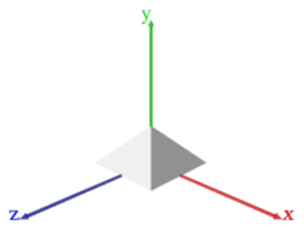
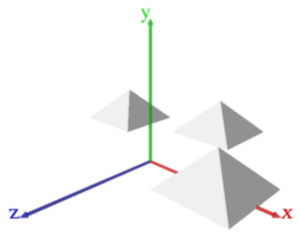
GRK 5

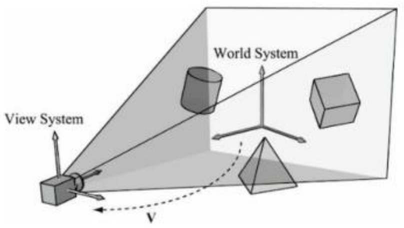
dr Wojciech Palubicki

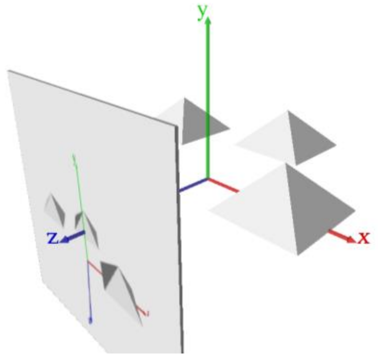
Simplified Rendering Pipeline

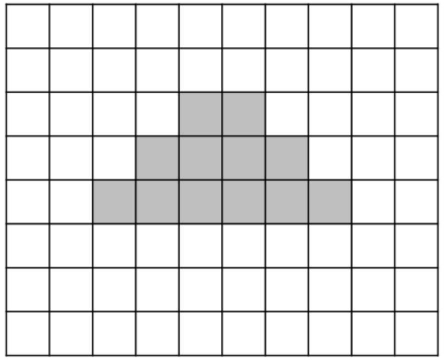
Model Matrix → View Matrix → Projection Matrix → Viewport Transform











Object Space

World Space

View Space

Clip Space

Screen Space

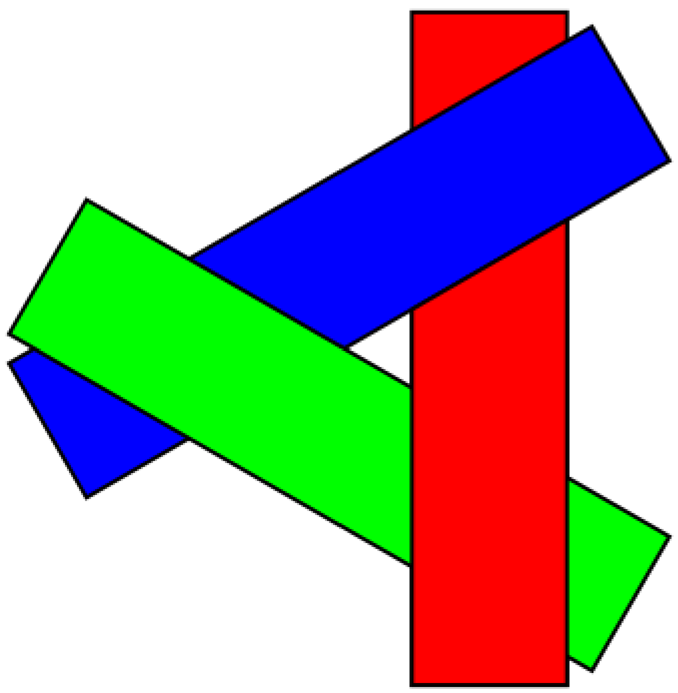
Drawing on the Display

- The following pseudo-code illustrates how to draw a line between two points a and b

compute M_{vp}
compute M_{per}
compute M_{cam}
$M = M_{vp} M_{per} M_{cam}$

for each line segment (a, b) do
    p = M a
    q = M b
    drawline(p_x/p_w, p_y/p_w, q_x/q_w, q_y/q_w)

Partial polygon overlay



z-buffer / depth buffer

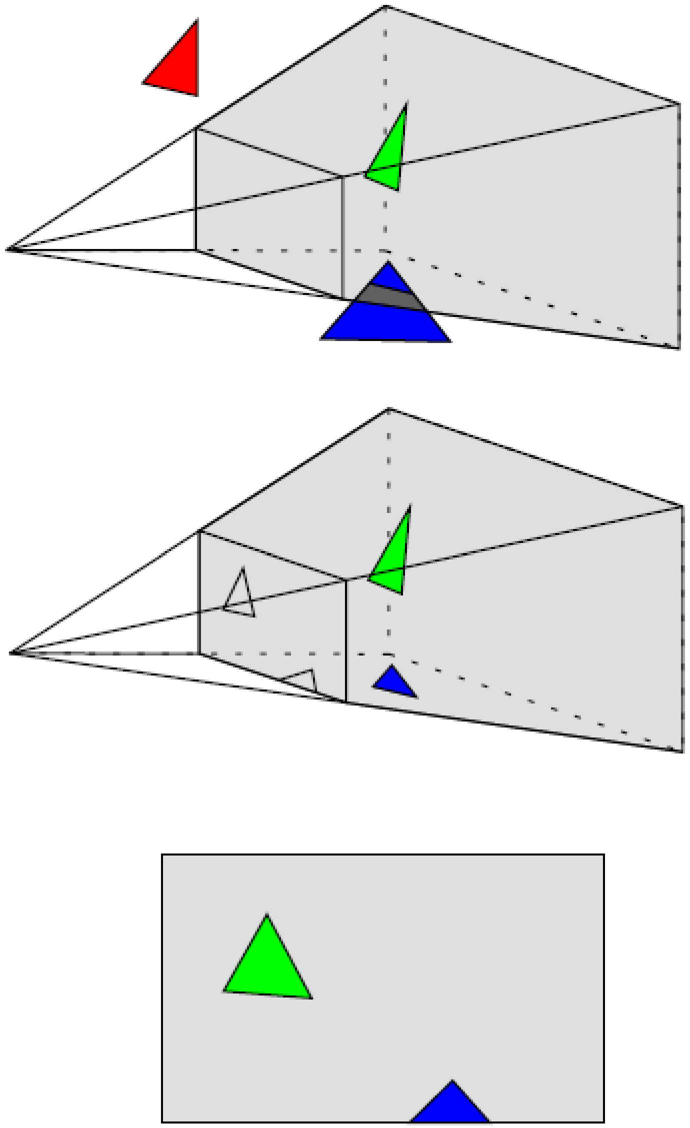
Algorithm 1 Z buffer

Require: a set of polygons P, a depth buffer array Z and a frame buffer array F

initialise Z to $z_{\max}$
for all polygons in P **do**
  for all pixels in the current polygon **do**
    calculate the z co-ordinate of the point corresponding to the current pixel
    if $z < Z(x, y)$ **then**
      Replace $Z(x, y)$ with z
      Replace $F(x, y)$ with the colour of the current polygon
    end if
  end for
end for
Display F on screen

Clipping/Culling

- Triangles that lie (partly) outside of the view frustum don’t have to be projected and are culled (**clipping/culling**)
- The remaining triangles are projected on the view plane



