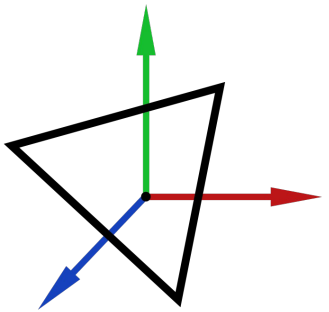


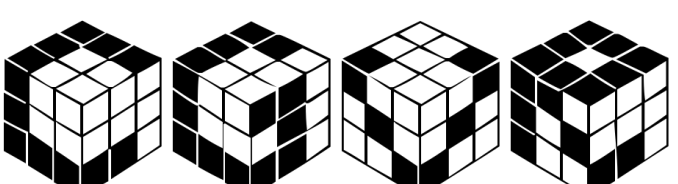
Computer Graphics Seminar

MTAT.03.305

Fall 2020

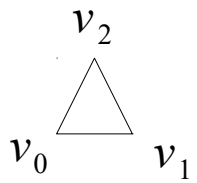
Raimond Tunnel

UNIVERSITY OF TARTU
Institute of Computer Science



Previously...

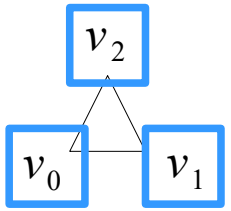
Data



$$M = M_1 \cdot M_2 \cdot M_3 \cdot \ldots$$

OpenGL

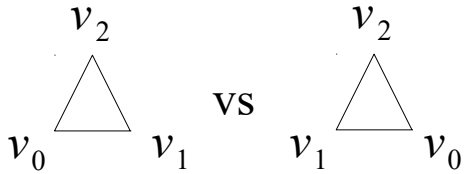
Vertex transformations



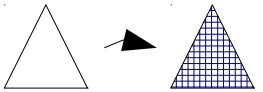
$$P \cdot V \cdot M \cdot v \qquad \left(\frac{v_x}{v_w}, \frac{v_y}{v_w}, \frac{v_z}{v_w} \right)$$

Vertex shader

Culling & Clipping



Rasterization



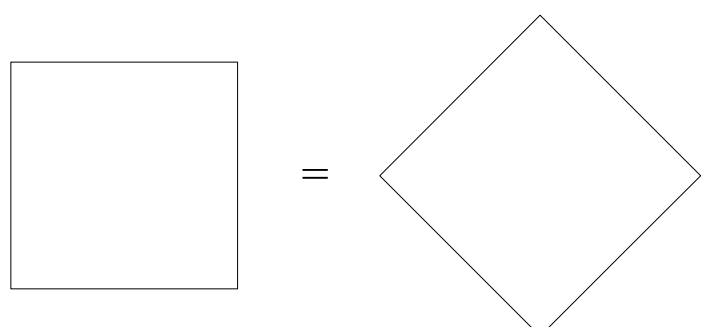
Fragment shading

Visibility tests & Blending

Previously...

- We define our geometry (points, lines, triangles)
- We apply transformations (matrices)

$$\begin{pmatrix} \cos(45°) & -\sin(45°) \\ \sin(45°) & \cos(45°) \end{pmatrix}$$



When is this true?

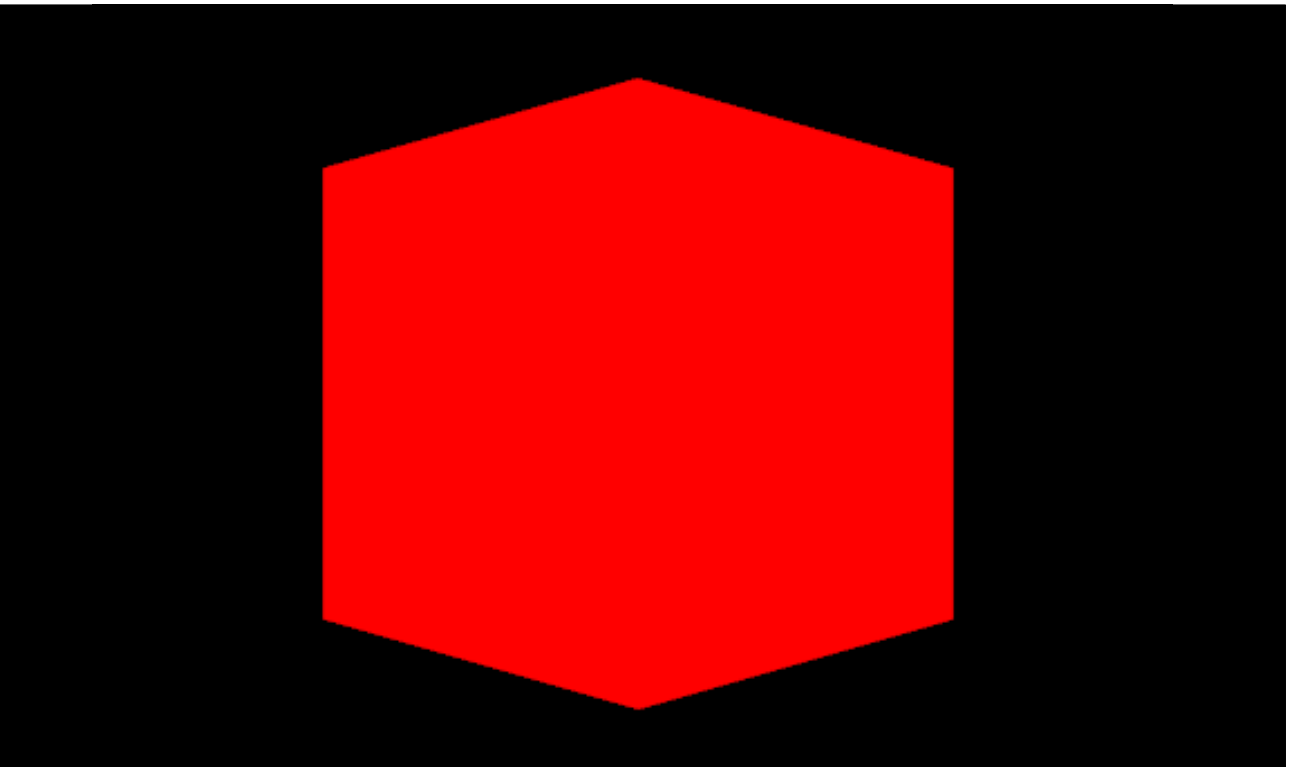
Now We Add Color?

What exactly is here?

Adding color... ?

Material Properties

- We want GPU to take into account a color property when rendering some geometry.

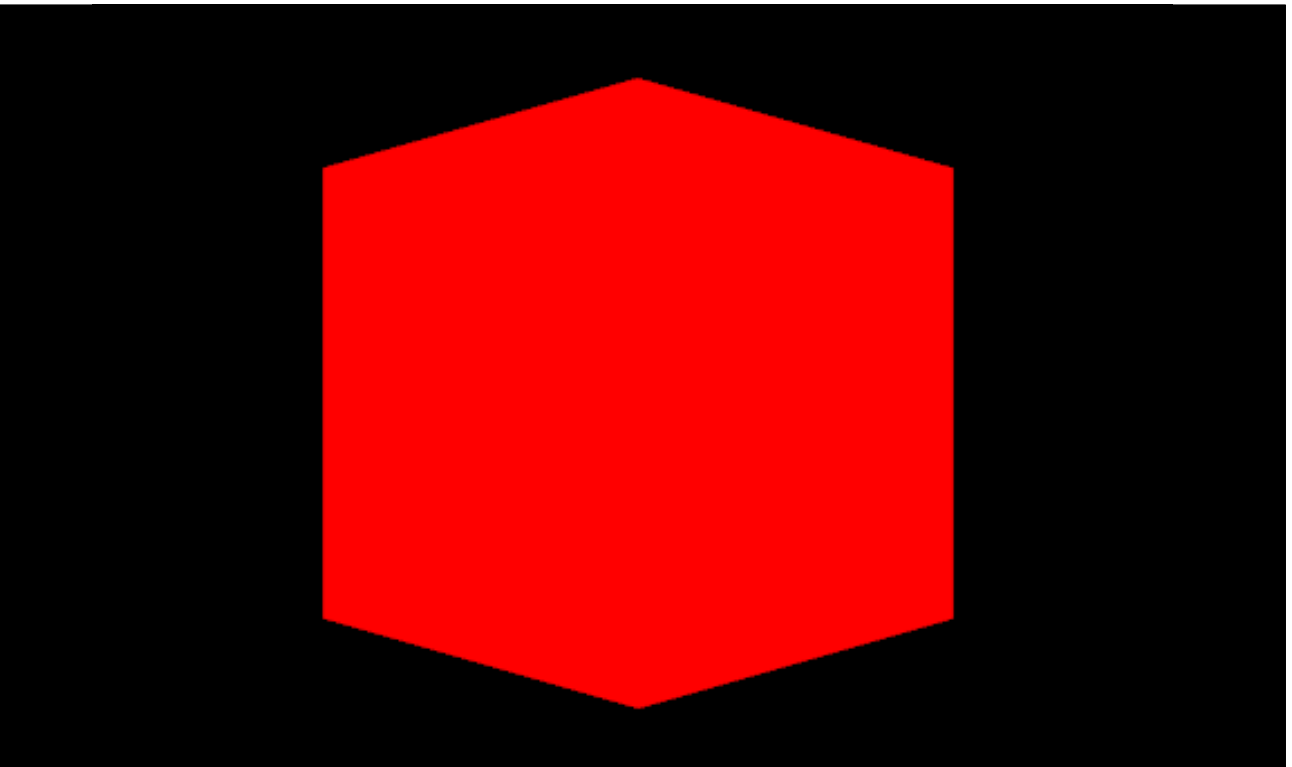


What is depicted here?

http://cgdemos.tume-maailm.pri.ee/

Material Properties

- We want GPU to take into account a color property when rendering some geometry.



Red cube?

Two red trapezoids?

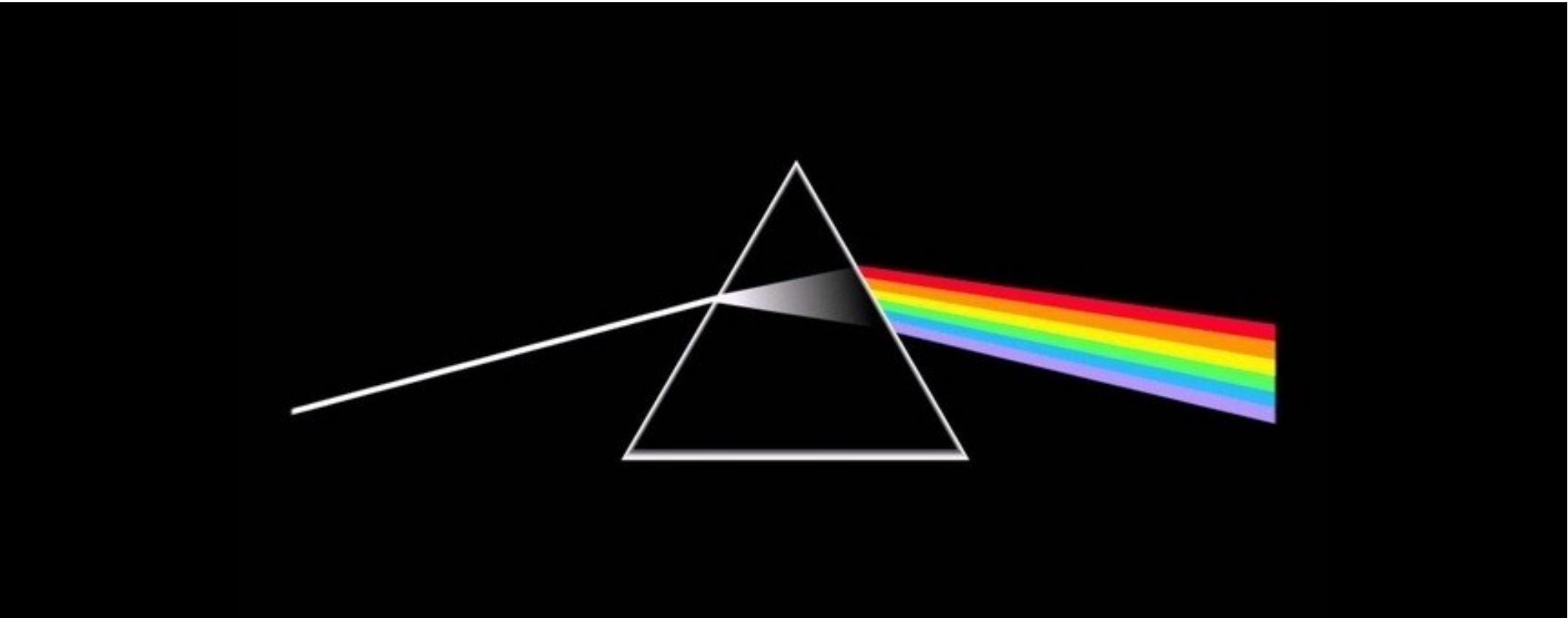
Flat red polygon?

http://cgdemos.tume-maailm.pri.ee/

What is color?

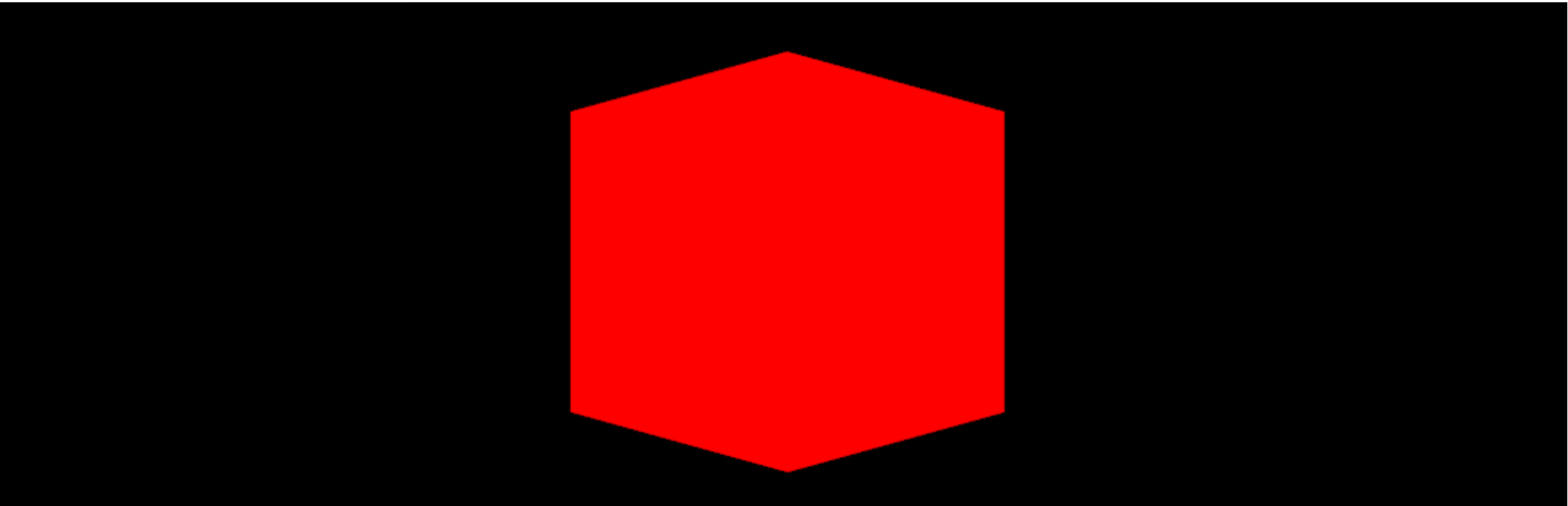
What Is Color?

- Spectrum of the **light reflected** off a surface.



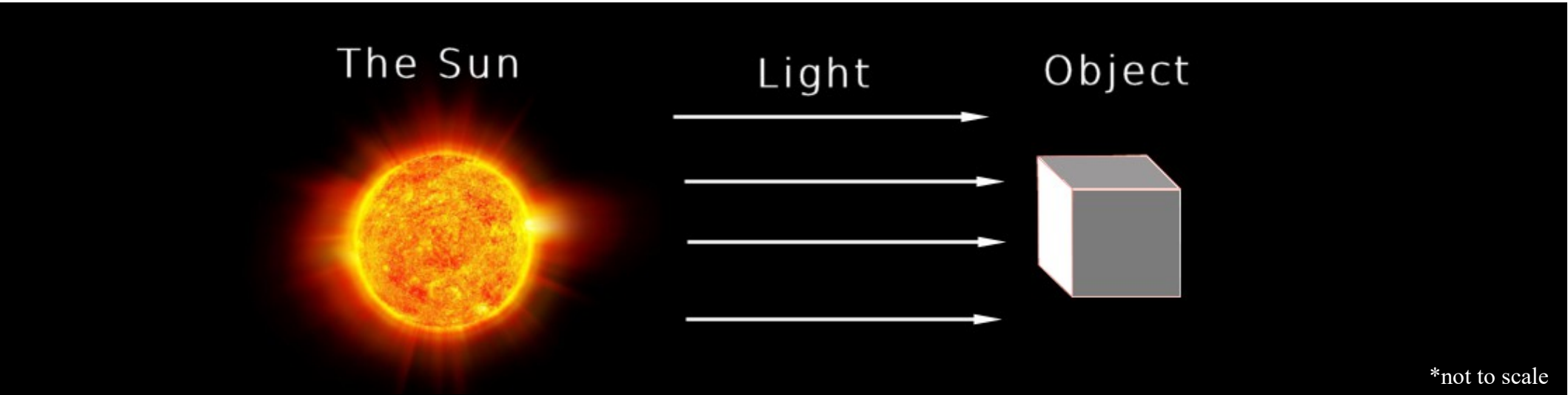
What Is Color?

- Spectrum of the **light reflected** off a surface.
- In 3D it is not enough to just say that *a thing is red*.



