mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)\cos^e\theta$

Types of Light Sources

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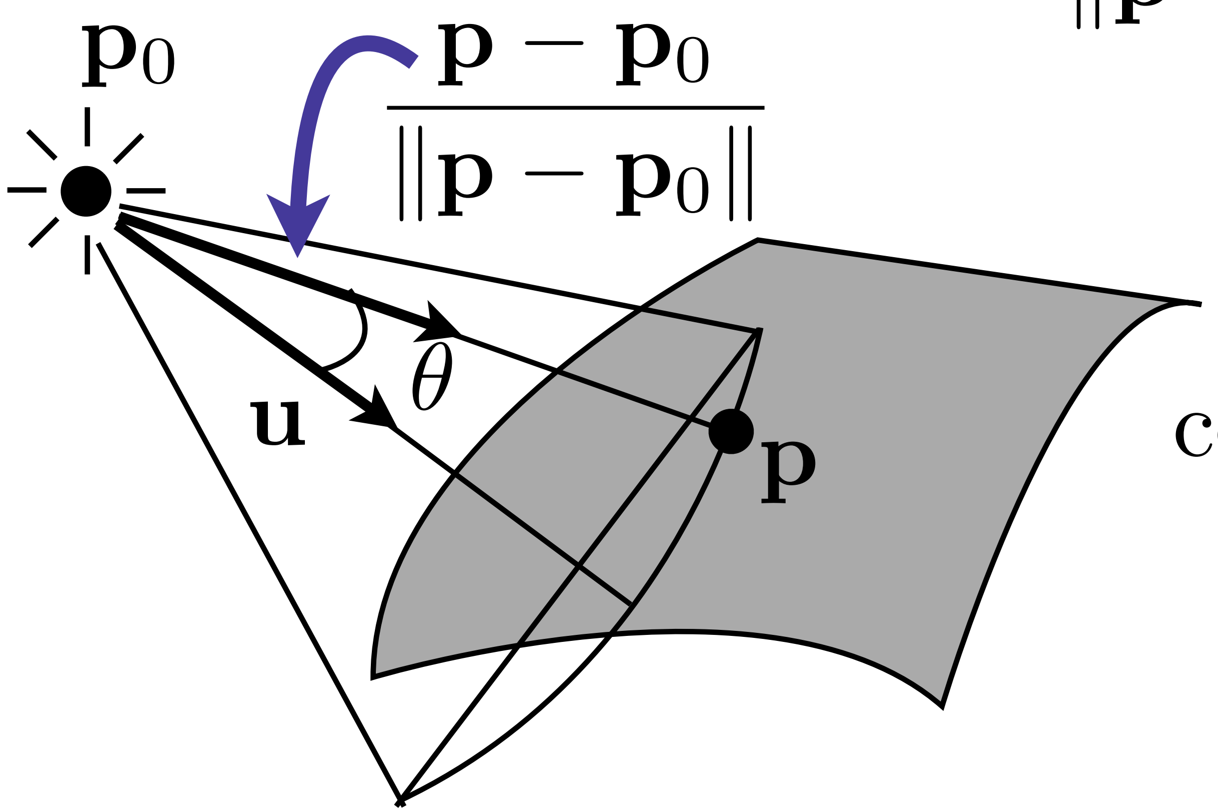
Unit vector along direction from $\mathbf{p}_0$ to $\mathbf{p}$: $\dfrac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}$



$$\cos\theta = \mathbf{u} \cdot \left(\frac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}\right)$$

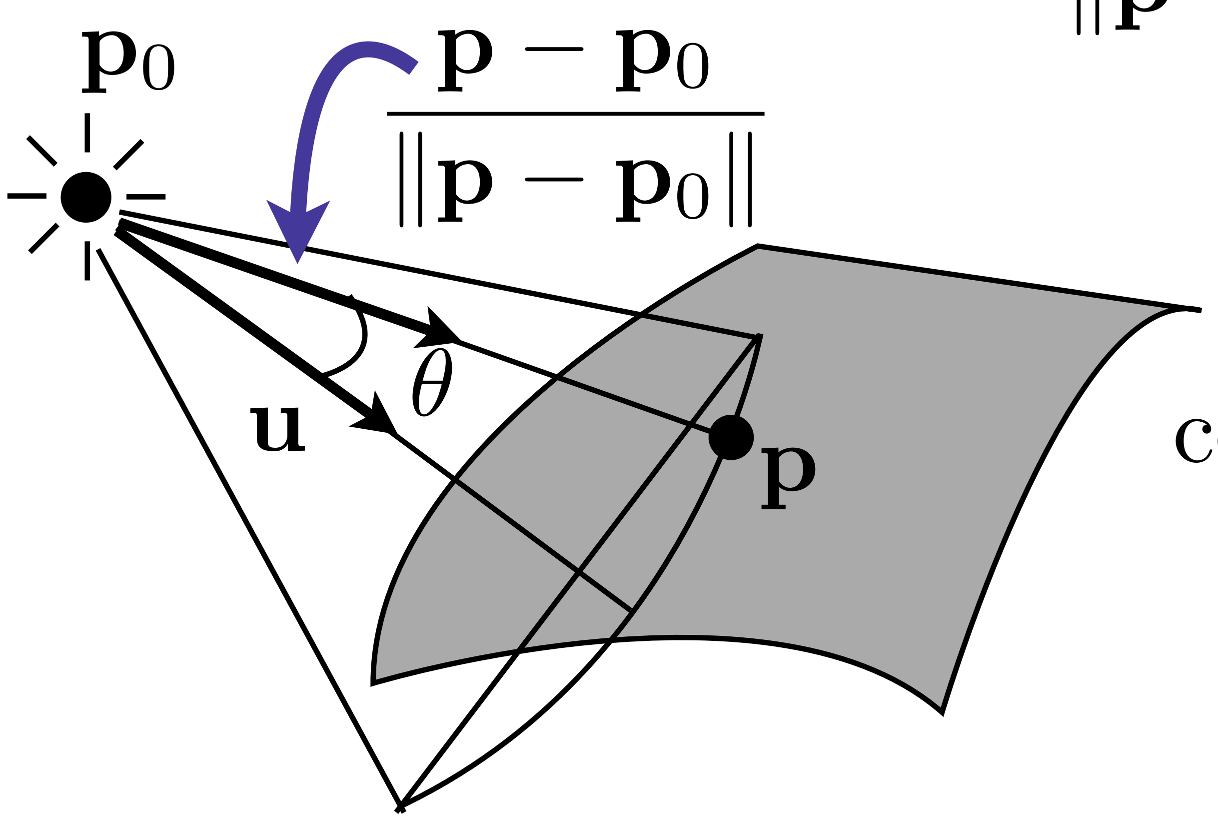
Dot product

Brightness at point $\mathbf{p}$: $\mathbf{I}(\mathbf{p},\mathbf{p}_0) = \dfrac{1}{\|\mathbf{p}-\mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)\cos^e\theta$

Types of Light Sources

Need source location $\mathbf{p}_0$ and direction of maximum intensity $\mathbf{u}$

Unit vector along direction from $\mathbf{p}_0$ to $\mathbf{p}$: $\dfrac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}$



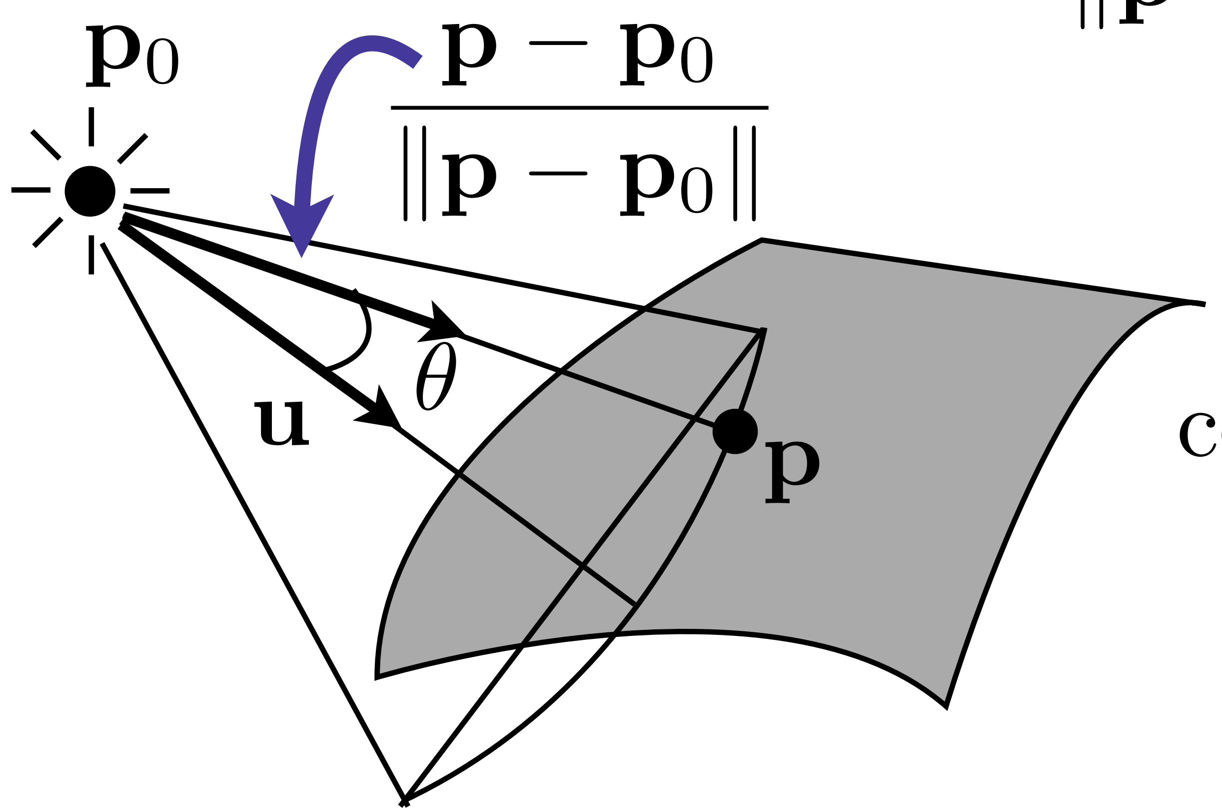
$$\cos\theta = \mathbf{u}\cdot\left(\frac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}\right)$$

Brightness at point $\mathbf{p}$: $\mathbf{I}(\mathbf{p},\mathbf{p}_0) = \dfrac{1}{\|\mathbf{p}-\mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)\cos^e\theta$

Types of Light Sources

Need source location **p**$_0$ and direction of maximum intensity **u**

Unit vector along direction from **p**$_0$ to **p**: $\dfrac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}$



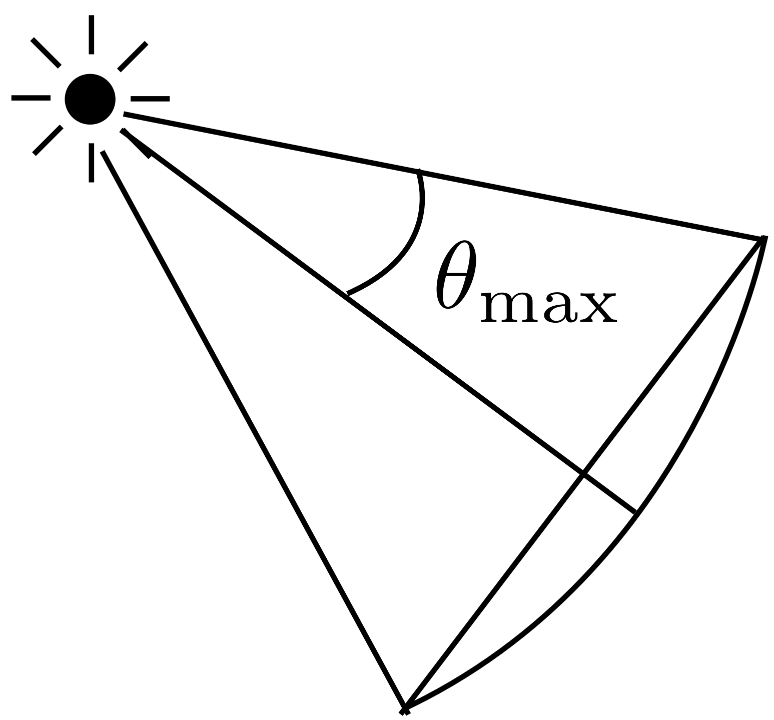
$$\cos\theta = \mathbf{u}\cdot\left(\frac{\mathbf{p}-\mathbf{p}_0}{\|\mathbf{p}-\mathbf{p}_0\|}\right)$$

Remember: brightness is still a vector with three components: red, green, and blue.

Brightness at point **p**: $\mathbf{I}(\mathbf{p},\mathbf{p}_0) = \dfrac{1}{\|\mathbf{p}-\mathbf{p}_0\|^2}\mathbf{I}(\mathbf{p}_0)\cos^e\theta$

Types of Light Sources

What do you get if θ_{max} is 180 degrees?



Types of Light Sources

Distant Light Sources (Directional Light)

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These are so far away,
you might as well assume that they are at infinity.

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The sun!

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What is one such light source?

The sun!

Others: the stars, Venus, the moon, a supernova.

Types of Light Sources

Distant Light Sources (Directional Light)

These are so far away,
you might as well assume that they are at infinity.

What is one such light source?

The sun!

Others: the stars, Venus, the moon, a supernova.

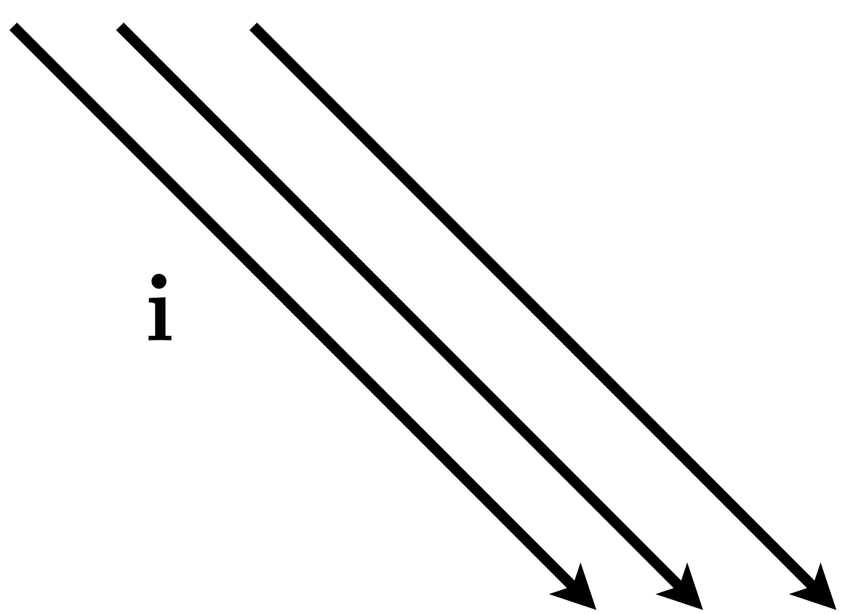
Often, it really depends on how small your object is compared to the distance of your light source.
A bulb to a little ant may be the same as the sun to us.

Types of Light Sources

Distant Light Sources (Directional Light)

These are so far away,
you might as well assume that they are at infinity.

The point of origin is at infinity. Which means all we know is the direction **i** the light is coming from.



Types of Light Sources

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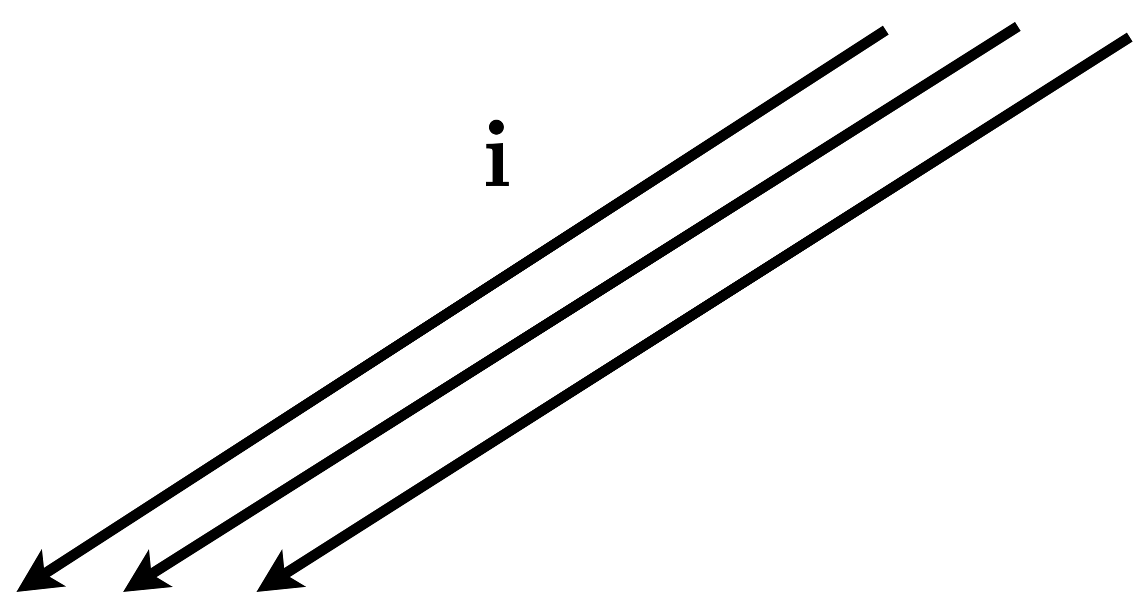
Types of Light Sources

Distant Light Sources (Directional Light)

The point of origin is at infinity. Which means all we know is the direction **i** the light is coming from.

Example: in the morning, the sun rays slant in from the east.

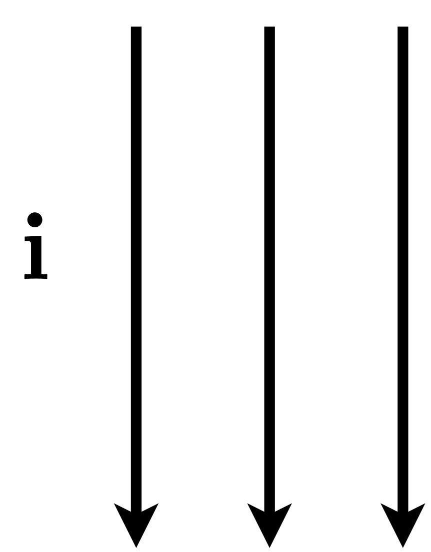


Types of Light Sources

Distant Light Sources (Directional Light)

The point of origin is at infinity. Which means all we know is the direction **i** the light is coming from.

Example: at noon, the sun rays shine directly from above.

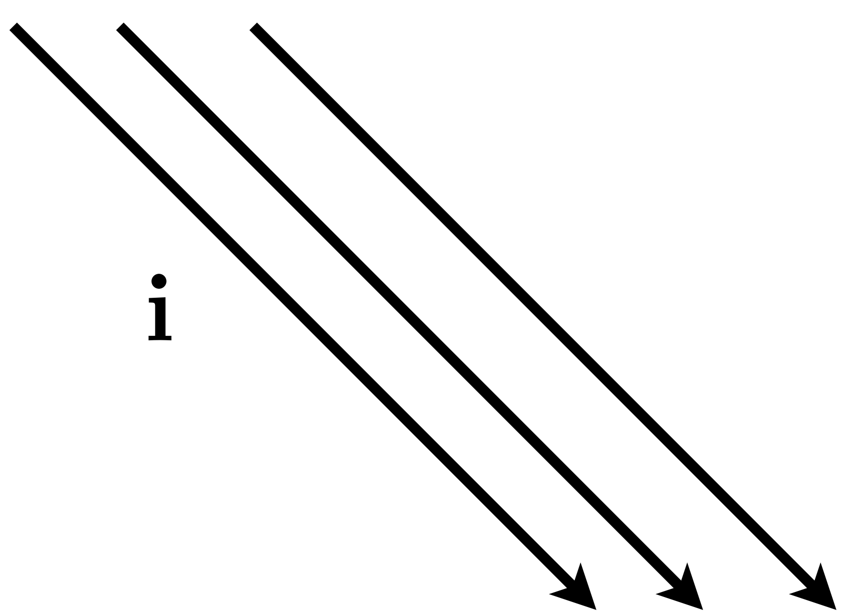


Types of Light Sources

Distant Light Sources (Directional Light)

The point of origin is at infinity. Which means all we know is the direction **i** the light is coming from.

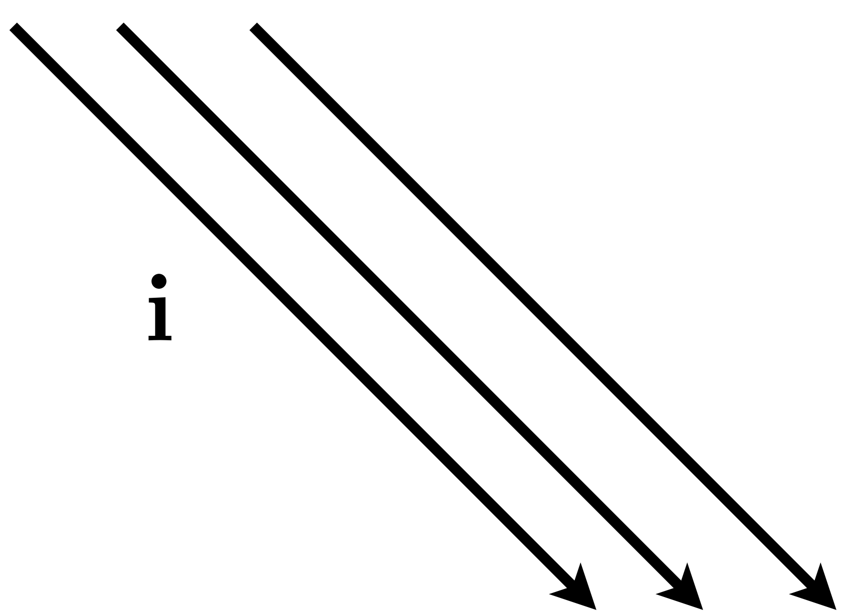
Example: in the evening, the sun rays slant in from the west.



Types of Light Sources

Distant Light Sources (Directional Light)

The point of origin is at infinity. Which means all we know is the direction **i** the light is coming from.



$$\mathbf{I}(\mathbf{i}) = \begin{bmatrix} I_r(\mathbf{i}) \\ I_g(\mathbf{i}) \\ I_b(\mathbf{i}) \end{bmatrix}$$

Types of Light Sources

Ambient Light:

Specify intensity $\mathbf{I}_a$.

Point Light Sources:

Specify point $\mathbf{p_0}$ and intensity $\mathbf{I}(\mathbf{p_0})$ at point $\mathbf{p_0}$.

Spotlight:

Specify point $\mathbf{p_0}$, intensity $\mathbf{I}(\mathbf{p_0})$ at point $\mathbf{p_0}$, and angle θ_{max}.

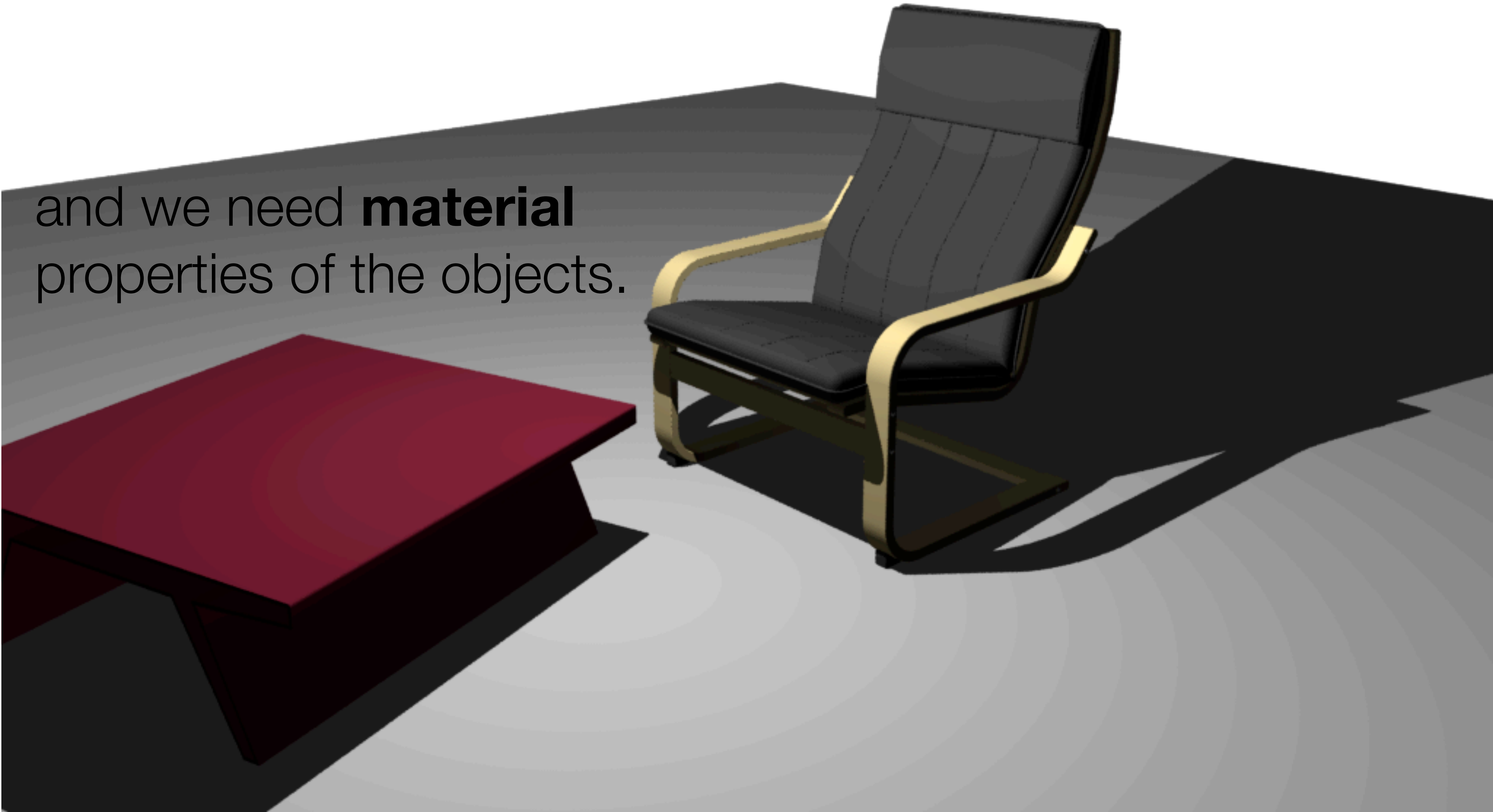
Directional (Distant) Light Sources:

Specify direction $\mathbf{i}$ and intensity along direction $\mathbf{I}(\mathbf{i})$.