Lighting

Without lighting

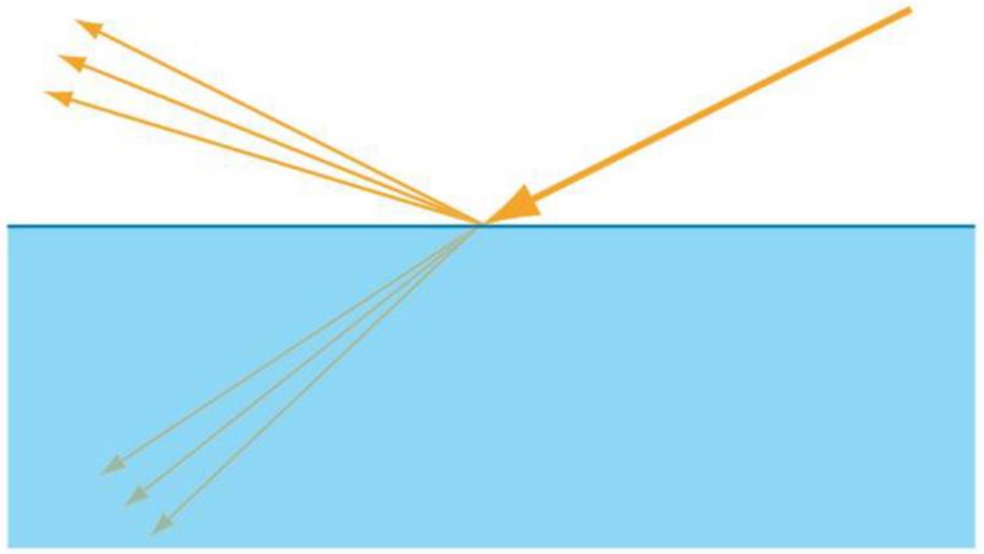
Lighting

Without lighting

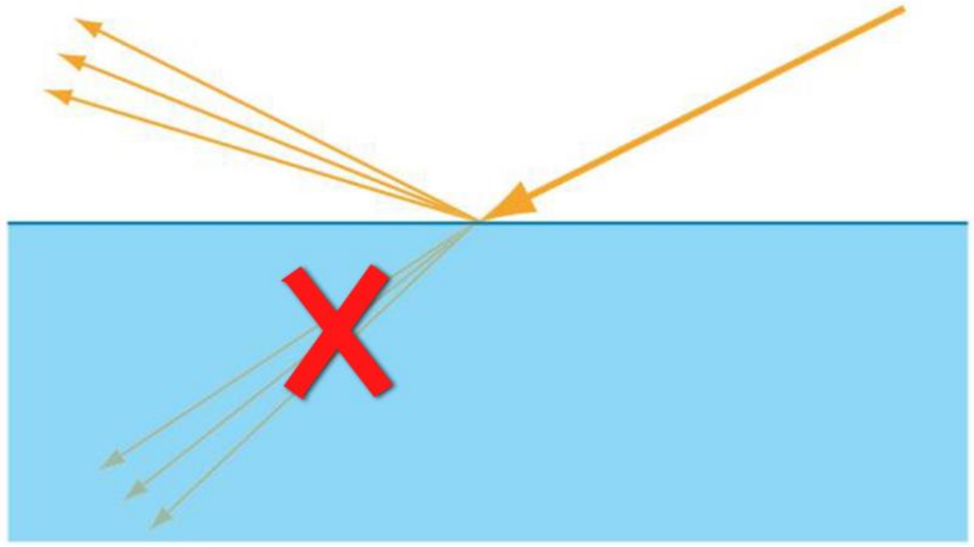
With lighting

Light

- Non-metal material
  - A portion of light is reflected
  - Another portion enters the material