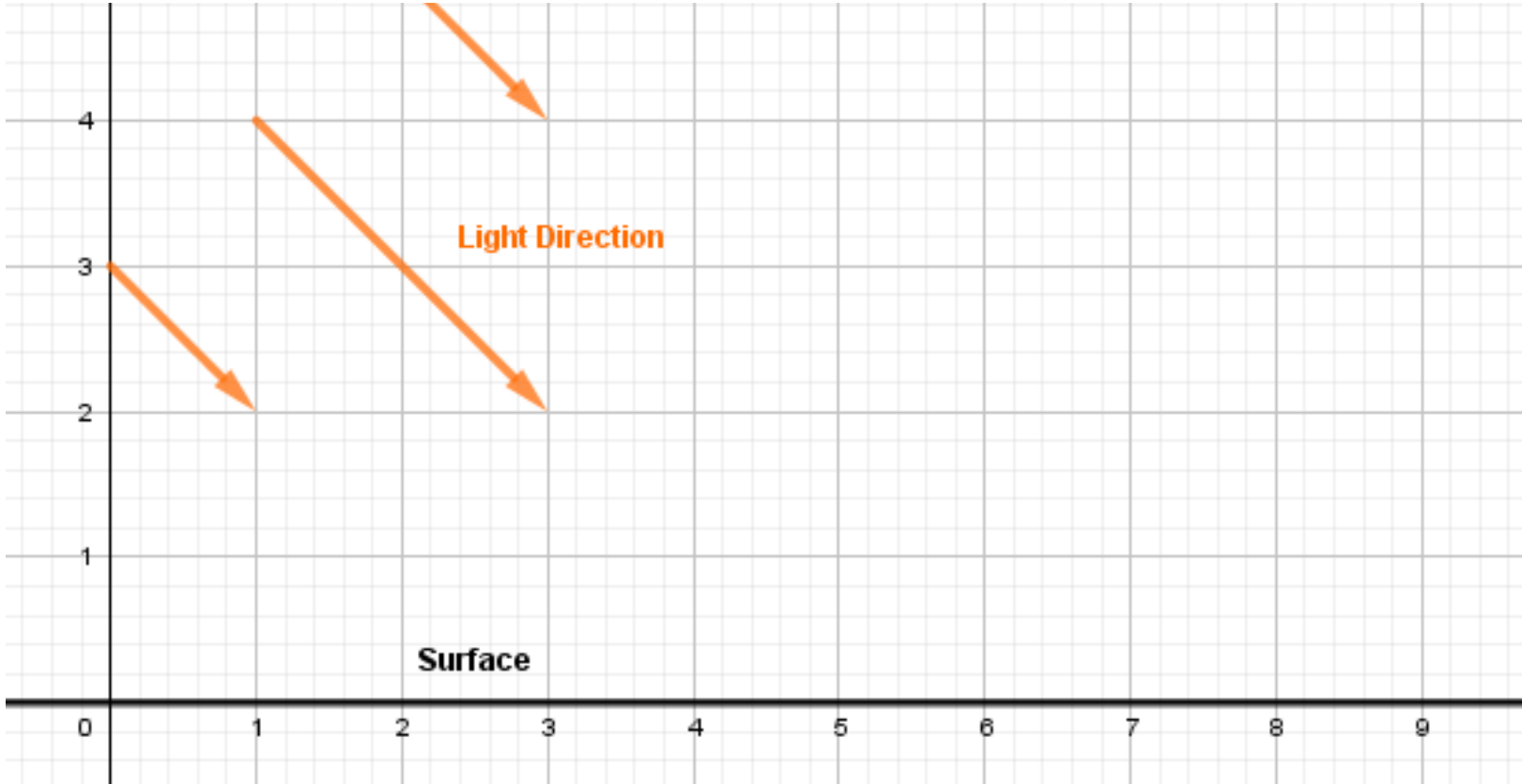
What Is Color?

- Spectrum of the **light reflected** off a surface.
- In 3D it is not enough to just say that *a thing is red*.
- We need to say that somewhere we have a some kind of **light source**.



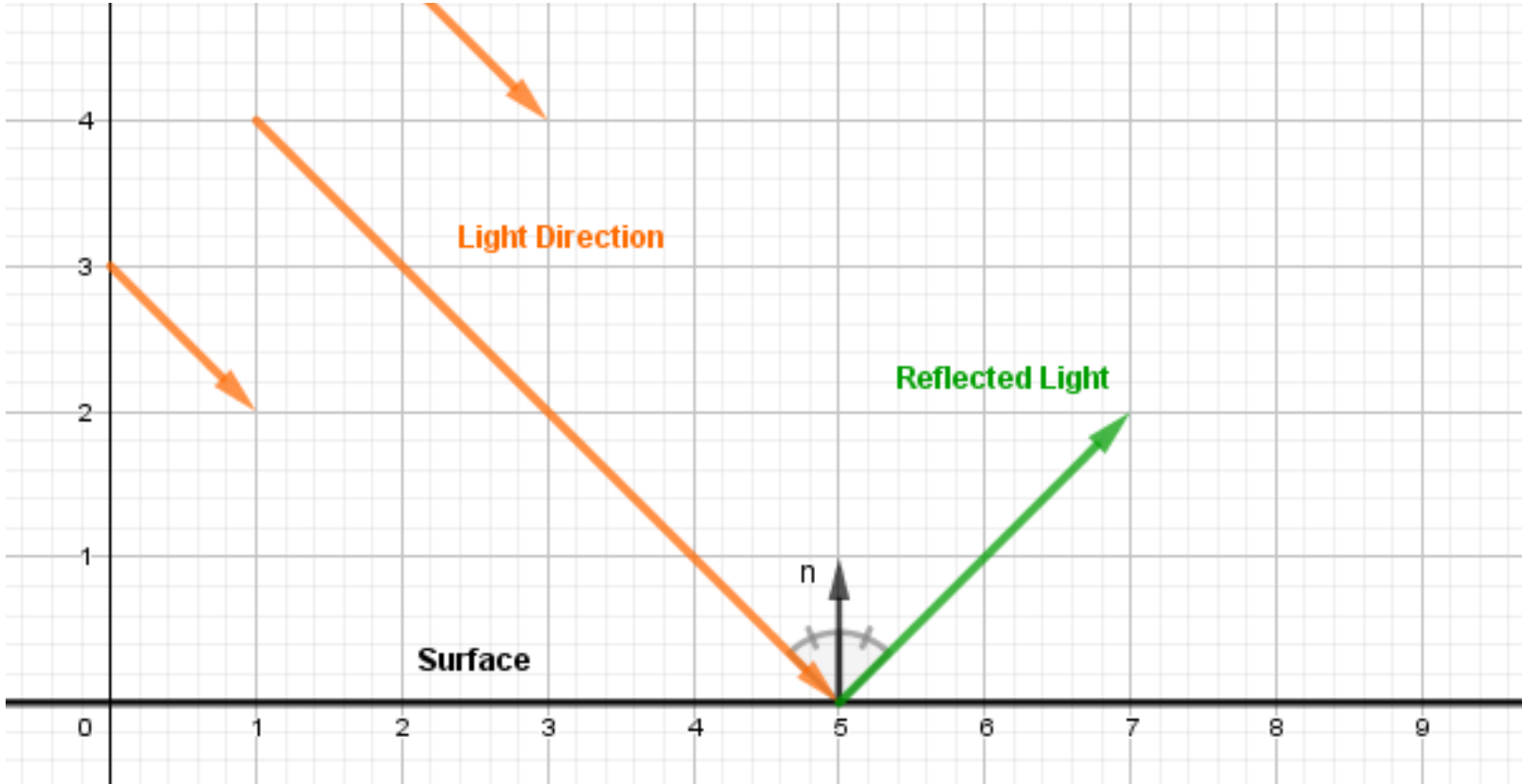
Directional Light

- Ok, we define a light direction and our surface



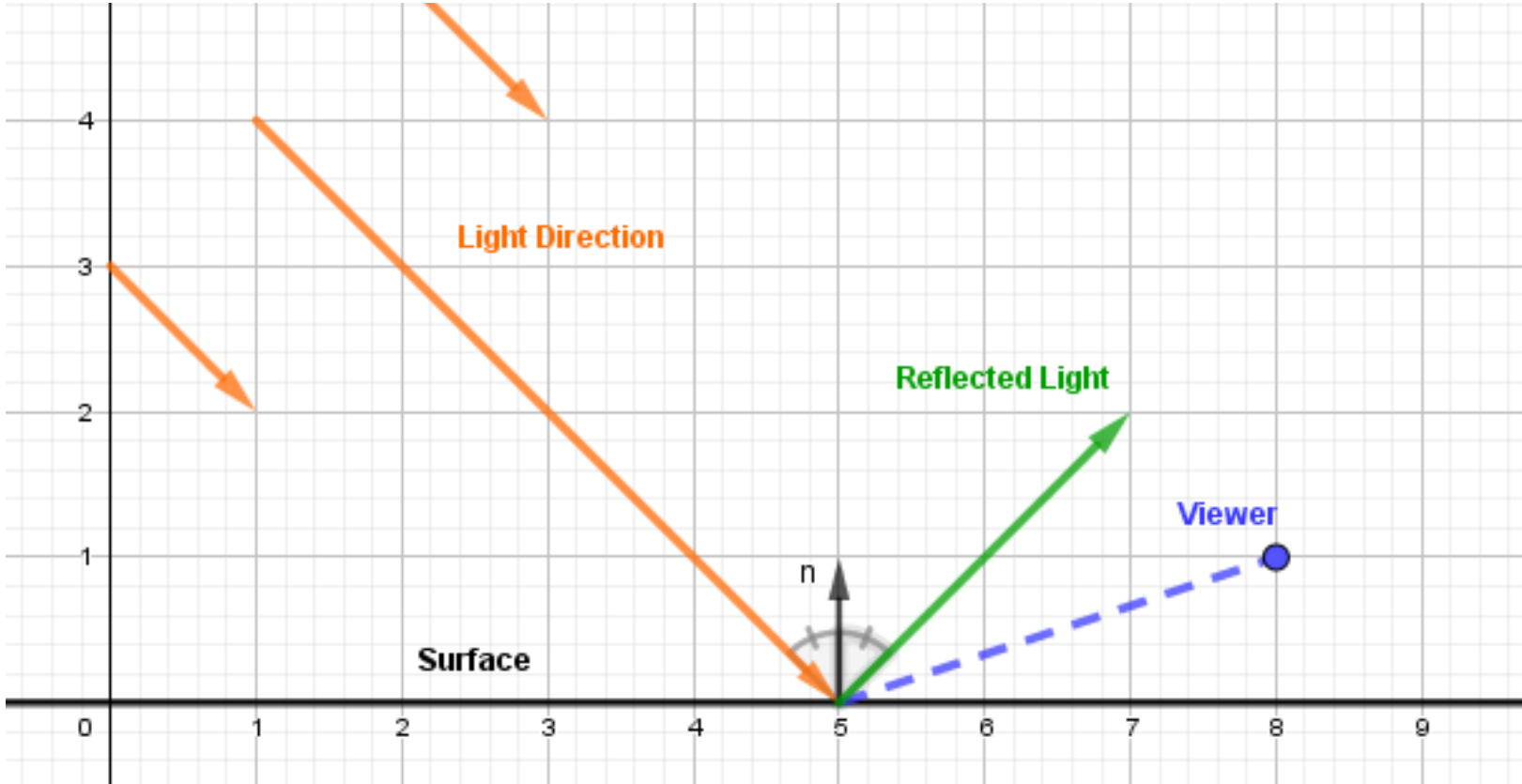
Directional Light

- Light reflects by the incident angle, right?



Directional Light

- The viewer does not see the surface at x=5?

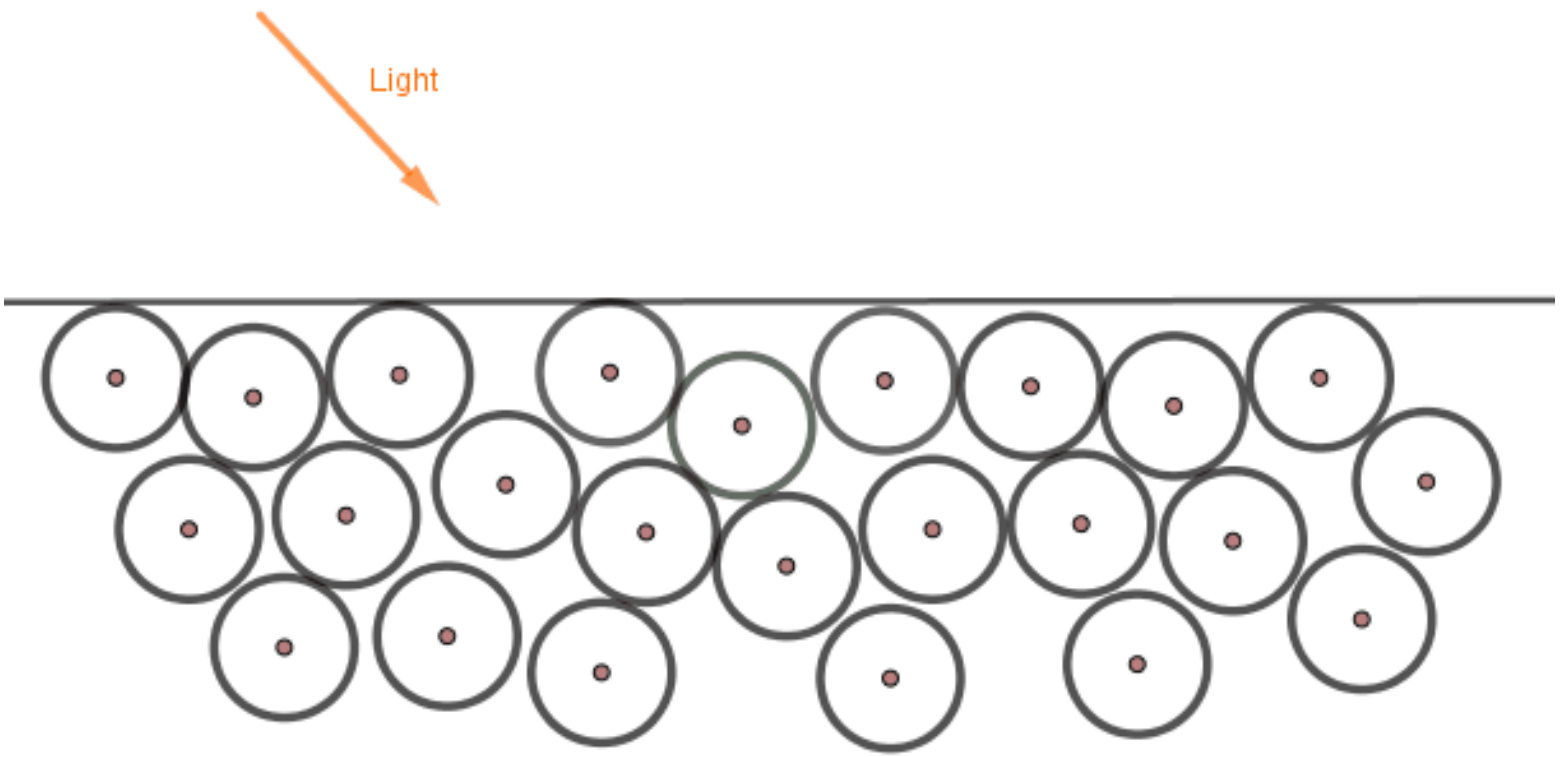


Diffuse Reflection

- Reality – our surfaces are diffusely reflective!