To light an object,

We need **light sources**,

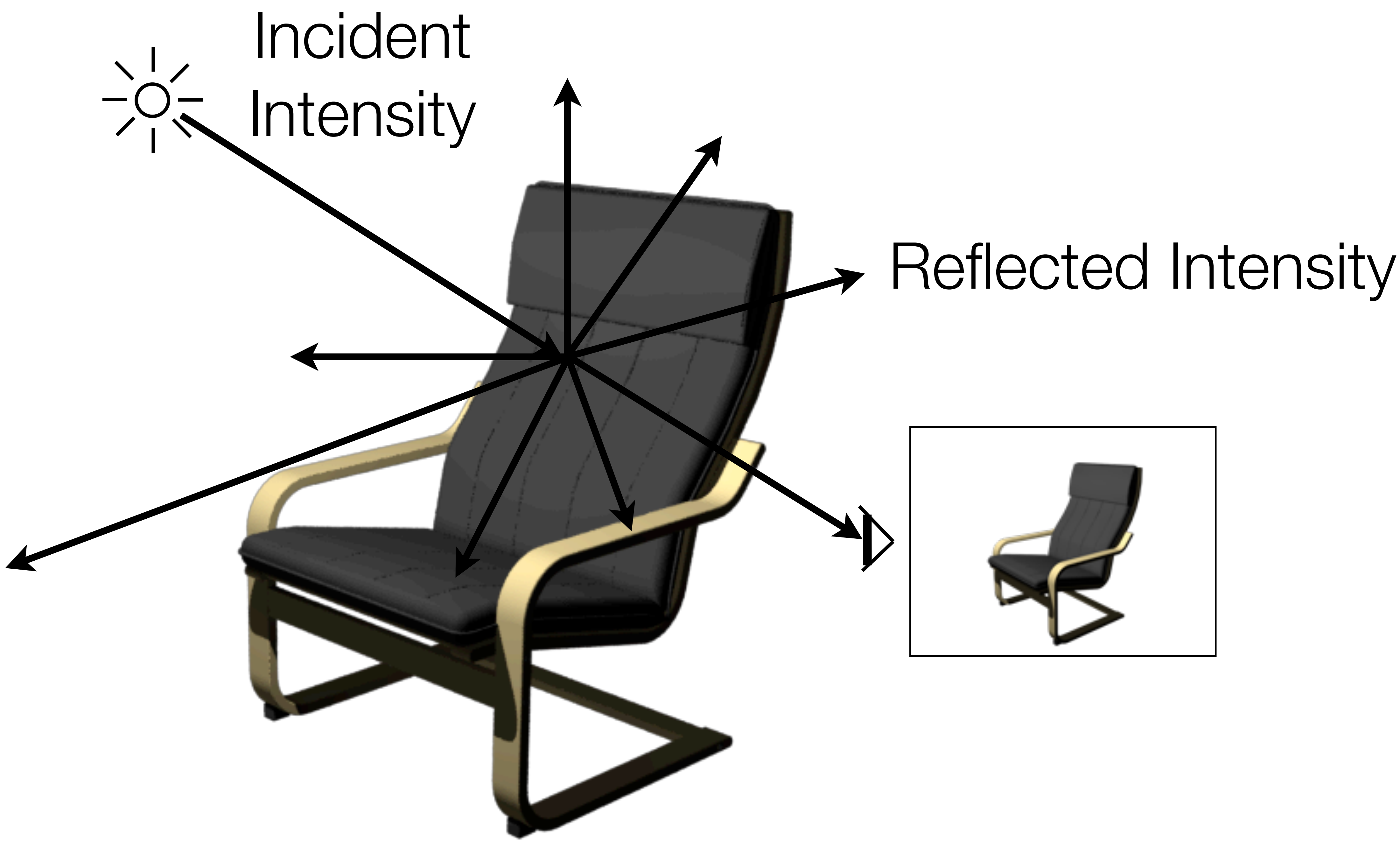
and we need **material** properties of the objects.



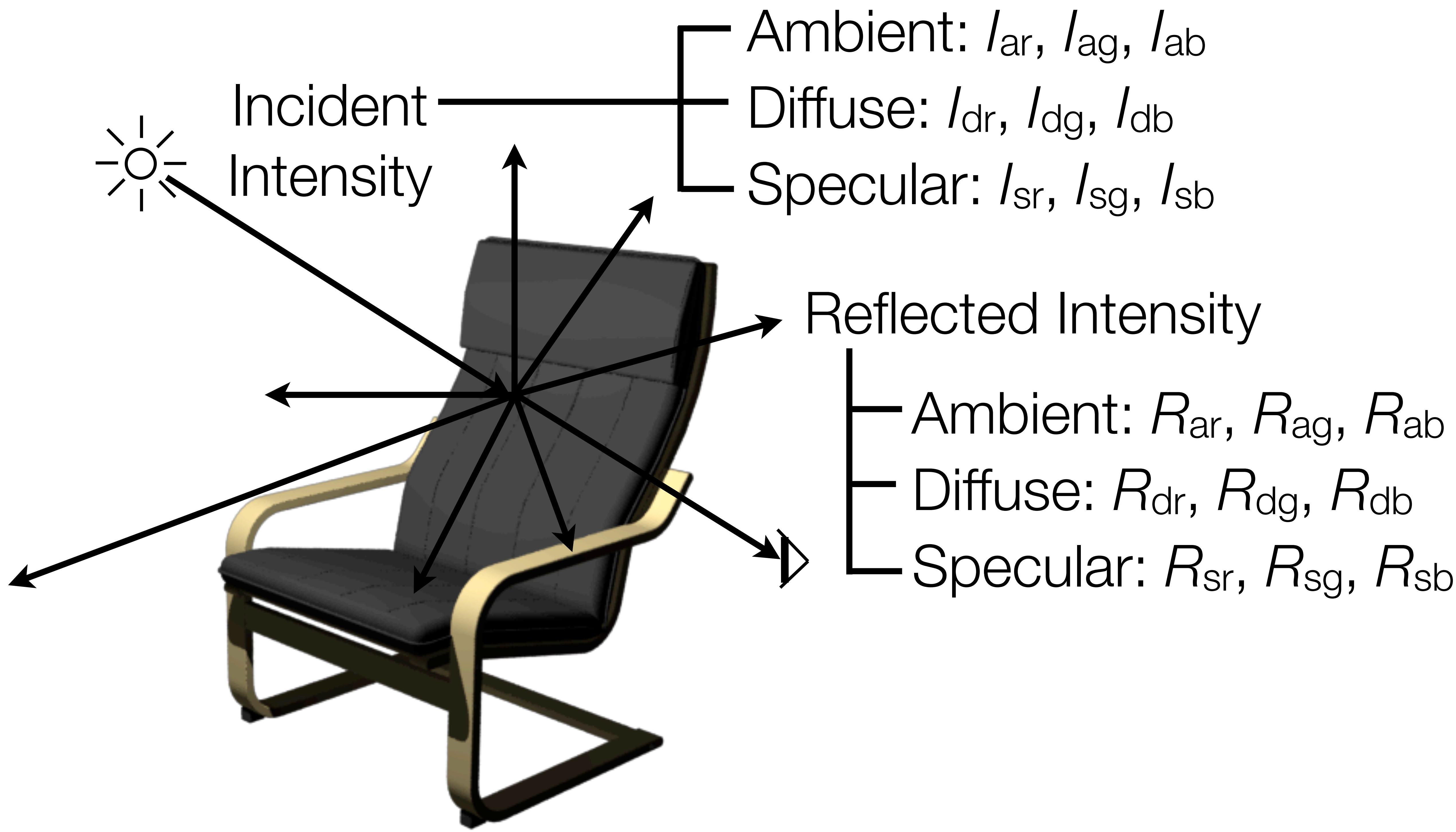
Phong Reflection Model

Most popular model in computer graphics to represent how light reflects off an object surface.

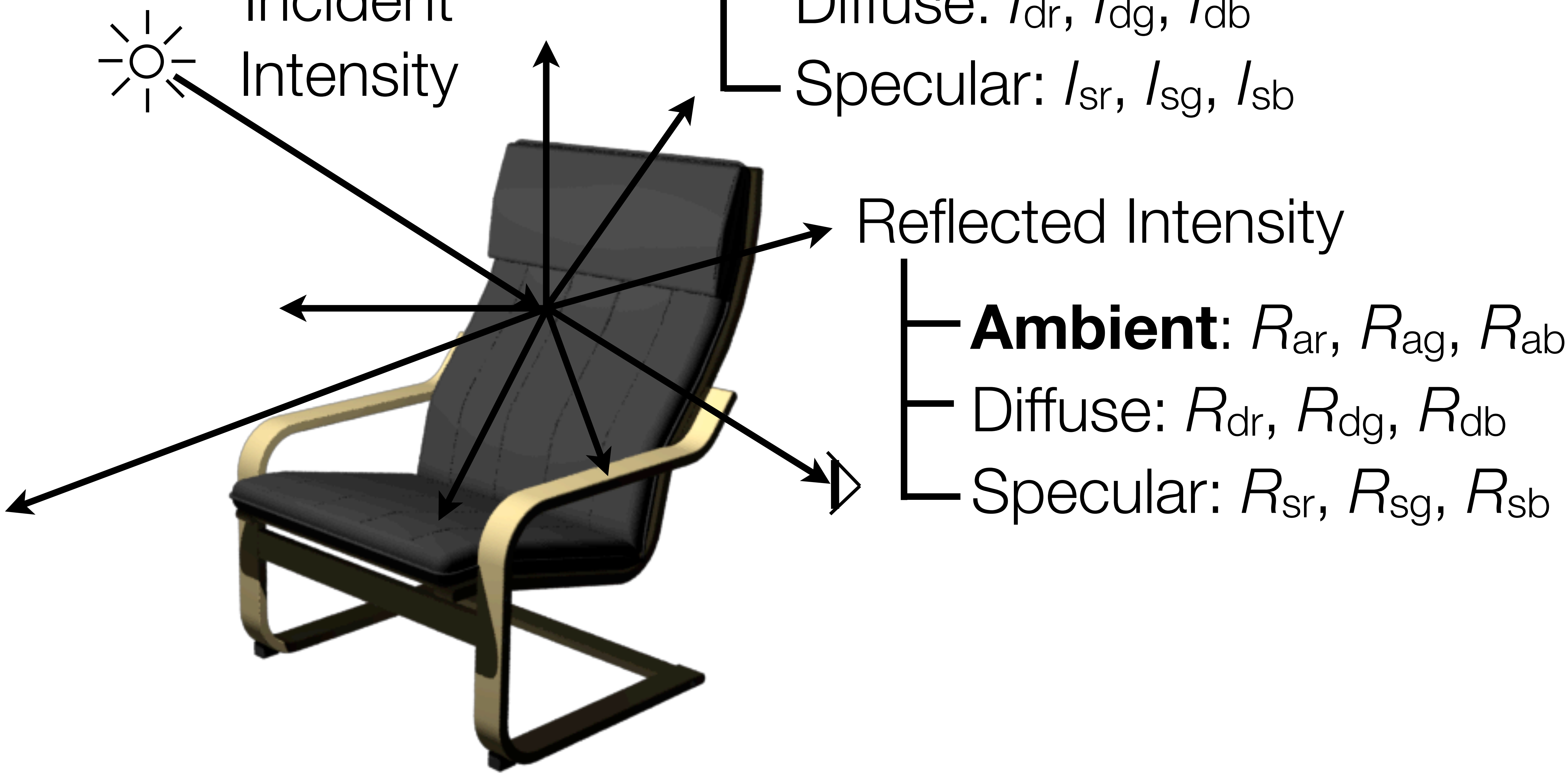
Phong Reflection Model



Phong Reflection Model



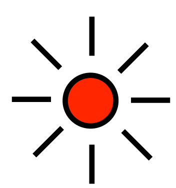
Phong Reflection Model



Ambient Reflection

Part of the incident light is reflected
without any directional dependence.

$$R_{ar} = k_{ar} I_{ar},\ 0 \le k_{ar} \le 1$$
$$R_{ag} = k_{ag} I_{ag},\ 0 \le k_{ag} \le 1$$
$$R_{ab} = k_{ab} I_{ab},\ 0 \le k_{ab} \le 1$$



I_{ar}, I_{ag}, I_{ab}
are ambient terms
in the incident light

k_{ar}, k_{ag}, k_{ab}
are termed **ambient reflectance coefficients**.

R_{ar}, R_{ag}, R_{ab}
are ambient terms
in the reflected light

Ambient Reflection

Part of the incident light is reflected without any directional dependence.

$$R_{ar} = k_{ar} I_{ar}, \ \ 0 \le k_{ar} \le 1$$

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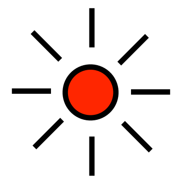
Ambient term in incident light has high amount of red



Object has high amount of white

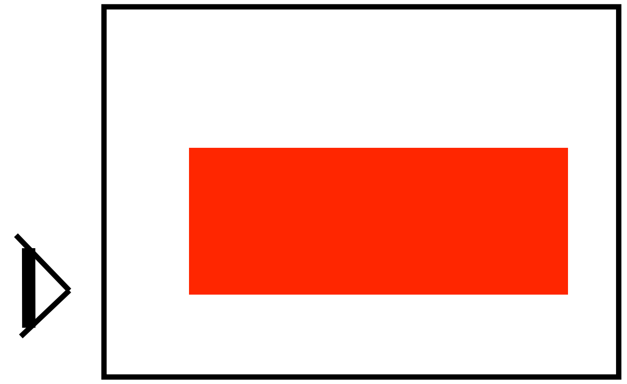
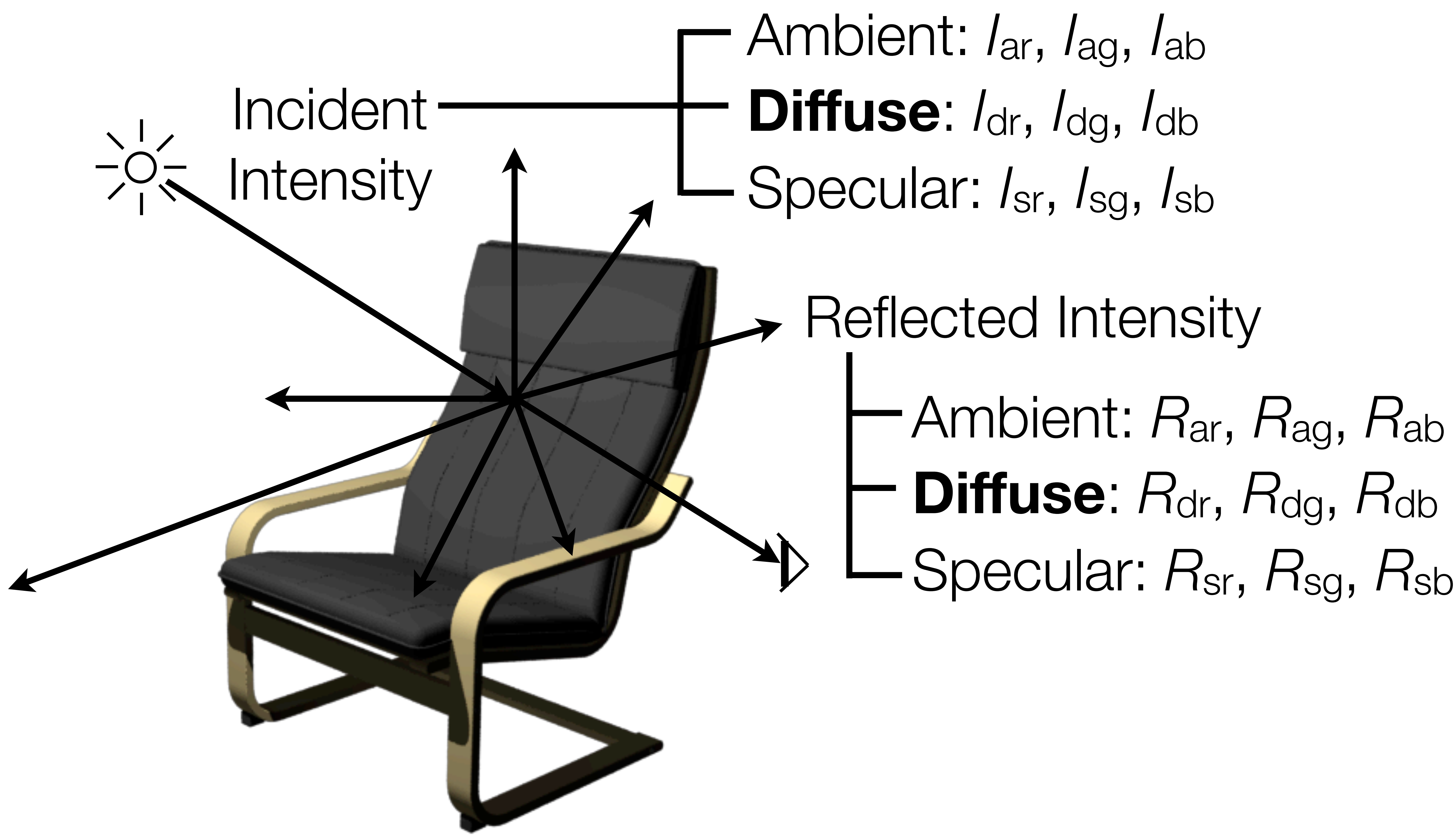


Image of object is red

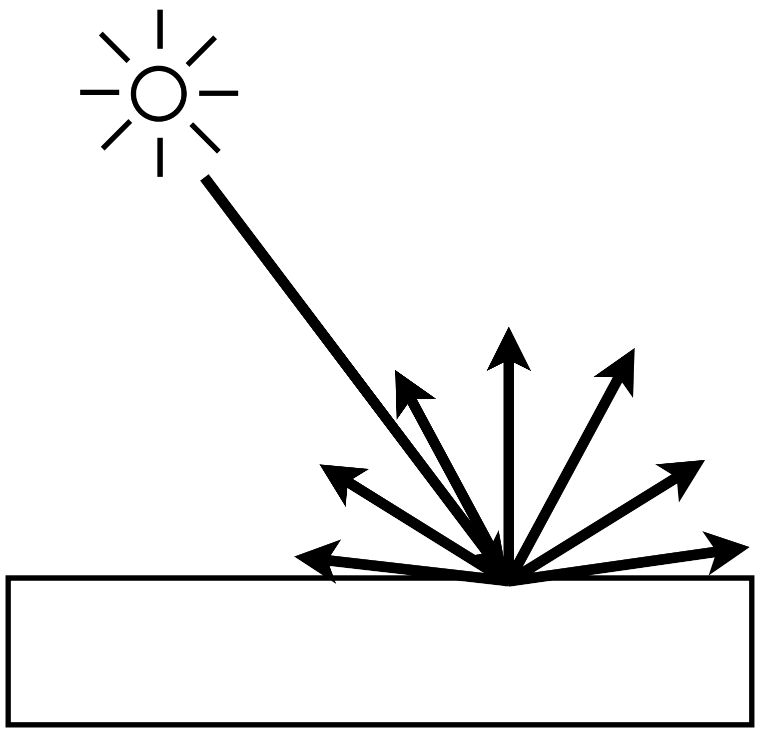
Ambient reflection tells you why on average a white box illuminated by red light appears red.

Phong Reflection Model



Diffuse Reflection

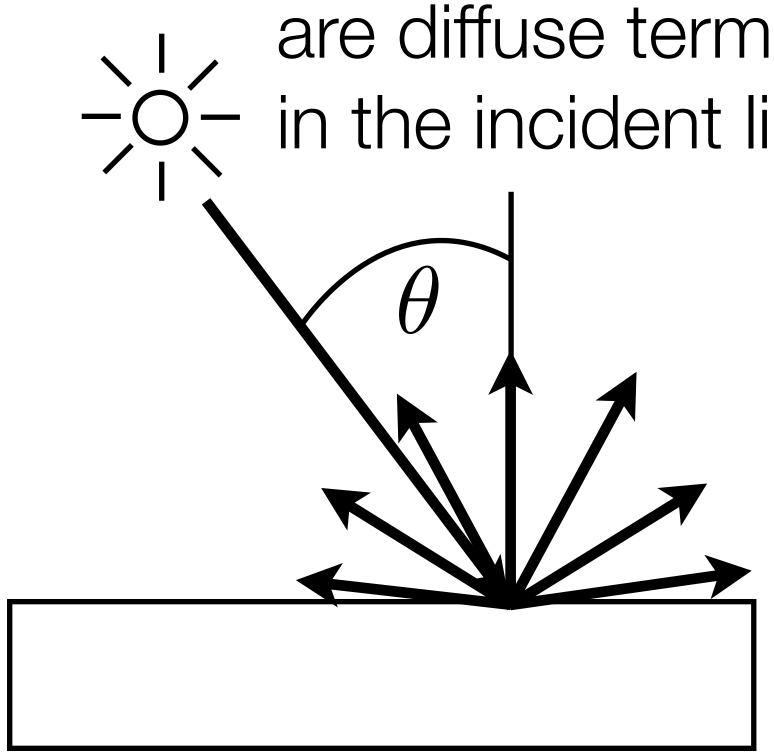
Part of the incident light is reflected uniformly in all directions.



Diffuse Reflection

Part of the incident light is reflected uniformly in all directions.
The reflection depends on the incident light direction.

I_{dr}, I_{dg}, I_{db}
are diffuse terms
in the incident light



$$R_{dr} = k_{dr} I_{dr} \cos\theta, \ 0 \le k_{dr} \le 1$$
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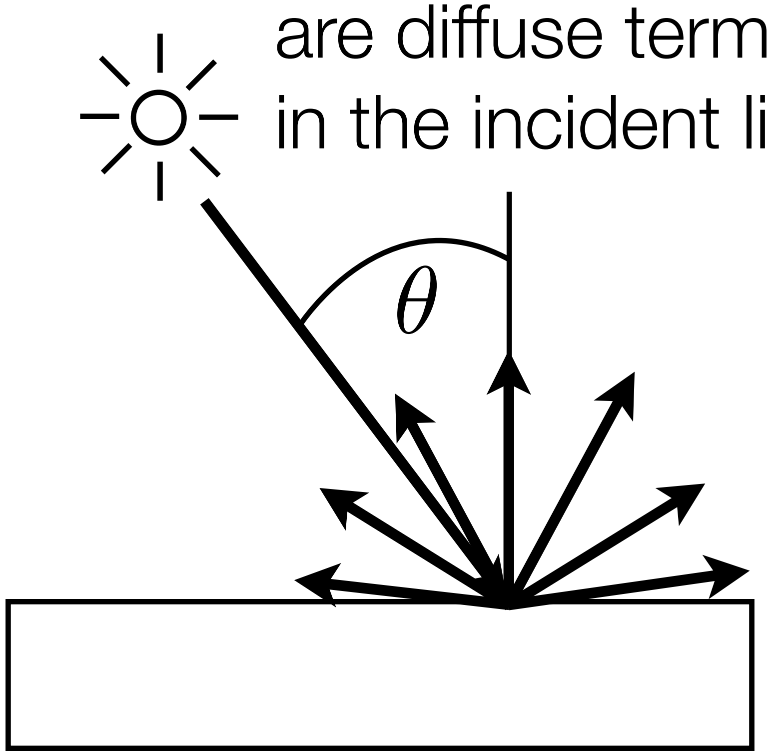

$$R_{dr} = k_{dr} I_{dr} \boxed{\cos\theta,} \; 0 \le k_{dr} \le 1$$
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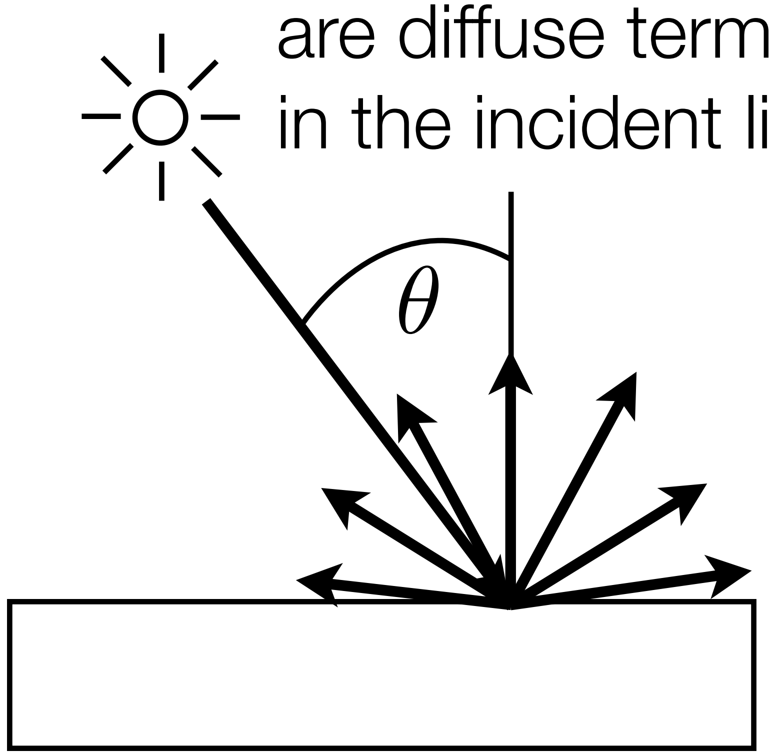

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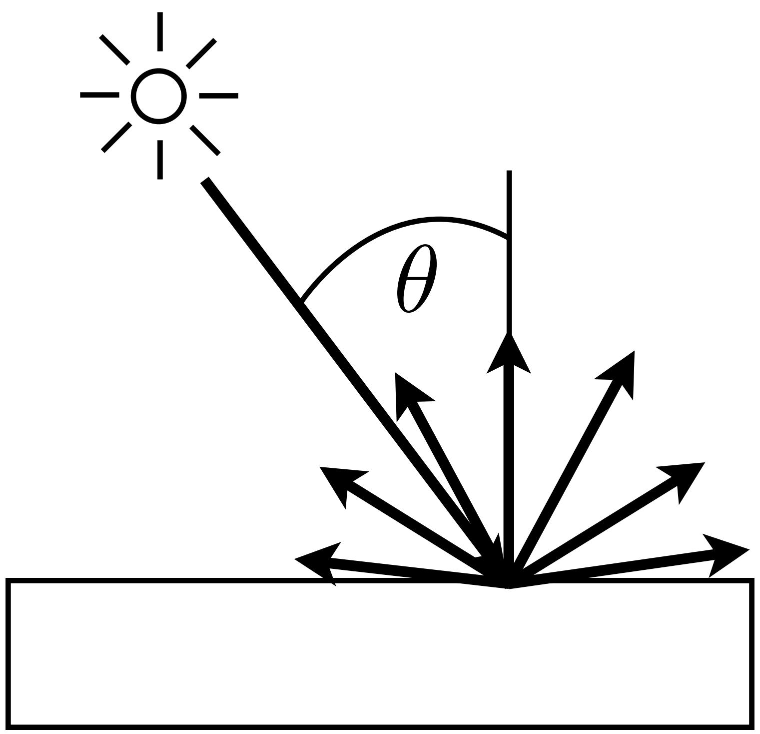
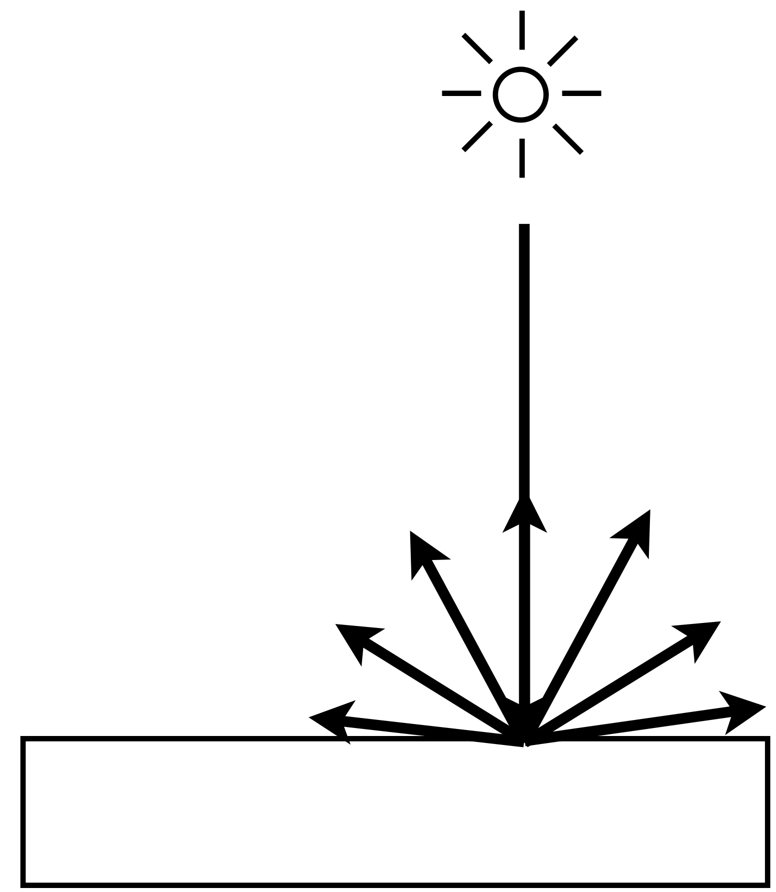


This surface appears darker.