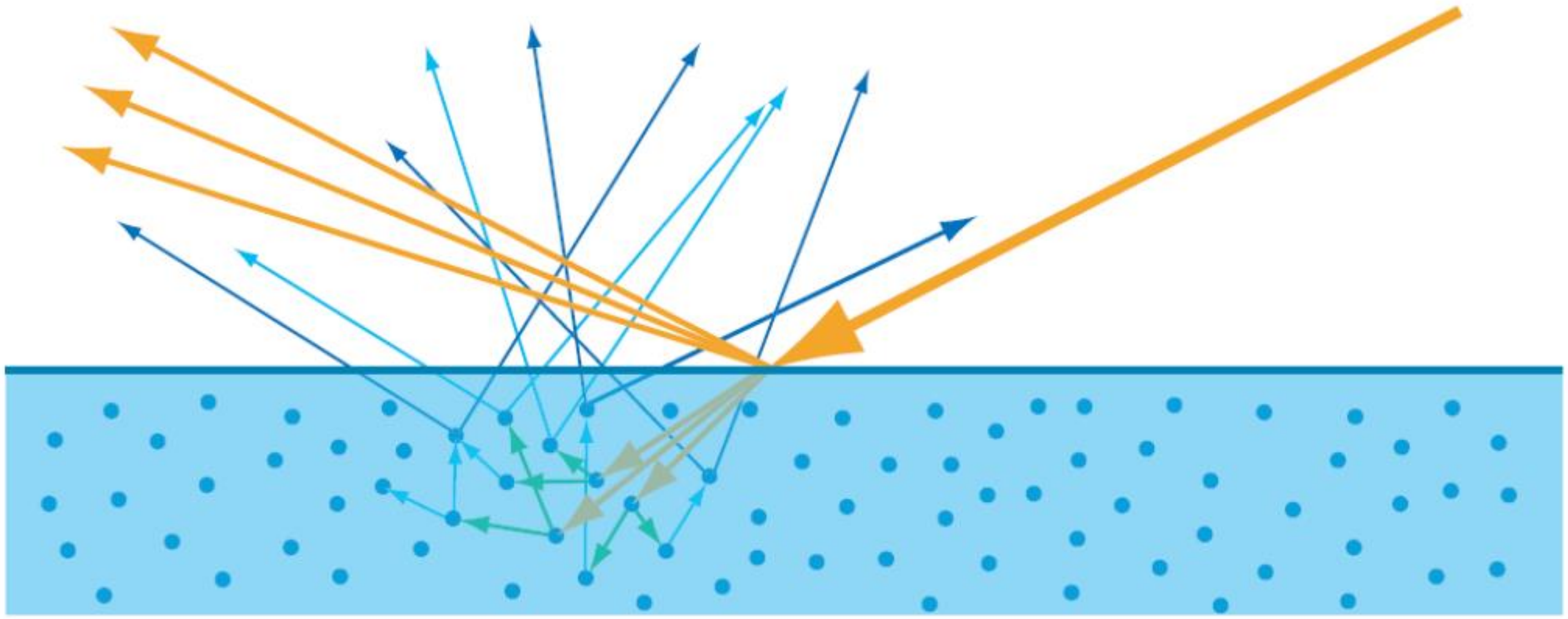


- Metal
  - A portion of light is reflected
  - Another portion is absorbed



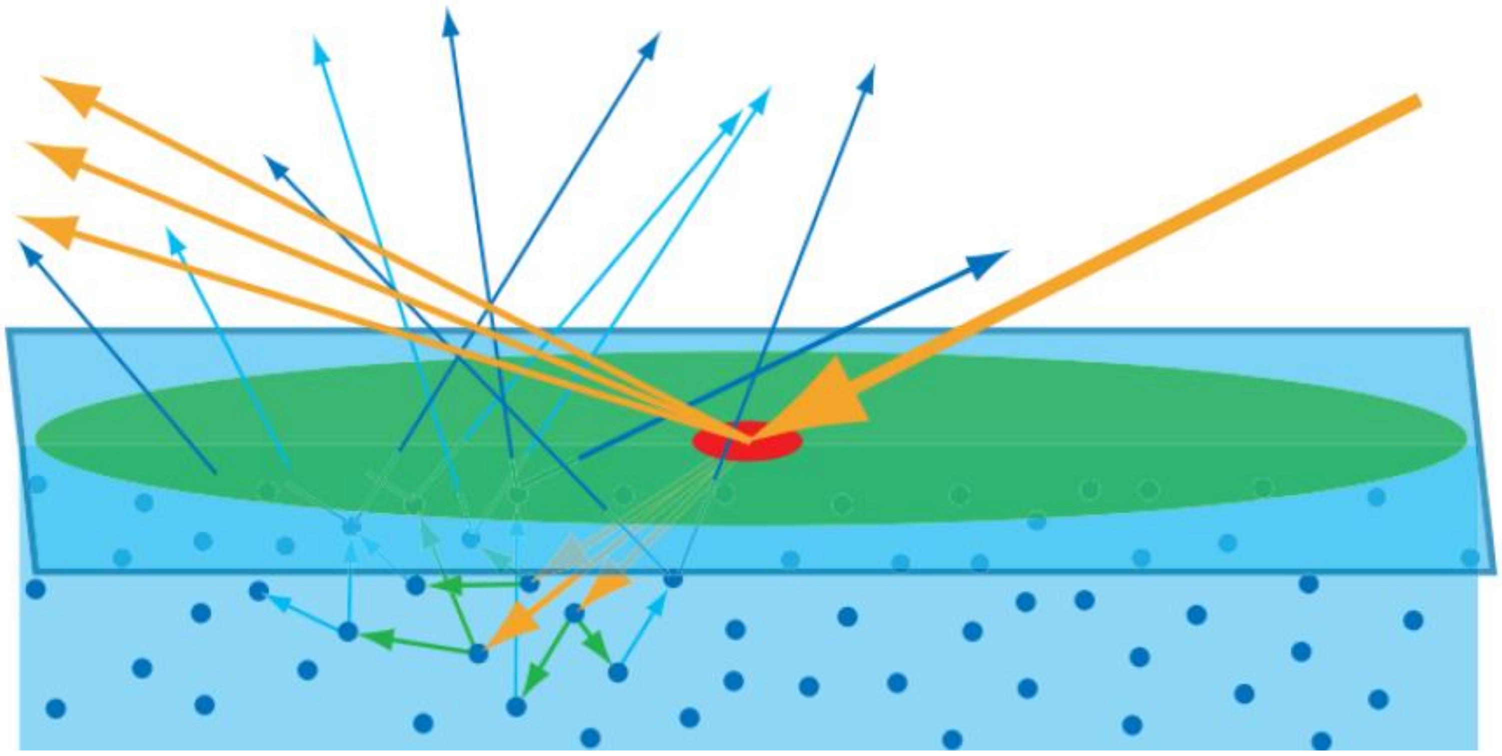
Non-metal materials

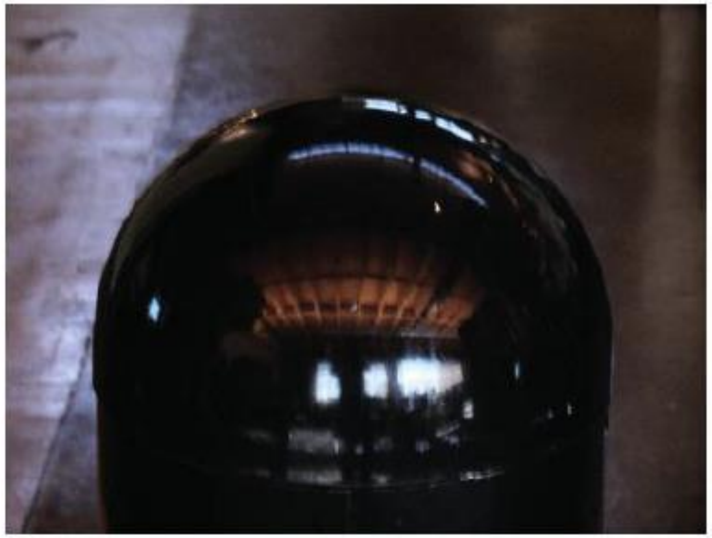
- Light that is entering the material
  - Is absorbed
  - Or re-emitted after a while

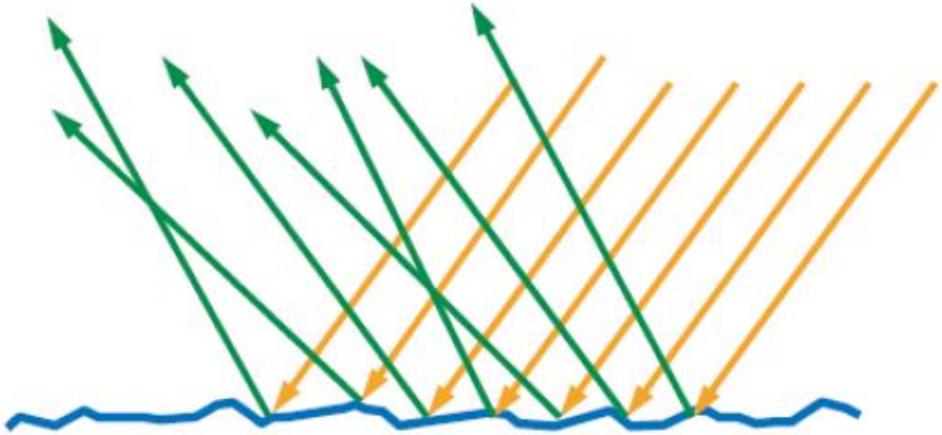


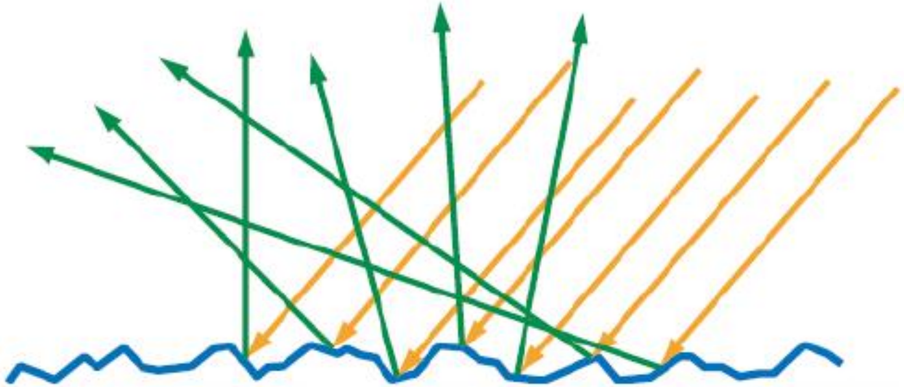
Subsurface scattering

- The distance between entry and exit points of light rays is specified by the material