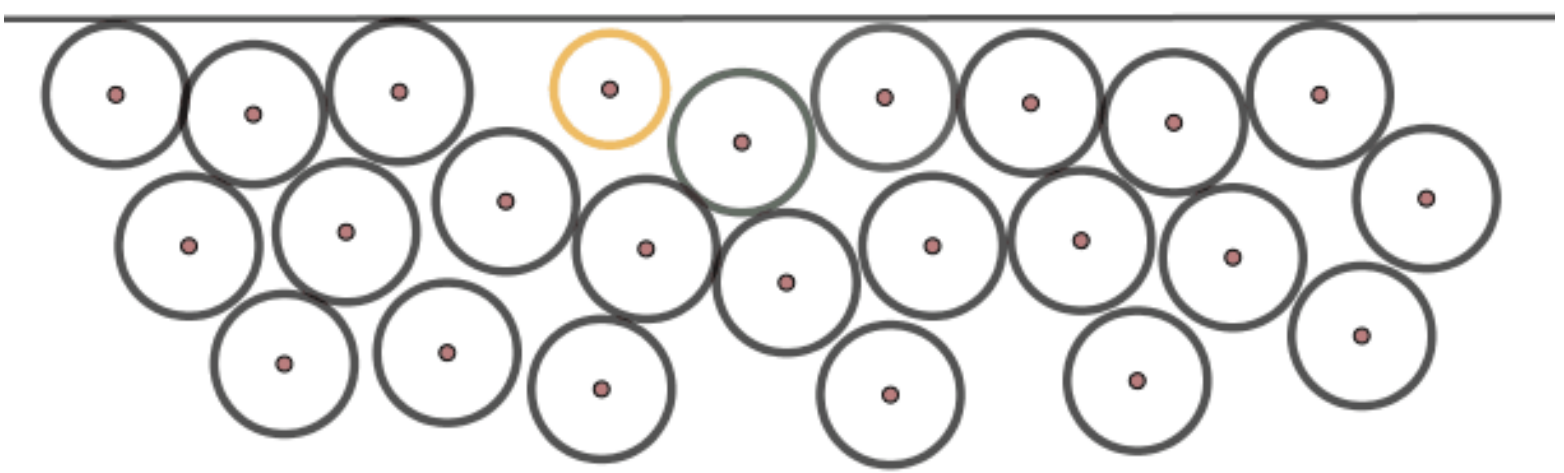
Diffuse Reflection

- Light entering at a specific angle



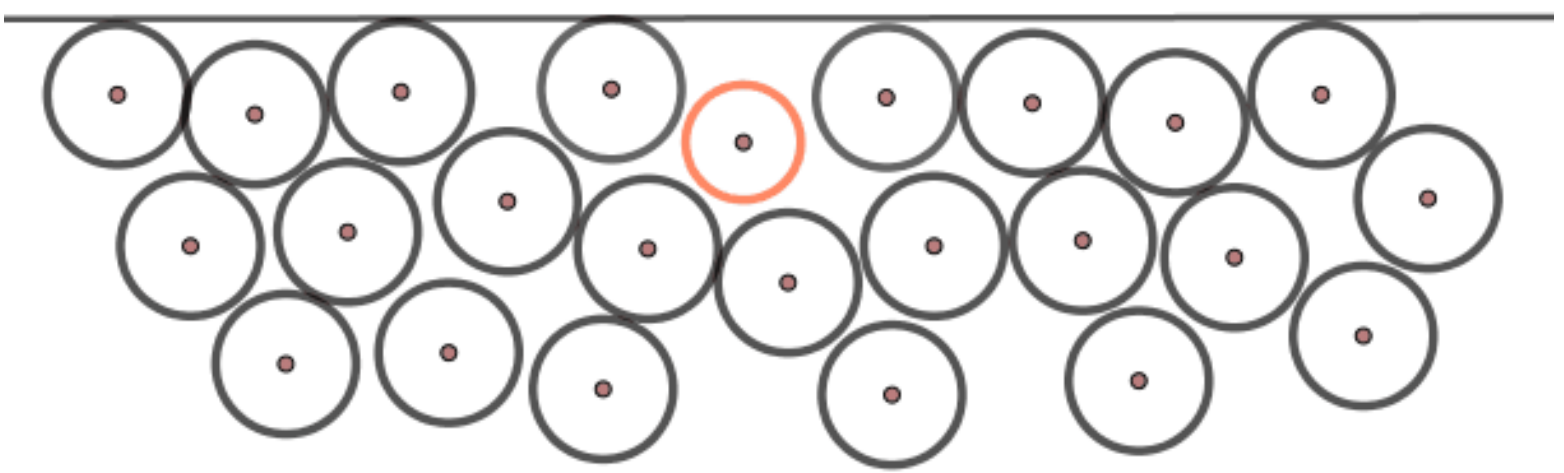
Diffuse Reflection

- Photon excites an atom



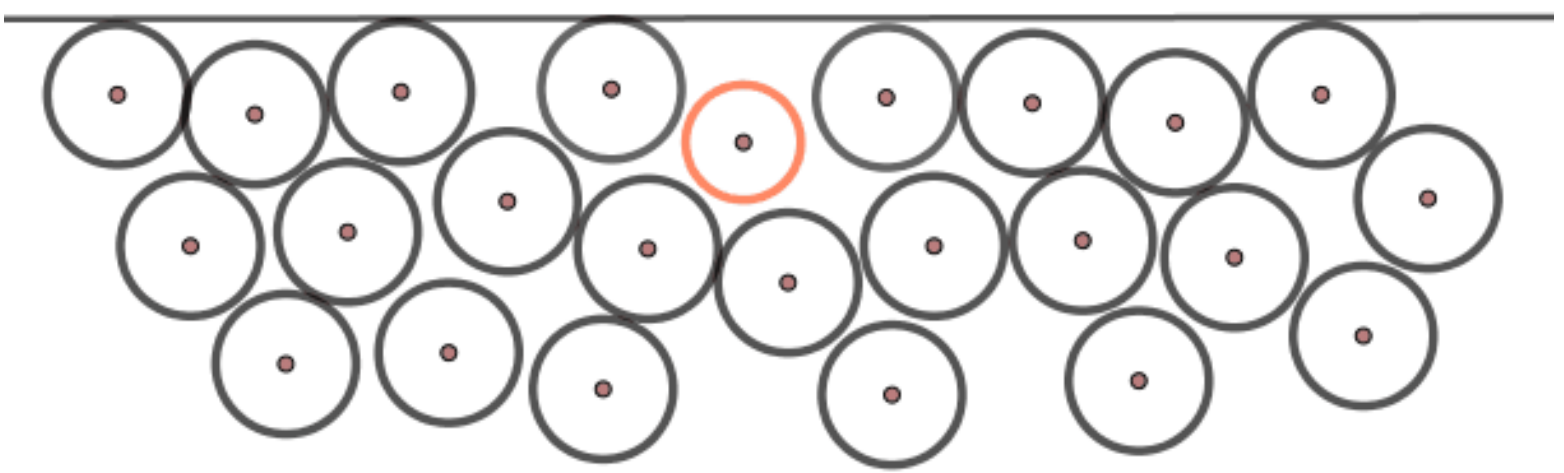
Diffuse Reflection

- The energy is transferred to the next atom



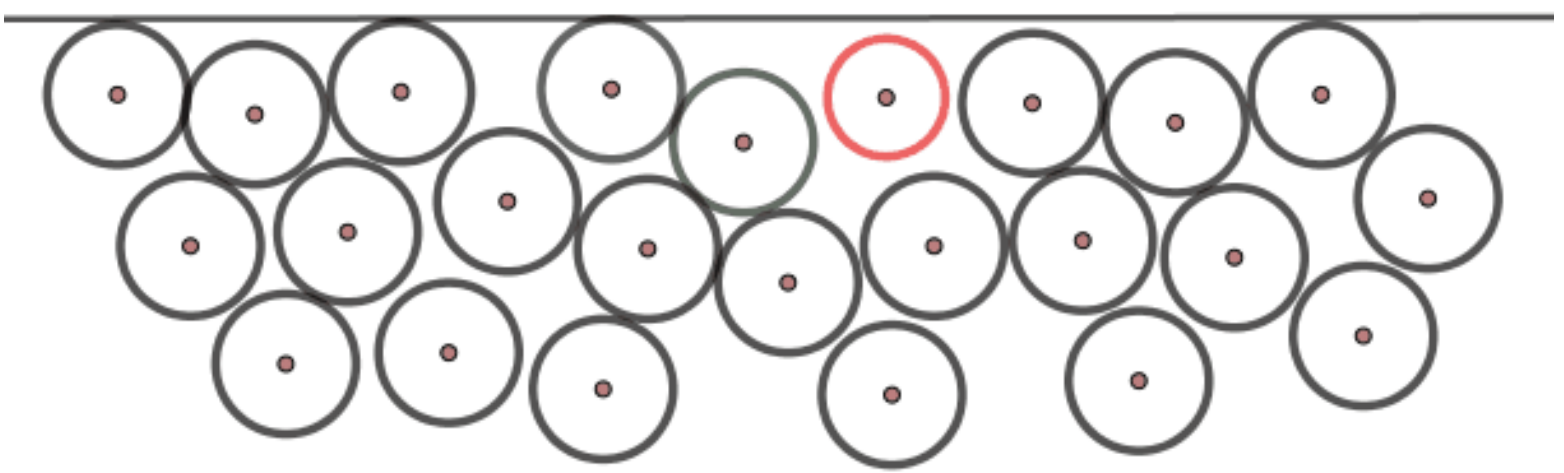
Diffuse Reflection

- The energy is transferred to the next atom
- Some energy is absorbed



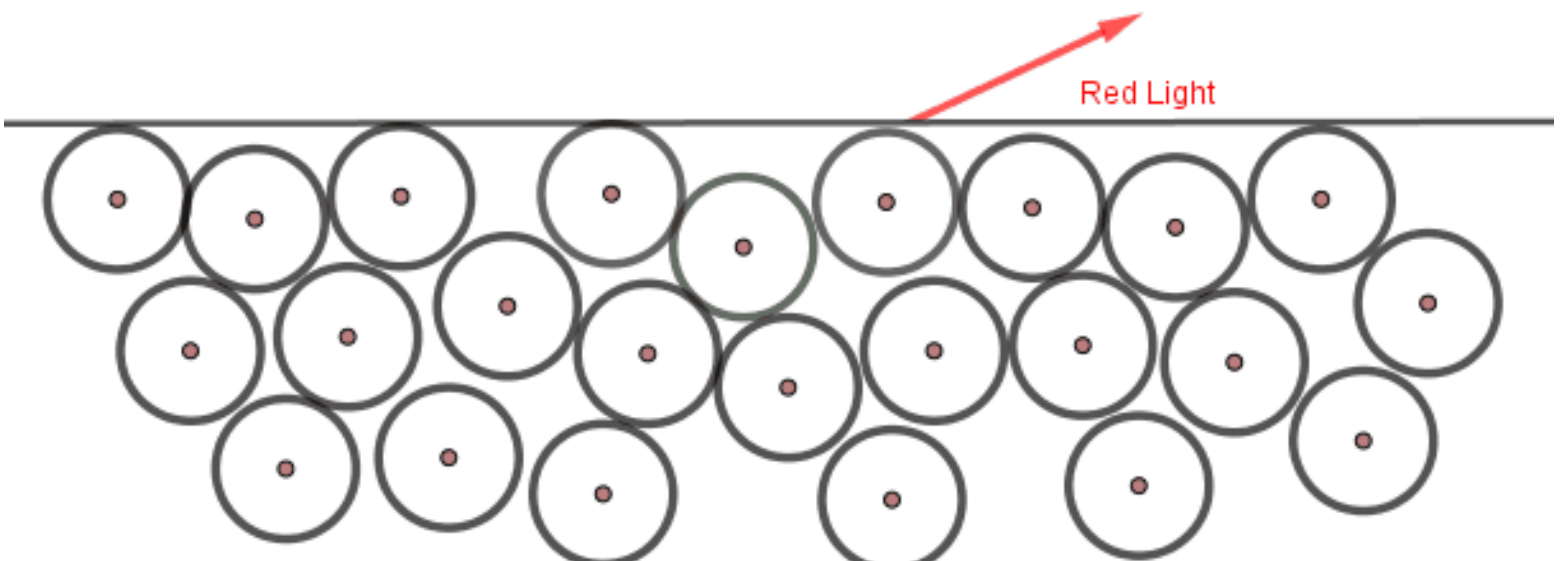
Diffuse Reflection

- Excited atoms vibrate, giving off heat



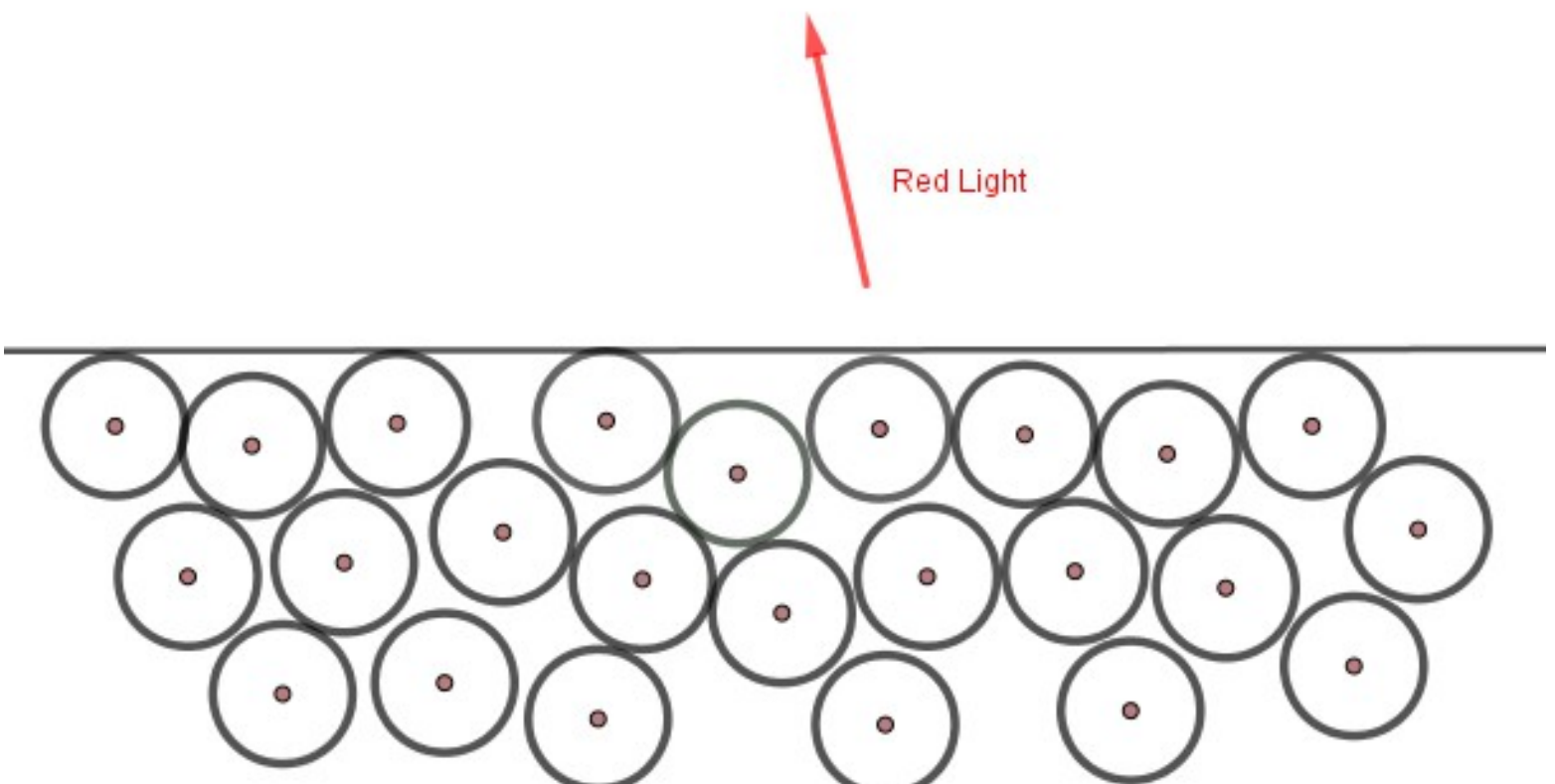
Diffuse Reflection

- Finally photon exits the surface



Diffuse Reflection

- In a quite random direction



Diffuse Reflection

- This is *generally* how pigments work

Nice post: https://physics.stackexchange.com/a/240848

Diffuse Reflection

- Can be caused by other reasons too!

Diffuse Reflection

- Can be caused by other reasons too!
- For example structural coloration in nature.

https://en.wikipedia.org/wiki/Pollia_condensata

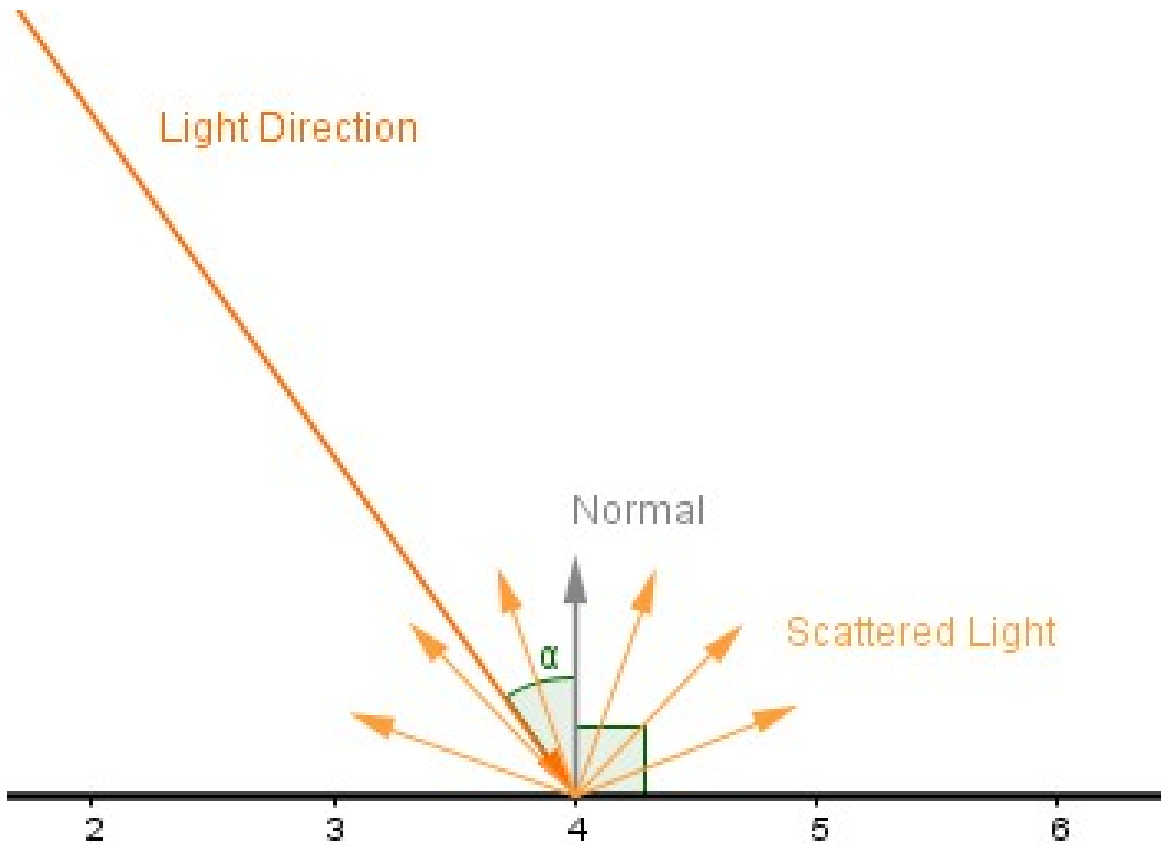
All of these feathers are actually brown.

Diffuse Reflection

- Can be caused by other reasons too!
- For example structural coloration in nature.

Diffuse Reflection

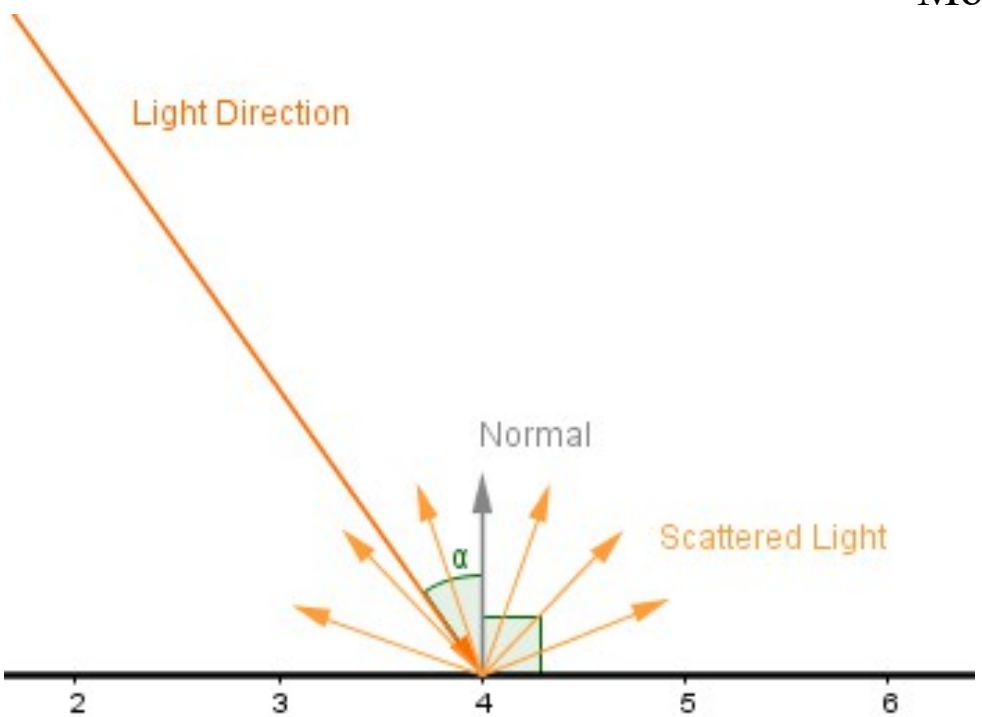
- We assume **diffuse light scatters uniformly**



Diffuse Reflection

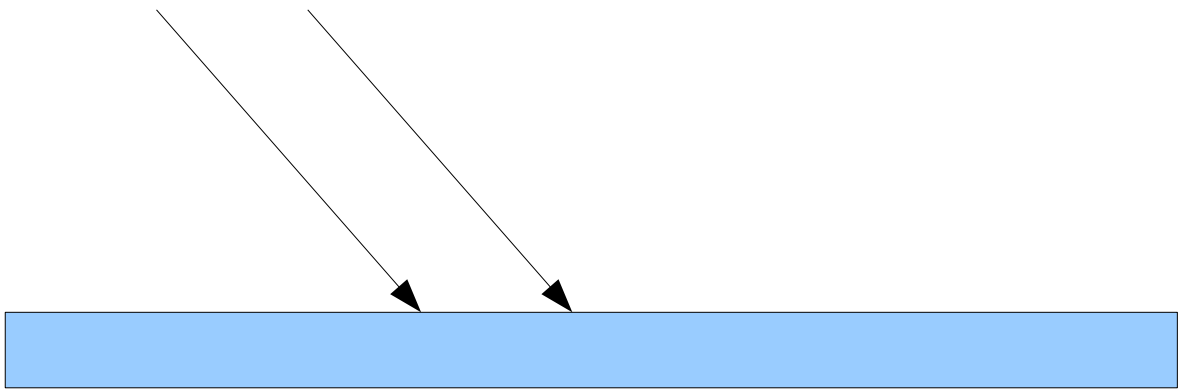
- So all we need now is the angle between the **surface normal** and the **Light Direction**.