This surface appears brighter.

Diffuse Reflection

Part of the incident light is reflected uniformly in all directions.
The reflection depends on the incident light direction.

I_{dr}, I_{dg}, I_{db}
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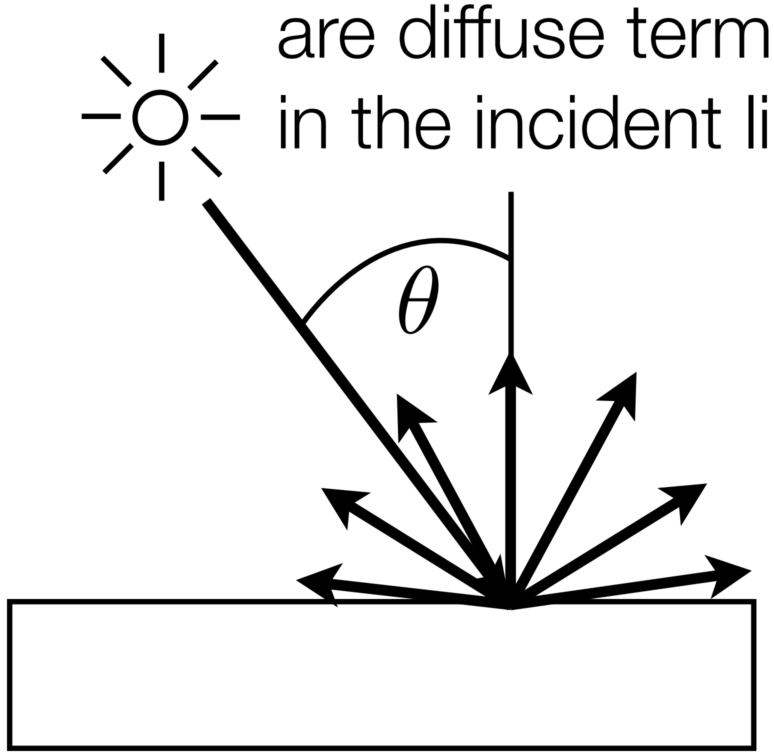

$$R_{dr} = k_{dr} I_{dr} \cos\theta,\ \ 0 \le k_{dr} \le 1$$

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k_{dr}, k_{dg}, k_{db}
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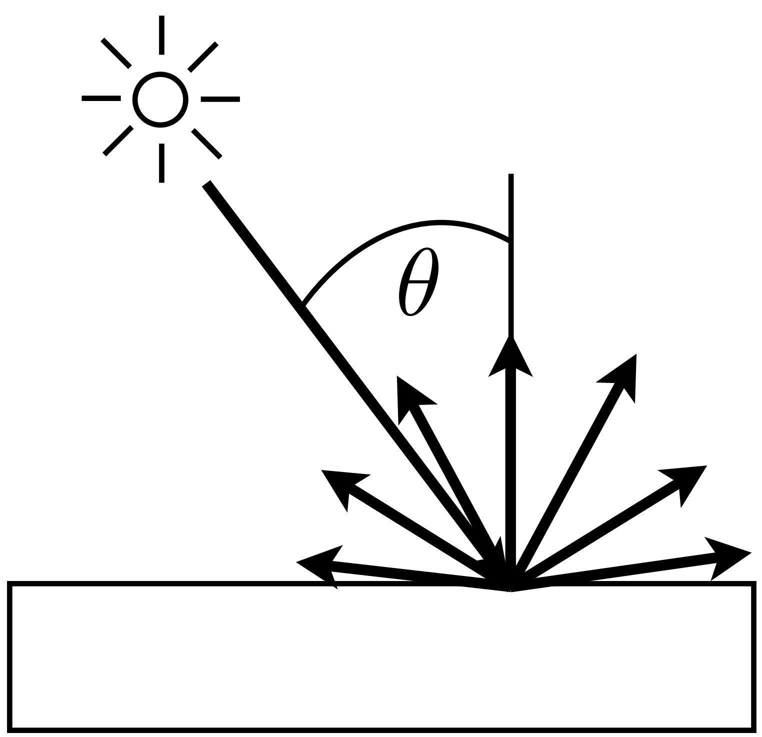
R_{dr}, R_{dg}, R_{db}
are diffuse terms
in the reflected light

Diffuse Reflection

How to calculate cos θ?



$$R_{dr} = k_{dr} I_{dr} \cos\theta,\ \ 0 \le k_{dr} \le 1$$
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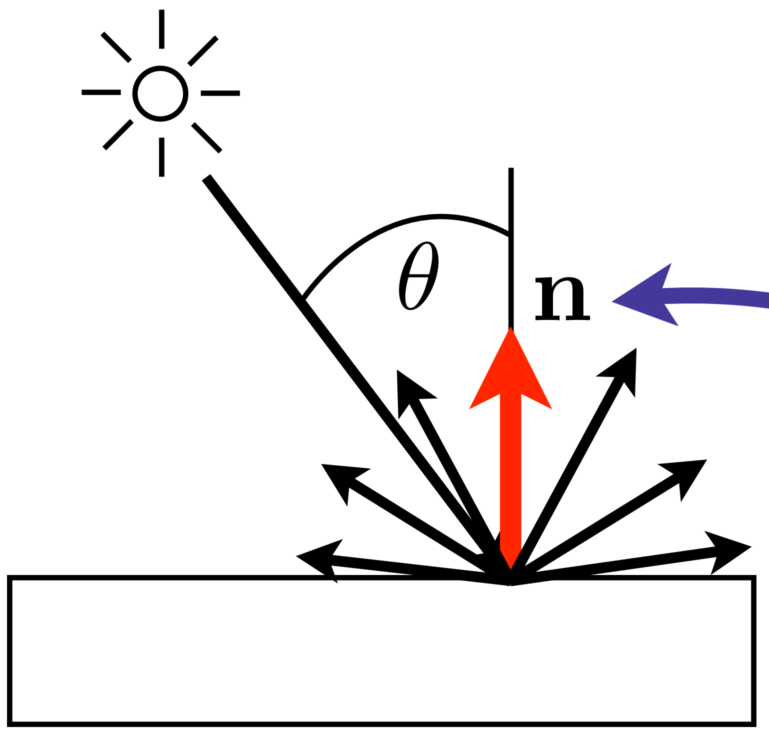
$$R_{db} = k_{db} I_{db} \cos\theta,\ \ 0 \le k_{db} \le 1$$

Diffuse Reflection

Need direction of incidence and **normal n**.



$$R_{dr} = k_{dr} I_{dr} \cos\theta,\ \ 0 \leq k_{dr} \leq 1$$
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$$R_{db} = k_{db} I_{db} \cos\theta,\ \ 0 \leq k_{db} \leq 1$$

Normal: unit vector
perpendicular to surface.

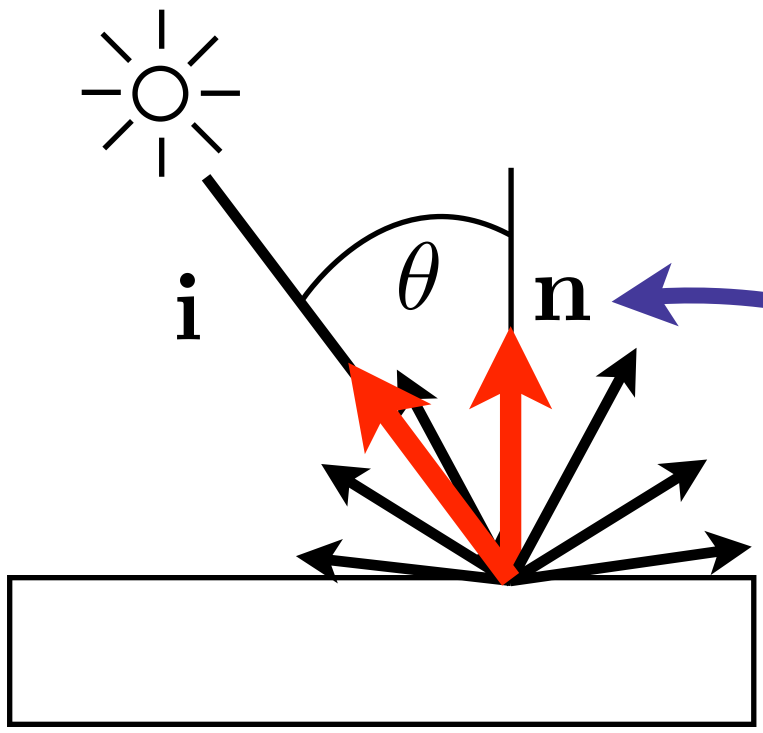
Diffuse Reflection

Typically, we use a unit vector **i** against the direction of incidence (i.e., from surface to light source), and normal **n**.

$$R_{dr} = k_{dr} I_{dr} \cos\theta,\ \ 0 \le k_{dr} \le 1$$

$$R_{dg} = k_{dg} I_{dg} \cos\theta,\ \ 0 \le k_{dg} \le 1$$

$$R_{db} = k_{db} I_{db} \cos\theta,\ \ 0 \le k_{db} \le 1$$



Normal: unit vector perpendicular to surface.

Diffuse Reflection

Typically, we use a unit vector **i** against the direction of incidence (i.e., from surface to light source), and normal **n**.

$$R_{dr} = k_{dr} I_{dr} \cos\theta, \;\; 0 \leq k_{dr} \leq 1$$

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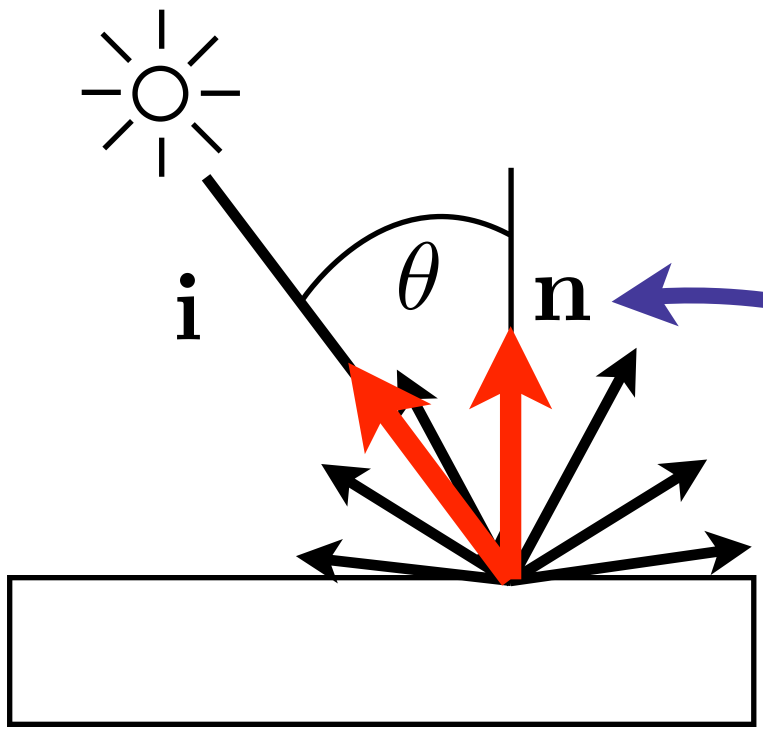
$$R_{db} = k_{db} I_{db} \cos\theta, \;\; 0 \leq k_{db} \leq 1$$

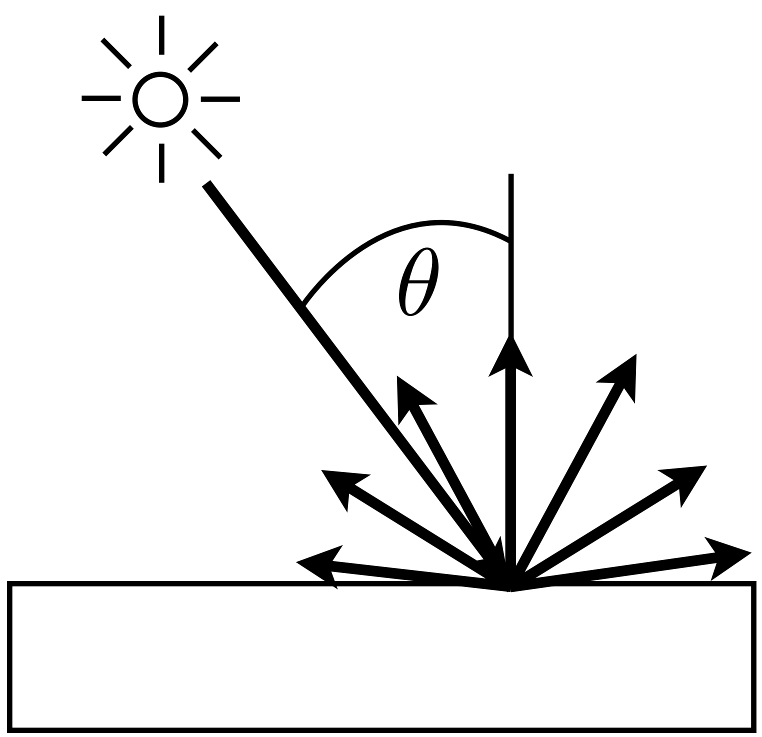


Normal: unit vector perpendicular to surface.

$$\cos\theta = \mathbf{i} \cdot \mathbf{n}$$

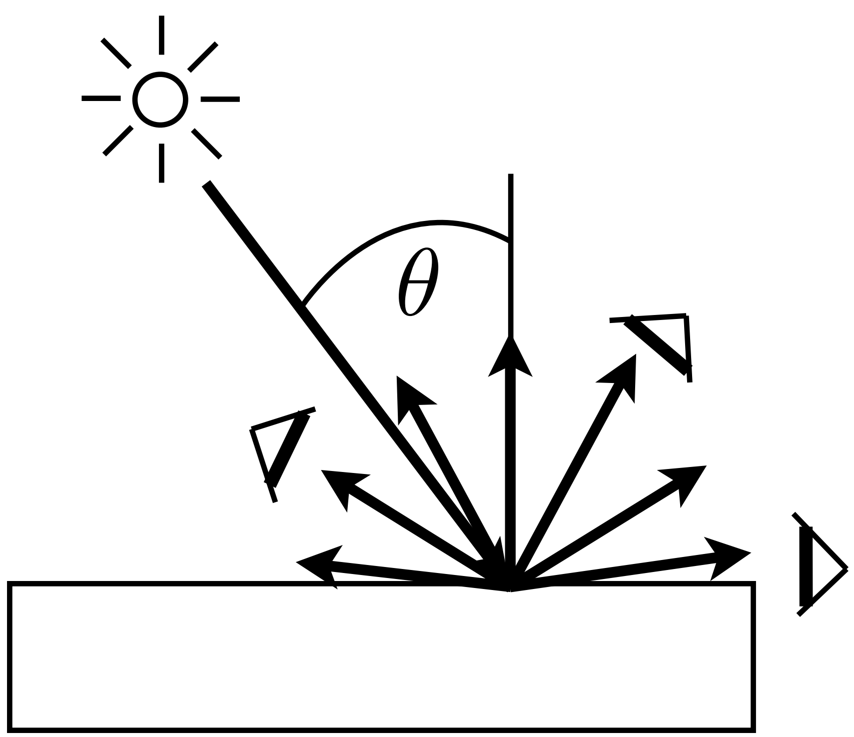
Diffuse Reflection

Part of the incident light is reflected uniformly in all directions.
The reflection depends on the incident light direction.



Diffuse Reflection

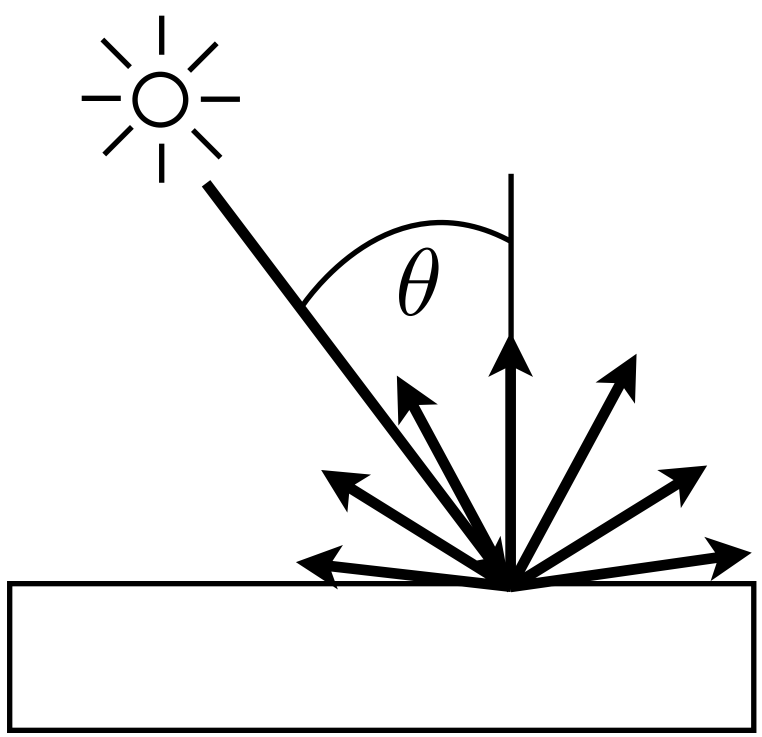
Part of the incident light is reflected uniformly in all directions.
The reflection depends on the incident light direction.
But the reflection **does not** depend upon viewer location.



All viewers get the same amount of diffuse reflection.

Diffuse Reflection

θ should be between -90 and 90 degrees.



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$$R_{db} = k_{db} I_{db} \cos\theta,\ \ 0 \leq k_{db} \leq 1$$

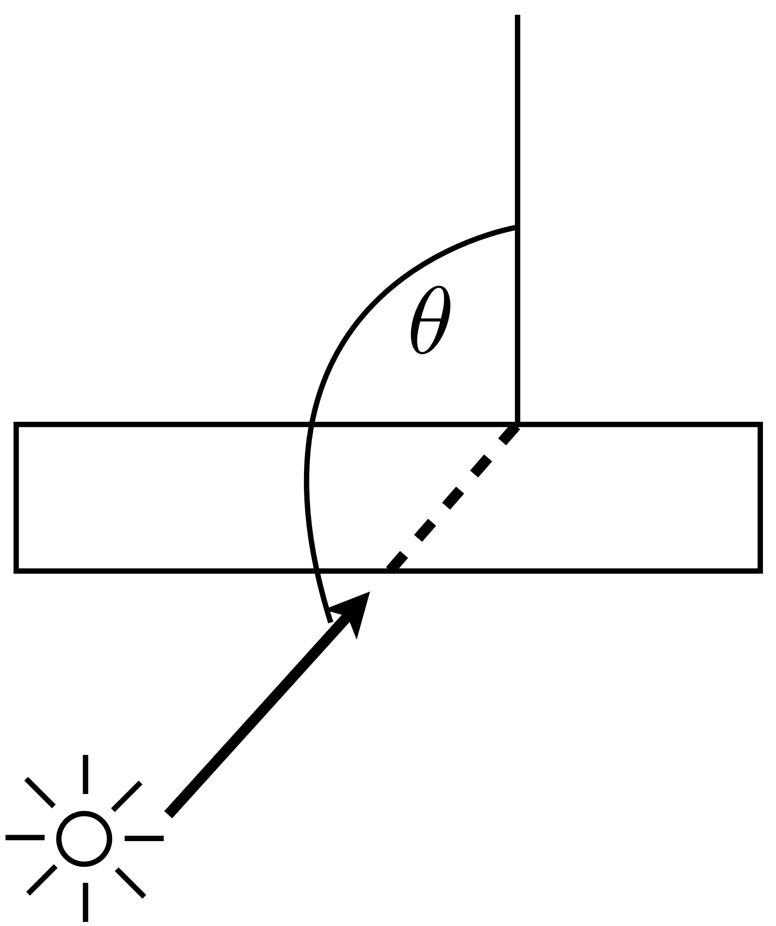
Diffuse Reflection

If θ > 90 degrees or < -90 degrees, no light reaches the surface of interest.

$$R_{dr} = k_{dr} I_{dr} \cos\theta,\ \ 0 \leq k_{dr} \leq 1$$

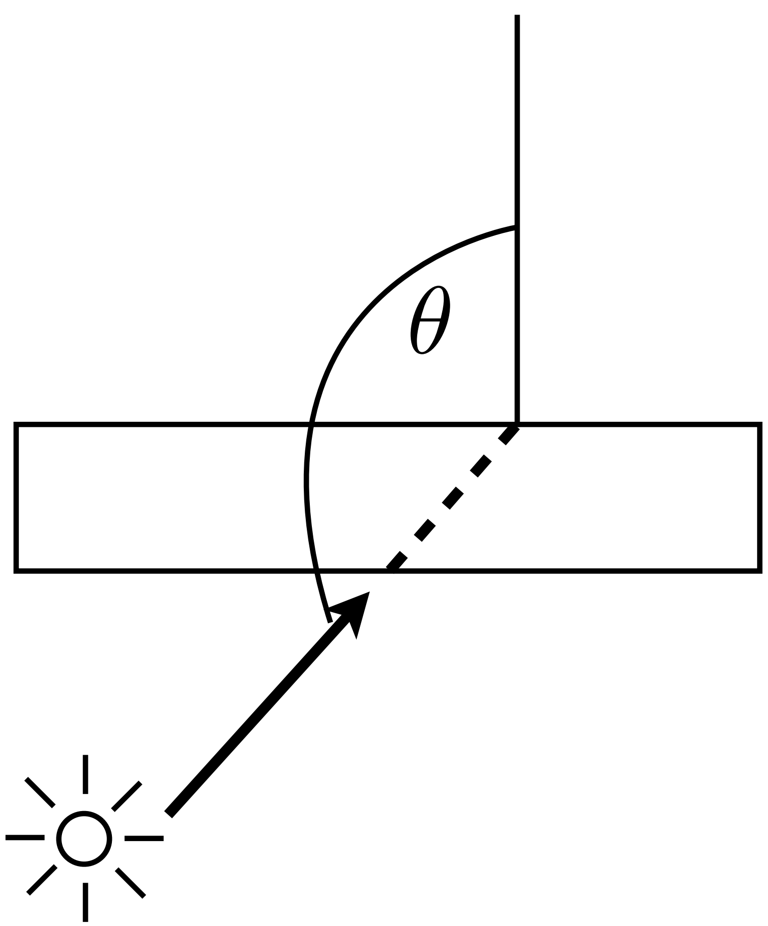
$$R_{dg} = k_{dg} I_{dg} \cos\theta,\ \ 0 \leq k_{dg} \leq 1$$

$$R_{db} = k_{db} I_{db} \cos\theta,\ \ 0 \leq k_{db} \leq 1$$



Diffuse Reflection

To capture this, we modify the equations a bit.



$$R_{dr} = k_{dr} I_{dr} \max(\cos\theta, 0), \;\; 0 \leq k_{dr} \leq 1$$

$$R_{dg} = k_{dg} I_{dg} \max(\cos\theta, 0), \;\; 0 \leq k_{dg} \leq 1$$

$$R_{db} = k_{db} I_{db} \boxed{\max(\cos\theta, 0)}, \;\; 0 \leq k_{db} \leq 1$$

When abs(θ) > 90,
cos θ < 0,
max forces the term to 0.

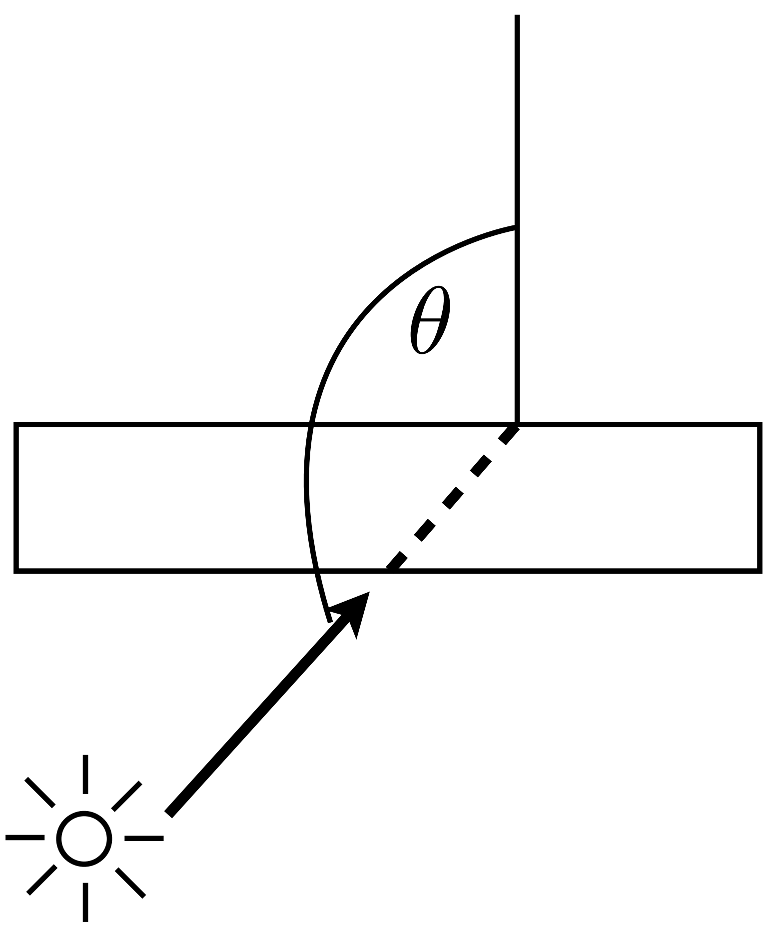
Diffuse Reflection

To capture this, we modify the equations a bit.

$$R_{dr} = k_{dr} I_{dr} \max(\cos\theta, 0), \;\; 0 \leq k_{dr} \leq 1$$

$$R_{dg} = k_{dg} I_{dg} \max(\cos\theta, 0), \;\; 0 \leq k_{dg} \leq 1$$

$$R_{db} = k_{db} I_{db} \boxed{\max(\cos\theta, 0),} \;\; 0 \leq k_{db} \leq 1$$

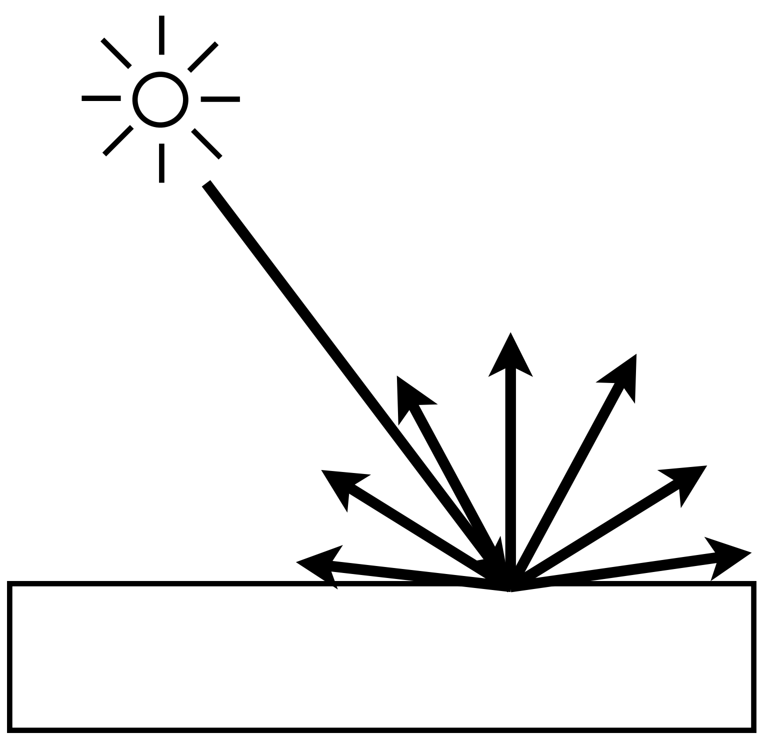


When abs(θ) > 90,
cos θ < 0,
max forces the term to 0.