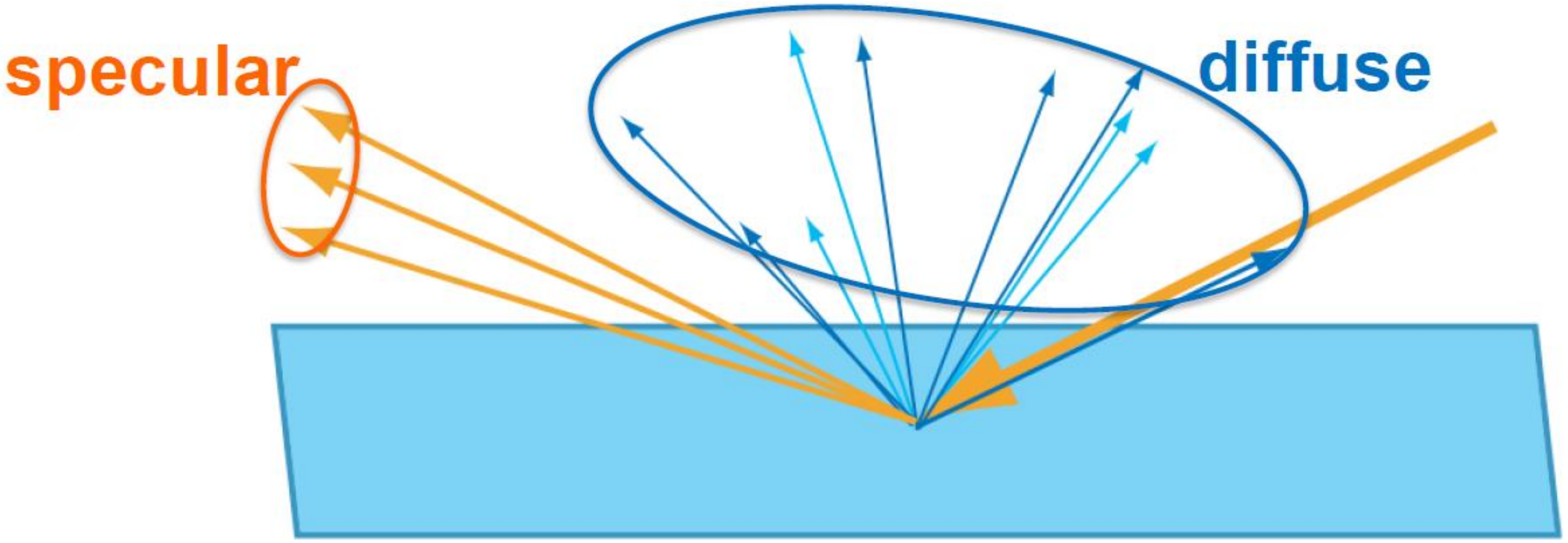


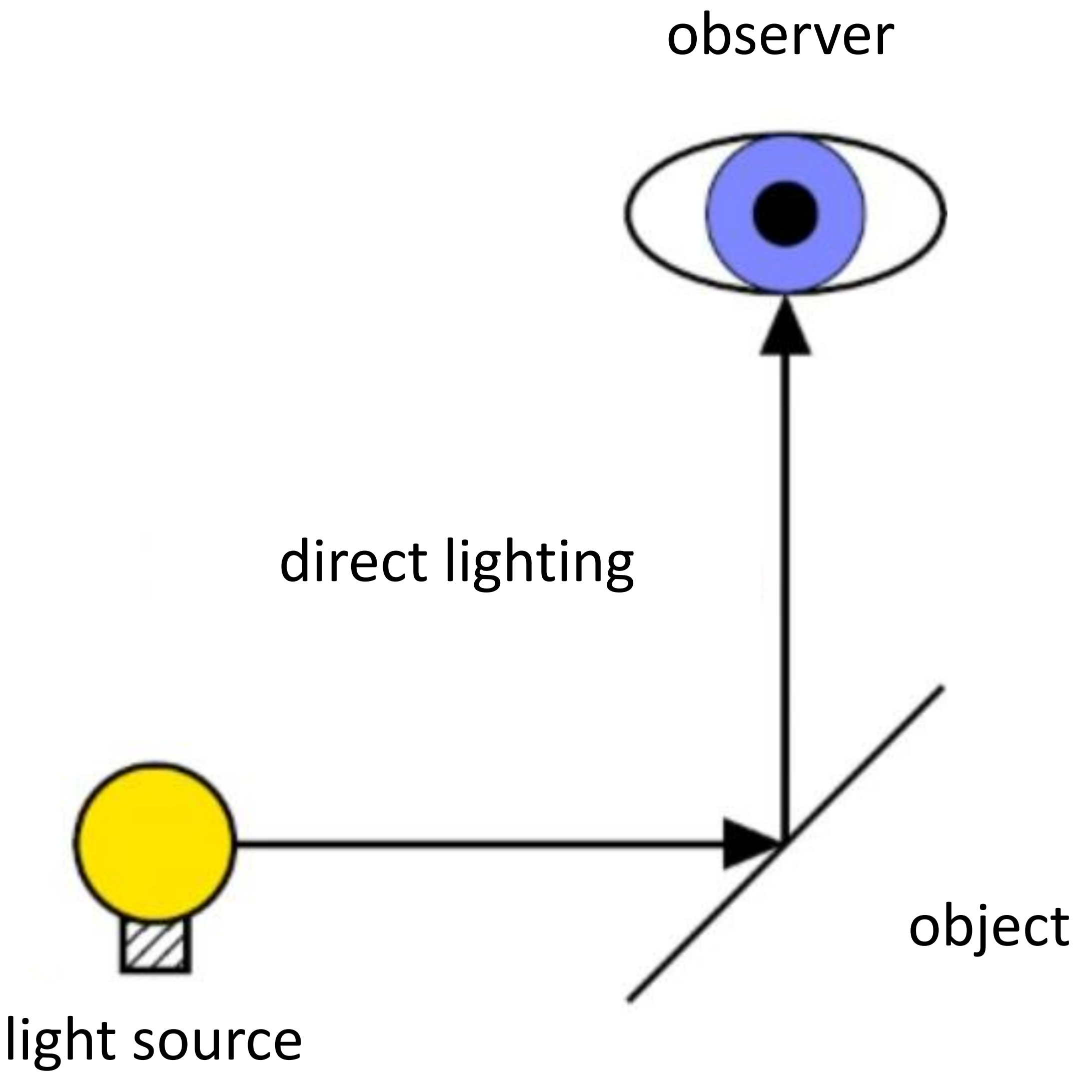


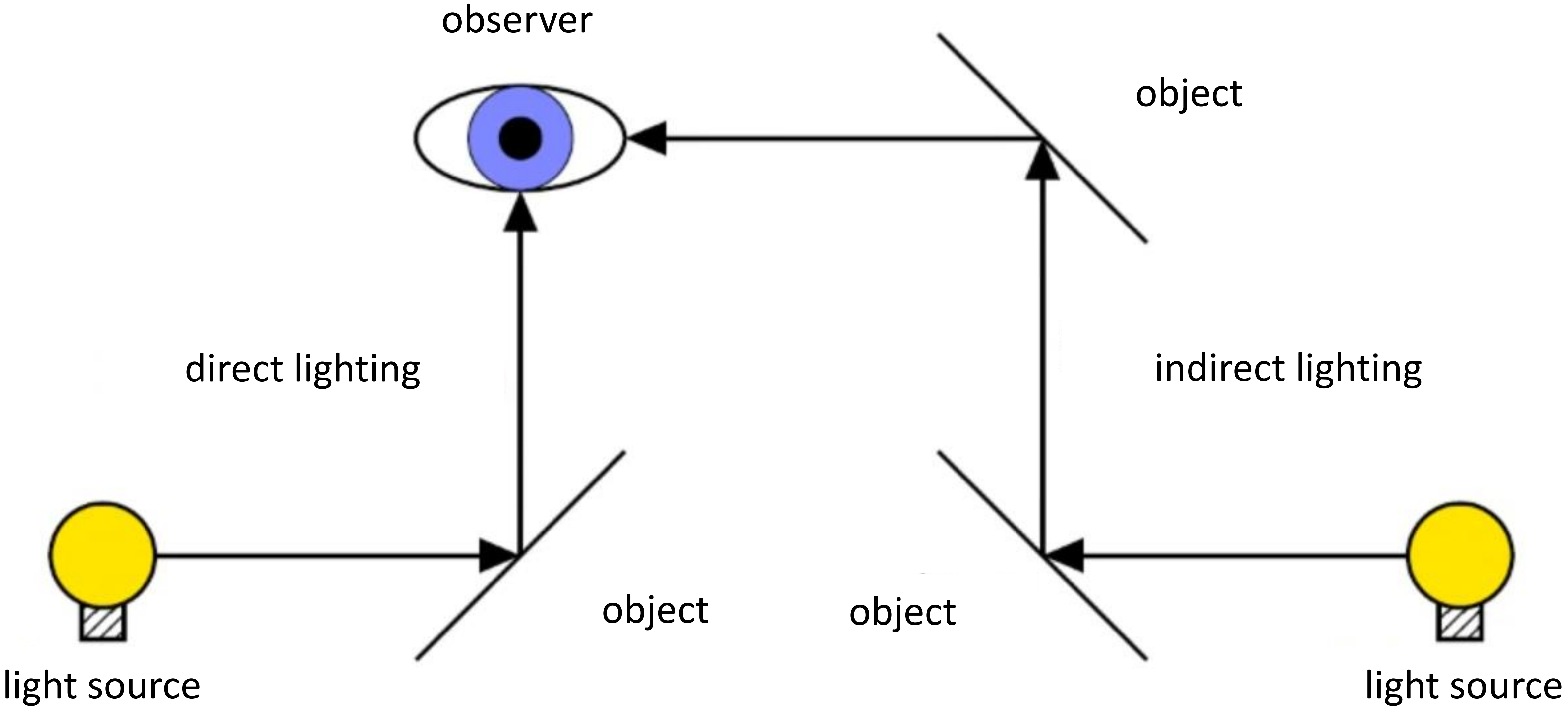


Modeling Light with BRDF’s

- BRDF stands for *Bidirectional Reflectance Distribution Function*
- BRDF’s are modeling light by ignoring the difference between entry and exit points of a material