More correct is: ***direction towards the light***

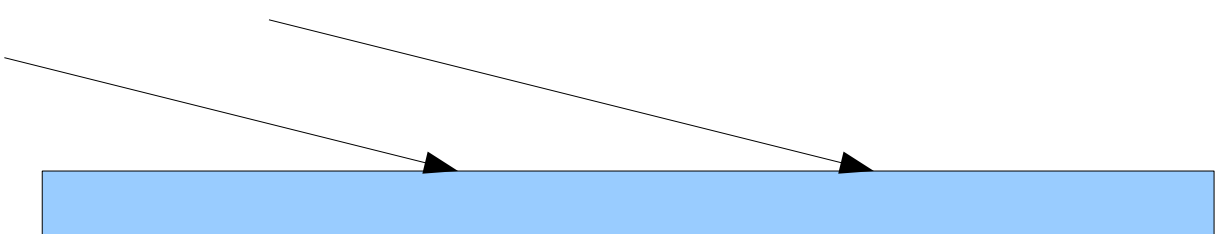


- Why this angle?

Diffuse Reflection



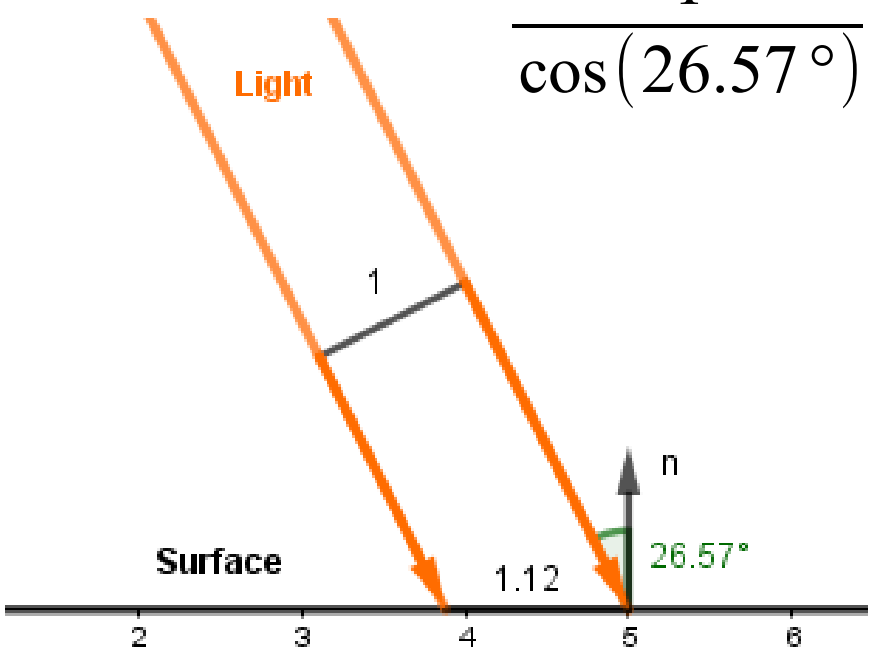
Hint?



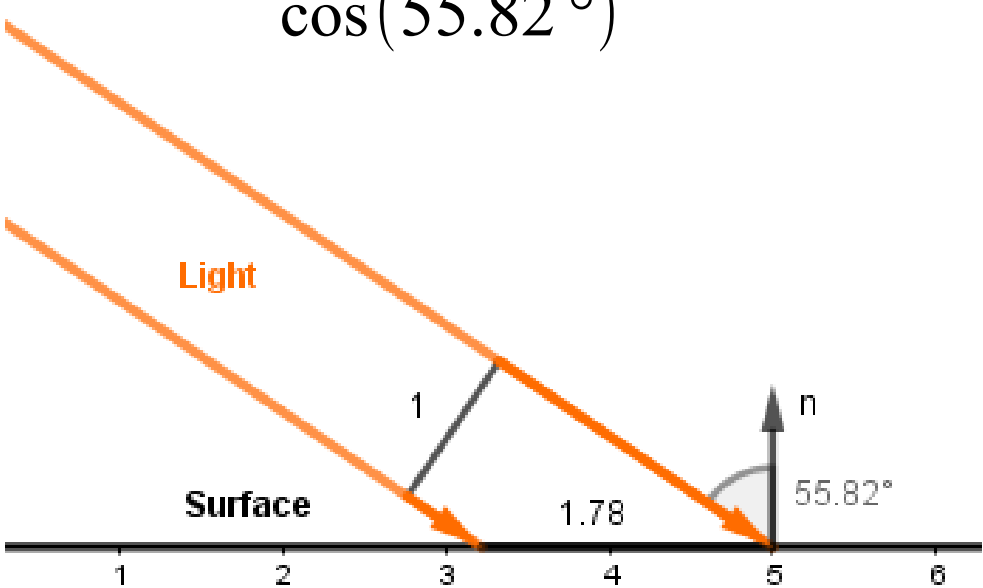
Diffuse Reflection

- The actual light energy per surface unit depends on the angle.

$$\frac{1}{\cos(26.57°)} \approx 1.12$$

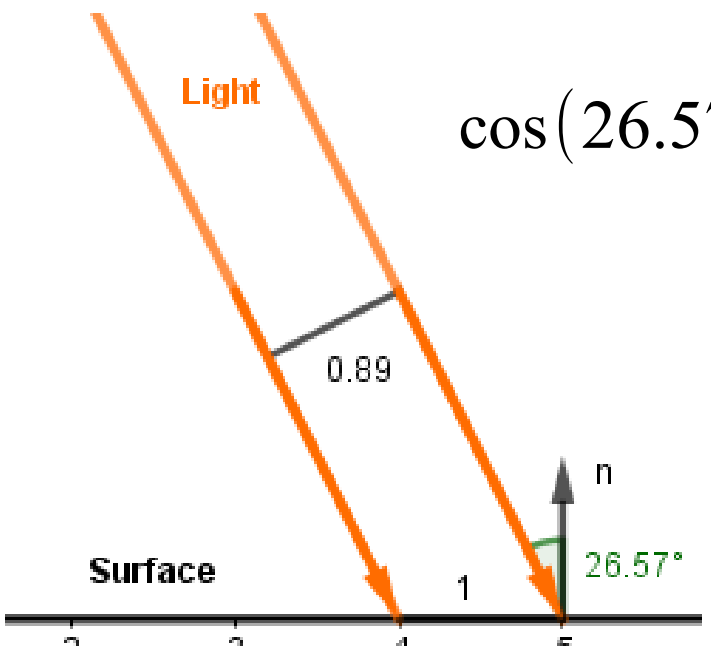


$$\frac{1}{\cos(55.82°)} \approx 1.72$$



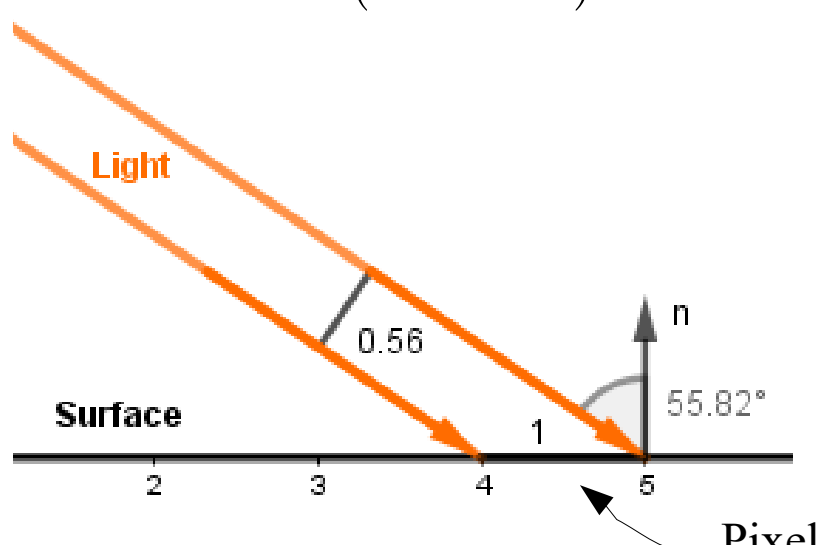
Diffuse Reflection

- In CG we are interested in how much light reaches 1 surface unit (pixel).



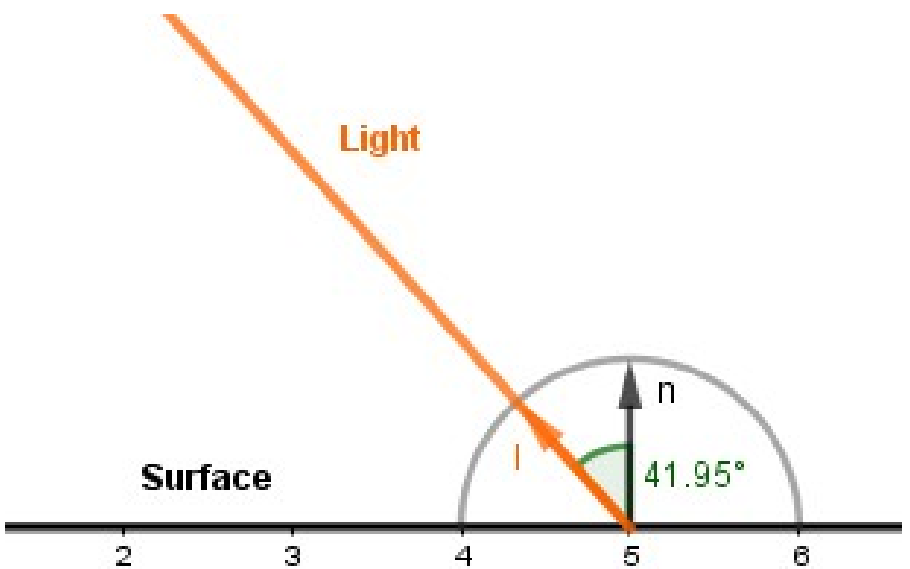
$$\cos(26.57°) \approx 0.89$$

$$\cos(55.82°) \approx 1.72$$



Diffuse Reflection & Directional Light

- Given a surface point and a light source, we can calculate the color of that surface point.
- We use a **cosine** between the **surface normal** and a **vector l going towards the light source**.



The Dot Product

- To find the cosine of the angle, we can use a scalar / **dot product** operation.

$$v \cdot u = \|v\| \cdot \|u\| \cdot \cos\left(\angle\left(u, v\right)\right)$$

Geometric definition

The Dot Product

- To find the cosine of the angle, we can use a scalar / **dot product** operation.

$$v \cdot u = \|v\| \cdot \|u\| \cdot \cos(\angle(u, v))$$

$$v \cdot u = v_1 \cdot u_1 + v_2 \cdot u_2 + v_3 \cdot u_3$$

Algebraic definition

The Dot Product

- To find the cosine of the angle, we can use a scalar / **dot product** operation.

$$v \cdot u = \|v\| \cdot \|u\| \cdot \cos(\angle(u, v))$$

Geometric definition

$$v \cdot u = v_1 \cdot u_1 + v_2 \cdot u_2 + v_3 \cdot u_3$$

Algebraic definition

- When we have normalized (unit) vectors, geometric definition simplifies to:

$$v \cdot u = \|v\| \cdot \|u\| \cdot \cos(\alpha) = 1 \cdot 1 \cdot \cos(\alpha) = \cos(\alpha)$$

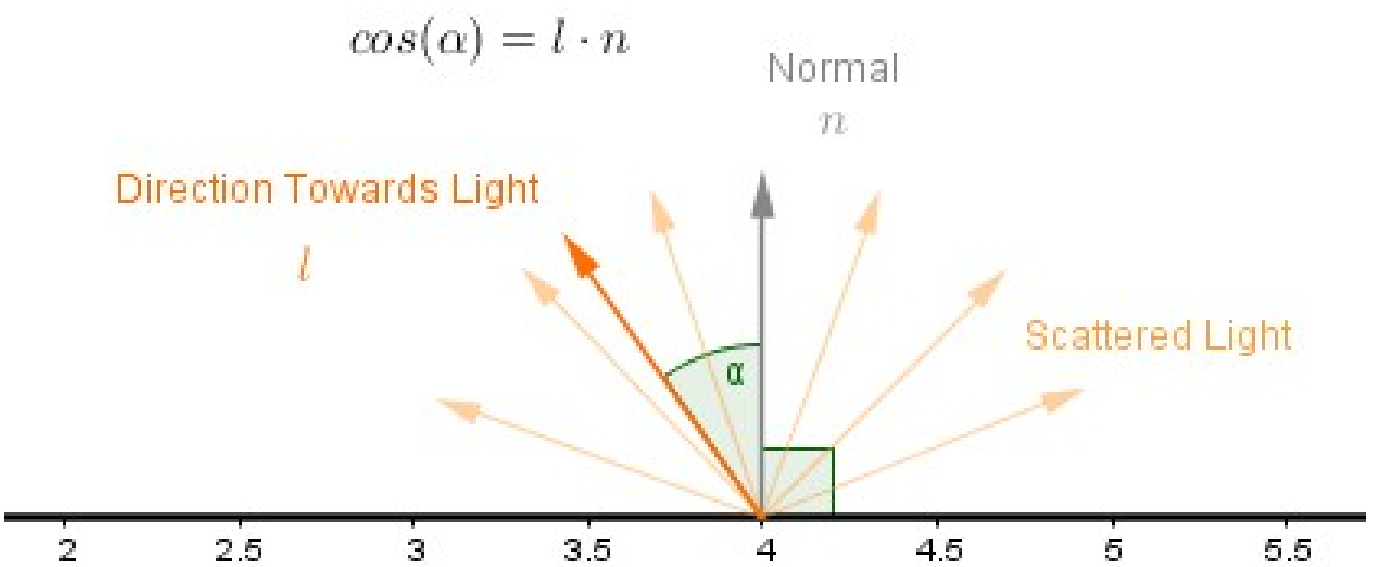
The Dot Product

- So if we put those two definitions together:

$$v \cdot u = \underbrace{v_1 \cdot u_1 + v_2 \cdot u_2 + v_3 \cdot u_3}_{\text{This should be quite easy for the computer to calculate...}} = \cos(\alpha)$$

The Dot Product

- The dot product and the cosine between two vectors are used quite often in CG.



The Dot Product

- Dot product of two vectors *u* and *v* is the same as vector multiplication.

$$v \cdot u = v_1 \cdot u_1 + v_2 \cdot u_2 + v_3 \cdot u_3 = \begin{pmatrix} v_1 & v_2 & v_3 \end{pmatrix} \cdot \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} = v^T u$$

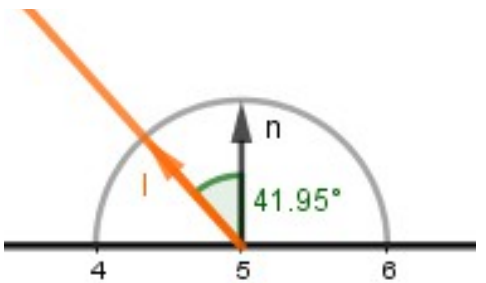
- So for our surface point we get:

$$Intensity = directionTowardsLight^T \cdot surfaceNormal$$

$$I = l^T \cdot n$$

$$I \in [0,1]$$

What is the visual result of that?



Diffuse Reflection & Directional Light

- Two missing things:
  - Intensity of the light source $L \in [0, 1]$
  - Reflectivity of our material $M \in [0, 1]$

Diffuse Reflection & Directional Light

- Also the color!
- We apply to each of 3 RGB channels.