This helps to ensure that
all light contributions are **positive**.
Negative values do not make sense for light.

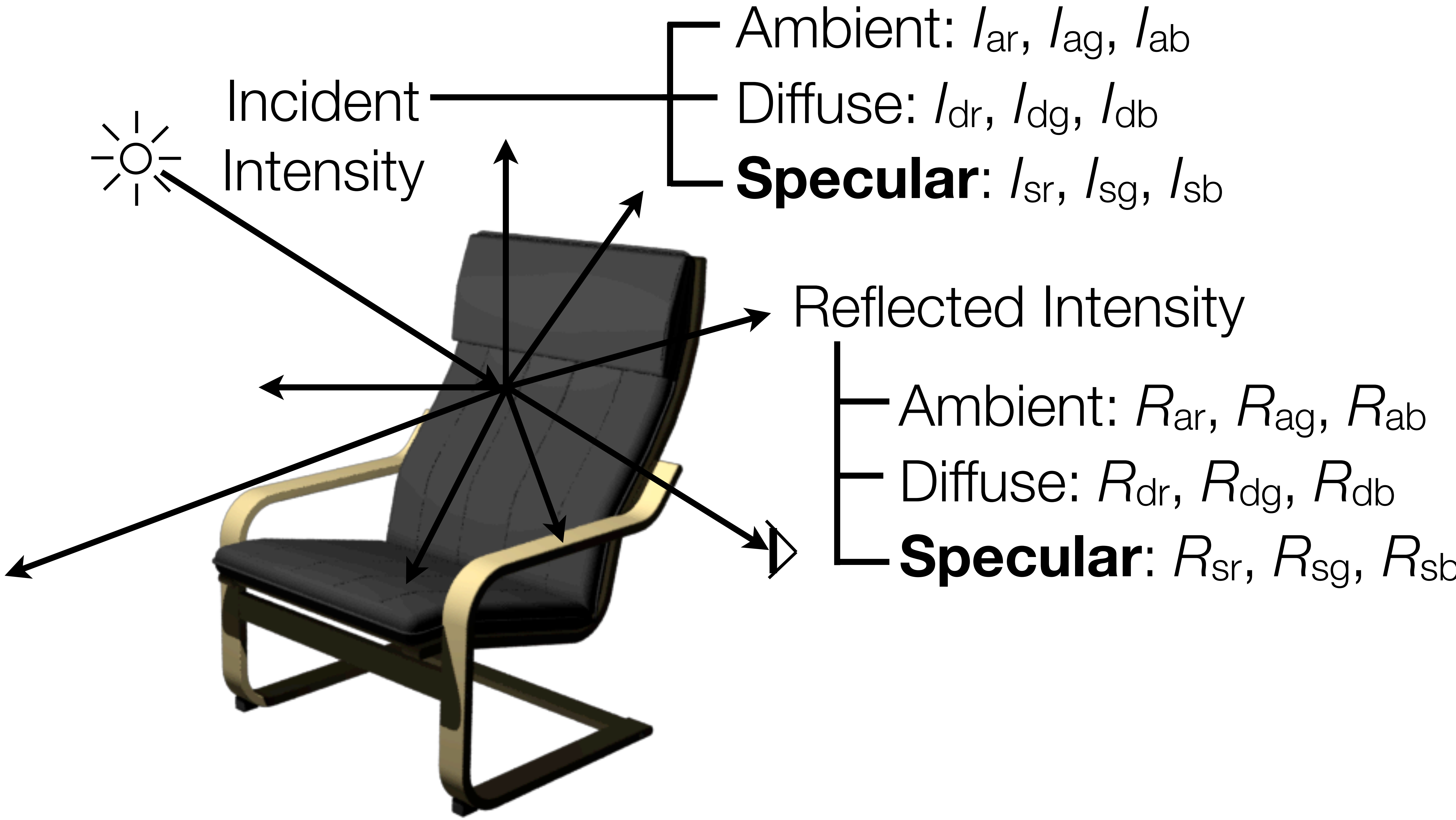
Diffuse Reflection

Part of the incident light is reflected uniformly in all directions.



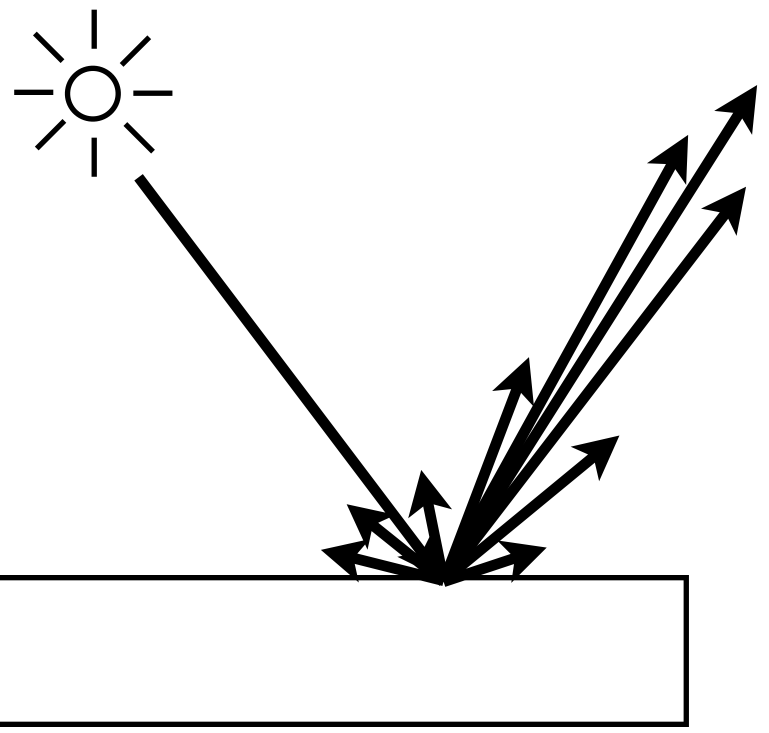
Result of Diffuse Reflection

Phong Reflection Model



Specular Reflection

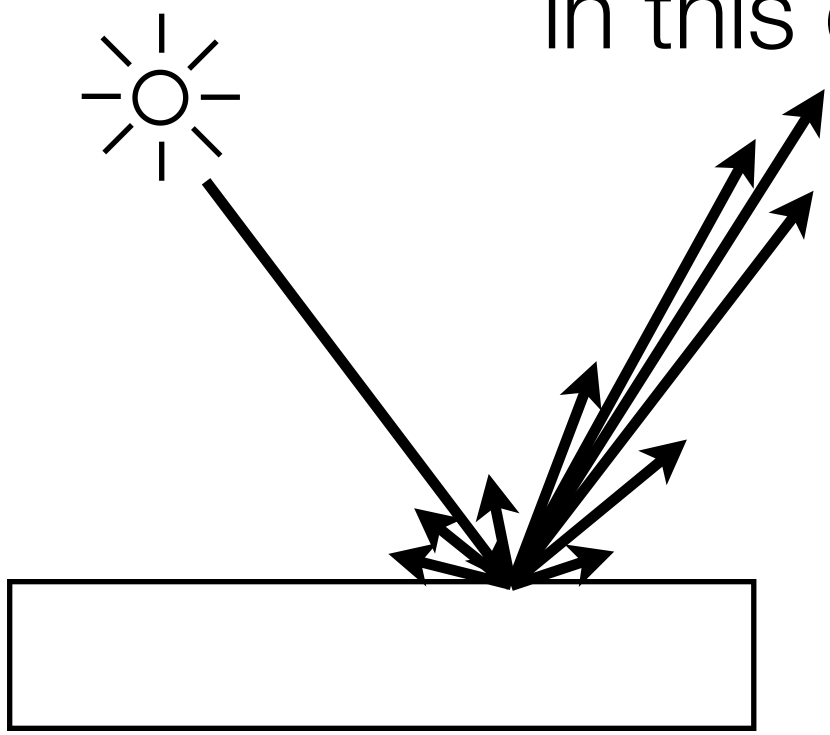
Part of the incident light is reflected largely in one direction.



Specular Reflection

Part of the incident light is reflected largely in one direction.

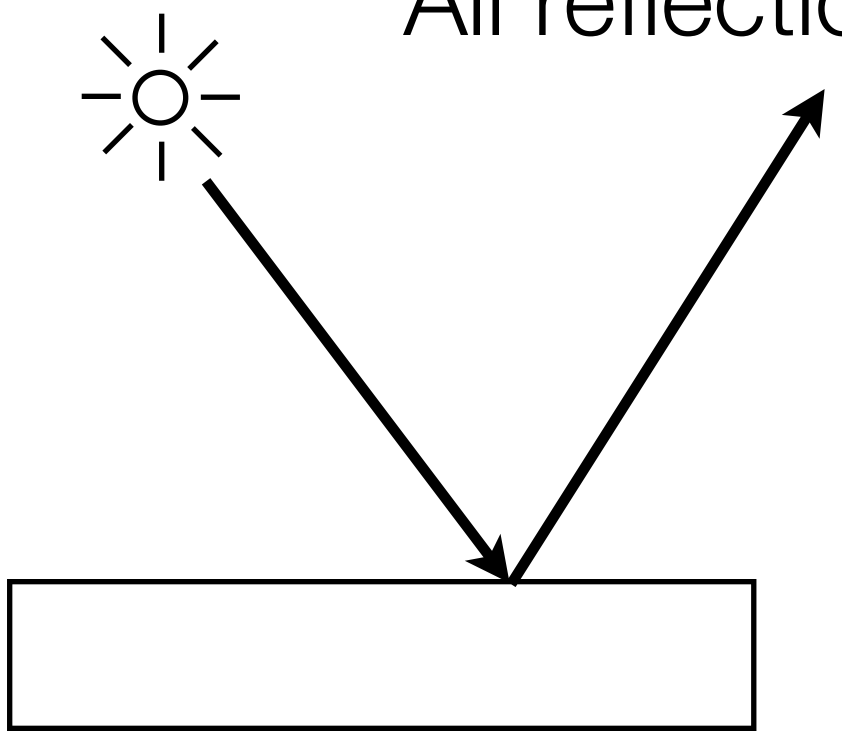
Lot of reflection
in this direction.



Very little reflection
anywhere else.

Mirror Reflection

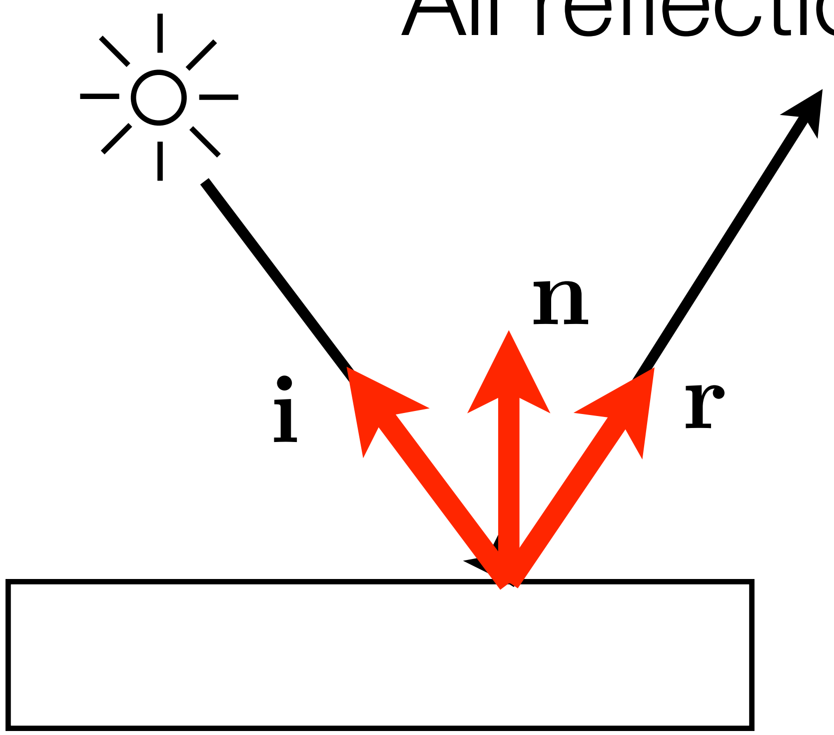
If the surface is a perfect mirror, the reflection is along exactly one direction.



Mirror Reflection

If the surface is a perfect mirror, the reflection is along exactly one direction. We can calculate this direction.

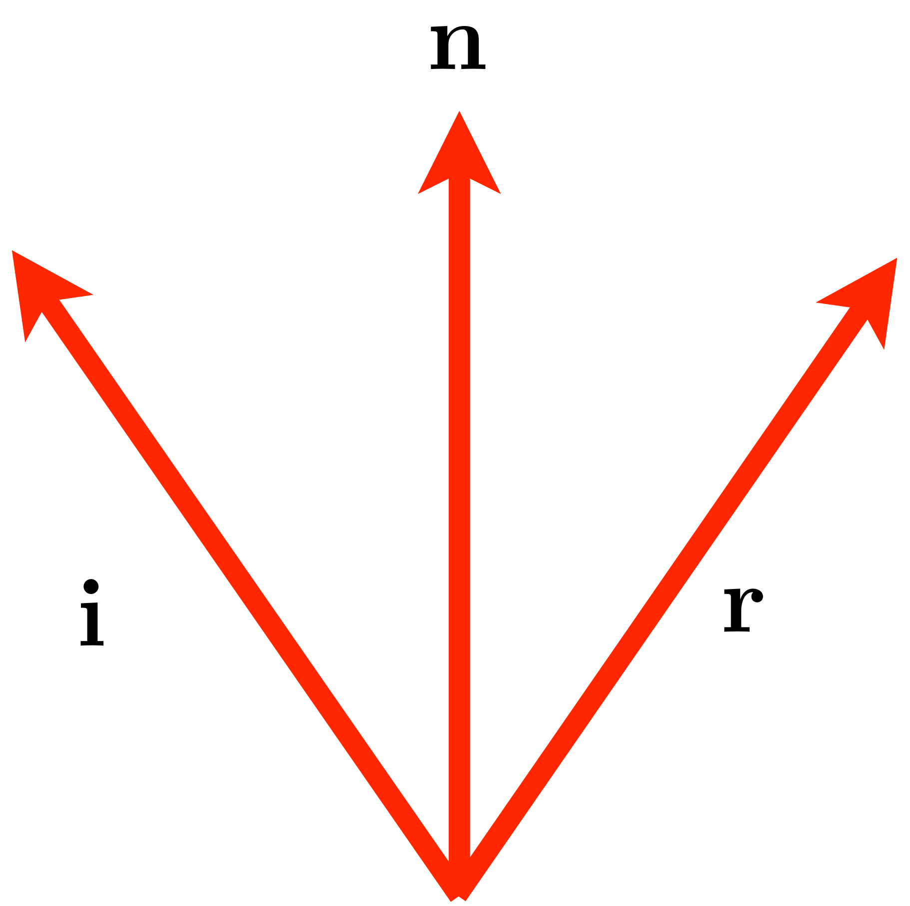
All reflection in this direction.



r is just **i** mirrored around **n**.

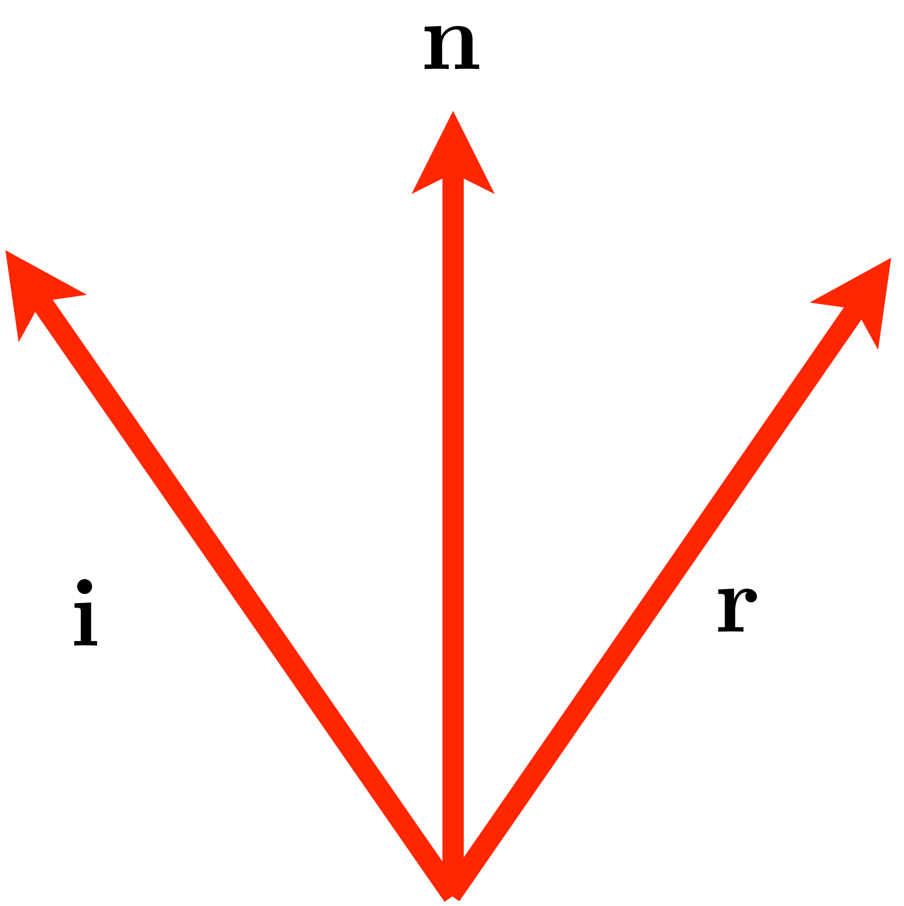
No reflection anywhere else.

Mirroring a Vector about Another

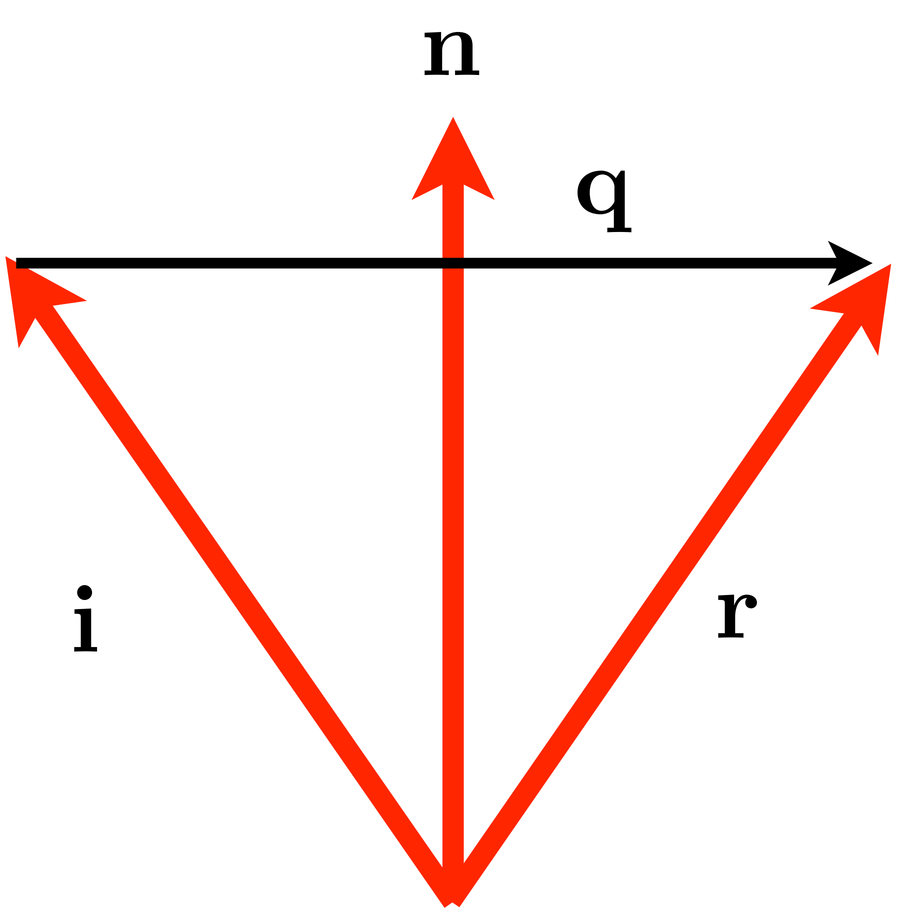


Mirroring a Vector about Another

We will use vector addition.

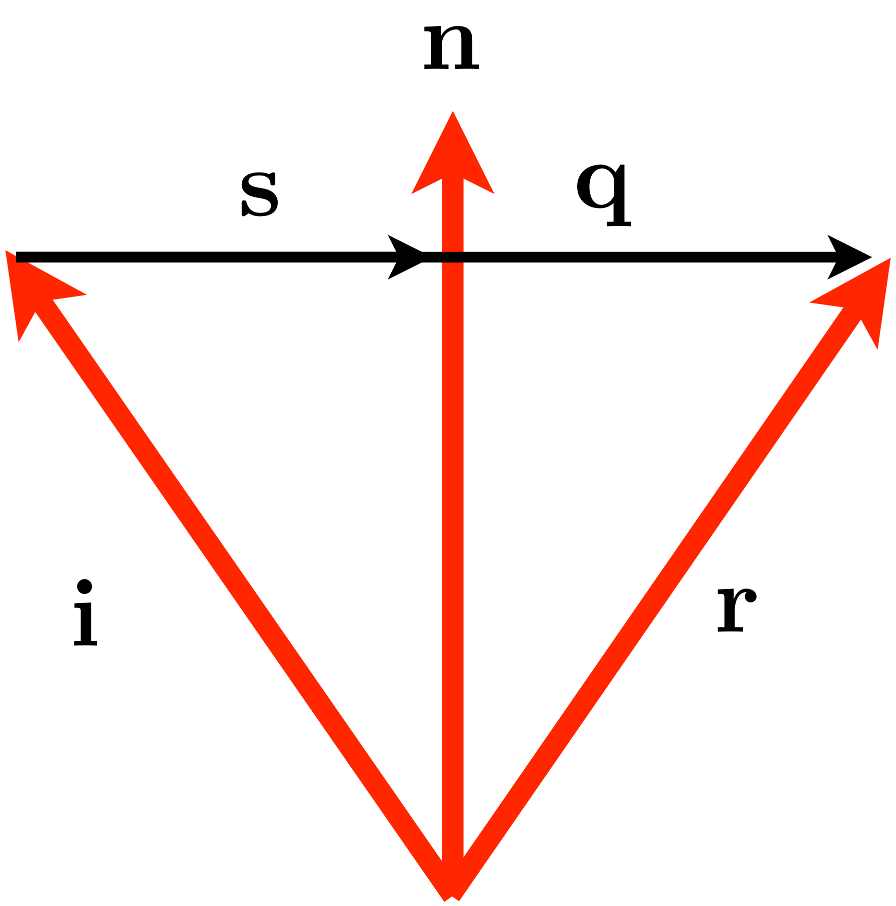


Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

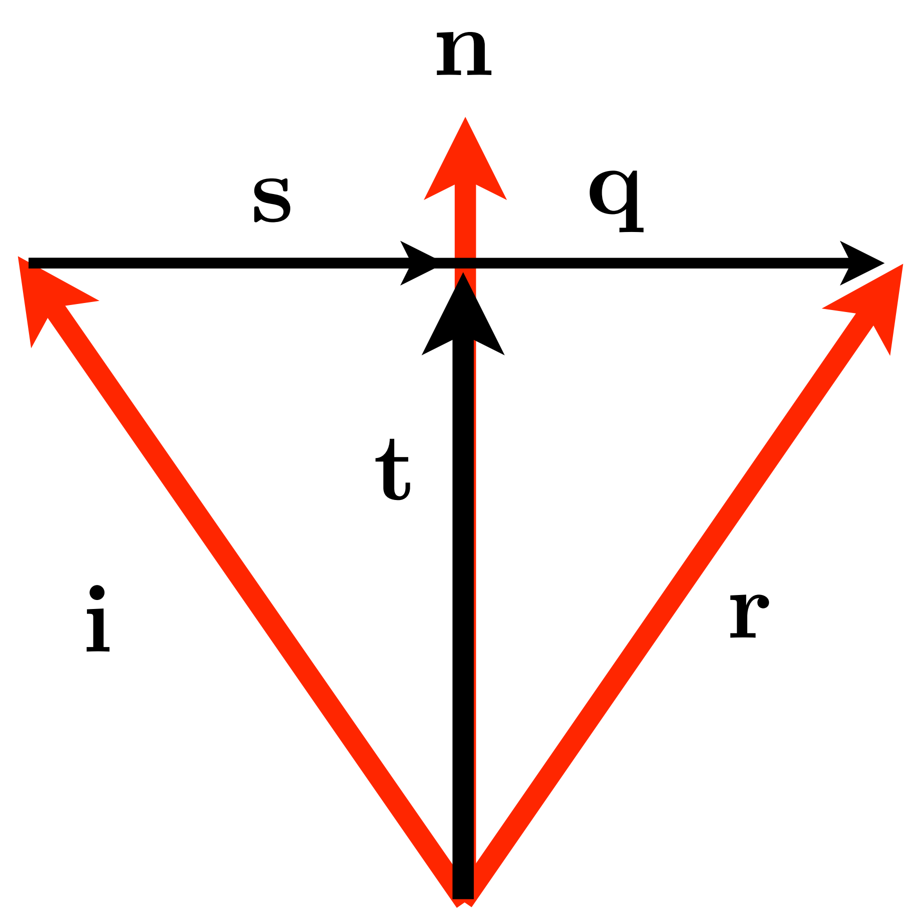
Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