observer
direct lighting
object
light source


observer
object
direct lighting
indirect lighting
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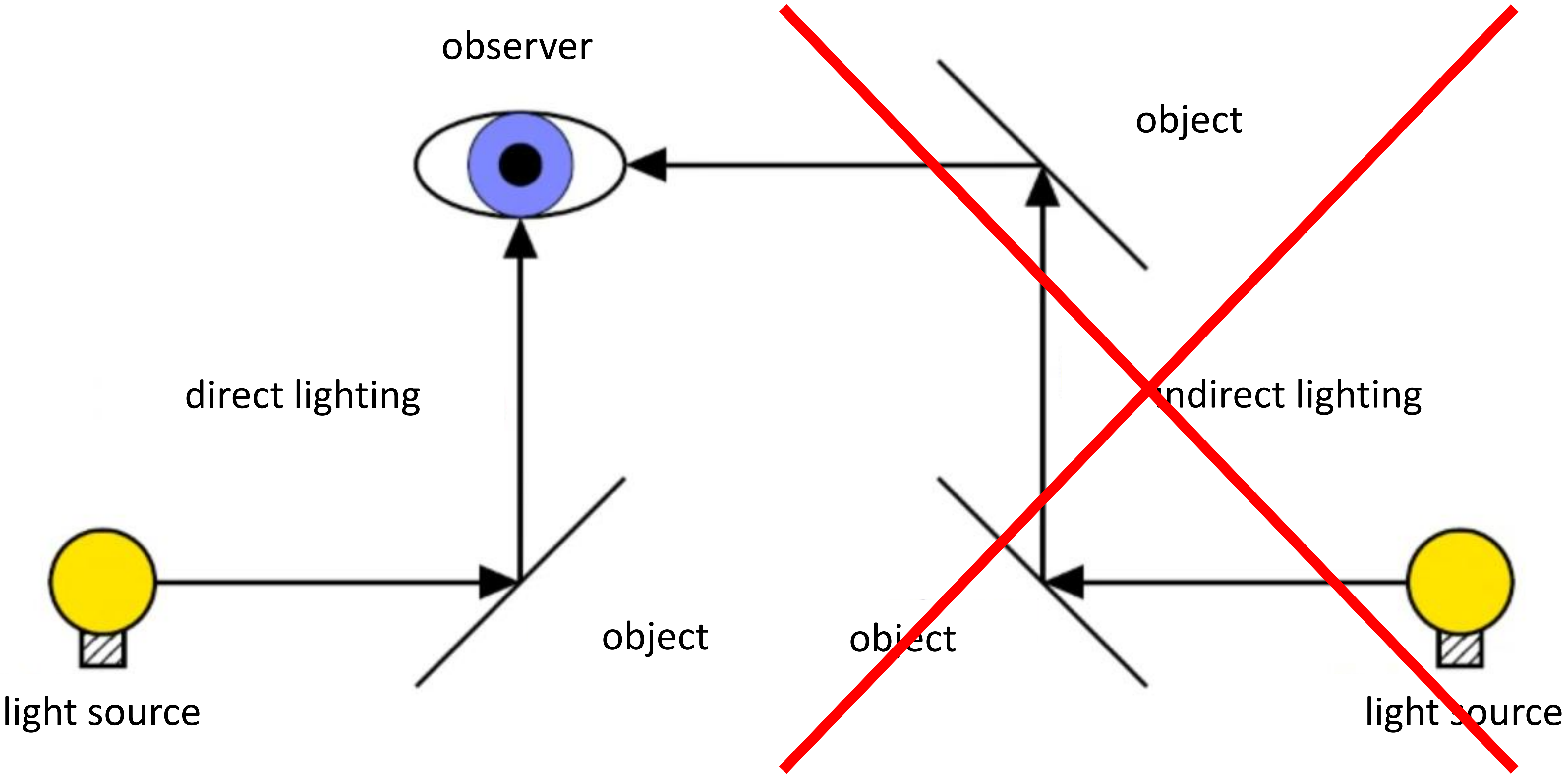
light source
light source


observer
object
direct lighting
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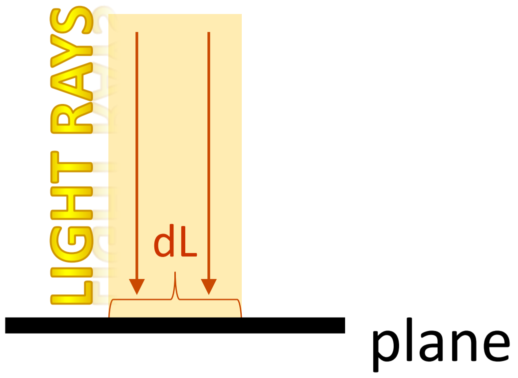
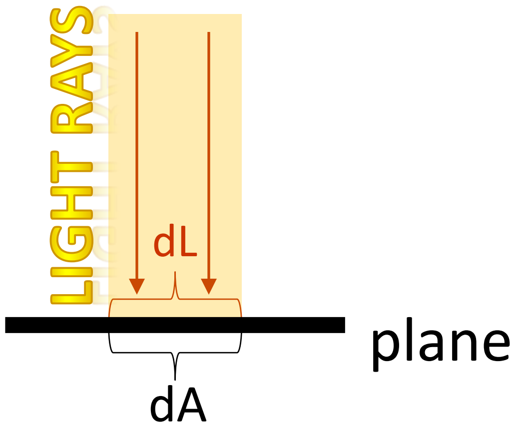
Observation



Observation



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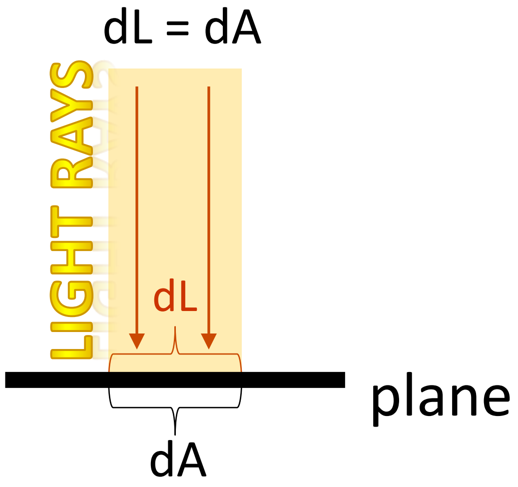

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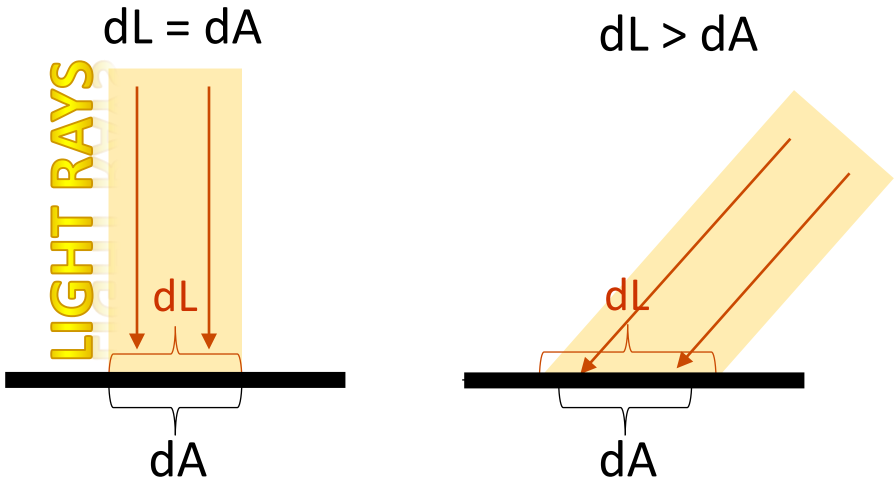
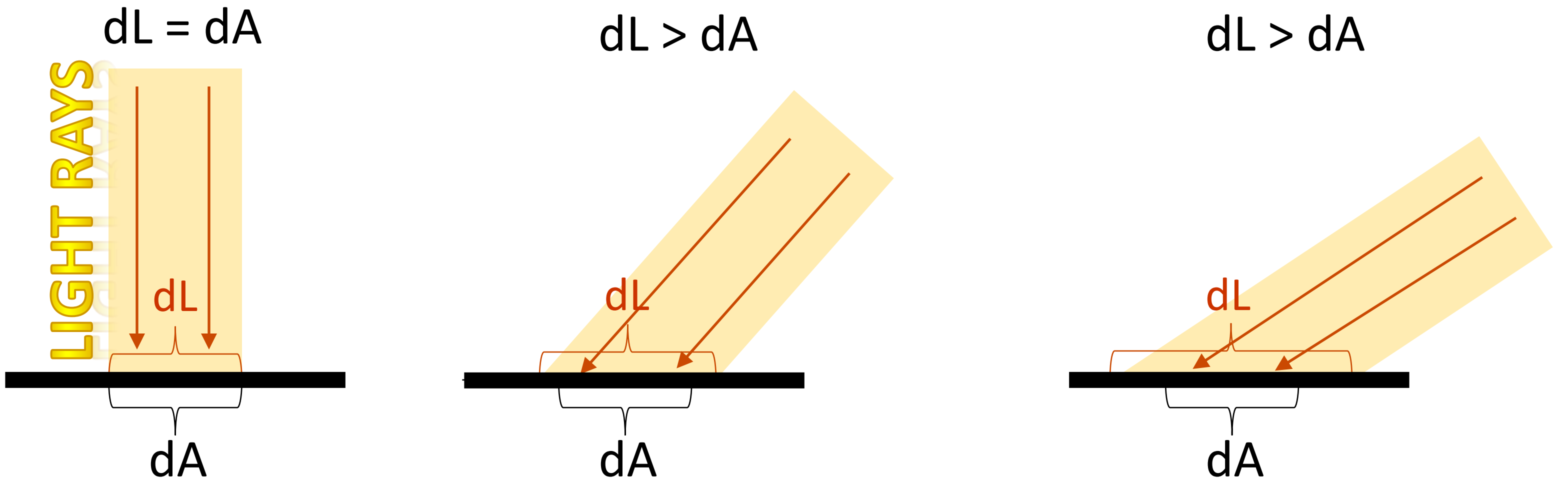
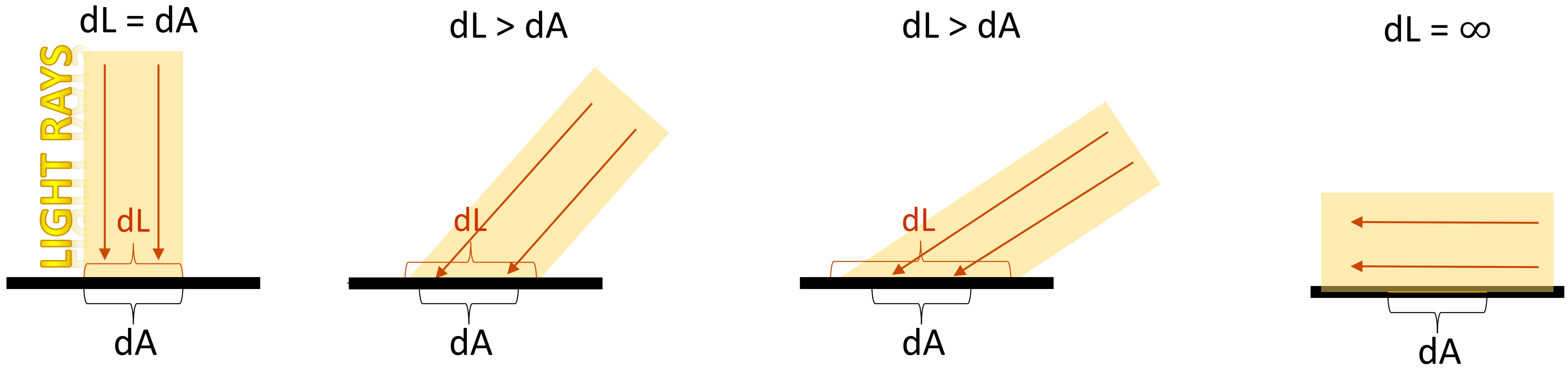