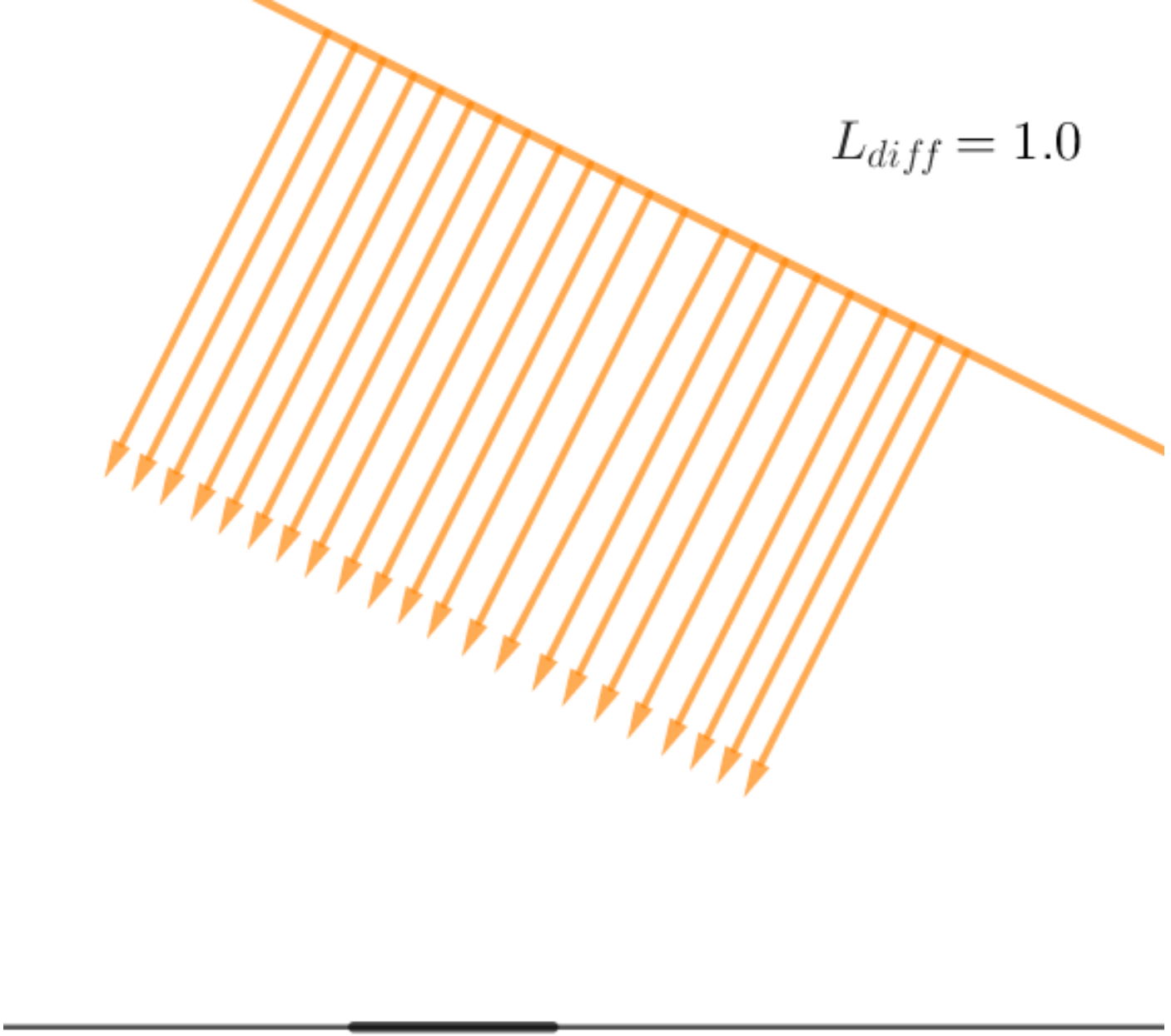
$$I_R = n^T \cdot l \cdot L_R \cdot M_R$$

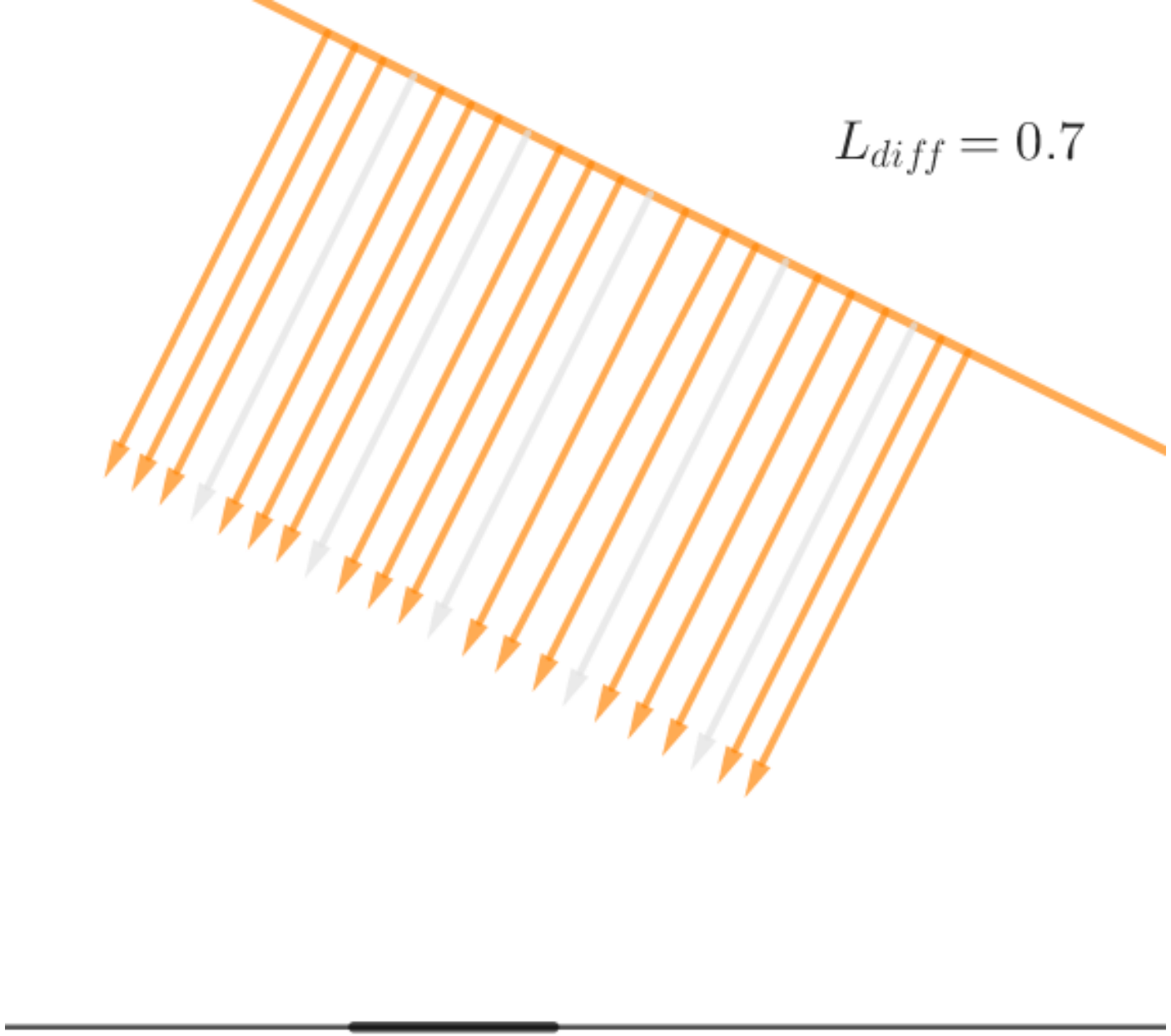
$$I_G = n^T \cdot l \cdot L_G \cdot M_G$$

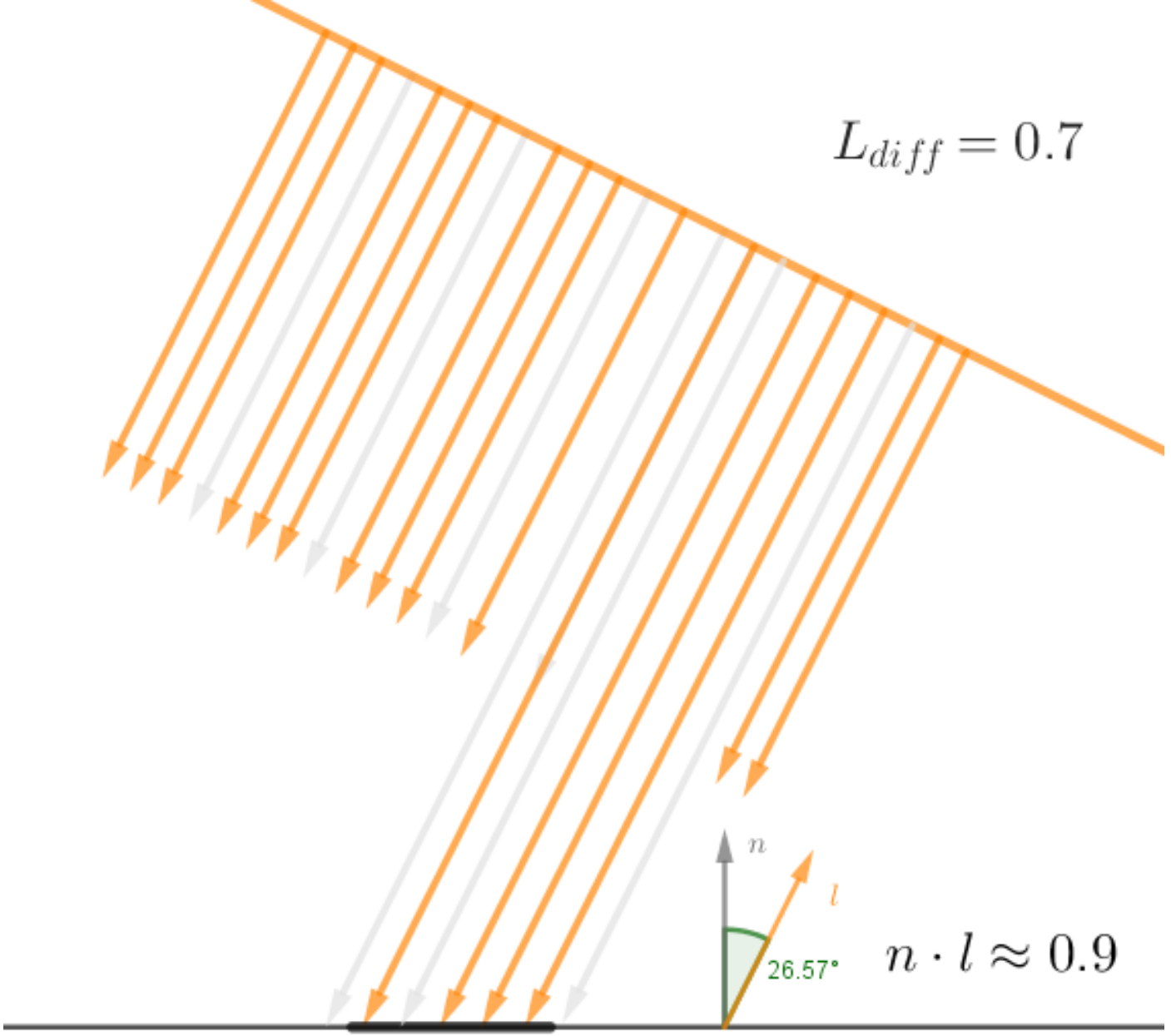
$$I_B = n^T \cdot l \cdot L_B \cdot M_B$$

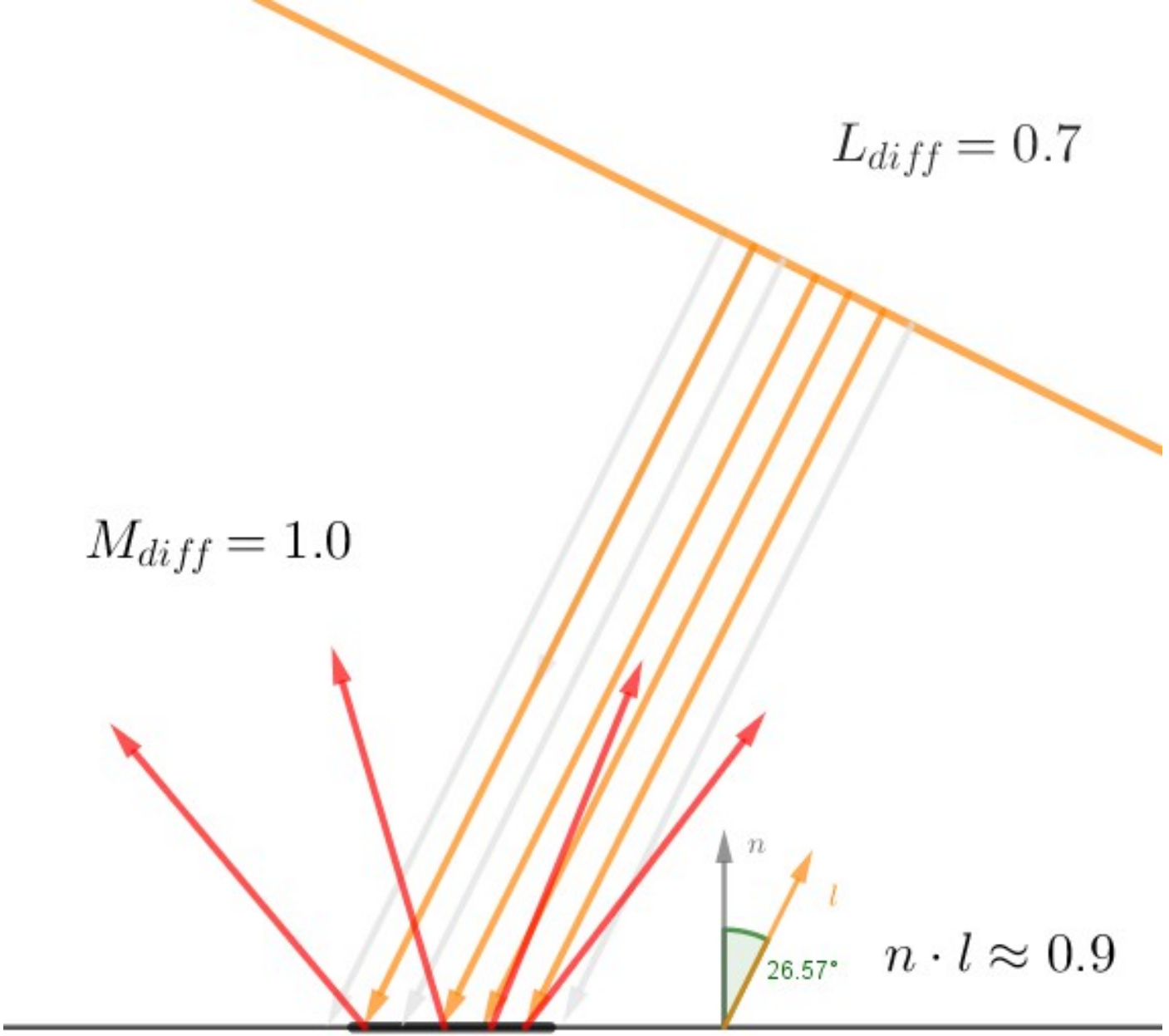
Light that light source emits

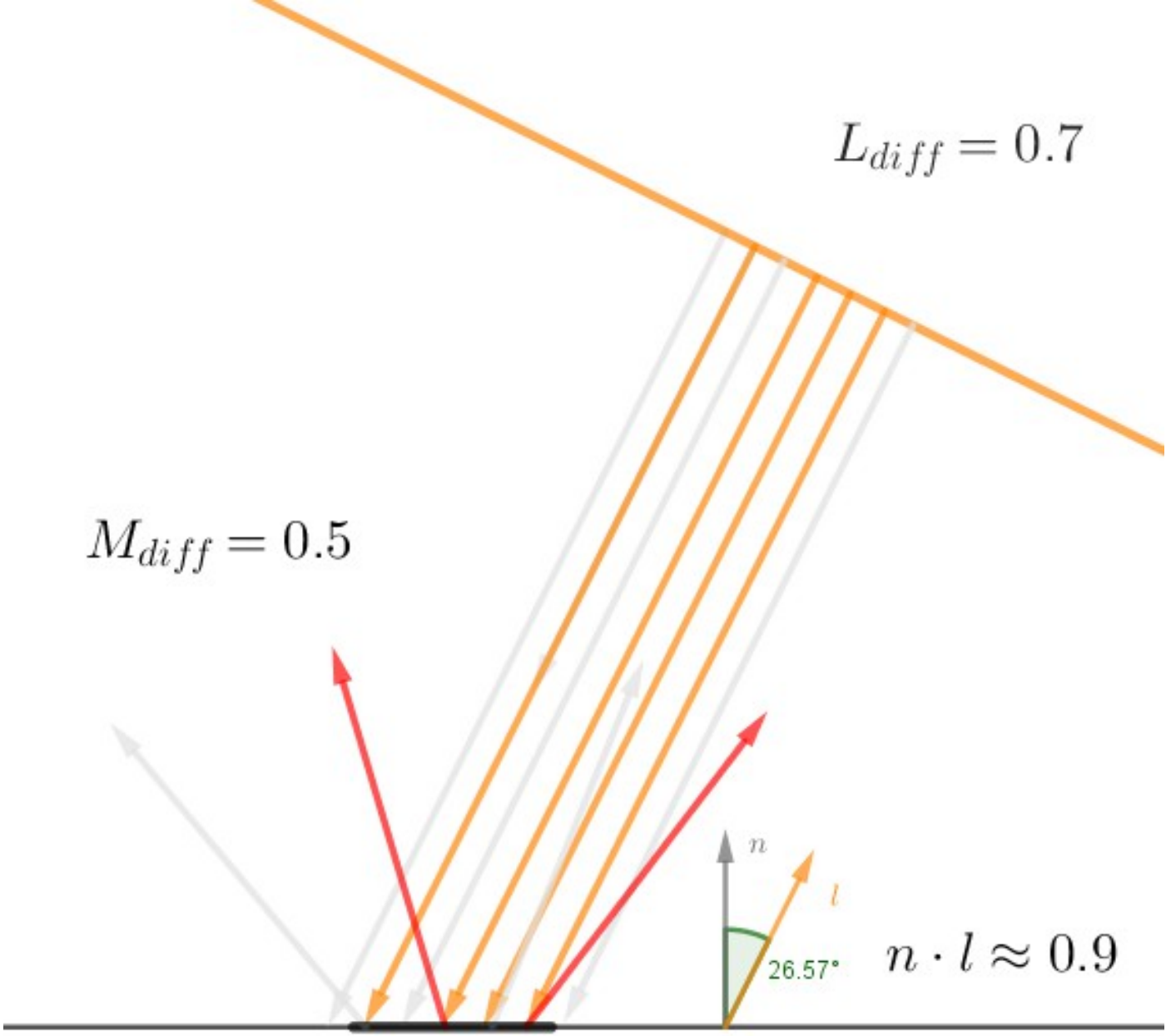
Light that material reflects


$L_{diff} = 1.0$


$L_{diff} = 0.7$


$L_{diff} = 0.7$
n
l
26.57°
$n \cdot l \approx 0.9$


$L_{diff} = 0.7$
$M_{diff} = 1.0$
n
l
26.57°
$n \cdot l \approx 0.9$


$L_{diff} = 0.7$
$M_{diff} = 0.5$
n
l
26.57°
$n \cdot l \approx 0.9$

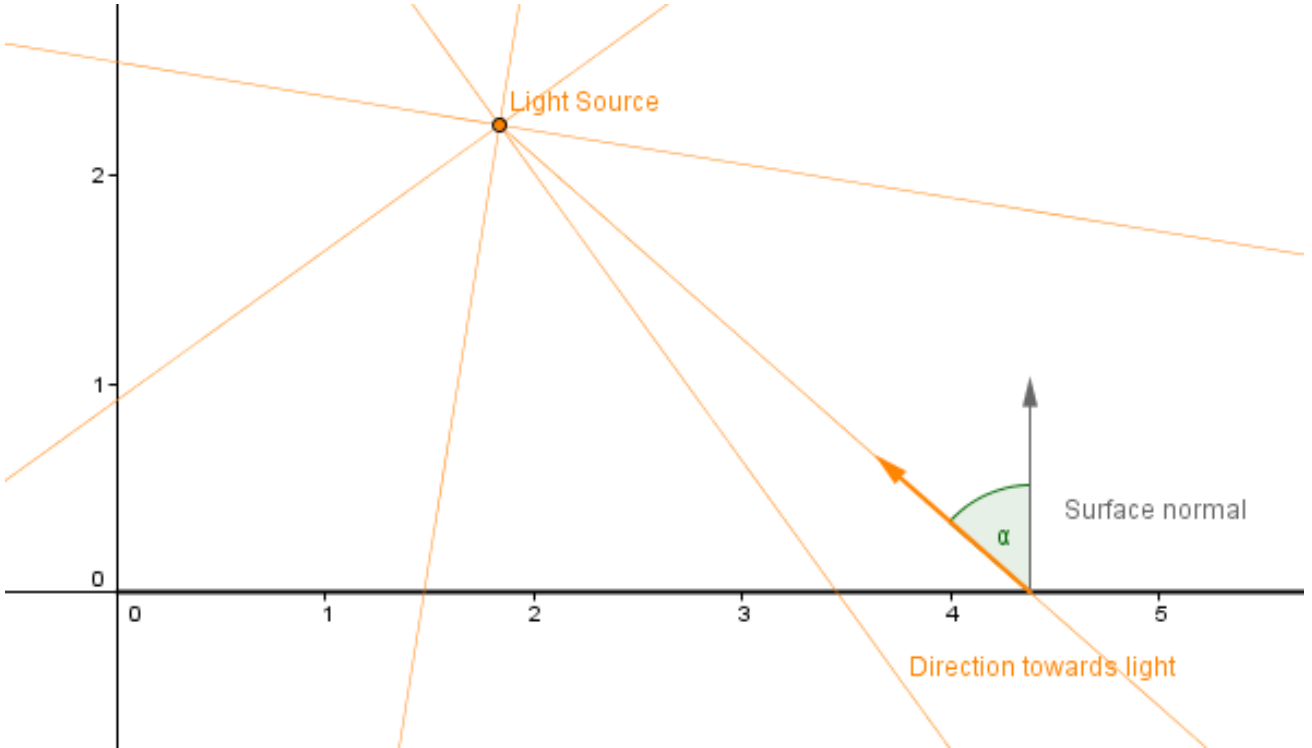
Diffuse Reflection & Directional Light

What color are the apples if red light shines upon them?