$$\mathbf{q} = 2\mathbf{s}$$

Mirroring a Vector about Another

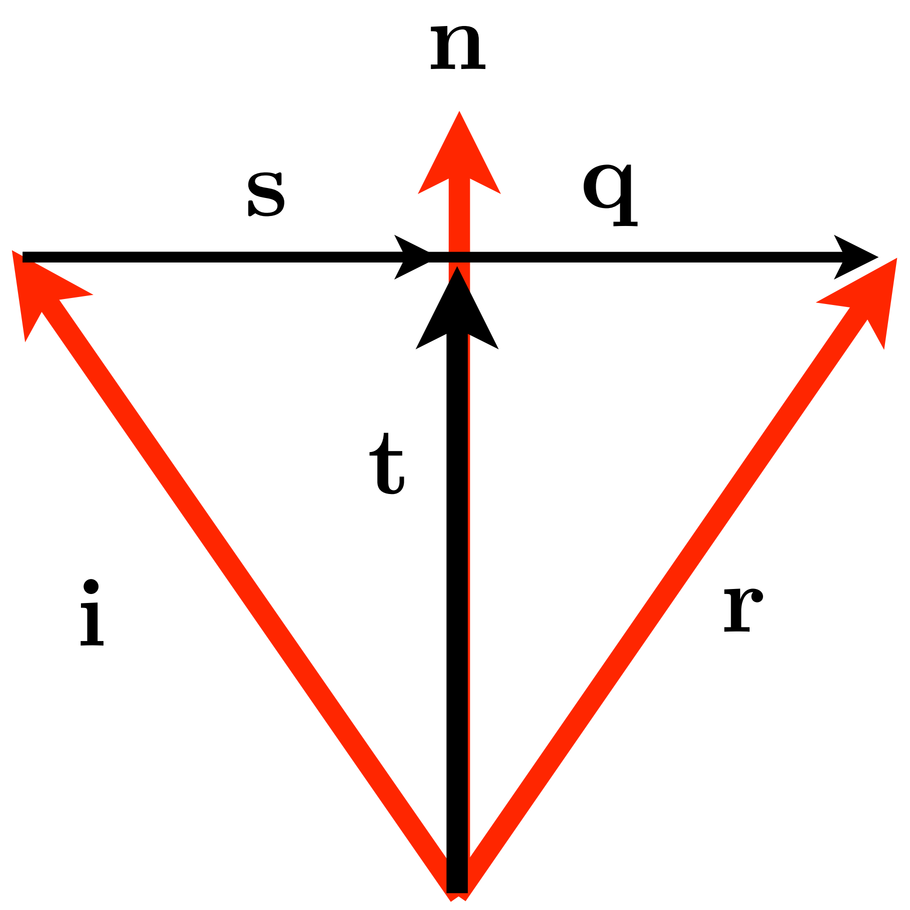


$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

Mirroring a Vector about Another



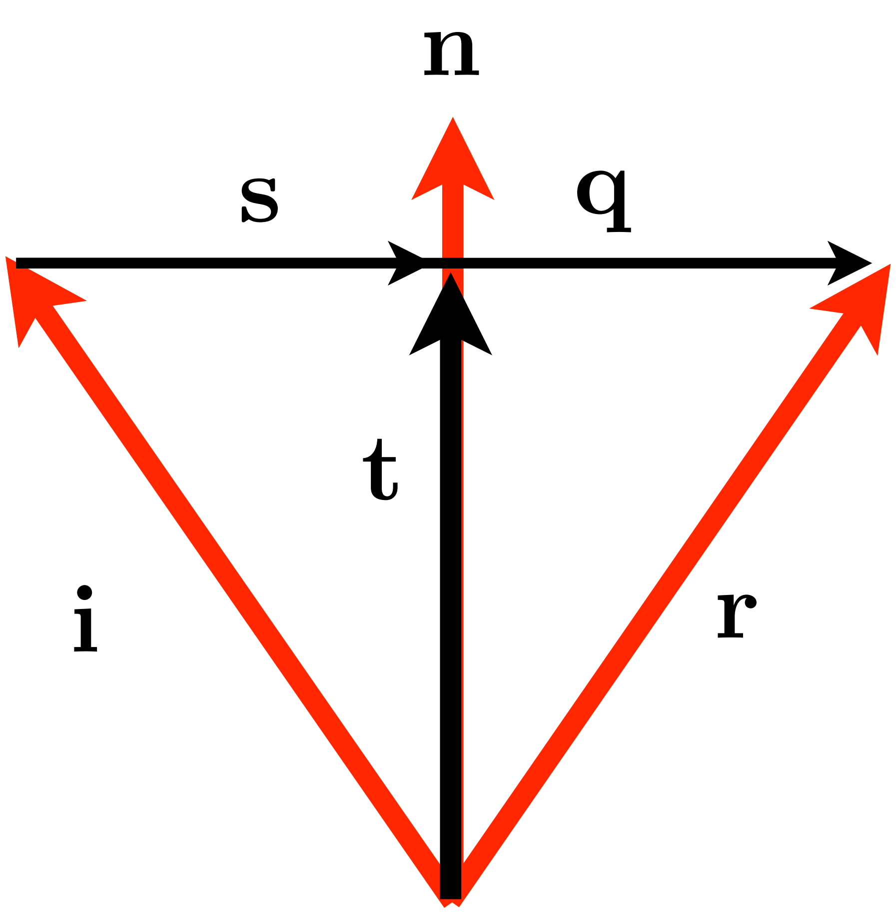
$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\,\mathbf{n}$$

Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

$$\mathbf{q} = 2\mathbf{s}$$

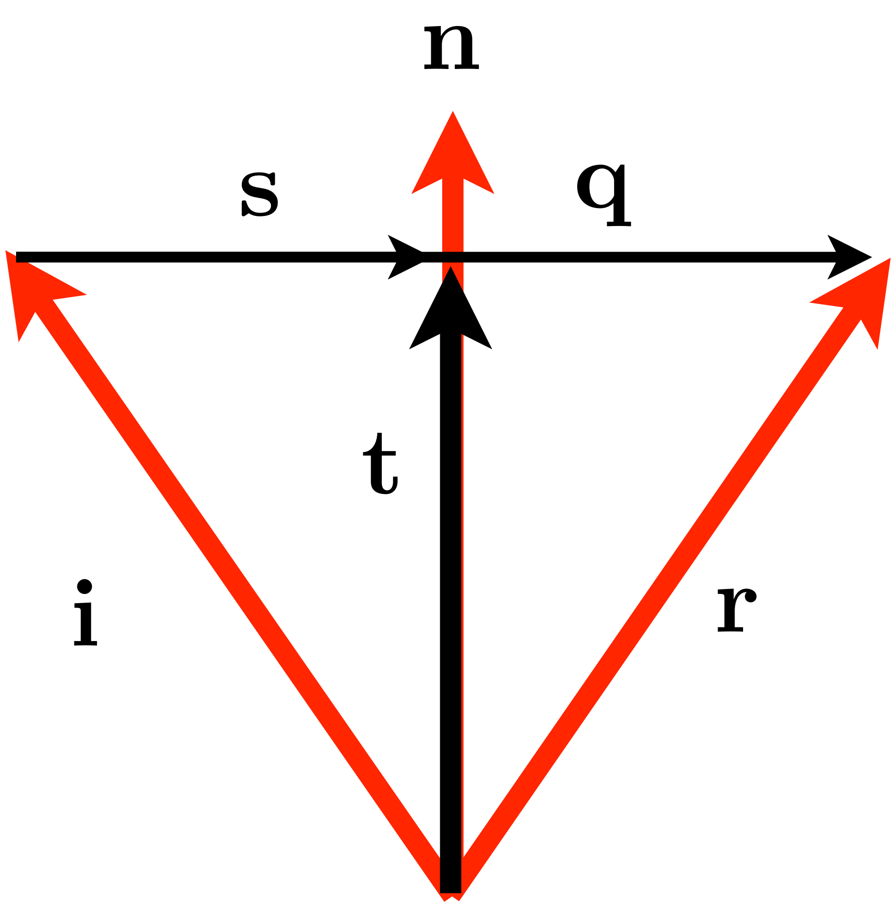
$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\,\mathbf{n}$$

magnitude of **t** is dot product between **i** and **n**

t is along unit vector **n**

Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

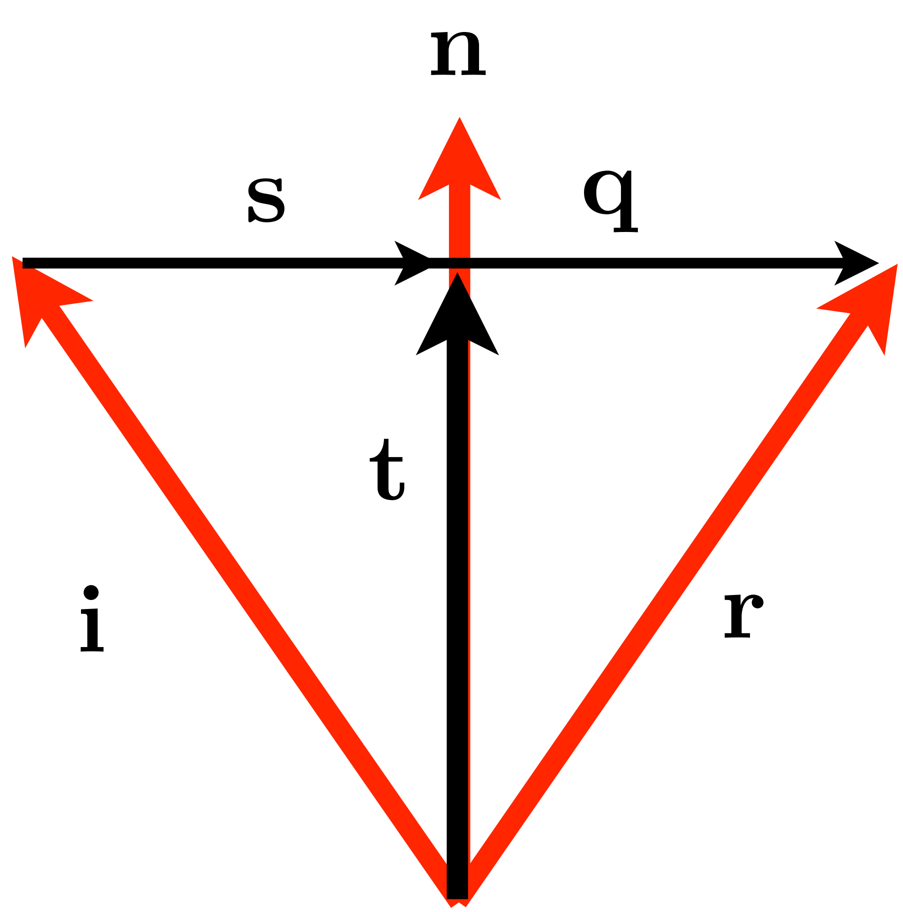
$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\, \mathbf{n}$$

$$\mathbf{r} = \mathbf{i} + 2\left((\mathbf{i} \cdot \mathbf{n})\, \mathbf{n} - \mathbf{i}\right)$$

Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

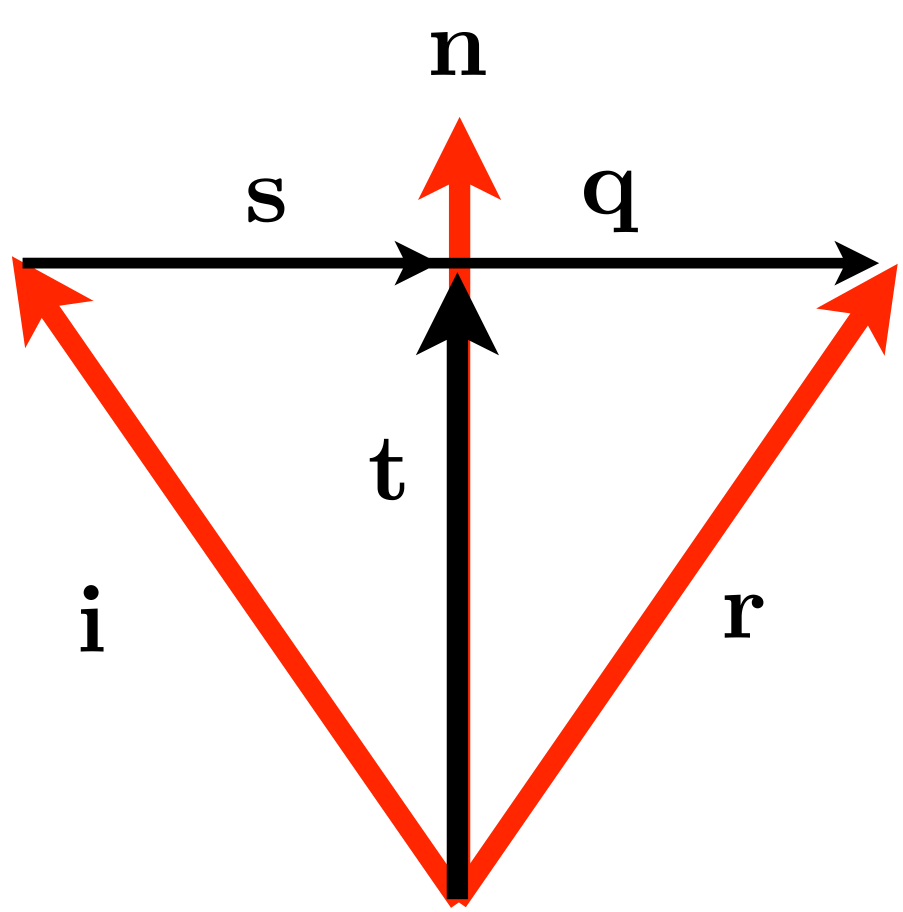
$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\,\mathbf{n}$$

$$\begin{aligned}\mathbf{r} &= \mathbf{i} + 2\left((\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - \mathbf{i}\right) \\ &= \mathbf{i} + 2\,(\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - 2\mathbf{i}\end{aligned}$$

Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

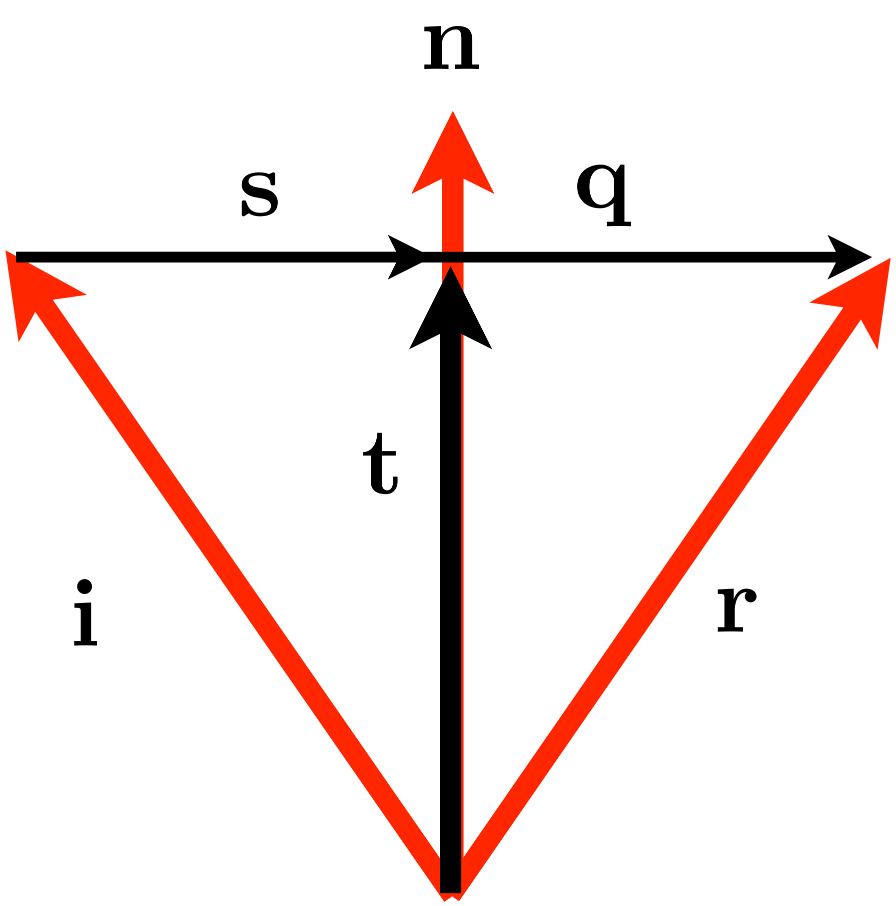
$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\,\mathbf{n}$$

$$\begin{aligned}\mathbf{r} &= \mathbf{i} + 2\left((\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - \mathbf{i}\right) \\ &= \underline{\mathbf{i}} + 2\,(\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - \underline{2\mathbf{i}}\end{aligned}$$

Mirroring a Vector about Another



$$\mathbf{r} = \mathbf{i} + \mathbf{q}$$

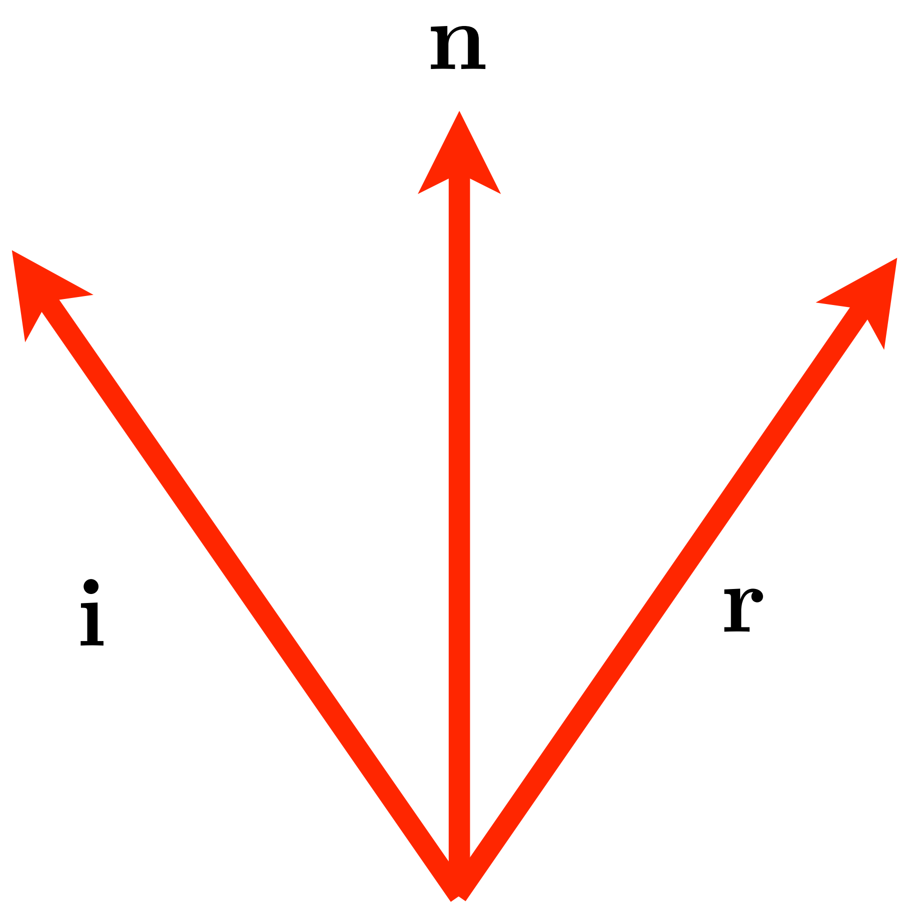
$$\mathbf{q} = 2\mathbf{s}$$

$$\mathbf{s} = \mathbf{t} - \mathbf{i}$$

$$\mathbf{t} = (\mathbf{i} \cdot \mathbf{n})\,\mathbf{n}$$

$$\begin{aligned}\mathbf{r} &= \mathbf{i} + 2\left((\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - \mathbf{i}\right) \\ &= \mathbf{i} + 2\,(\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - 2\mathbf{i} \\ &= 2\,(\mathbf{i} \cdot \mathbf{n})\,\mathbf{n} - \mathbf{i}\end{aligned}$$

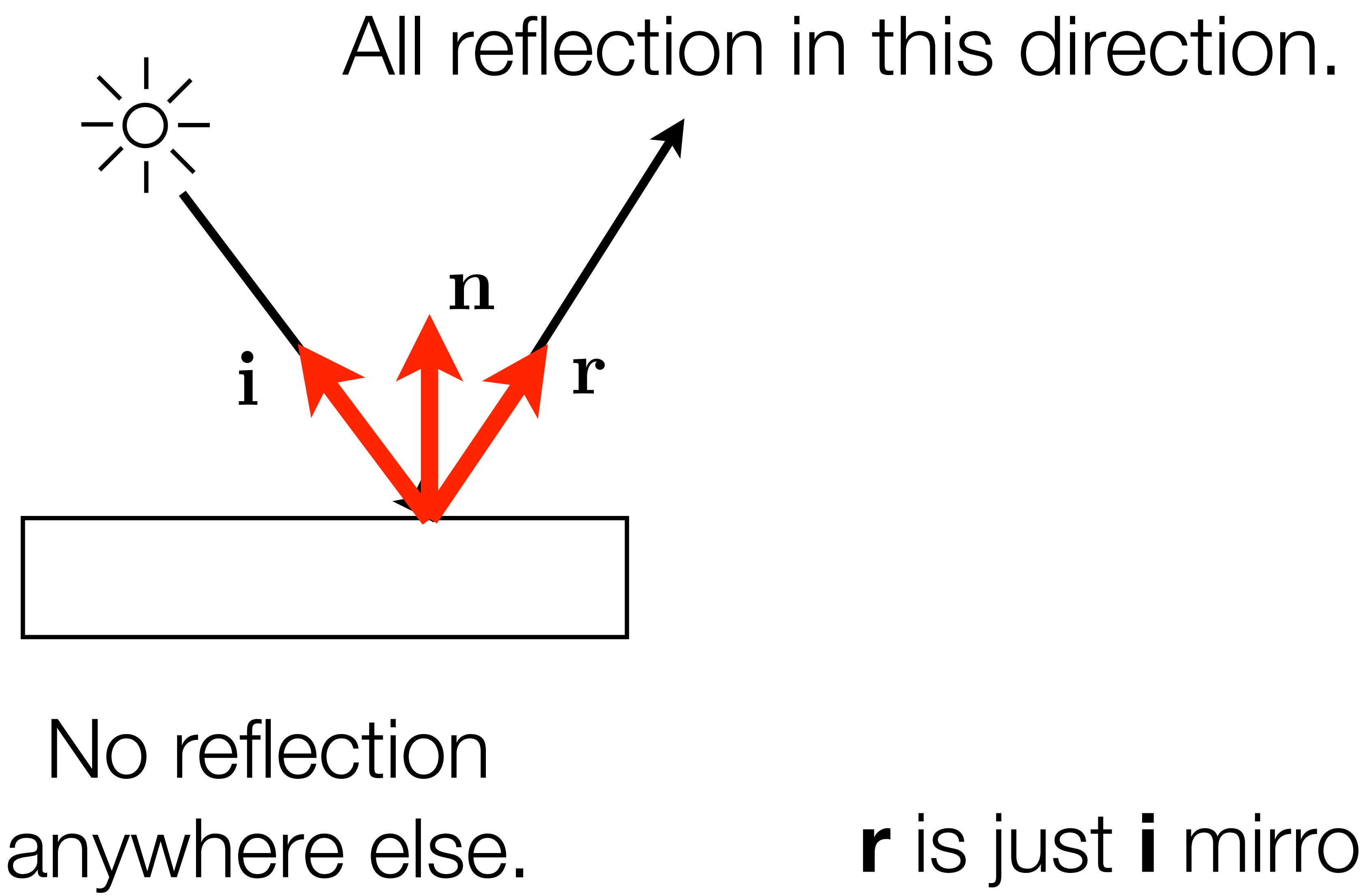
Mirroring a Vector about Another



$$
\begin{aligned}
\mathbf{r} &= \mathbf{i} + 2\left(\left(\mathbf{i}\cdot\mathbf{n}\right)\mathbf{n} - \mathbf{i}\right) \\
&= \mathbf{i} + 2\left(\mathbf{i}\cdot\mathbf{n}\right)\mathbf{n} - 2\mathbf{i} \\
&= 2\left(\mathbf{i}\cdot\mathbf{n}\right)\mathbf{n} - \mathbf{i}
\end{aligned}
$$

Mirror Reflection

If the surface is a perfect mirror, the reflection is along exactly one direction **r**.



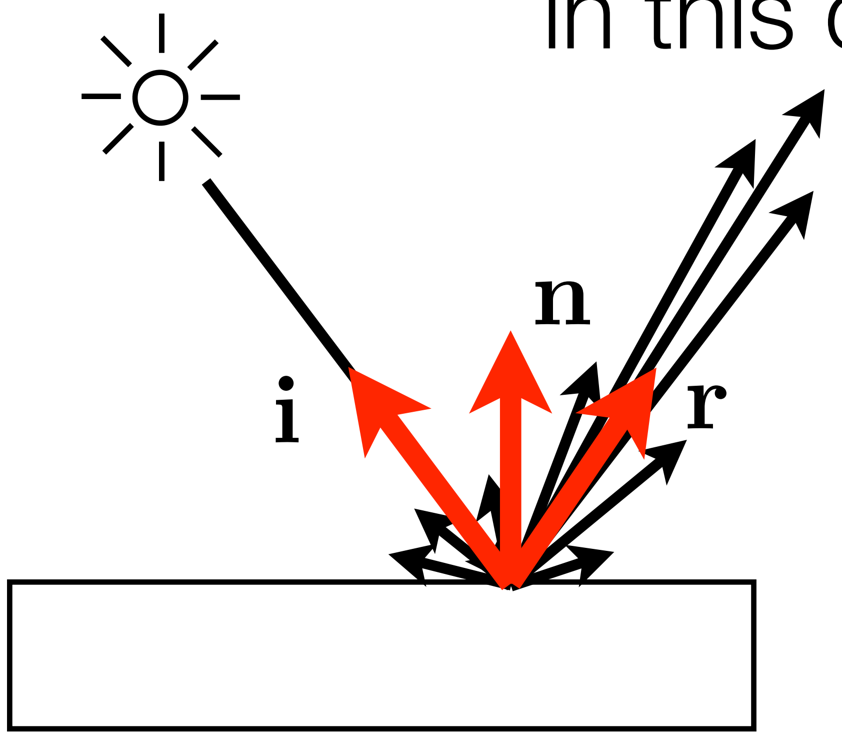
r is just **i** mirrored around **n**.

$$\mathbf{r} = 2\left(\mathbf{i} \cdot \mathbf{n}\right)\mathbf{n} - \mathbf{i}$$

Specular Reflection

Most surfaces are not perfect mirrors. So the specular reflection appears spread out around **r**.

Lot of reflection in this direction.



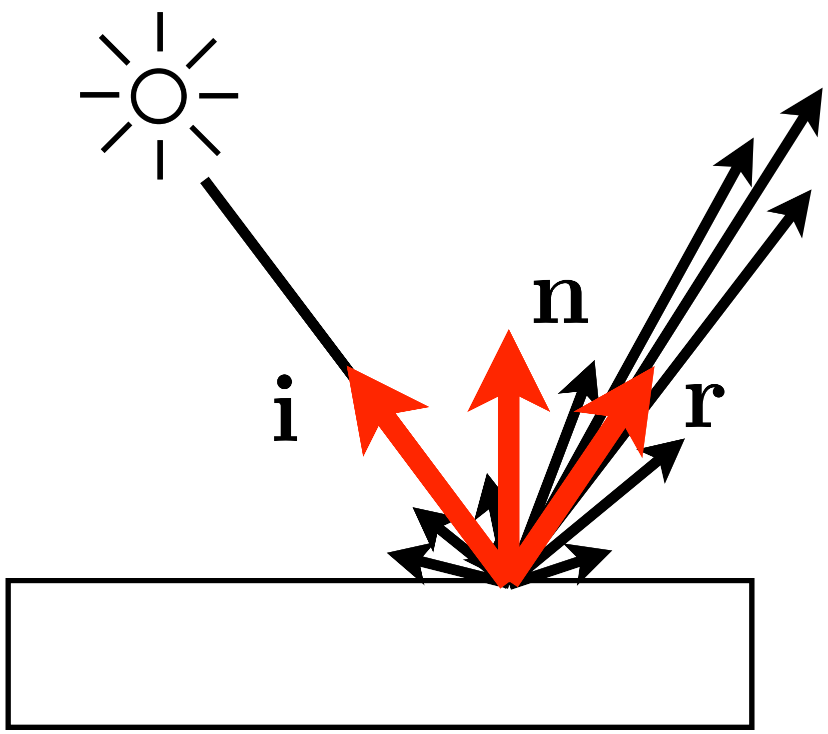
Very little reflection anywhere else.

r is just **i** mirrored around **n**.

$$\mathbf{r} = 2\left(\mathbf{i} \cdot \mathbf{n}\right)\mathbf{n} - \mathbf{i}$$

Specular Reflection

Most surfaces are not perfect mirrors. So the specular reflection appears spread out around **r**.