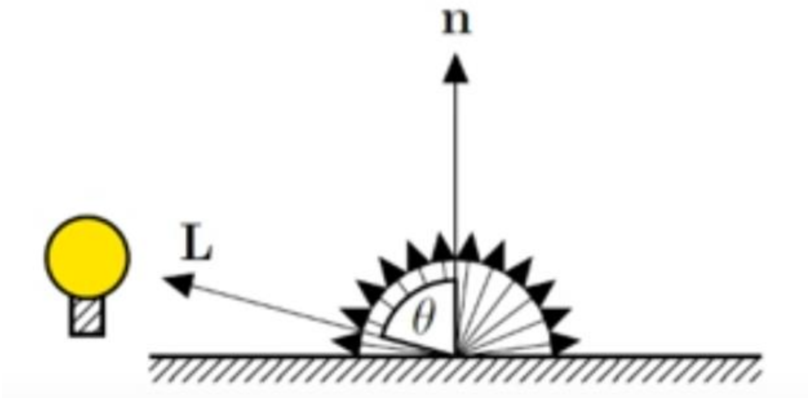
Observation



Observation



Phong model of diffuse lighting



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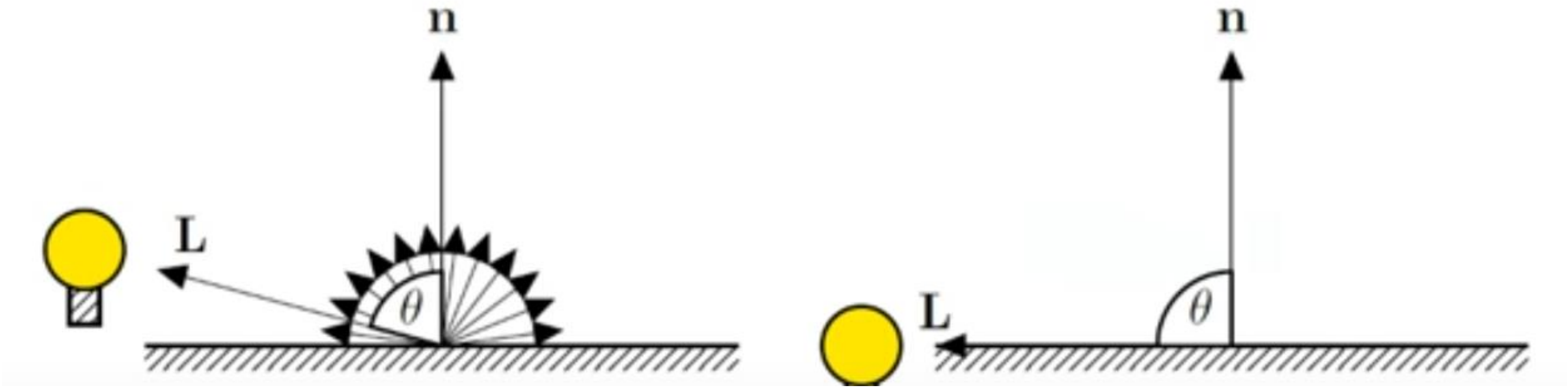

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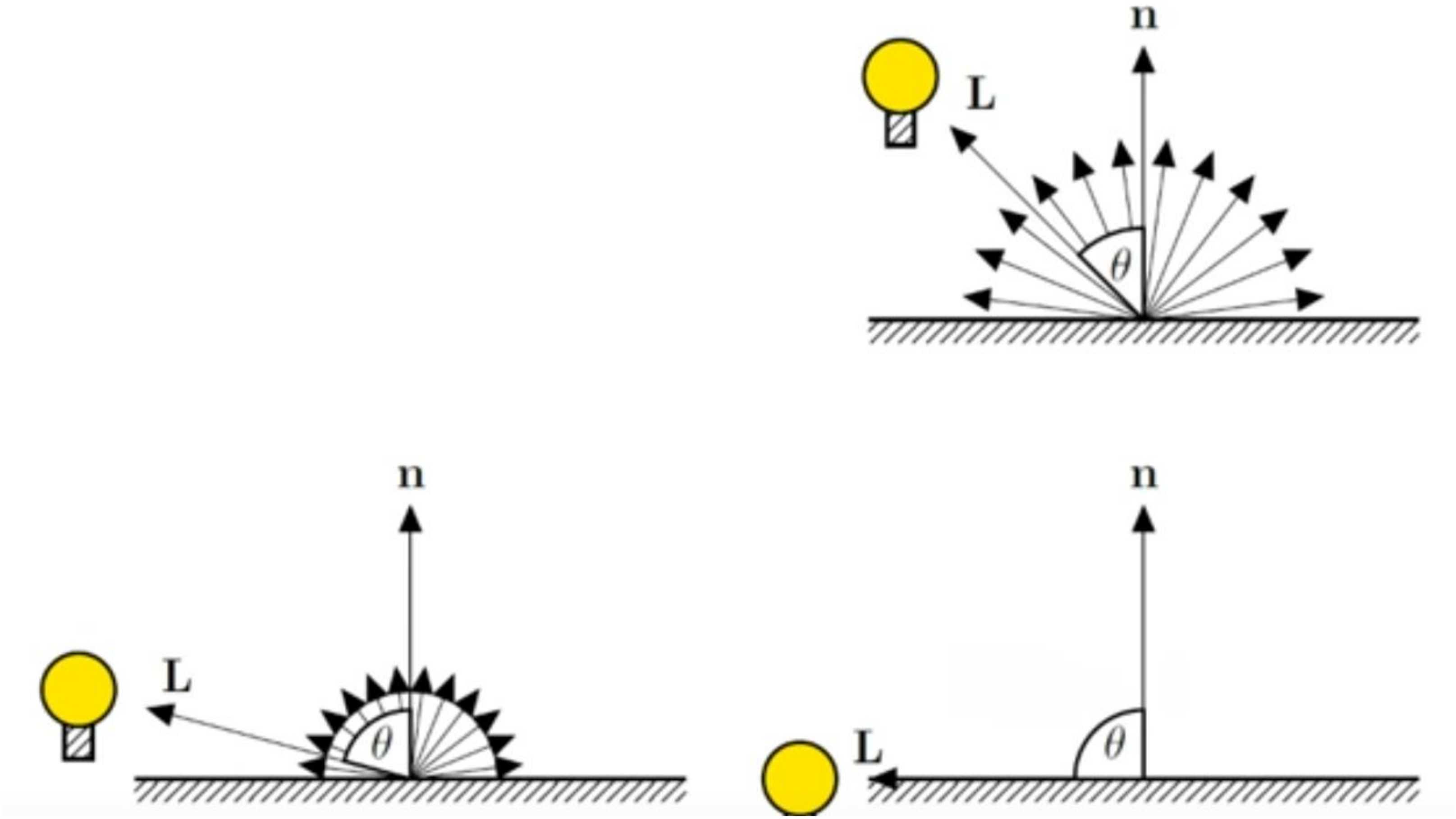