What is wrong with this example? (2+ things)

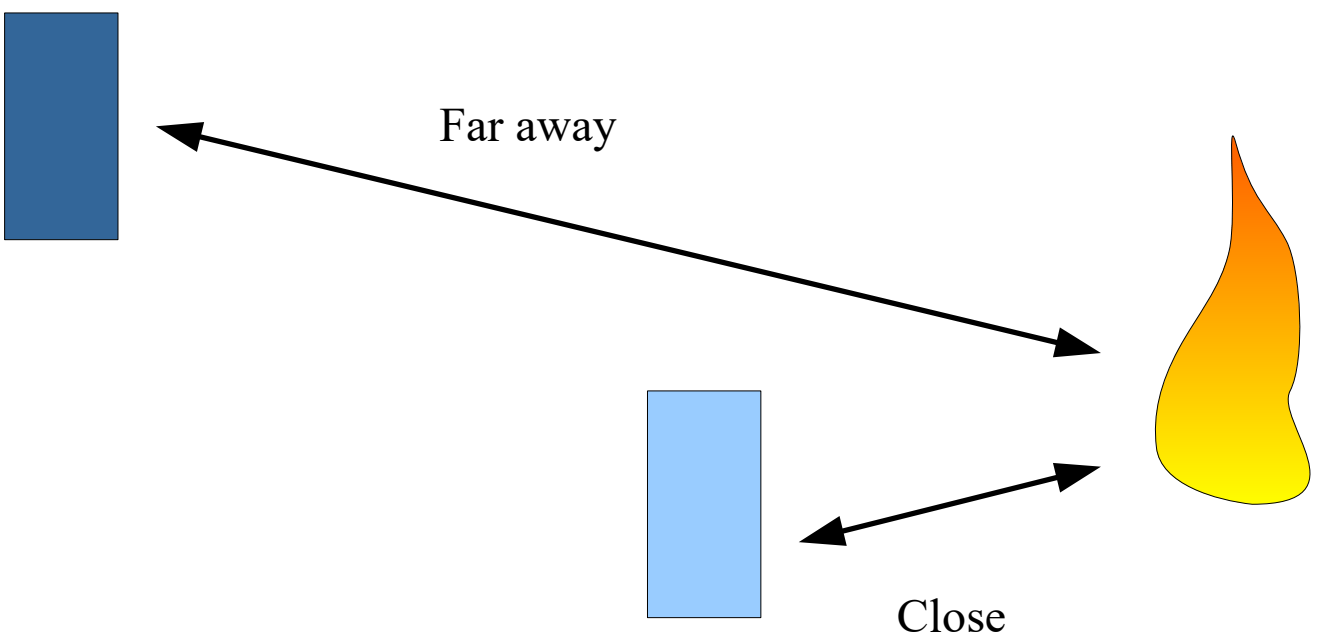
Point Light

- Point lights work the same way, but the light source is a point.



Point Light

- Sometimes distance **attenuation** parameters are added.



Point Light

- Distance **attenuation** parameters:
  - In OpenGL:

$$attenuation = \frac{1}{k_c + k_l \cdot d + k_q \cdot d^2}$$

Usually 1 (why?)

This is physically correct

  - In Three.js:

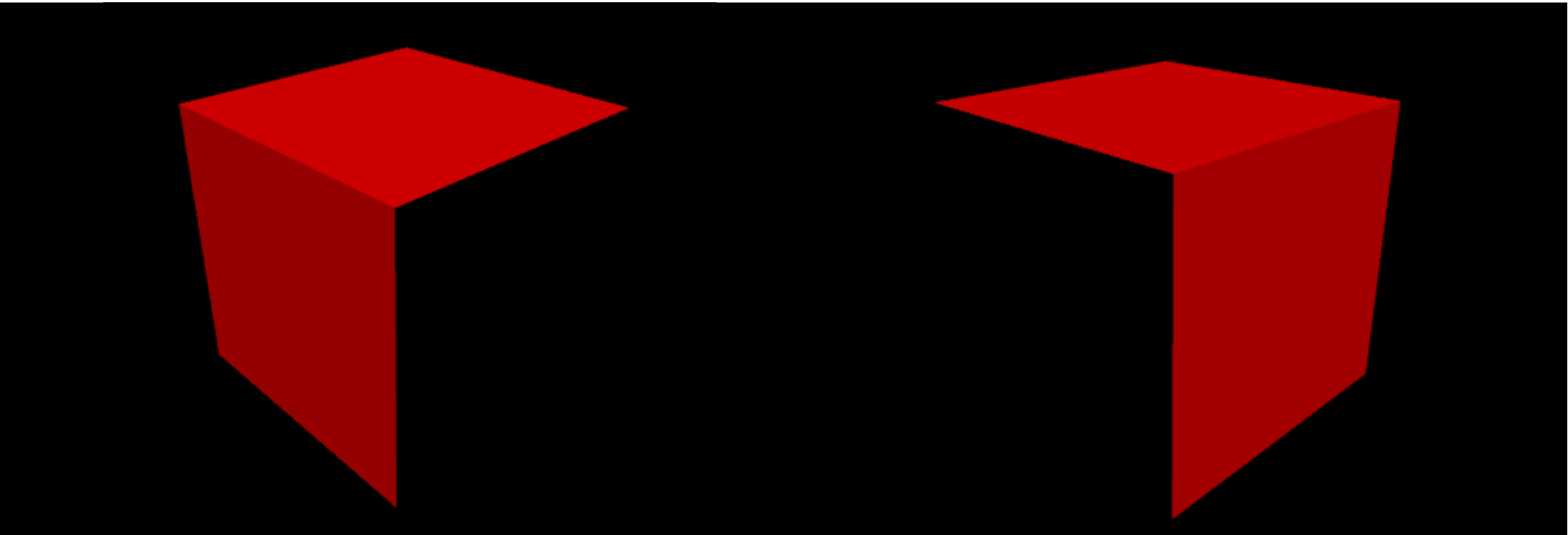
PointLight(hex, intensity, distance)

Distance - If non-zero, light will attenuate linearly from maximum intensity at light position down to zero at distance.

https://threejs.org/docs/#api/en/lights/PointLight

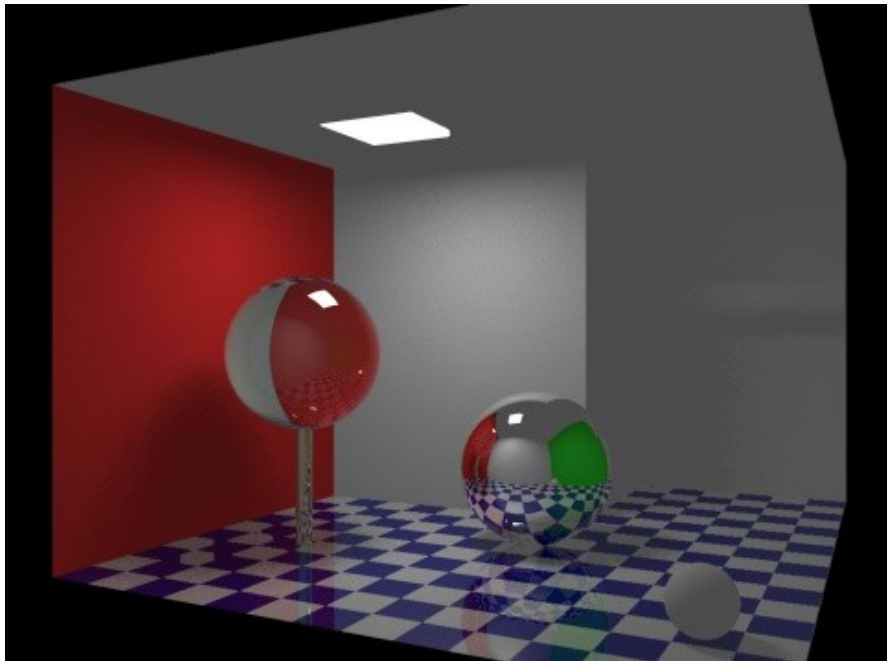
Ambient Light

- So, now we have 2 lights and a diffuse surface.
- Are we OK?



Ambient Light

- World contains much more than 1 cube and a light source.
- Do you know what scene this is?



- Calculating every reflection from every other object is time-consuming.
- **What can we do?**

Ambient Light

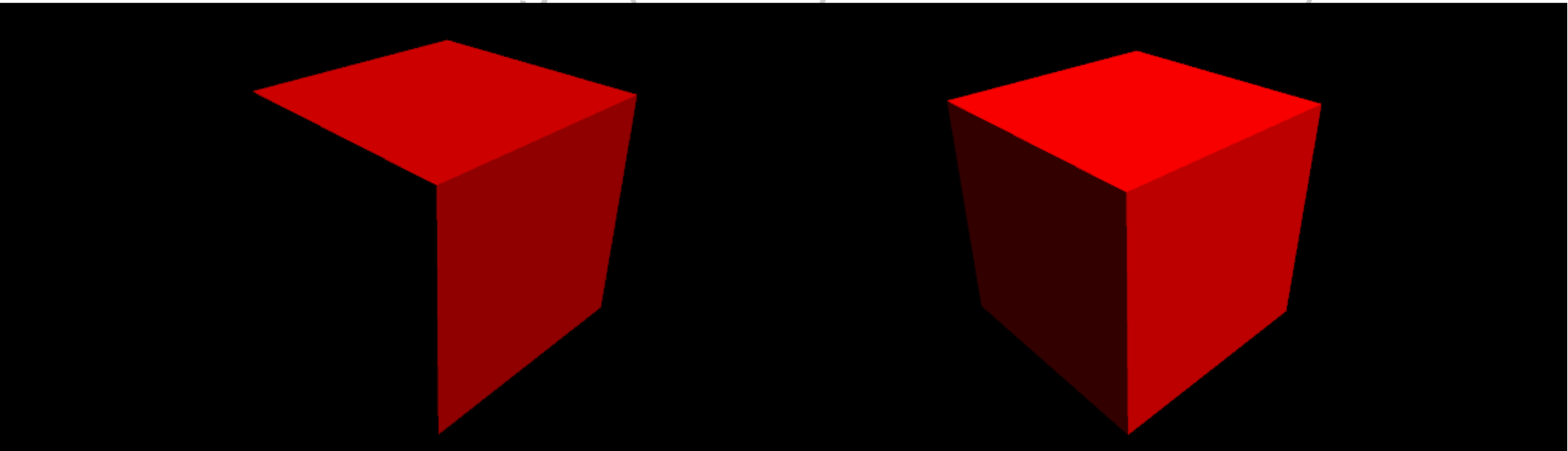
- Ambient light source – estimates the light reflected off of other objects in the scene

Ambient Light

- Ambient light source – estimates the light reflected off of other objects in the scene
- Ambient material property – how much object reflects that light (usually same as diffuse)

Ambient Light

- Ambient light source – estimates the light reflected off of other objects in the scene
- Ambient material property – how much object reflects that light (usually same as diffuse)



Lambert Material

- So together with diffuse lighting we get:

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R}$$ ← **Red** channel

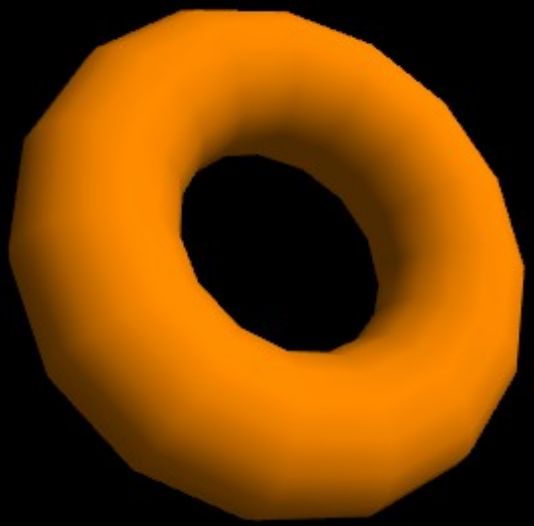
$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G}$$ ← **Green** channel

$$I_B = \underbrace{L_{A_B} \cdot M_{A_B}}_{\text{Ambient term}} + \underbrace{n^T \cdot l \cdot L_{D_B} \cdot M_{D_B}}_{\text{Diffuse term}}$$ ← **Blue** channel

What could go wrong?

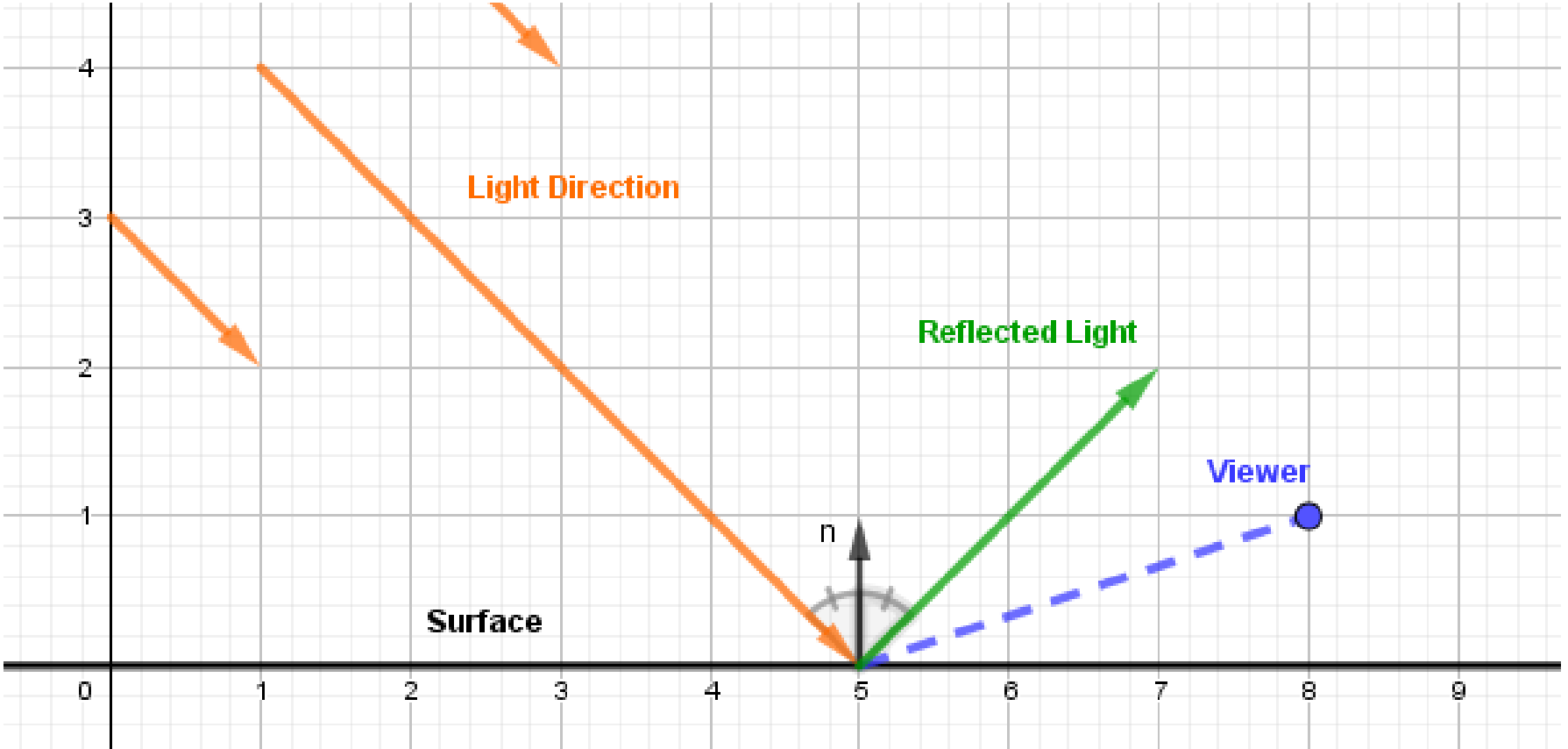
Is this it?

- Well, we have already made a very rough approximation of reality with the ambient term.
- Is there anything else that we have forgotten?



Specular Reflection

- Materials also do reflect light specularly.