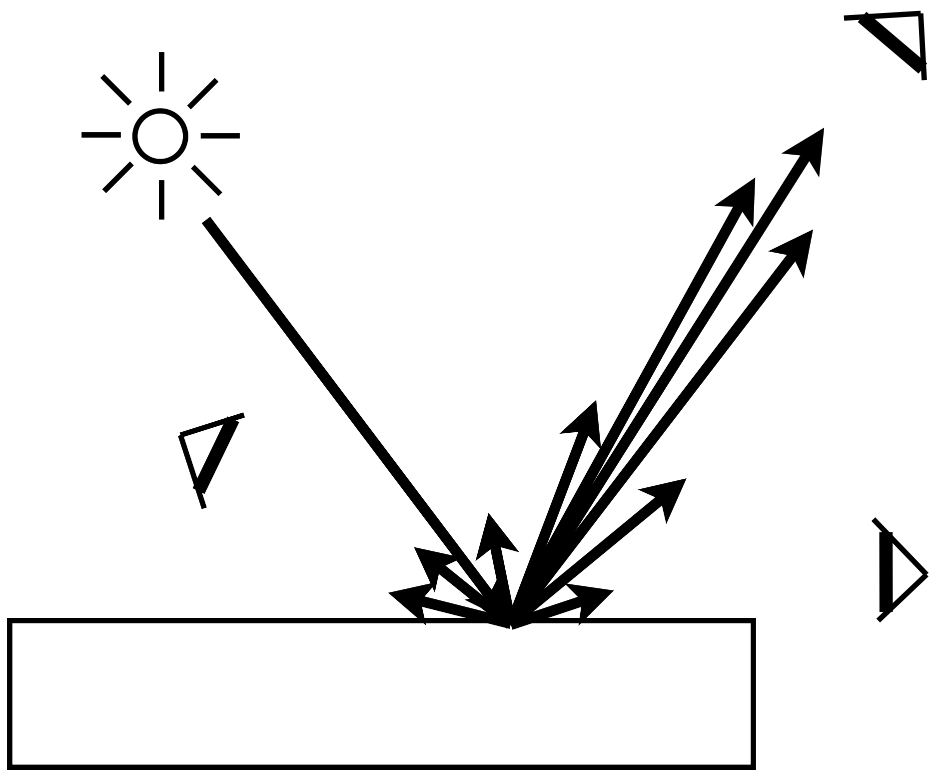


r is just **i** mirrored around **n**.

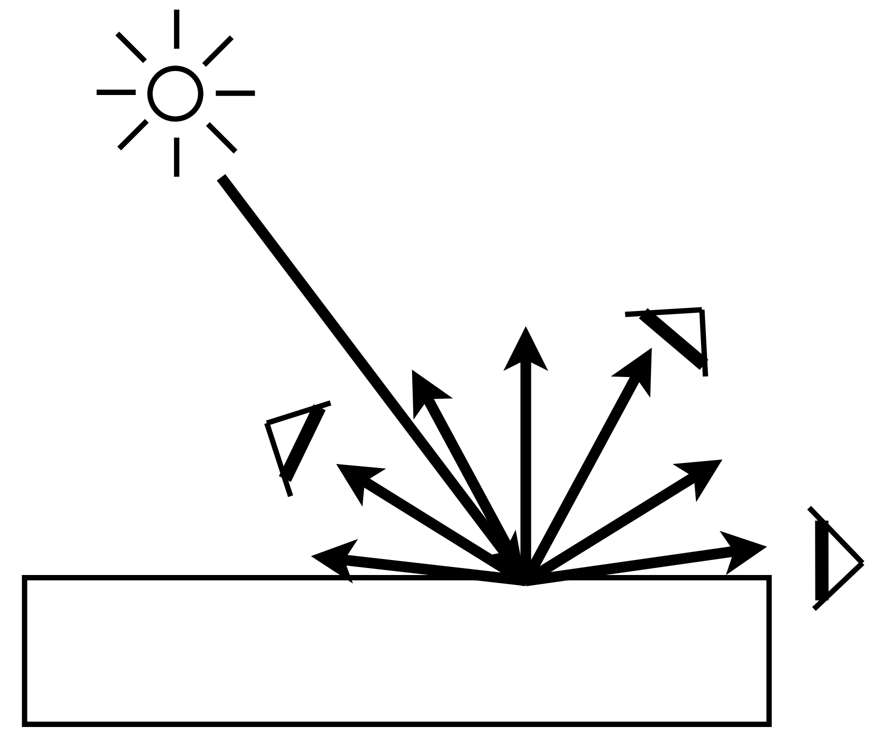
$$\mathbf{r} = 2\left(\mathbf{i} \cdot \mathbf{n}\right)\mathbf{n} - \mathbf{i}$$

Specular Reflection

Unlike diffuse reflection, specular reflection depends on viewer.

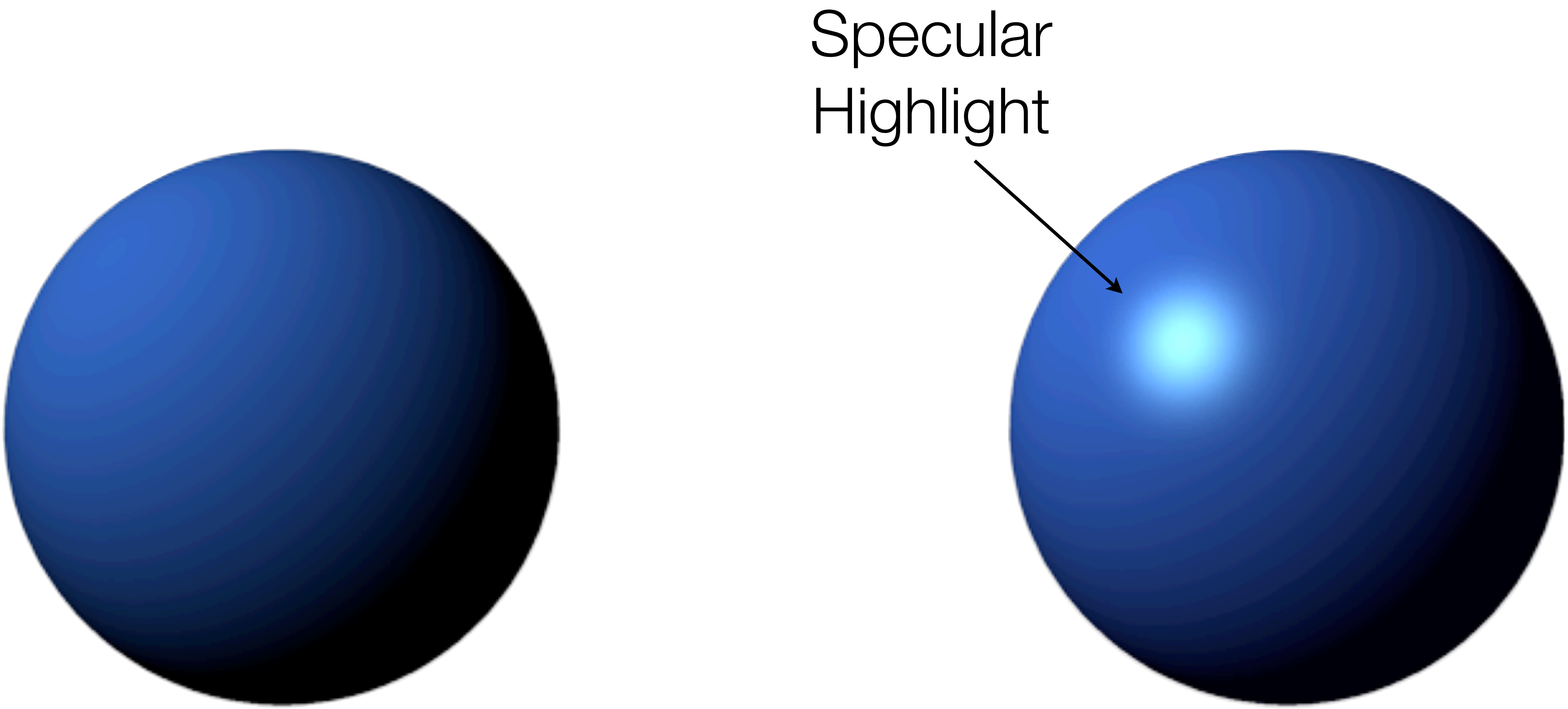


Specular Reflection



Diffuse Reflection

Diffuse versus Specular Reflections

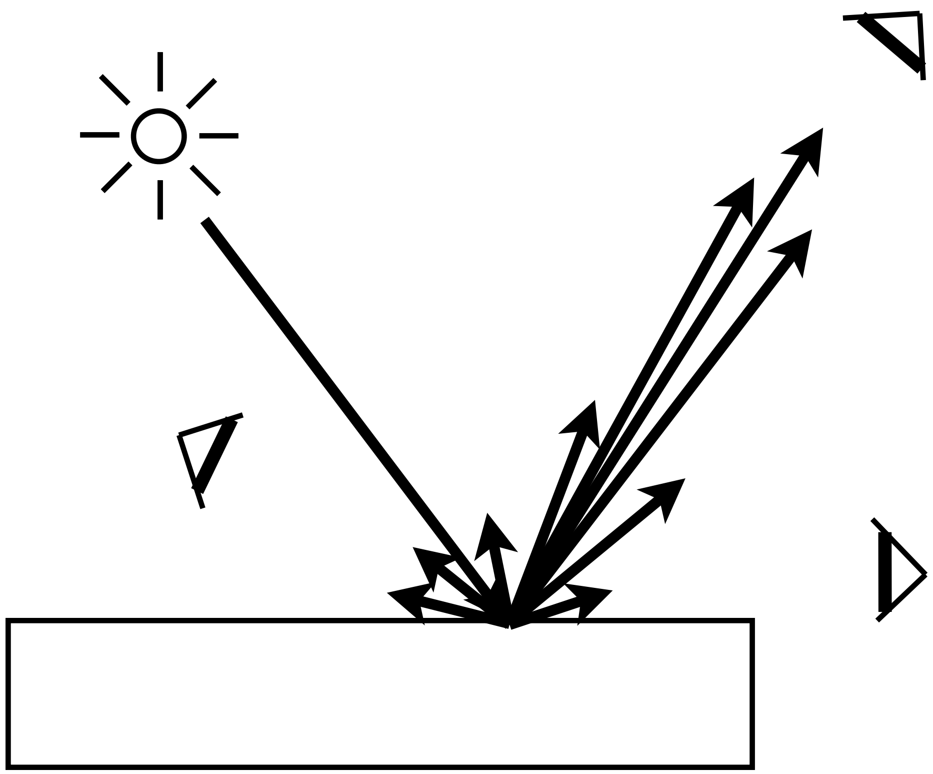


Diffuse Only

Diffuse + Specular

Specular Reflection

Unlike diffuse reflection, specular reflection depends on viewer.



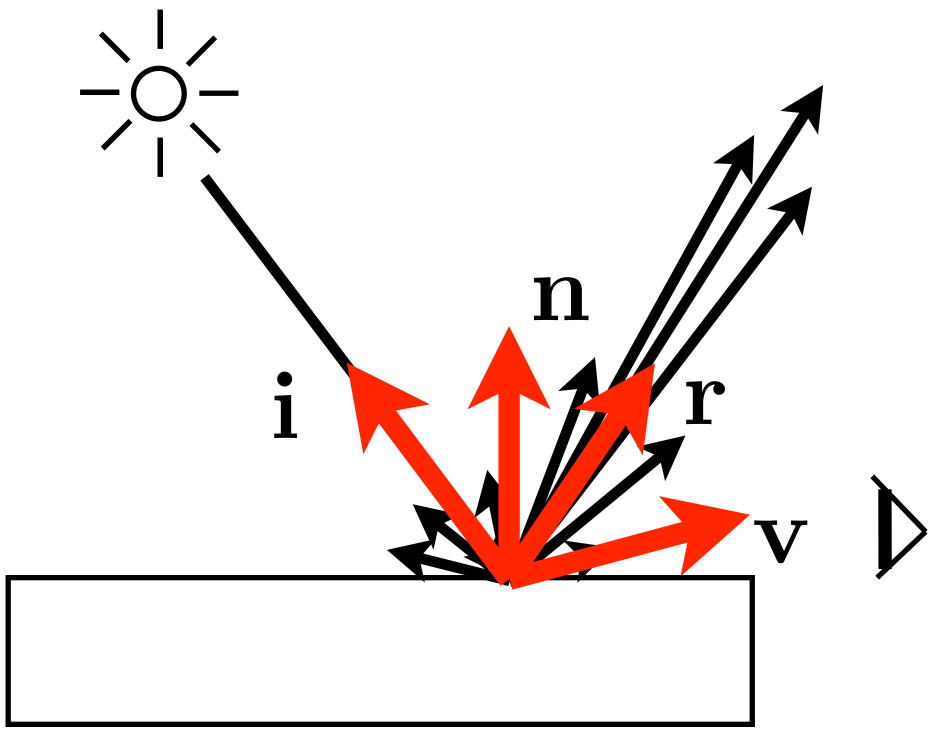
This viewer sees
a lot of
specular reflection.

This viewer sees
very little
specular reflection.

Specular Reflection

Specular Reflection

Unlike diffuse reflection, specular reflection depends on viewer.
Calculations for specular reflection require viewer direction **v**.

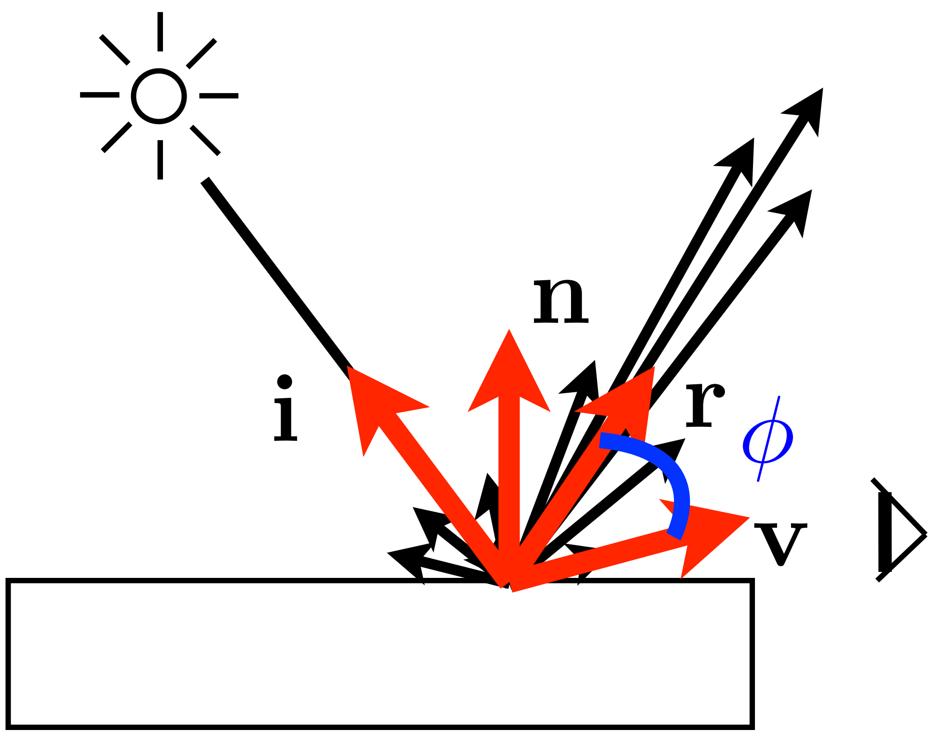


Specular Reflection

Specular Reflection

I_{sr}, I_{sg}, I_{sb}
are diffuse terms
in the incident light

$$R_{sr} = k_{sr} I_{sr} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sr} \leq 1$$
$$R_{sg} = k_{sg} I_{sg} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sg} \leq 1$$
$$R_{sb} = k_{sb} I_{sb} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sb} \leq 1$$
$$\cos\phi = \mathbf{r} \cdot \mathbf{v}$$



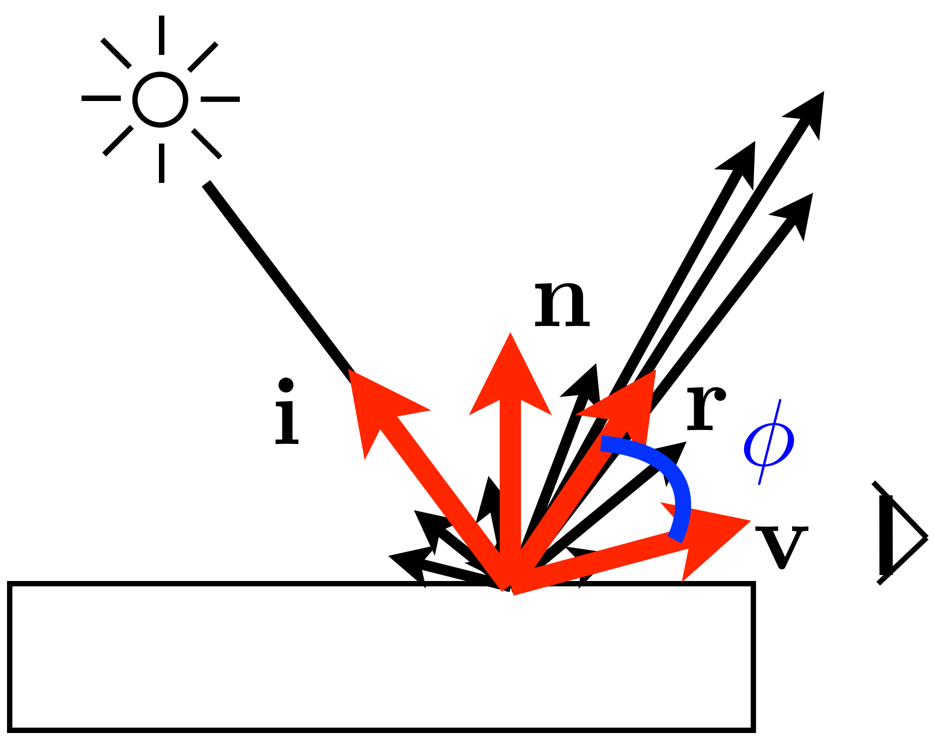
k_{sr}, k_{sg}, k_{sb}
are termed **specular reflectance coefficients**.

R_{sr}, R_{sg}, R_{sb}
are diffuse terms
in the reflected light

Specular Reflection

I_{sr}, I_{sg}, I_{sb}
are diffuse terms
in the incident light

$$R_{sr} = k_{sr} I_{sr} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sr} \leq 1$$
$$R_{sg} = k_{sg} I_{sg} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sg} \leq 1$$
$$R_{sb} = k_{sb} I_{sb} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \;\; 0 \leq k_{sb} \leq 1$$
$$\cos \phi = \mathbf{r} \cdot \mathbf{v}$$



k_{sr}, k_{sg}, k_{sb}
are termed **specular reflectance coefficients**.

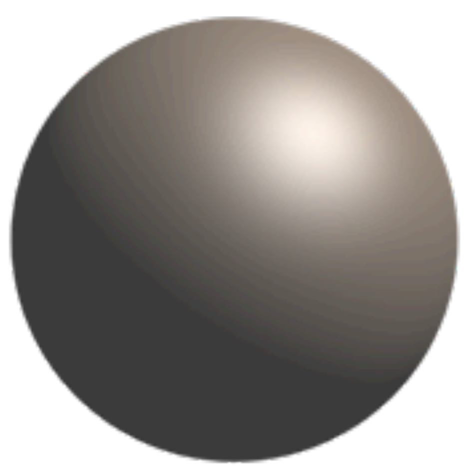
R_{sr}, R_{sg}, R_{sb}
are diffuse terms
in the reflected light

α is called **shininess**.

Specular Reflection: Shininess

$$R_{sr} = k_{sr} I_{sr} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sr} \leq 1$$
$$R_{sg} = k_{sg} I_{sg} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sg} \leq 1$$
$$R_{sb} = k_{sb} I_{sb} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sb} \leq 1$$

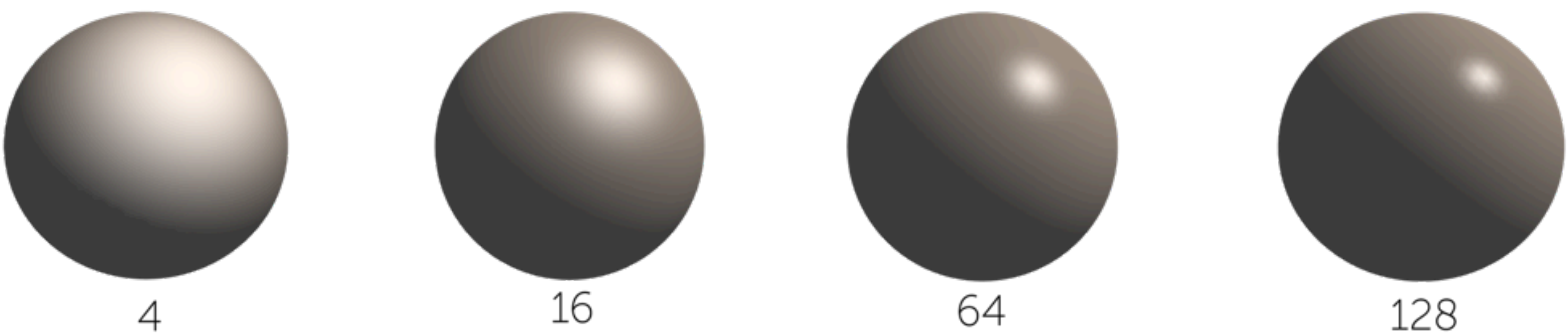
Specular reflections create
specular highlights on object surfaces.



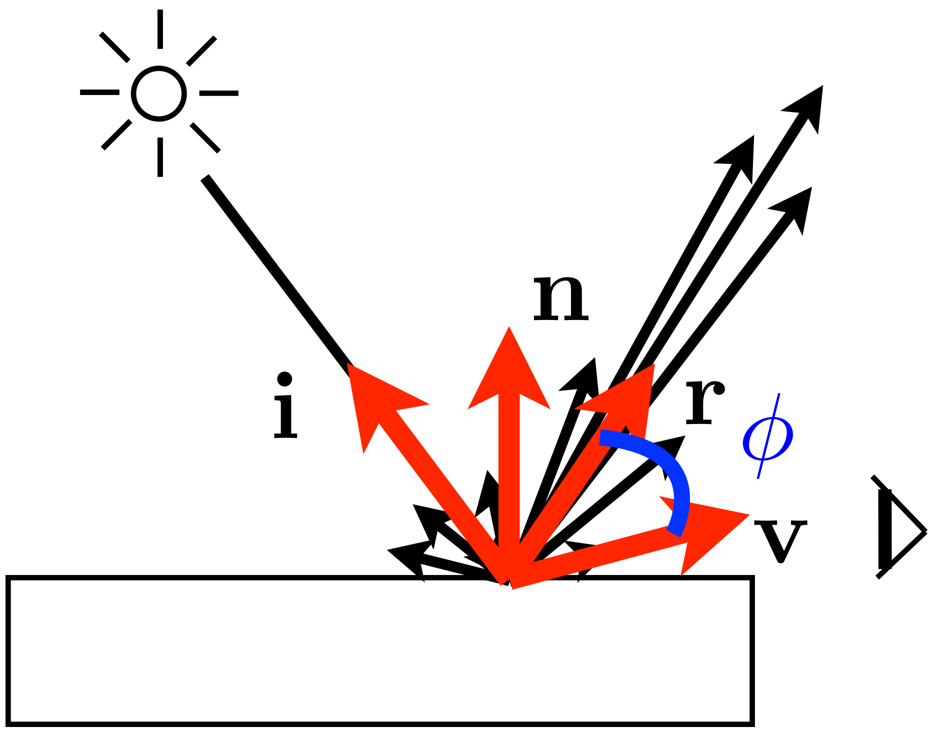
Specular Reflection: Shininess

$$R_{sr} = k_{sr} I_{sr} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sr} \leq 1$$
$$R_{sg} = k_{sg} I_{sg} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sg} \leq 1$$
$$R_{sb} = k_{sb} I_{sb} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha},\ 0 \leq k_{sb} \leq 1$$

The shininess coefficient *α* shrinks the size of the highlight. The higher the coefficient, the smaller the highlight, i.e., the 'shinier' the object appears.