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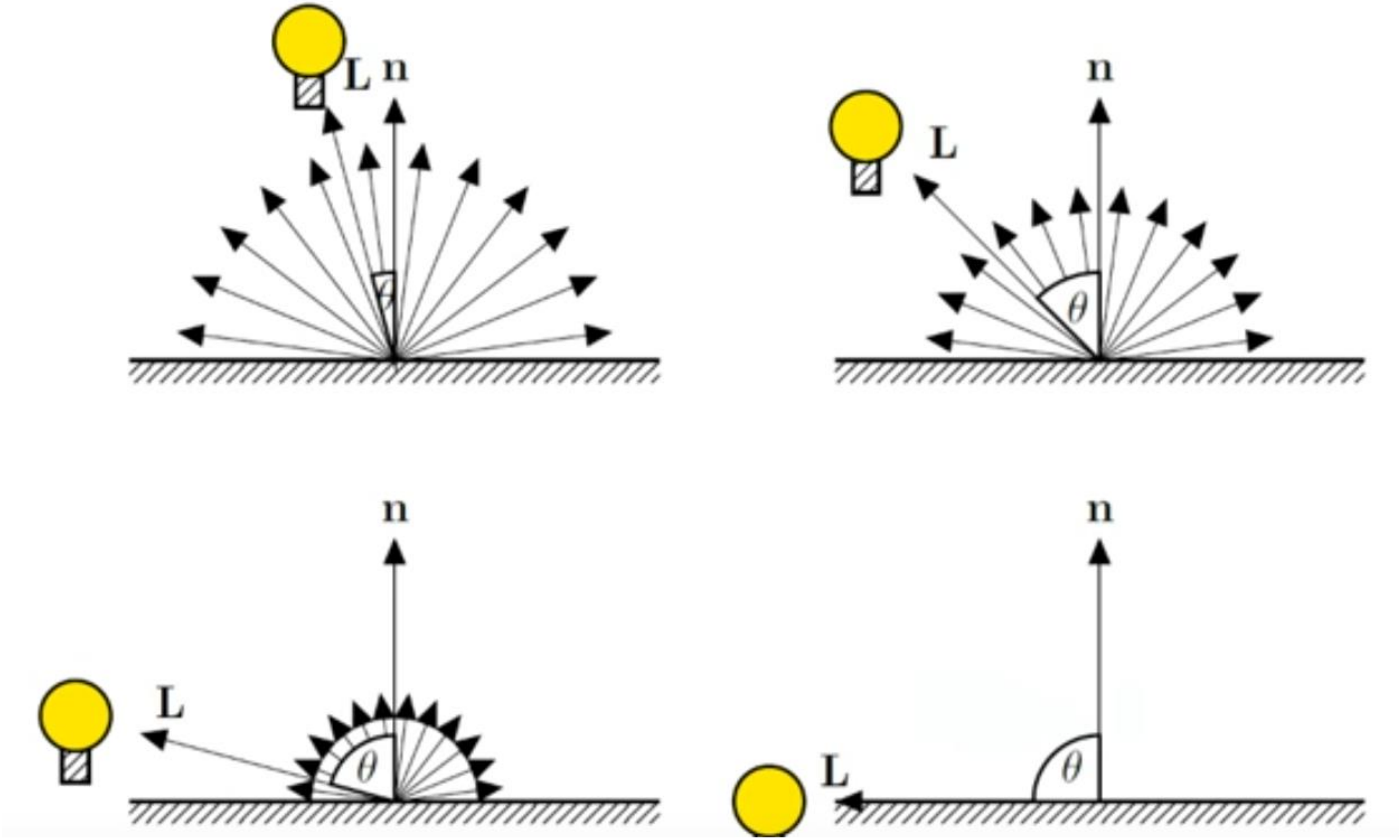

Phong model of diffuse lighting

- Phong model of diffuse lighting depends on the position of the light source relative to the object surface
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- $\boldsymbol{D = I_p k_d} \, \mathbf{max}[\mathbf{cos}(\boldsymbol{\theta}), \mathbf{0}]$
- Where
  - I_p is the light intensity of the light source
  - $k_d \in [0, 1]$ is a diffuse lighting coefficient
  - θ is the angle between L and the normal of the object surface n

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- Where
  - I_p is the light intensity of the light source
  - $k_d \in [0, 1]$ is a diffuse lighting coefficient
  - θ is the angle between L and the normal of the object surface n
- Function $\mathbf{max}[\mathbf{cos}(\boldsymbol{\theta}), \mathbf{0}]$ is used so that light is not reflected when the light source is behind the object surface