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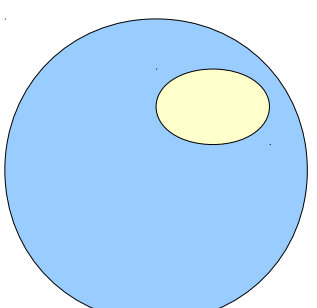
Specular Reflection

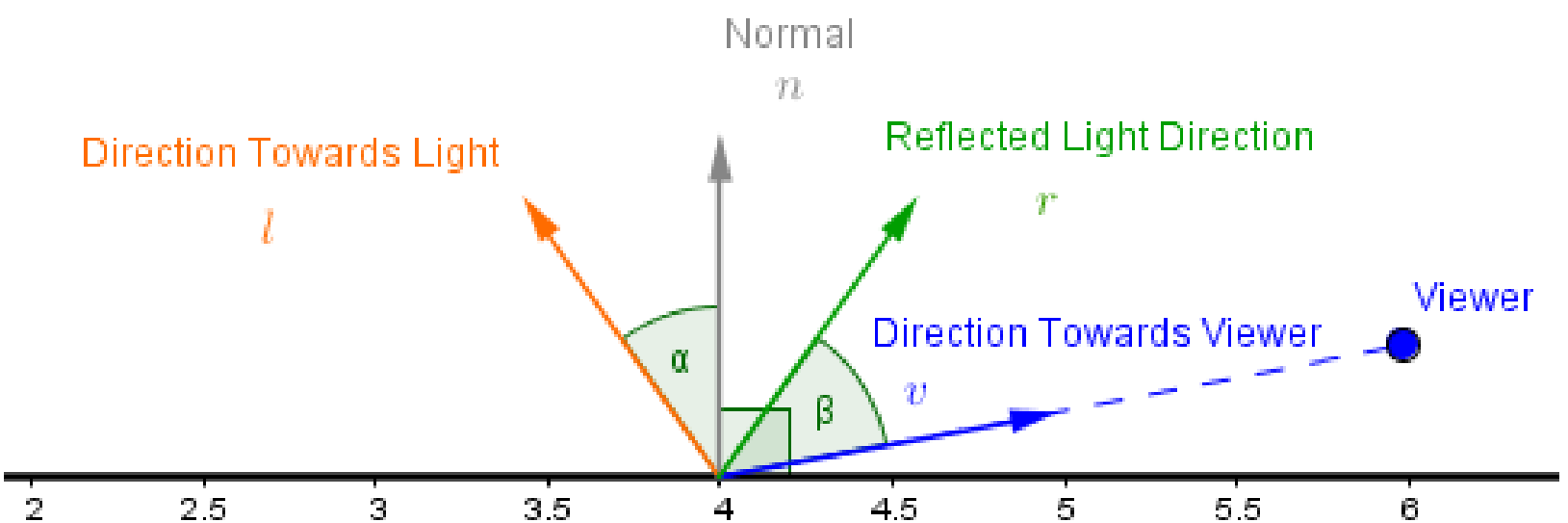
- Materials also reflect light specularly.
- Especially varnished materials and metals!
- Specular reflection is the direct reflection of the light from the environment.
- Often we want just a **specular highlight** –

  – that is the **reflection of the light source**!



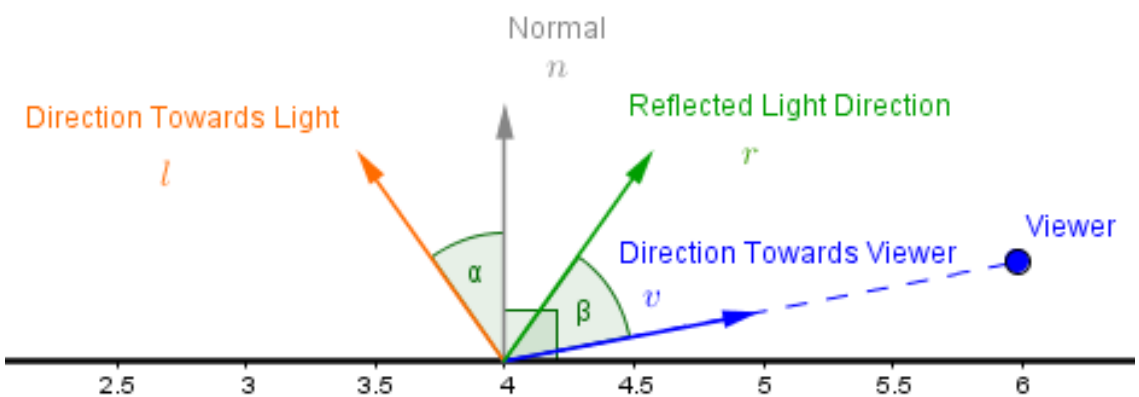
Specular Highlight

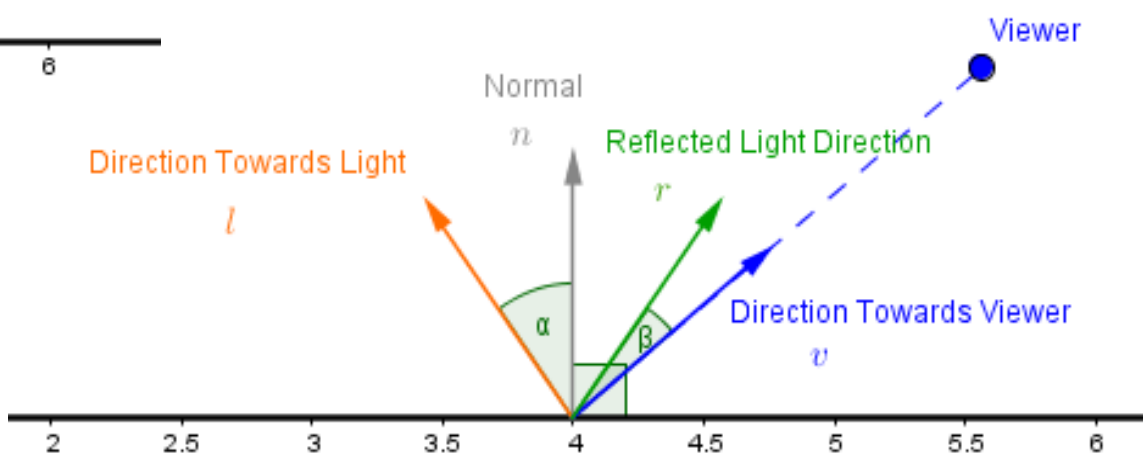
- Depends on the viewer's position.



Specular Highlight

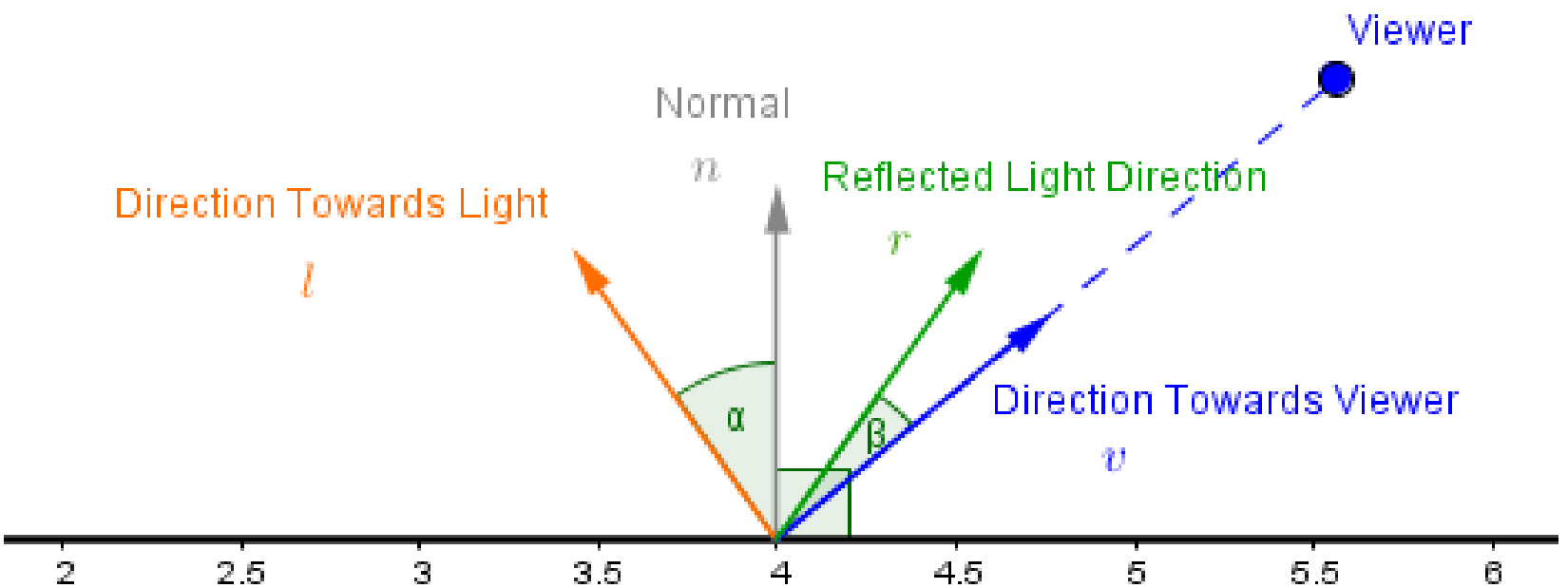
- At point 4, which viewer direction should produce more intense specular highlight?





Specular Highlight

- How to calculate that based on β?



Specular Highlights

- Ok, so add a specular term based on the actual reflection direction (*r*) and viewer direction (*v*).

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + r^T \cdot v \cdot L_{S_R} \cdot M_{S_R}$$

$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G} + r^T \cdot v \cdot L_{S_G} \cdot M_{S_G}$$

$$I_B = L_{A_B} \cdot M_{A_B} + n^T \cdot l \cdot L_{D_B} \cdot M_{D_B} + v^T \cdot r \cdot L_{S_B} \cdot M_{S_B}$$

Specular Highlights

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + r^T \cdot v \cdot L_{S_R} \cdot M_{S_R}$$

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Some properties are usually the same in the same channel.

Any errors on the slide?

Is there something missing?

Specular Highlights

- Specular highlight values for different angles:

M_s	L_s	β	~cos(β)	~I
0.25	1	10°	0.98	0,25
0.25	1	20°	0.94	0,24
0.25	1	30°	0.87	0,22
0.25	1	40°	0.77	0,19
0.25	1	50°	0.64	0,16
0.25	1	60°	0.5	0,12
0.25	1	70°	0.34	0,09
0.25	1	80°	0.17	0,04
0.25	1	90°	0	0

This is actually too little change in the result for such a big change from 10° to 20°.

This is too much for such big angles.

Assume we are dealing with one channel (e.g. red)
Assume the channel values are between [0, 1] (mapped later to [0, 255])

Specular Highlights

- How to increase the contrast? Use a power.

β	~$\cos^2(\beta)$	~I	~$\cos^3(\beta)$	~I	~$\cos^4(\beta)$	~I	~$\cos^5(\beta)$	~I
10°	0.97	0,24	0.96	0.24	0.94	0.23	0.92	0.23
20°	0.88	0,22	0.83	0.21	0.78	0.20	0.73	0.18
30°	0.75	0.19	0.65	0.16	0.56	0.14	0.49	0.12
40°	0.59	0.15	0.45	0.11	0.34	0.09	0.26	0.07
50°	0.41	0.10	0.27	0.07	0.17	0.04	0.11	0.03
60°	0.25	0.06	0.13	0.03	0.06	0.02	0.03	0.01
70°	0.12	0.04	0.04	0.01	0.01	0.00	0.00	0.00
80°	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
90°	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Values above 0.25 are in red

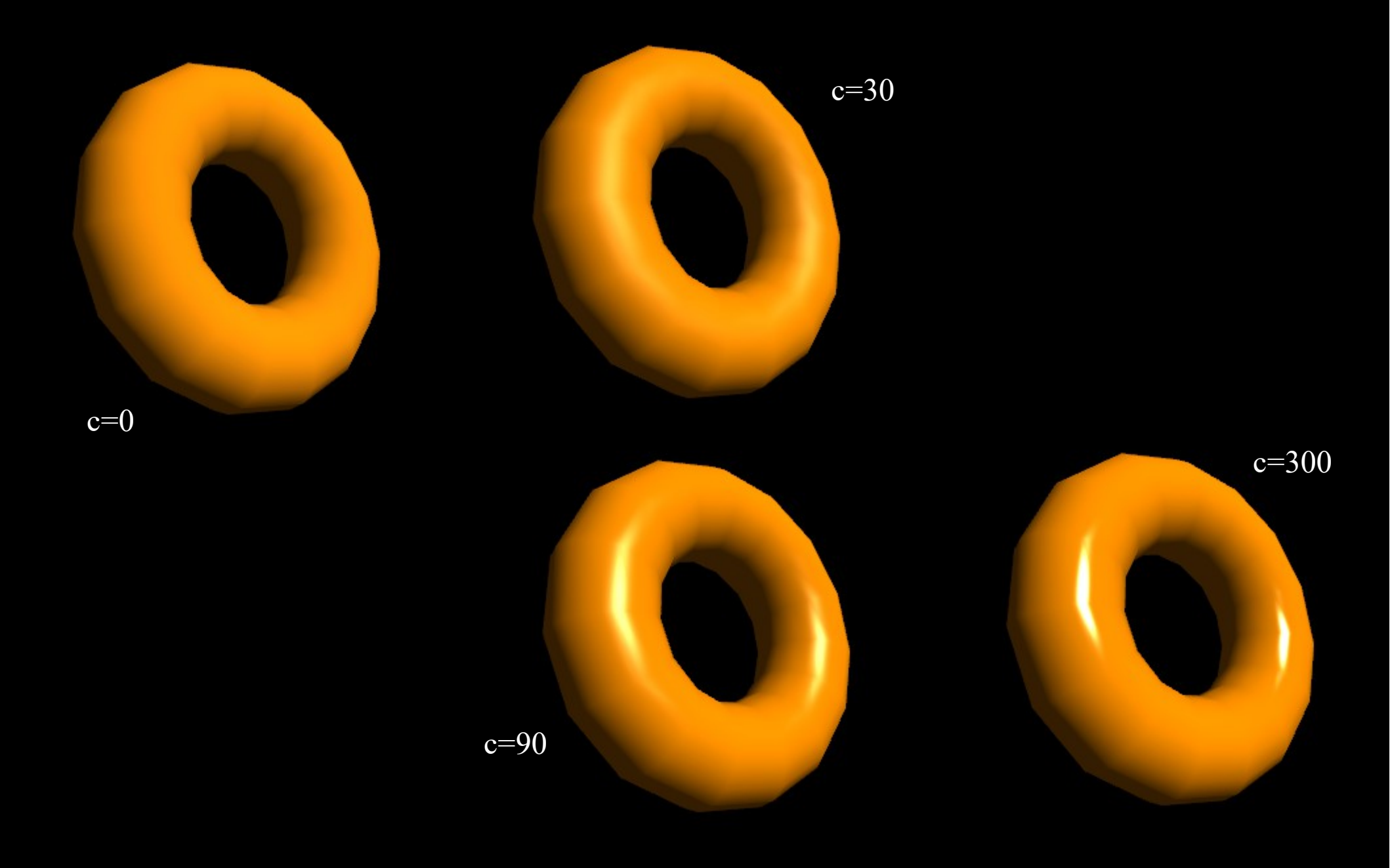
Specular Highlights

- Specify some **shininess** value *c* for the material

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + \left(r^T \cdot v\right)^c \cdot L_{S_R} \cdot M_{S_R}$$

$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G} + \left(r^T \cdot v\right)^c \cdot L_{S_G} \cdot M_{S_G}$$

$$I_B = L_{A_B} \cdot M_{A_B} + n^T \cdot l \cdot L_{D_B} \cdot M_{D_B} + \left(r^T \cdot v\right)^c \cdot L_{S_B} \cdot M_{S_B}$$


c=0
c=30
c=90
c=300

Phong's Lighting Model

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + \left(r^T \cdot v\right)^c \cdot L_{S_R} \cdot M_{S_R}$$

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$$I_B = \underline{L_{A_B} \cdot M_{A_B}} + n^T \cdot l \cdot L_{D_B} \cdot M_{D_B} + \left(r^T \cdot v\right)^c \cdot L_{S_B} \cdot M_{S_B}$$

Ambient light approximation.

Phong's Lighting Model

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + \left(r^T \cdot v\right)^c \cdot L_{S_R} \cdot M_{S_R}$$

$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G} + \left(r^T \cdot v\right)^c \cdot L_{S_G} \cdot M_{S_G}$$

$$I_B = L_{A_B} \cdot M_{A_B} + \underline{n^T \cdot l \cdot L_{D_B} \cdot M_{D_B}} + \left(r^T \cdot v\right)^c \cdot L_{S_B} \cdot M_{S_B}$$

Lambertian / diffuse reflectance

Phong's Lighting Model

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + (r^T \cdot v)^c \cdot L_{S_R} \cdot M_{S_R}$$

$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G} + (r^T \cdot v)^c \cdot L_{S_G} \cdot M_{S_G}$$

$$I_B = L_{A_B} \cdot M_{A_B} + n^T \cdot l \cdot L_{D_B} \cdot M_{D_B} + \underline{(r^T \cdot v)^c \cdot L_{S_B} \cdot M_{S_B}}$$

Phong's specular reflectance term

Phong's Lighting Model

$$I_R = L_{A_R} \cdot M_{A_R} + n^T \cdot l \cdot L_{D_R} \cdot M_{D_R} + \left(r^T \cdot v\right)^c \cdot L_{S_R} \cdot M_{S_R}$$

$$I_G = L_{A_G} \cdot M_{A_G} + n^T \cdot l \cdot L_{D_G} \cdot M_{D_G} + \left(r^T \cdot v\right)^c \cdot L_{S_G} \cdot M_{S_G}$$

$$I_B = L_{A_B} \cdot M_{A_B} + n^T \cdot l \cdot L_{D_B} \cdot M_{D_B} + \left(r^T \cdot v\right)^c \cdot L_{S_B} \cdot M_{S_B}$$

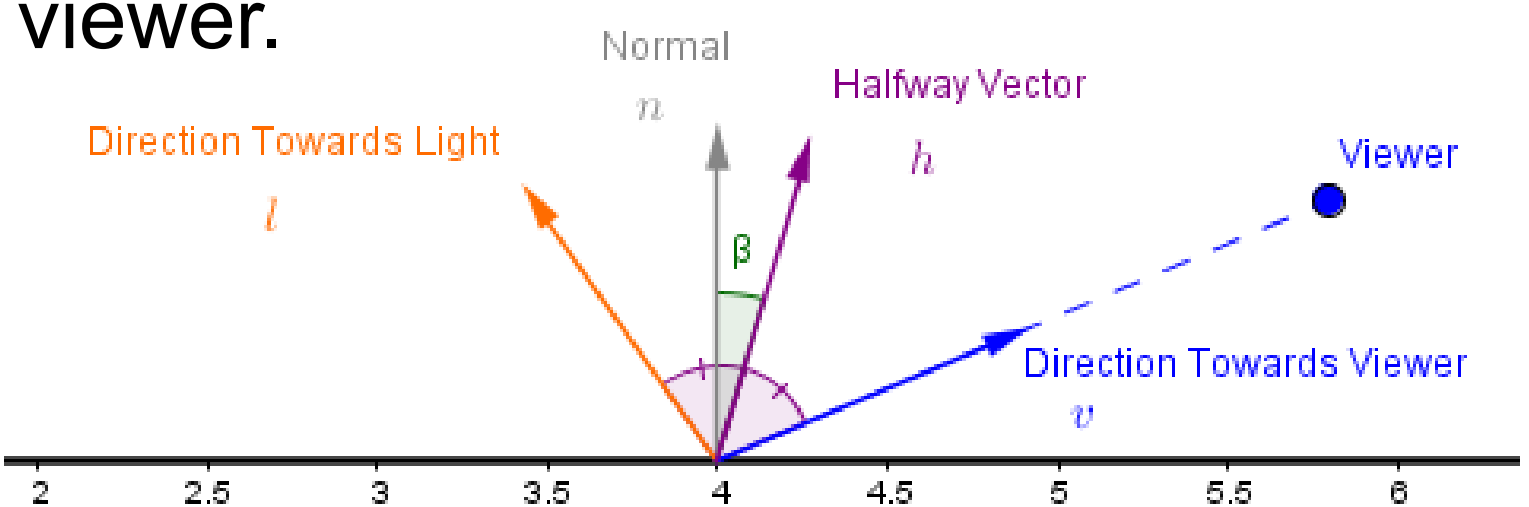
Something still missing?