Specular Reflection



$$R_{sr} = k_{sr} I_{sr} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \ 0 \leq k_{sr} \leq 1$$

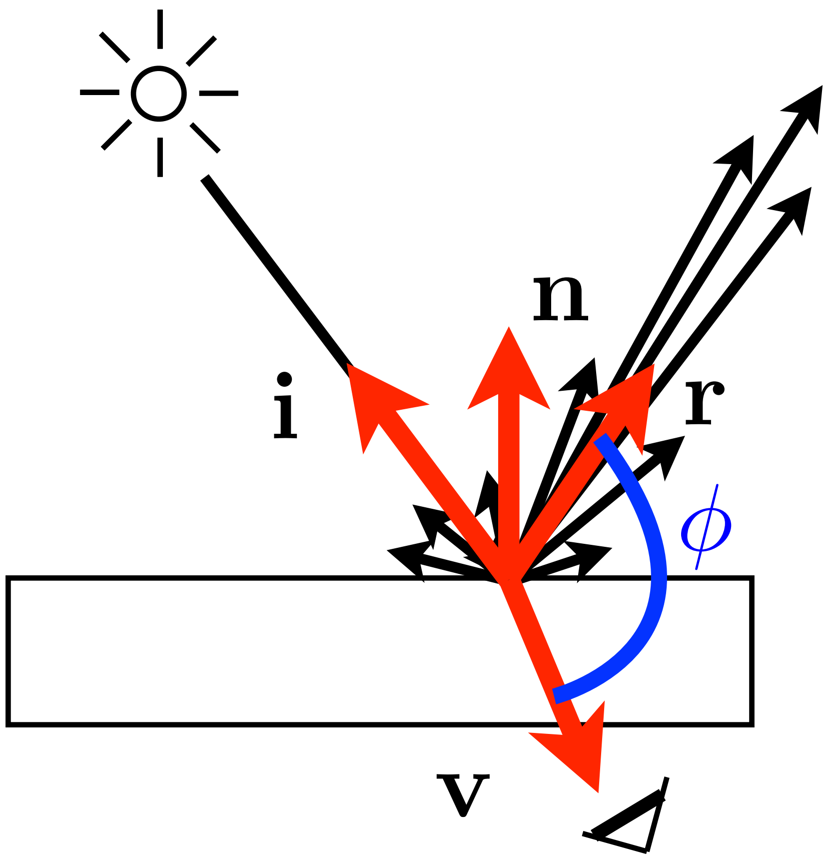
$$R_{sg} = k_{sg} I_{sg} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \ 0 \leq k_{sg} \leq 1$$

$$R_{sb} = k_{sb} I_{sb} \left(\mathbf{r} \cdot \mathbf{v}\right)^{\alpha}, \ 0 \leq k_{sb} \leq 1$$

$$\cos \phi = \mathbf{r} \cdot \mathbf{v}$$

Specular Reflection

If the viewing direction is below the surface, you cannot see it, so you should set the intensity to 0. Again, use max.



$$R_{sr} = k_{sr} I_{sr} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \; 0 \leq k_{sr} \leq 1$$

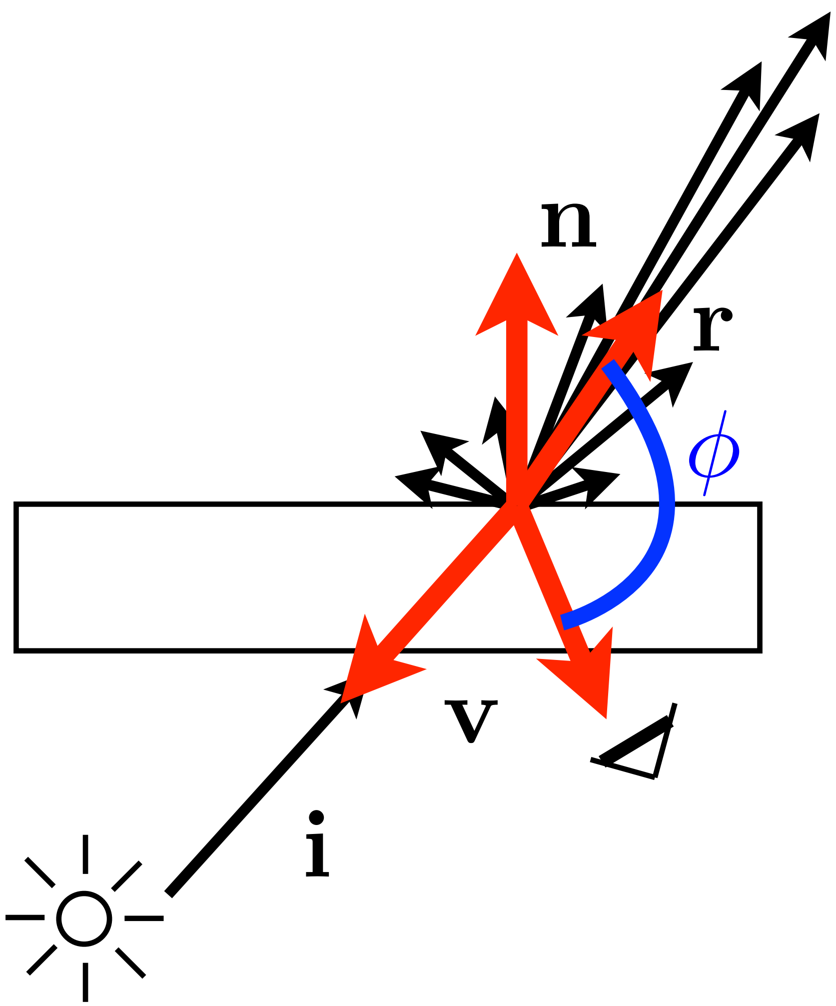
$$R_{sg} = k_{sg} I_{sg} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \; 0 \leq k_{sg} \leq 1$$

$$R_{sb} = k_{sb} I_{sb} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \; 0 \leq k_{sb} \leq 1$$

$$\cos \phi = \mathbf{r} \cdot \mathbf{v}$$

Specular Reflection

Finally, before calculating specular reflection, test to see if the light is seen or not.



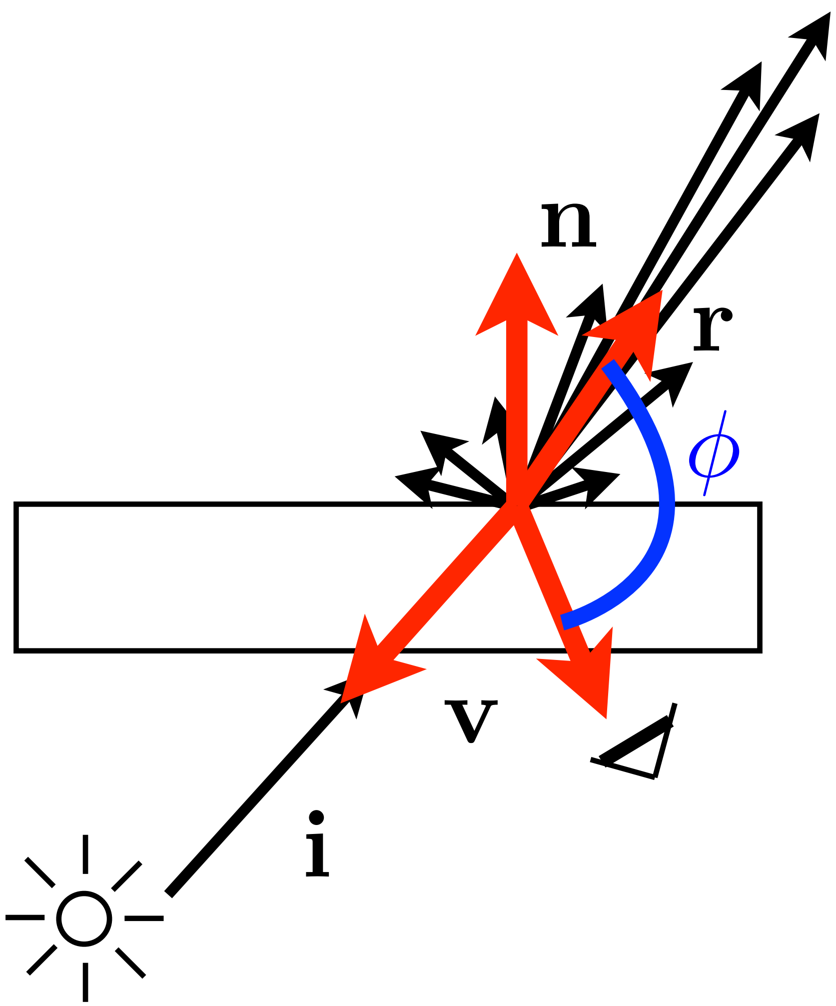
$$R_{sr} = k_{sr} I_{sr} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \le k_{sr} \le 1$$

$$R_{sg} = k_{sg} I_{sg} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \le k_{sg} \le 1$$

$$R_{sb} = k_{sb} I_{sb} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \le k_{sb} \le 1$$

Specular Reflection

Finally, before calculating specular reflection, test to see if the light is seen or not, i.e., if **i** . **n** > 0.



$$R_{sr} = k_{sr} I_{sr} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \leq k_{sr} \leq 1$$

$$R_{sg} = k_{sg} I_{sg} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \leq k_{sg} \leq 1$$

$$R_{sb} = k_{sb} I_{sb} \left(\max(\mathbf{r} \cdot \mathbf{v}, 0)\right)^{\alpha}, \ 0 \leq k_{sb} \leq 1$$

If **i** . **n** < 0, then do not compute specular reflection for that surface.

Diffuse Reflections: Microscopic Analysis

Rough Surfaces Tend to Be Diffuse.

Diffuse Reflections: Microscopic Analysis

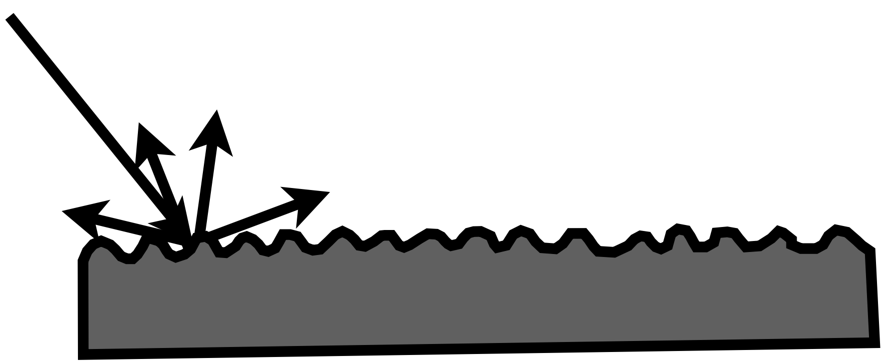
Rough Surfaces Tend to Be Diffuse. Let Us See Why.

Diffuse Reflections: Microscopic Analysis

Rough Surfaces Tend to Be Diffuse. Let Us See Why.

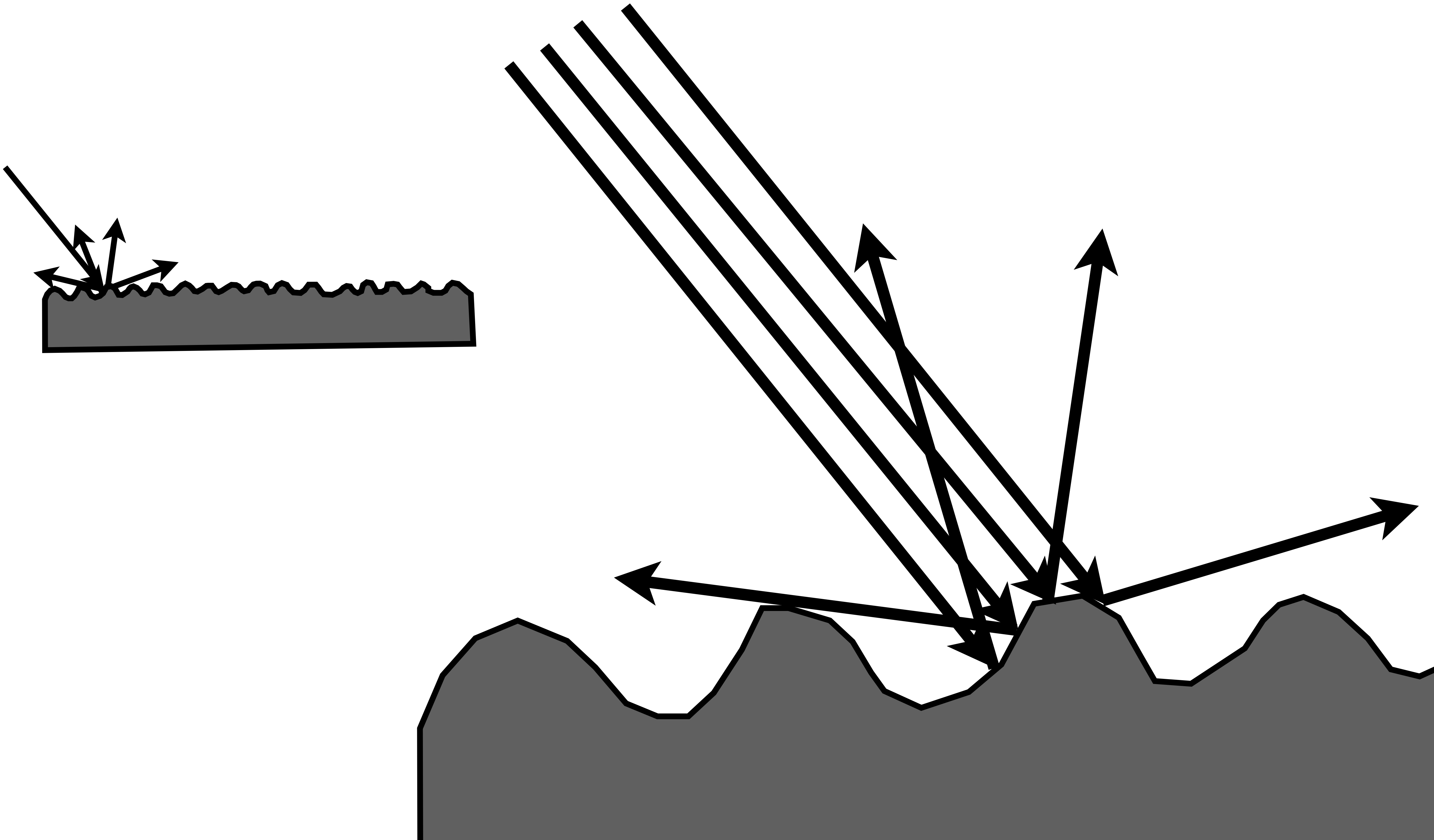
Diffuse Reflections: Microscopic Analysis

Microscopically, each ‘flat’ little bit of the rough surface performs a mirrored reflection.



Diffuse Reflections: Microscopic Analysis

Microscopically, each ‘flat’ little bit of the rough surface performs a mirrored reflection.



Diffuse Reflections: Microscopic Analysis

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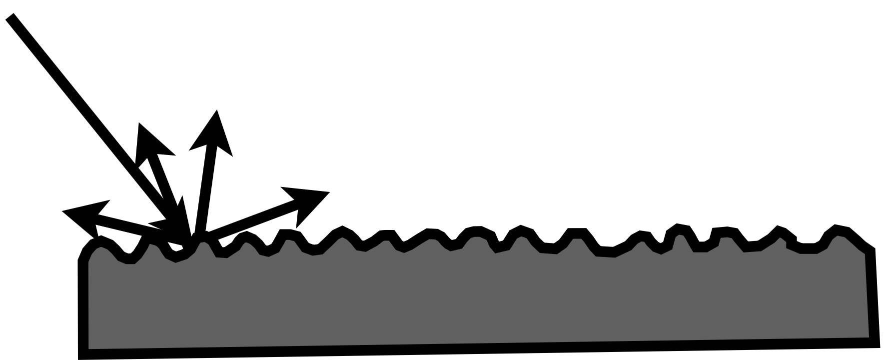
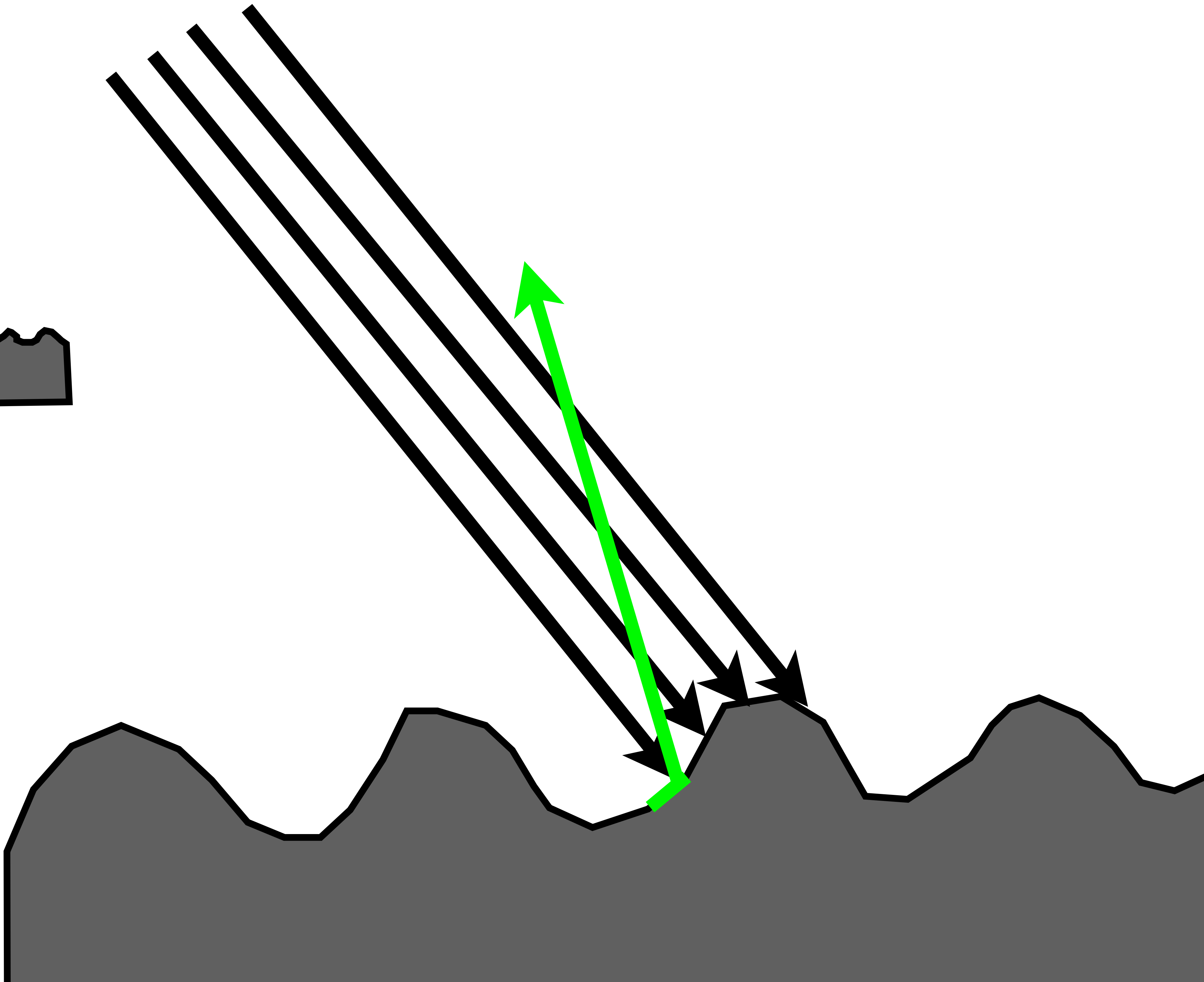
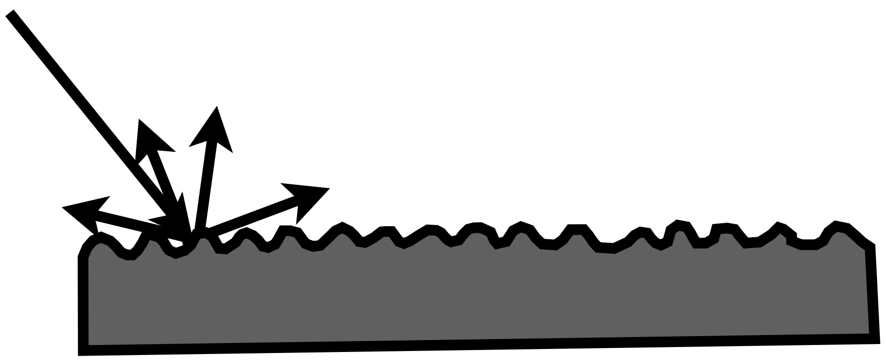
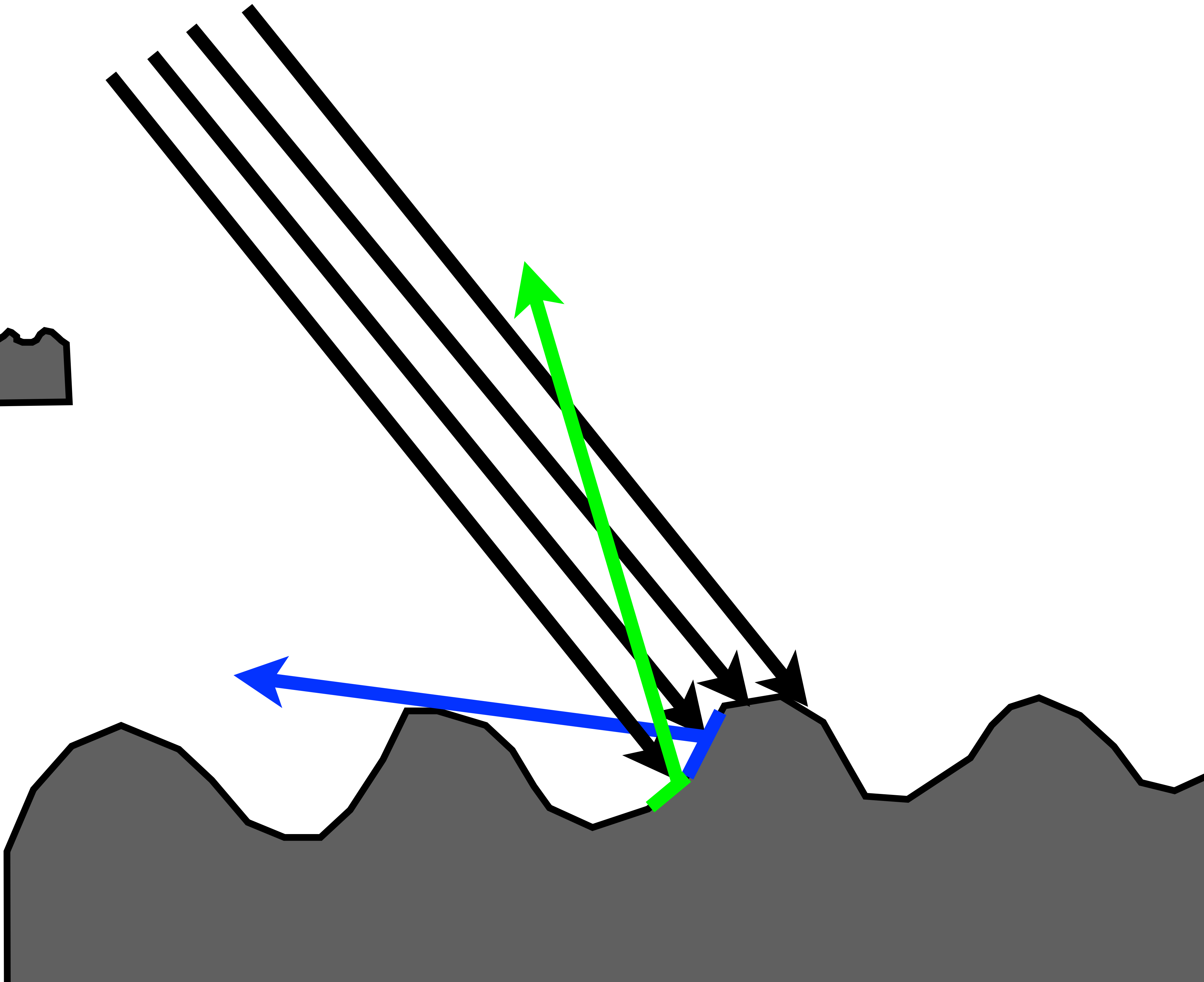




Diffuse Reflections: Microscopic Analysis

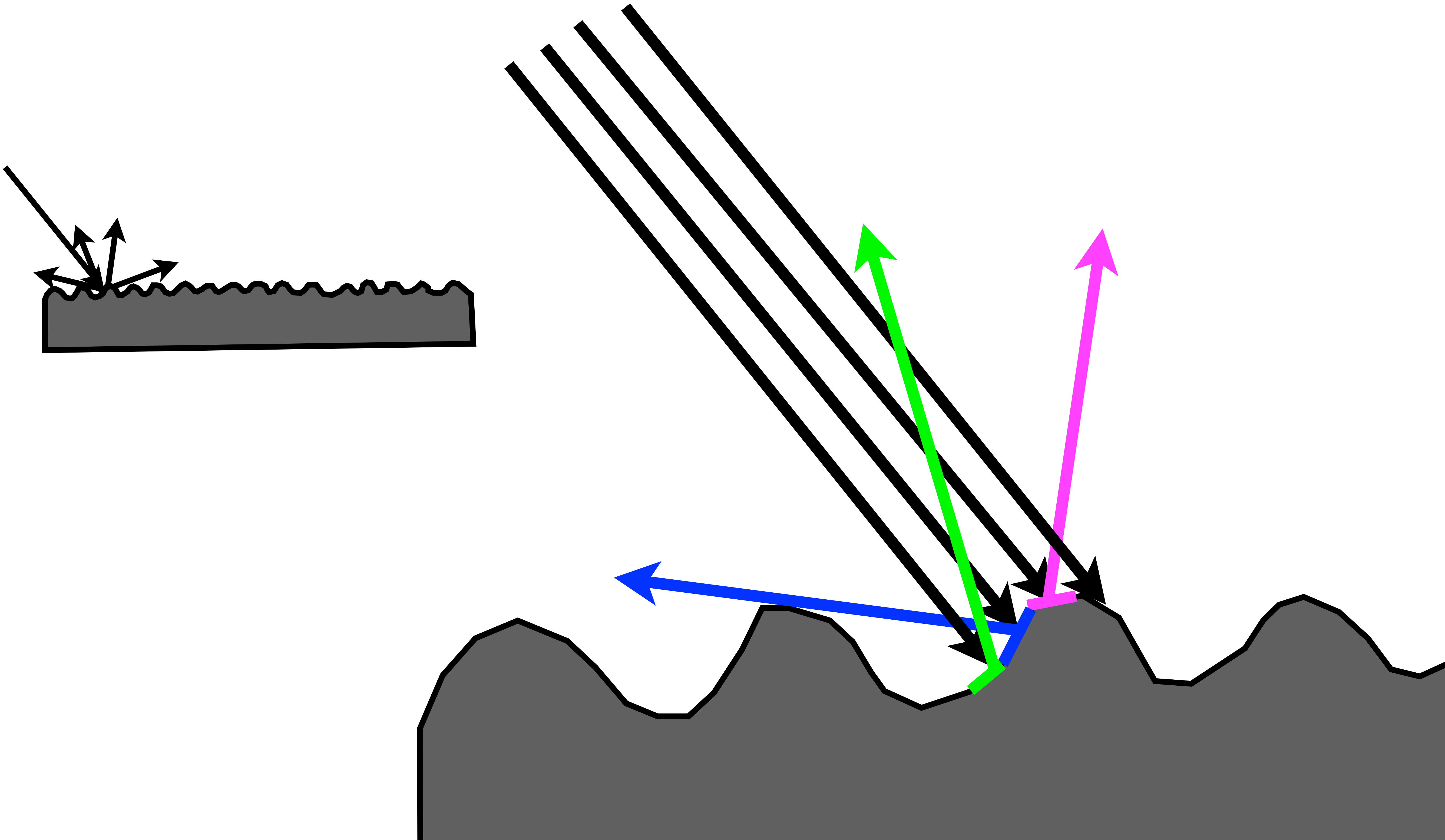
Microscopically, each ‘flat’ little bit of the rough surface performs a mirrored reflection.





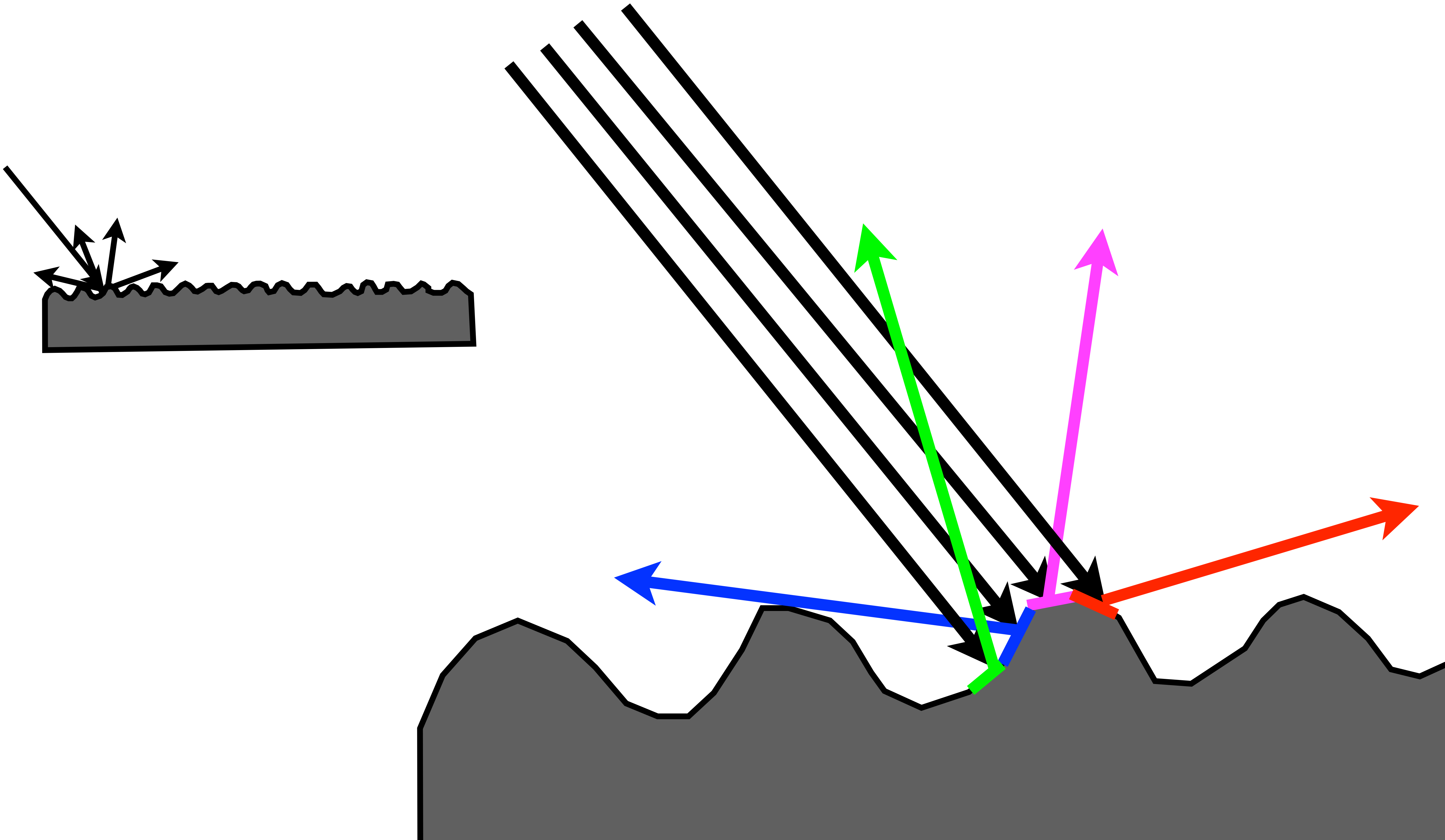
Diffuse Reflections: Microscopic Analysis

Microscopically, each ‘flat’ little bit of the rough surface performs a mirrored reflection.



Diffuse Reflections: Microscopic Analysis

Microscopically, each 'flat' little bit of the rough surface performs a mirrored reflection.



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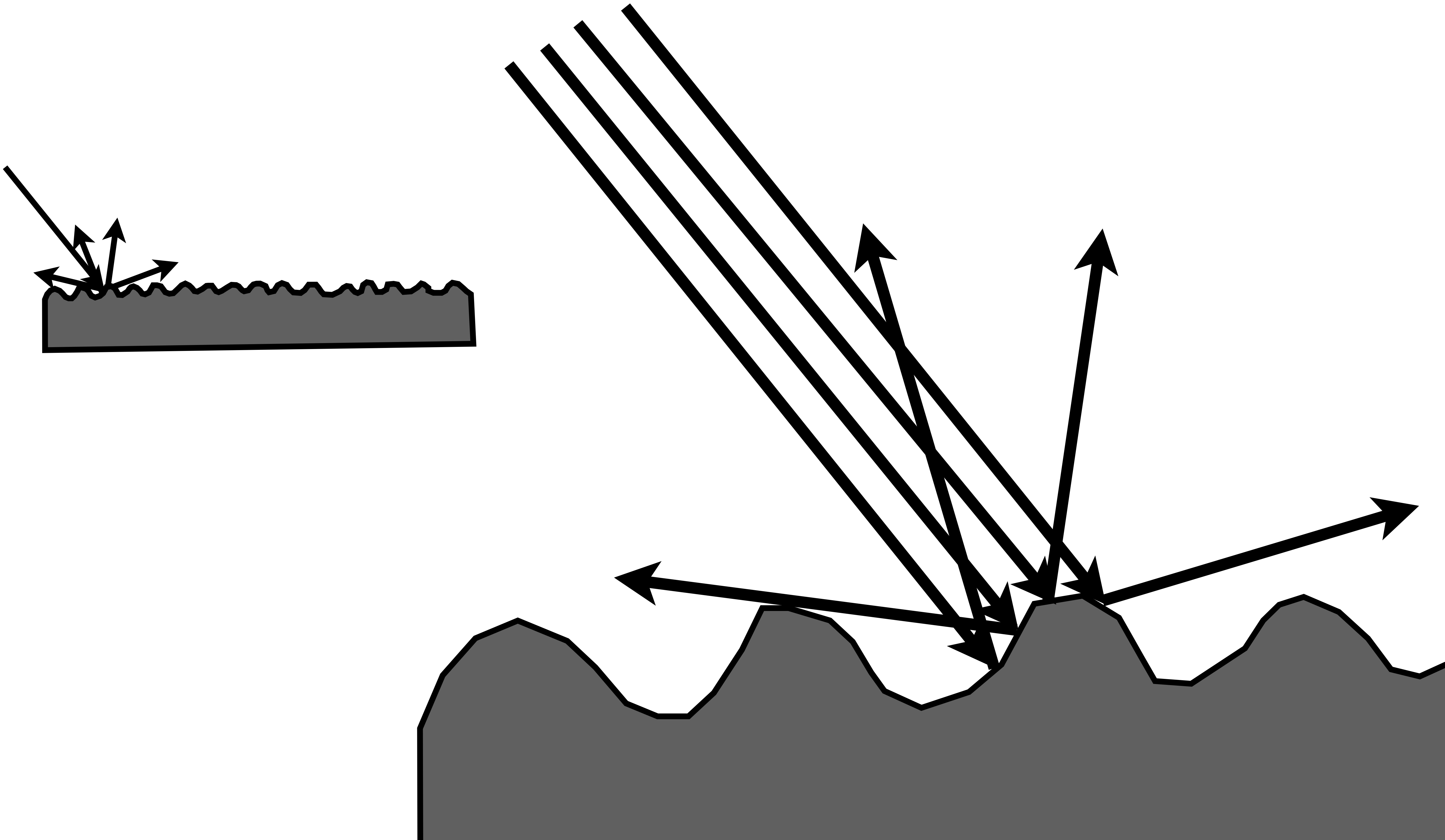
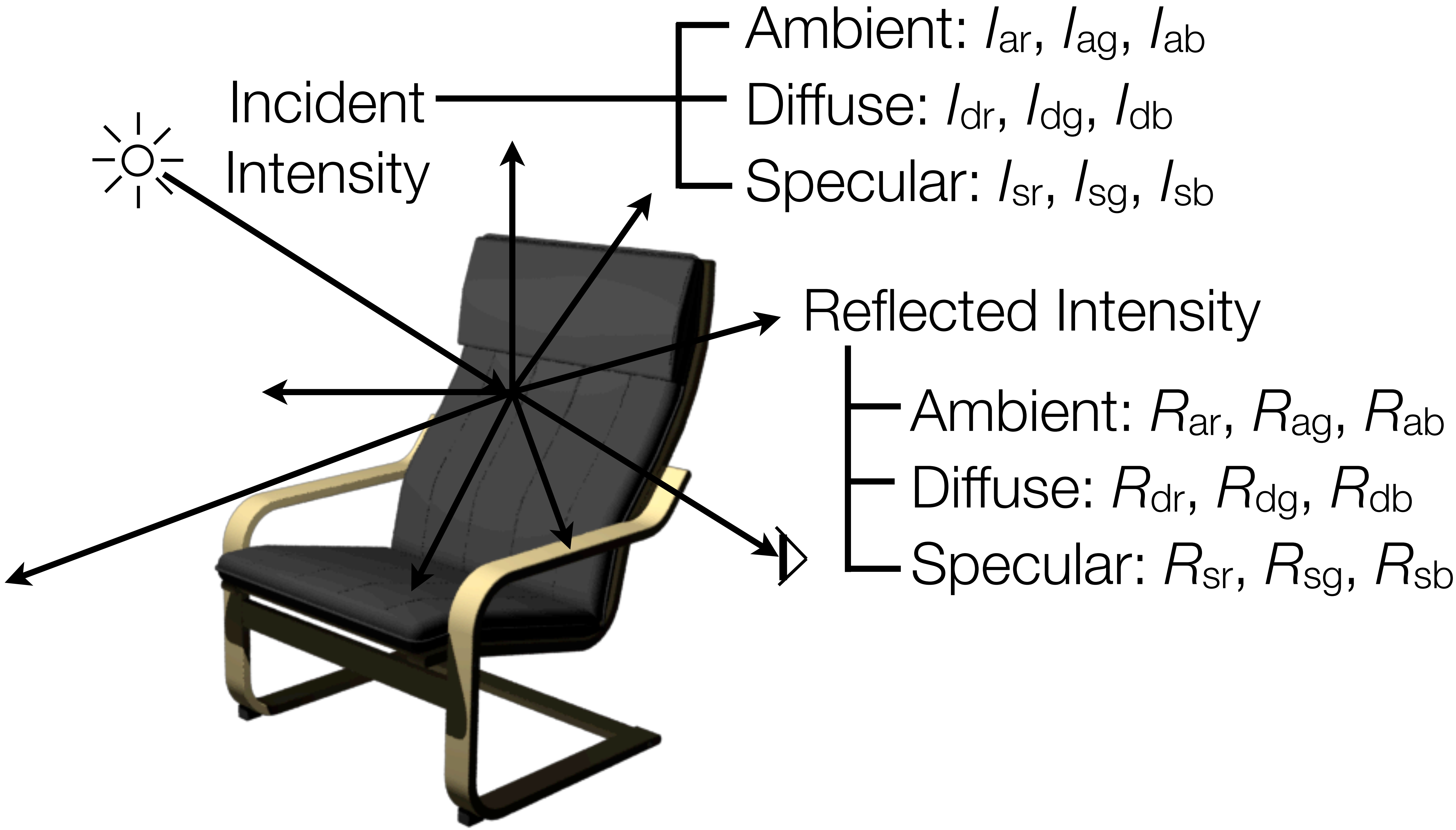
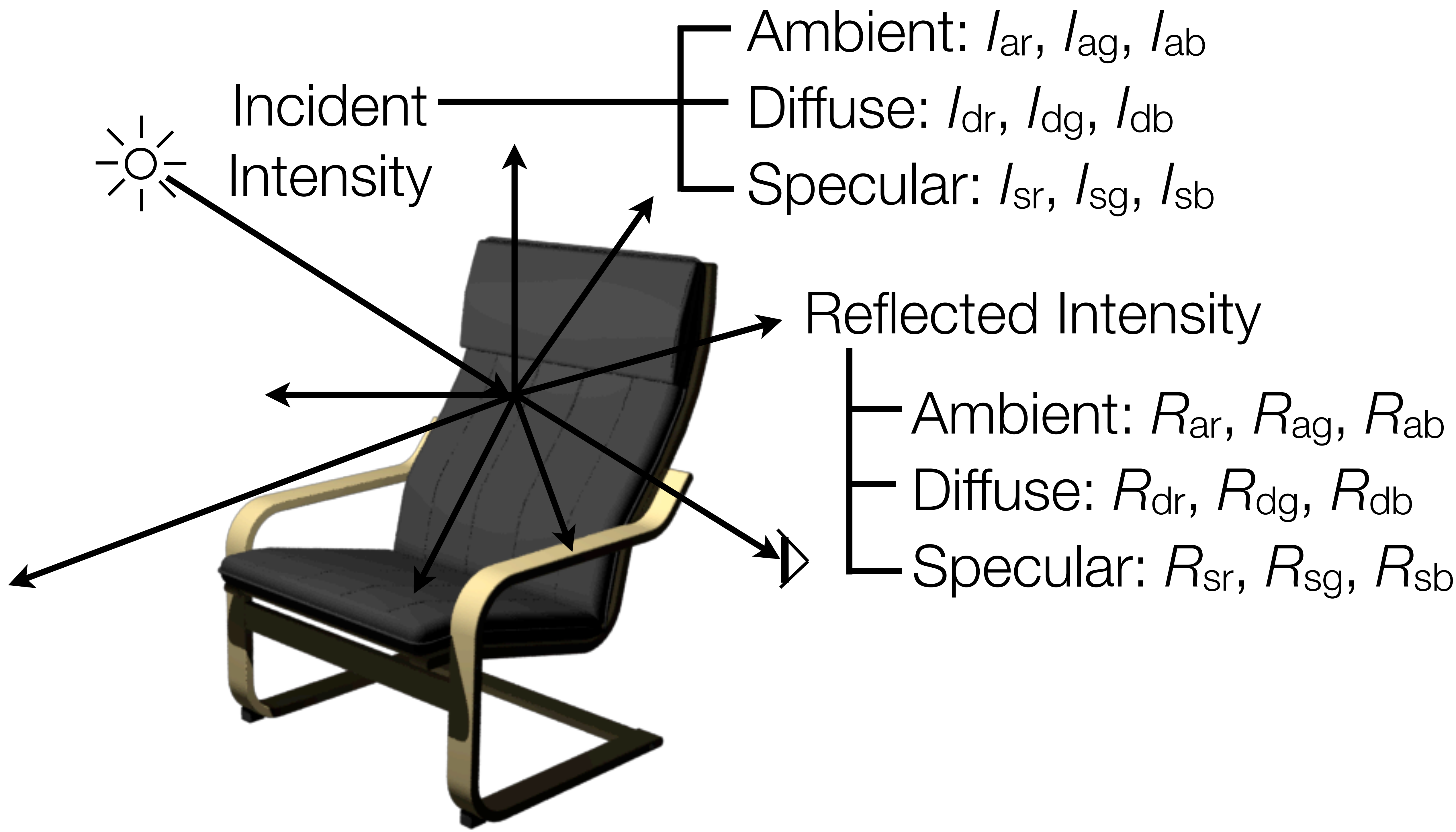


Phong Reflection Model



Phong Reflection Model



The total reflected intensity is the **sum** of all components.

Phong Reflection Model

$R_r = R_{ar} + R_{dr} + R_{sr}$ Ambient + Diffuse + Specular for Red

$R_g = R_{ag} + R_{dg} + R_{sg}$ Ambient + Diffuse + Specular for Green

$R_b = R_{ab} + R_{db} + R_{sb}$ Ambient + Diffuse + Specular for Blue

The total reflected intensity is the **sum** of all components.

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This is what you see in the end on the camera.

The total reflected intensity is the **sum** of all components.

Phong Reflection Model

$R_r = R_{ar} + R_{dr} + R_{sr}$ Ambient + Diffuse + Specular for Red

$R_g = R_{ag} + R_{dg} + R_{sg}$ Ambient + Diffuse + Specular for Green

$R_b = R_{ab} + R_{db} + R_{sb}$ Ambient + Diffuse + Specular for Blue

Example for red:

$$R_r = k_{ar} I_{ar} + k_{dr} I_{dr} \max(\cos\theta, 0) + k_{sr} I_{sr} \max((\mathbf{r} \cdot \mathbf{v}), 0)^{\alpha}$$

Supply ambient, diffuse, and specular for every triangle on your object.

The total reflected intensity is the **sum** of all components.

Phong Reflection Model

Point light, spotlight, and directional light can have all three components. Ambient light can only have ambient component.

Example for red:

$$R_r = k_{ar} I_{ar} + k_{dr} I_{dr} \max(\cos\theta, 0) + k_{sr} I_{sr} \max((\mathbf{r} \cdot \mathbf{v}), 0)^{\alpha}$$

Supply ambient, diffuse, and specular components for every light source.

The total reflected intensity is the **sum** of all components.

Phong Reflection Model

Multiple Light Sources

Point light, spotlight, and directional light can have all three components. Ambient light can only have ambient component.

Example for red:

$$\begin{aligned} R_r &= k_{ar} I_{ar1} + k_{dr} I_{dr1} \max(\cos\theta_1, 0) + k_{sr} I_{sr1} \max((\mathbf{r_1} \cdot \mathbf{v}), 0)^{\alpha_1} \\ &= k_{ar} I_{ar2} + k_{dr} I_{dr2} \max(\cos\theta_2, 0) + k_{sr} I_{sr2} \max((\mathbf{r_2} \cdot \mathbf{v}), 0)^{\alpha_2} \end{aligned}$$

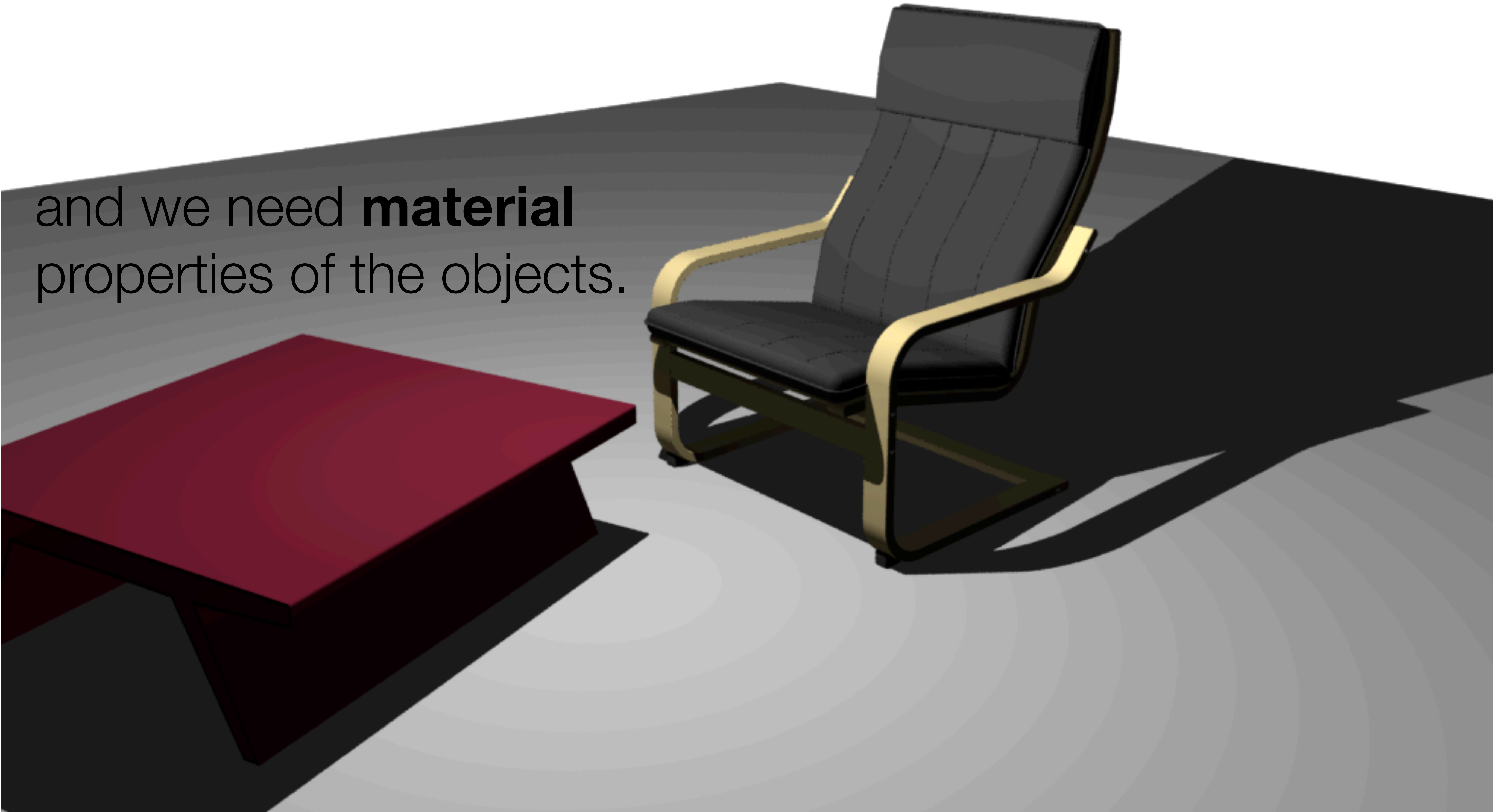
1 is first light source, 2 is second light source.

The total reflected intensity is the **sum** of all components for all light sources.

To light an object,

We need **light sources**,

and we need **material** properties of the objects.

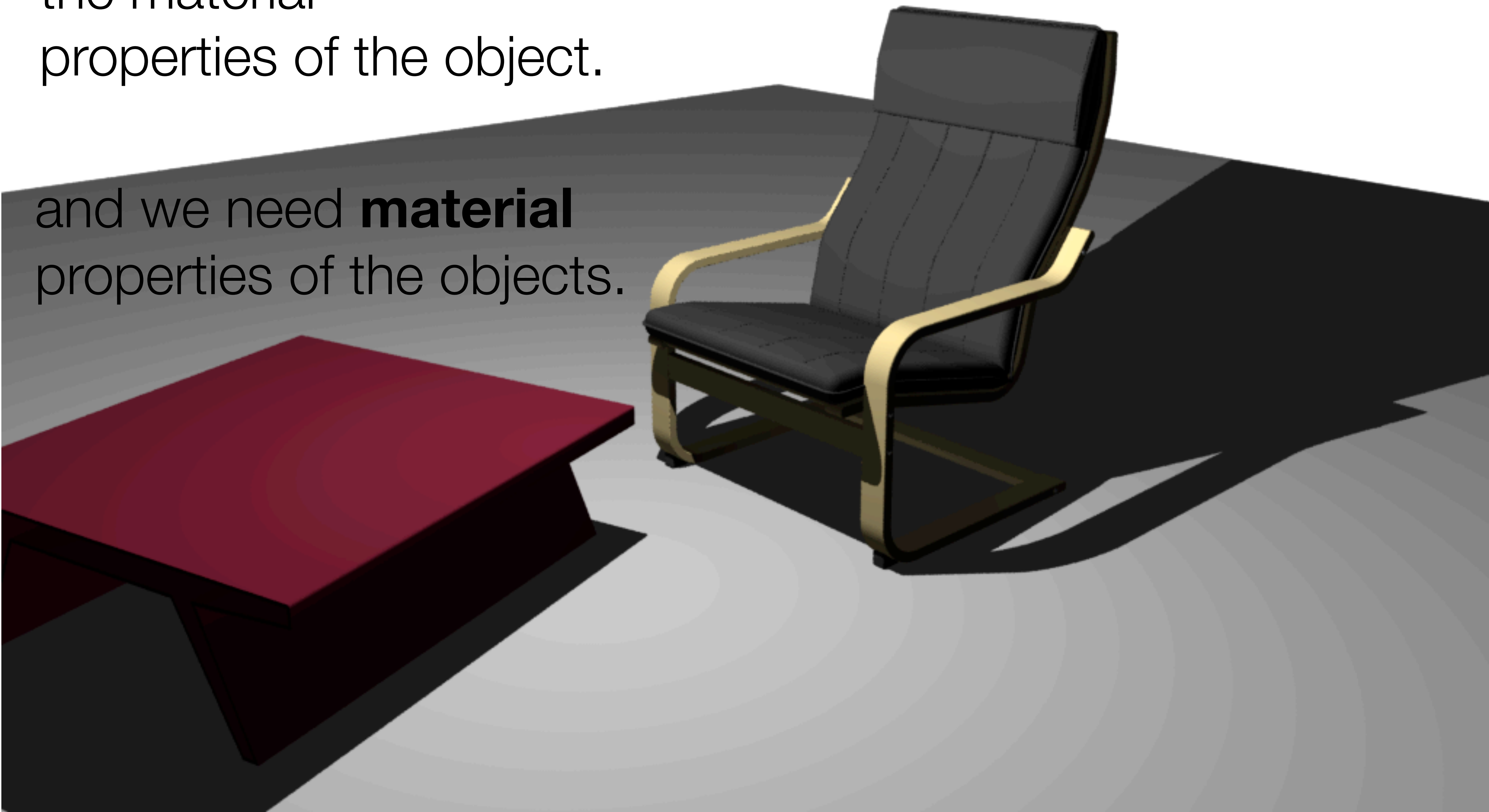


To light an object,

The reflectance coefficients form the material properties of the object.

We need **light sources**,

and we need **material** properties of the objects.



Examples of Reflectance Coefficients

This chair has no specular highlights, so its specular coefficients are zero.

$k_{sr} = 0$, $k_{sg} = 0$, $k_{sb} = 0$

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Examples of Reflectance Coefficients

This chair has no specular highlights, so its specular coefficients are zero.

$k_{sr} = 0, k_{sg} = 0, k_{sb} = 0$

It only has diffuse and ambient coefficients. For gray seat,

$k_{dr} = 0.2, k_{dg} = 0.2, k_{db} = 0.2$

$k_{ar} = 0.2, k_{ag} = 0.2, k_{ab} = 0.2$

Examples of Reflectance Coefficients

This chair has no specular highlights, so its specular coefficients are zero.

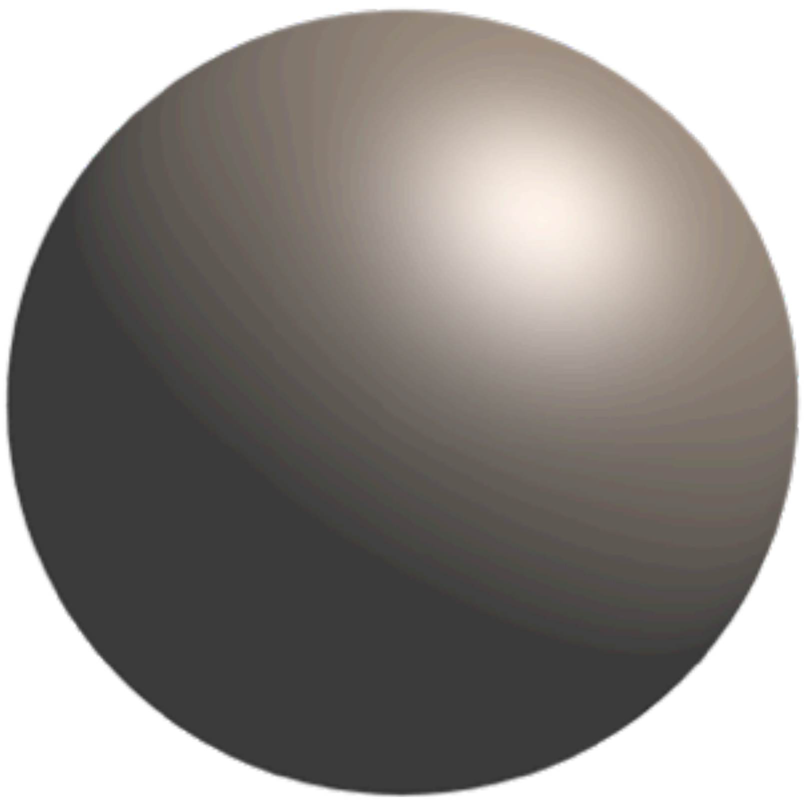
$k_{sr} = 0$, $k_{sg} = 0$, $k_{sb} = 0$

It only has diffuse and ambient coefficients. For beige armrests,

$k_{dr} = 1.0$, $k_{dg} = 0.9$, $k_{db} = 0.6$

$k_{ar} = 1.0$, $k_{ag} = 0.9$, $k_{ab} = 0.6$

Examples of Reflectance Coefficients



This ball has a specular highlight, so it has specular coefficients.

$k_{sr} = .8$, $k_{sg} = .8$, $k_{sb} = .8$

It als has diffuse and ambient coefficients, tending toward brown.

$k_{dr} = 0.5$, $k_{dg} = 0.5$, $k_{db} = 0.3$

$k_{ar} = 0.5$, $k_{ag} = 0.5$, $k_{ab} = 0.3$