Blinn-Phong Model

- Sometimes Phong's specular term is replaced with Blinn-Phong's specular term.

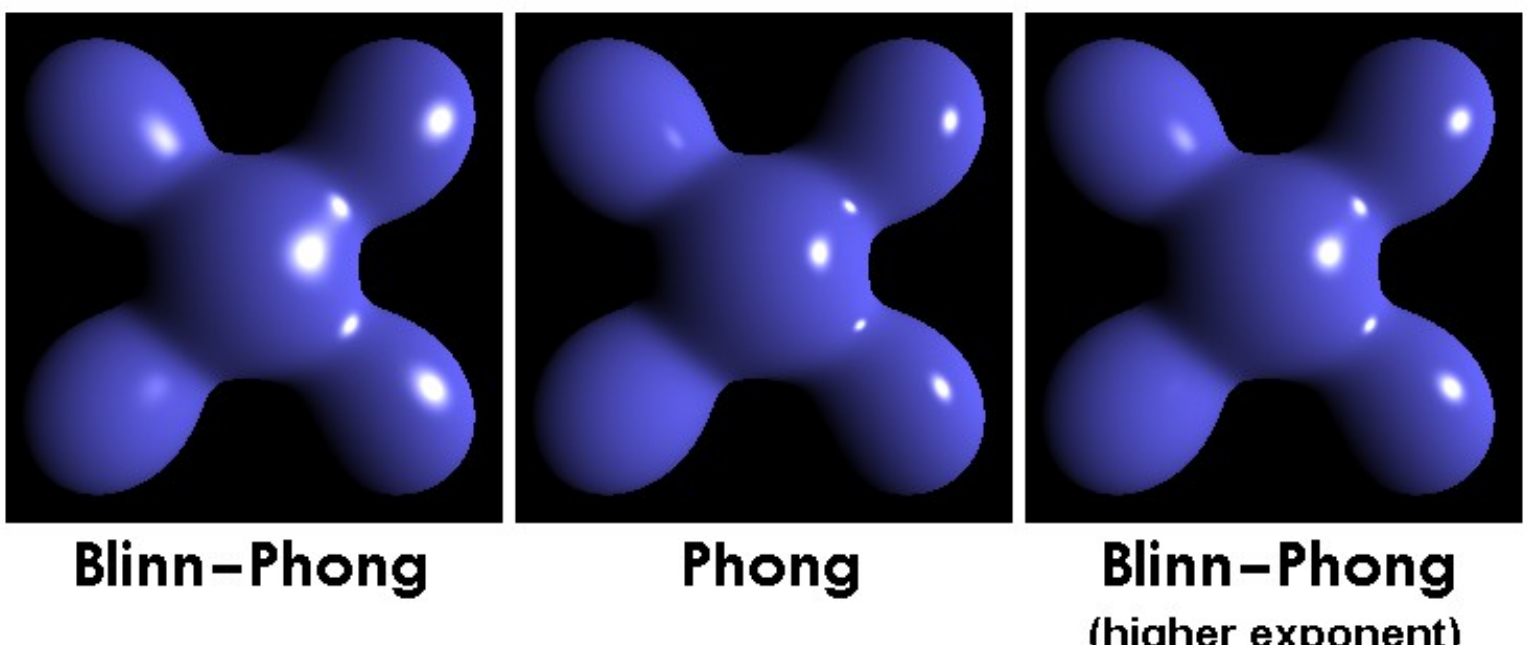
Blinn-Phong Model

- Sometimes Phong's specular term is replaced with Blinn-Phong's specular term.
- Instead of viewer direction and reflected light's direction, we use the **surface normal (n)** and a **half angle vector (h)** between the light source and the viewer.



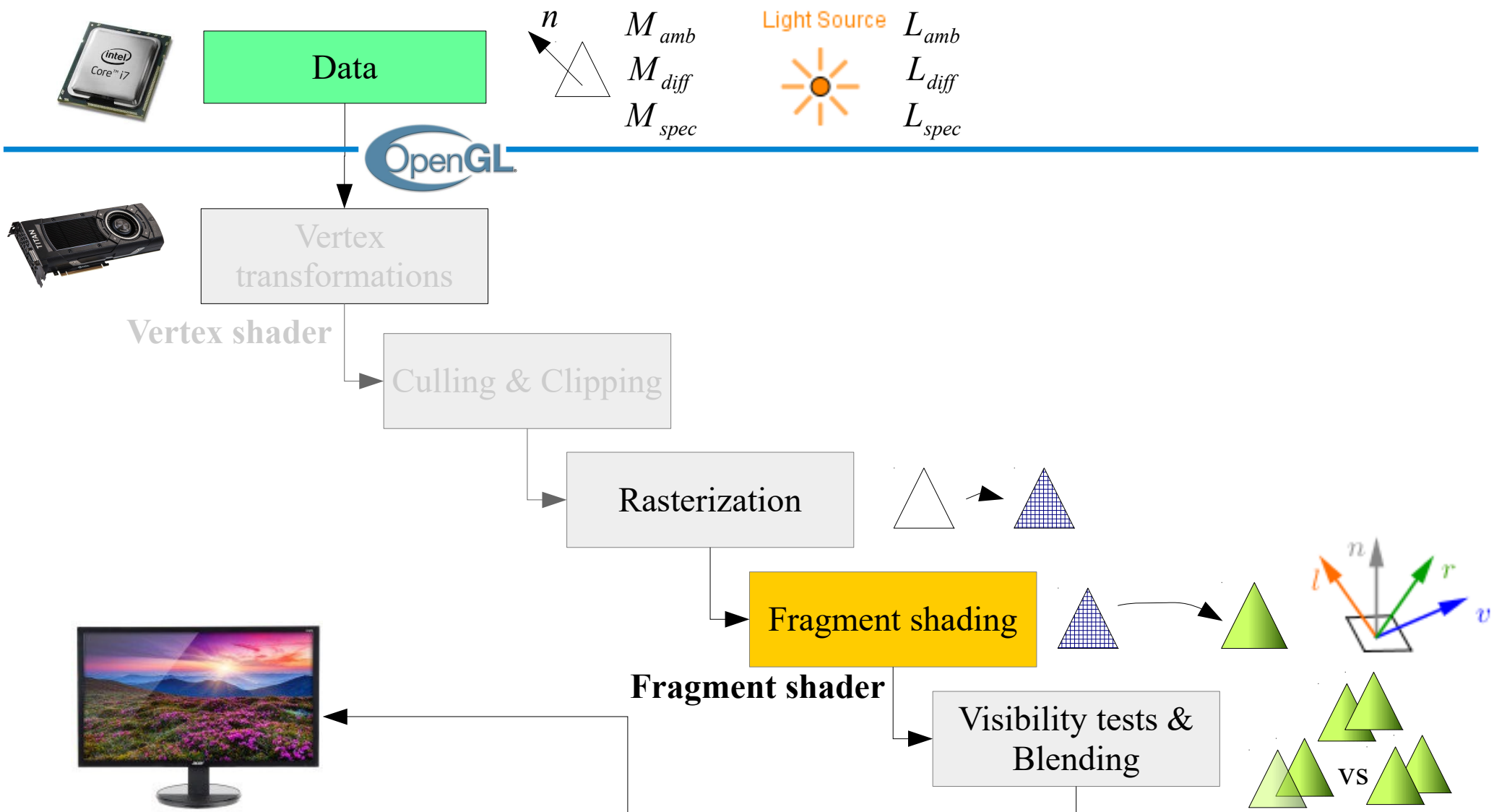
Blinn-Phong Model

- There are some differences
- These are not the only two possibilities

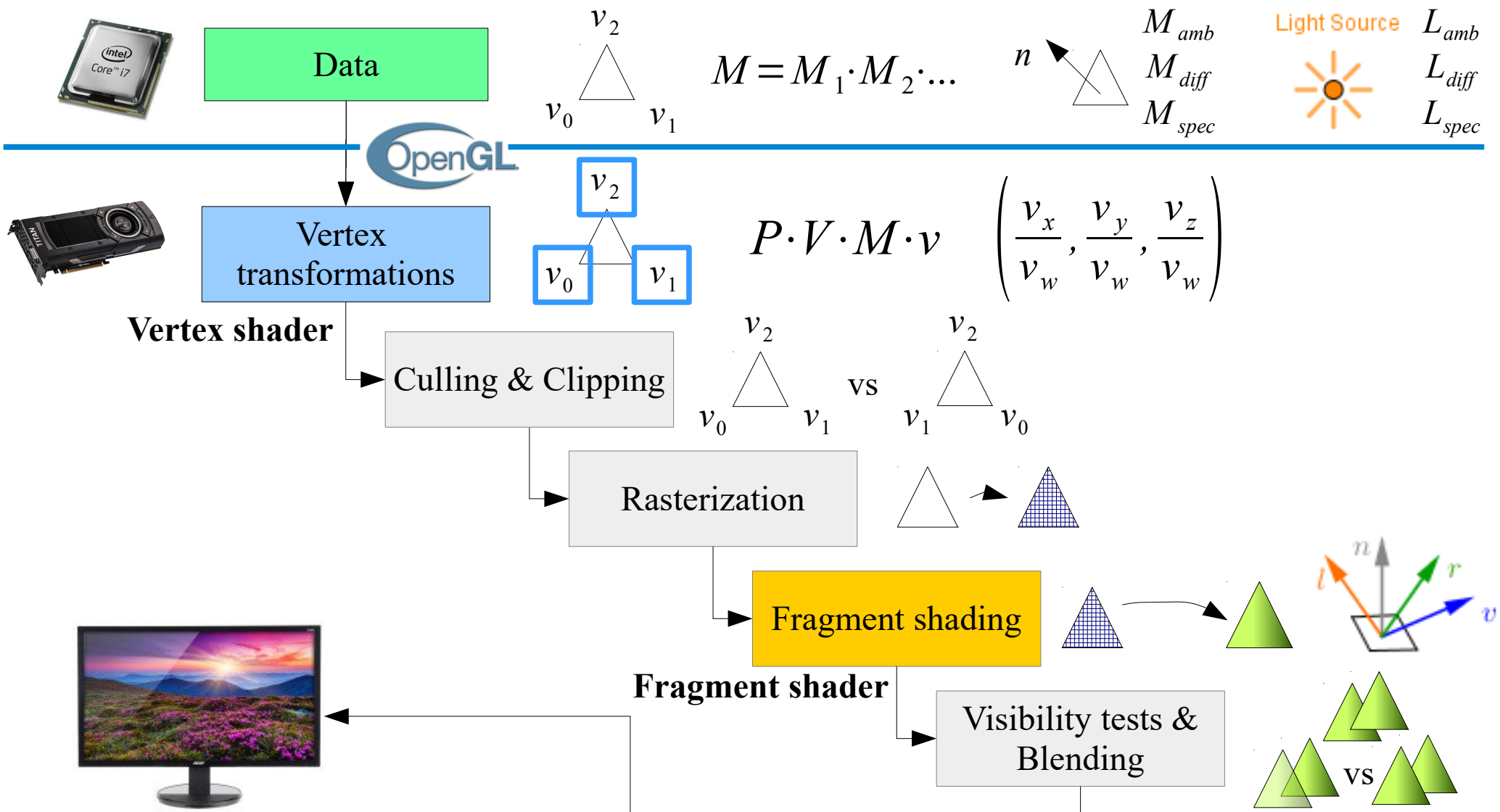


DEMO 2: http://cgdemos.tume-maailm.pri.ee/

Now You Know

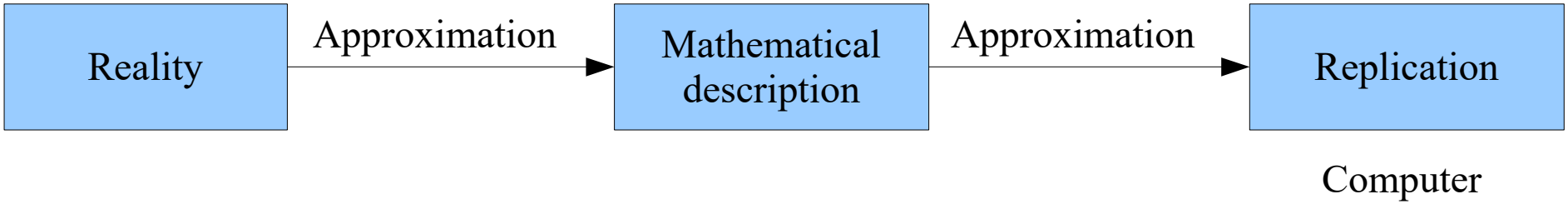

Data
n
M_{amb}
M_{diff}
M_{spec}
Light Source
L_{amb}
L_{diff}
L_{spec}
OpenGL
Vertex transformations
Vertex shader
Culling & Clipping
Rasterization
Fragment shading
Fragment shader
Visibility tests & Blending
vs

The Standard Graphics Pipeline

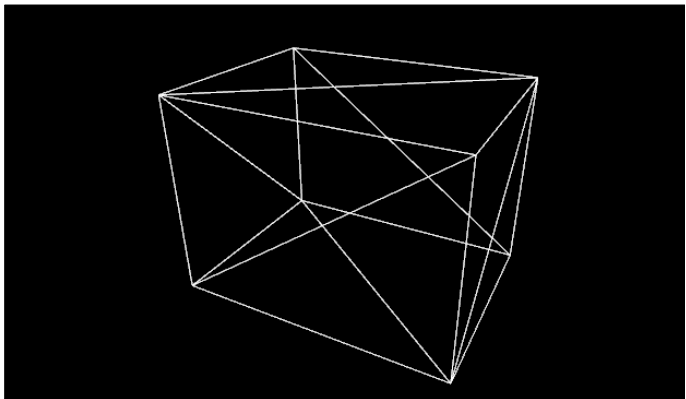


Conclusion

- Computer graphics can be used to create an illusion of reality



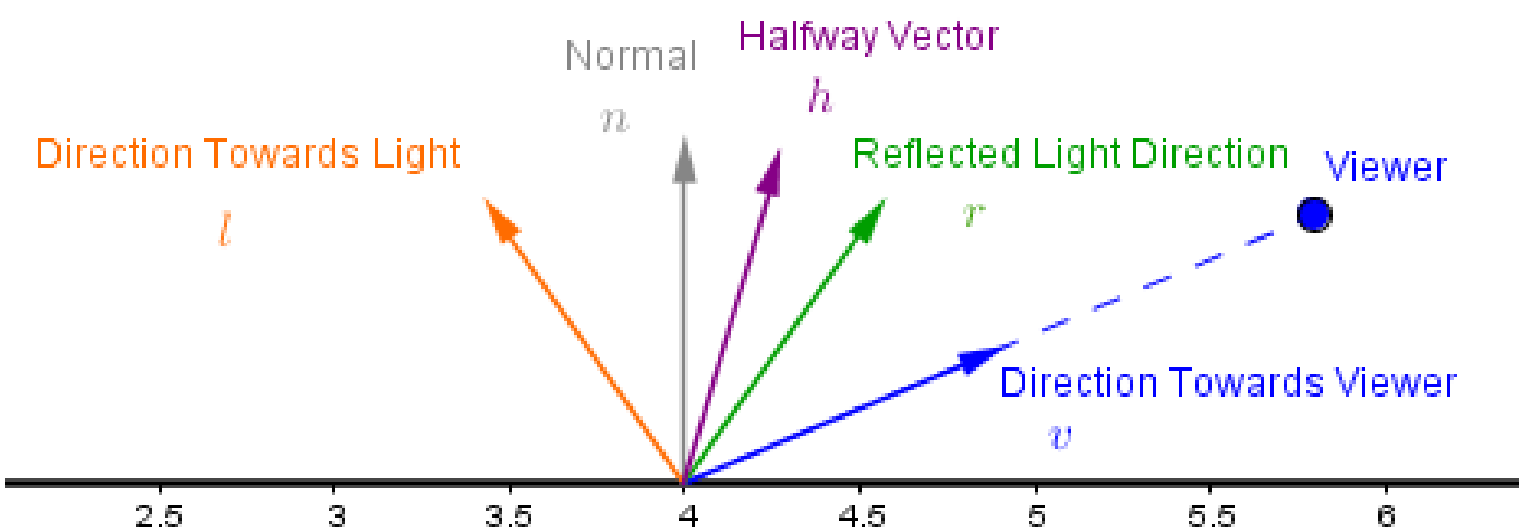
- First approximation is of the shape – geometry
- GPU wants those **triangles**
- **Vertices** and **transformation matrices**



Conclusion

- Many ways to approximate lighting (Lambert, Phong, Blinn), reflections, refractions, shadows...
- **Ambient**, **diffuse**, **specular** terms

$$I = L_A \cdot M_A + n^T \cdot l \cdot L_D \cdot M_D + \left(r^T \cdot v\right)^c \cdot L_S \cdot M_S$$



Thanks for Listening!

Next Time

- Shaders in WebGL
- Shader Programming Workshop (all of this in practice)
- Bring your laptop!

three.js

Notepad++

WebGL™