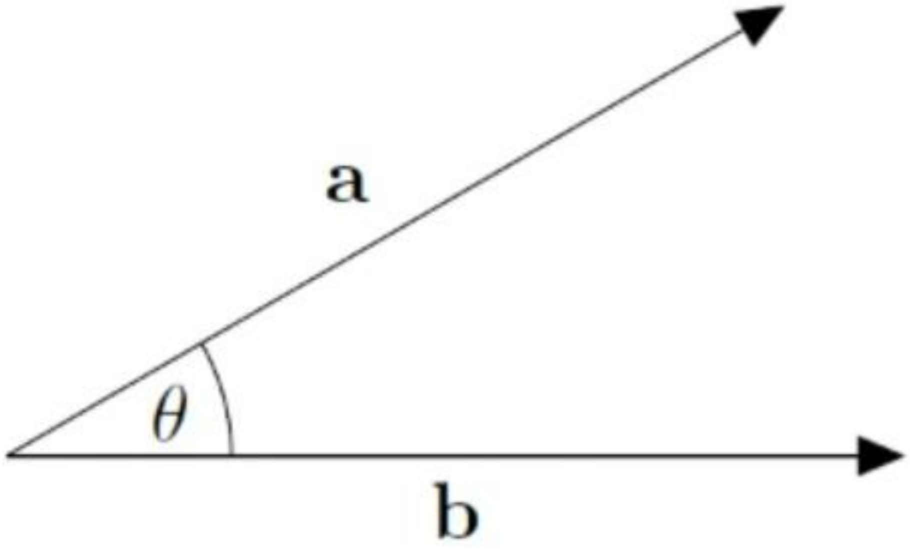
$k_d = 0.25$

$k_d = 0.5$

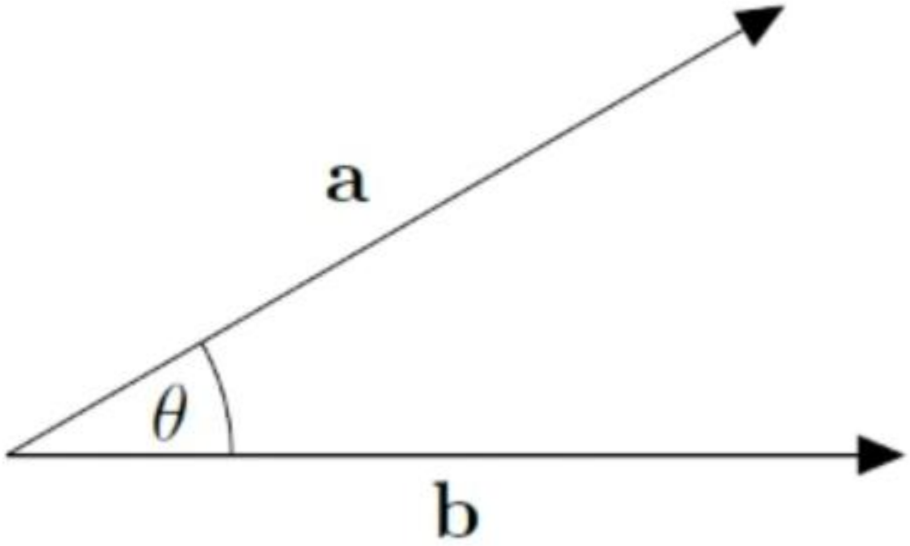
$k_d = 0.75$

$k_d = 1$

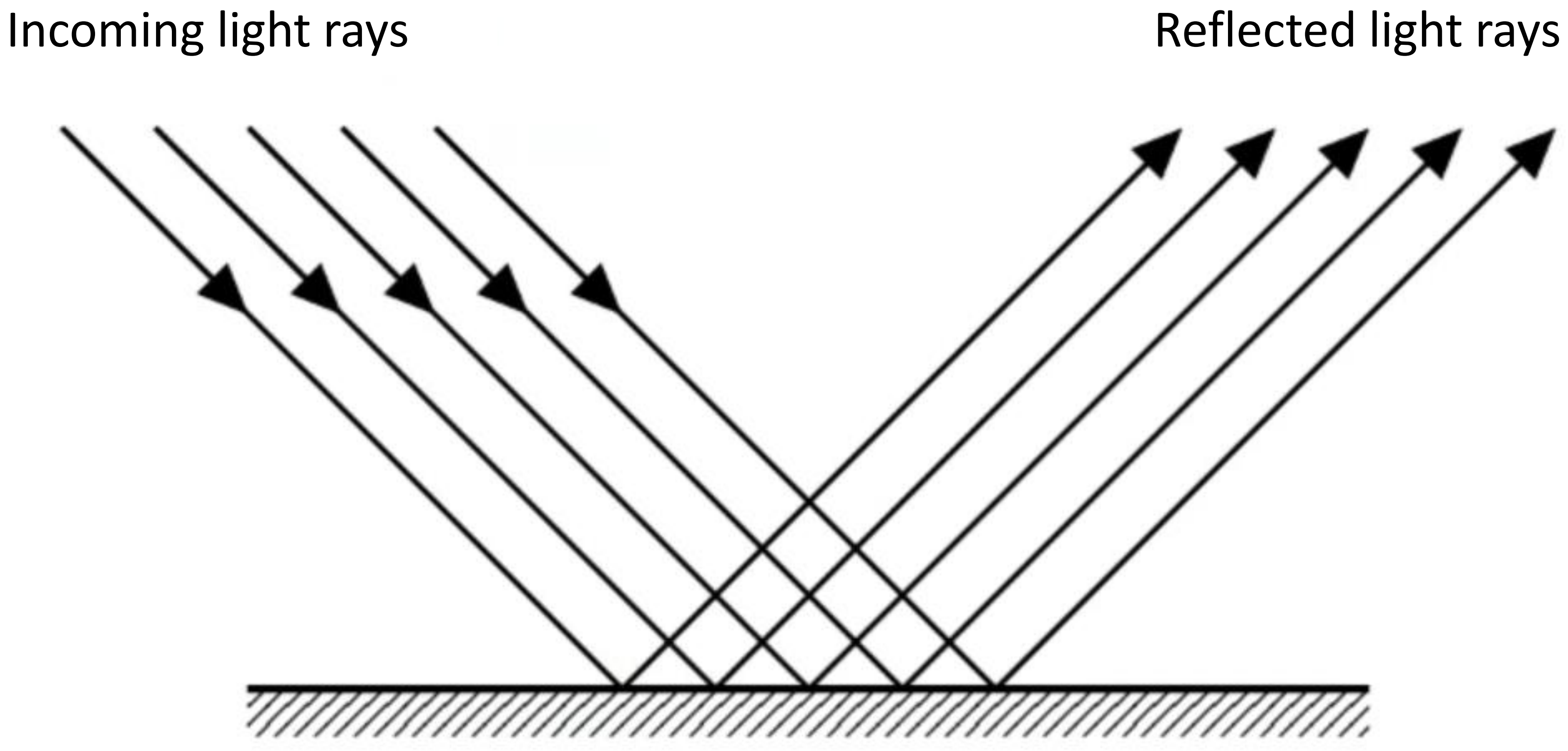
- Dot product between two vectors:
  - $a \cdot b = |a|\,|b| \cos(\theta)$
- However if the vectors are of unit length:
  - $L \cdot n = \cos(\theta)$



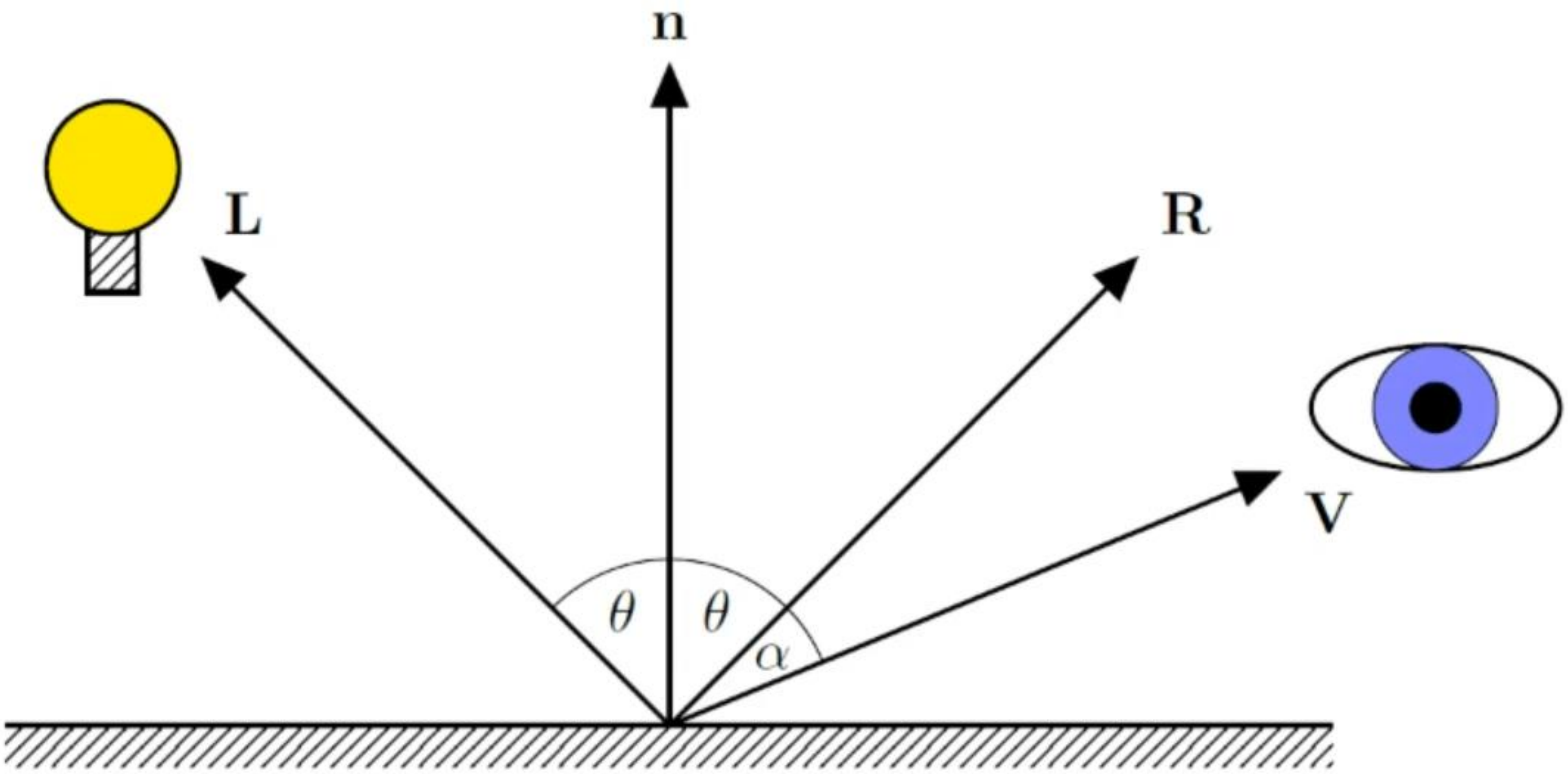
- Dot product between two vectors:
  - $a \cdot b = |a|\,|b|\cos(\theta)$
- However if the vectors are of unit length:
  - $L \cdot n = \cos(\theta)$
- We can substitute the costly cosine calculation with the dot product
  - $\boldsymbol{D = I_p k_d \max[L \cdot n, 0]}$



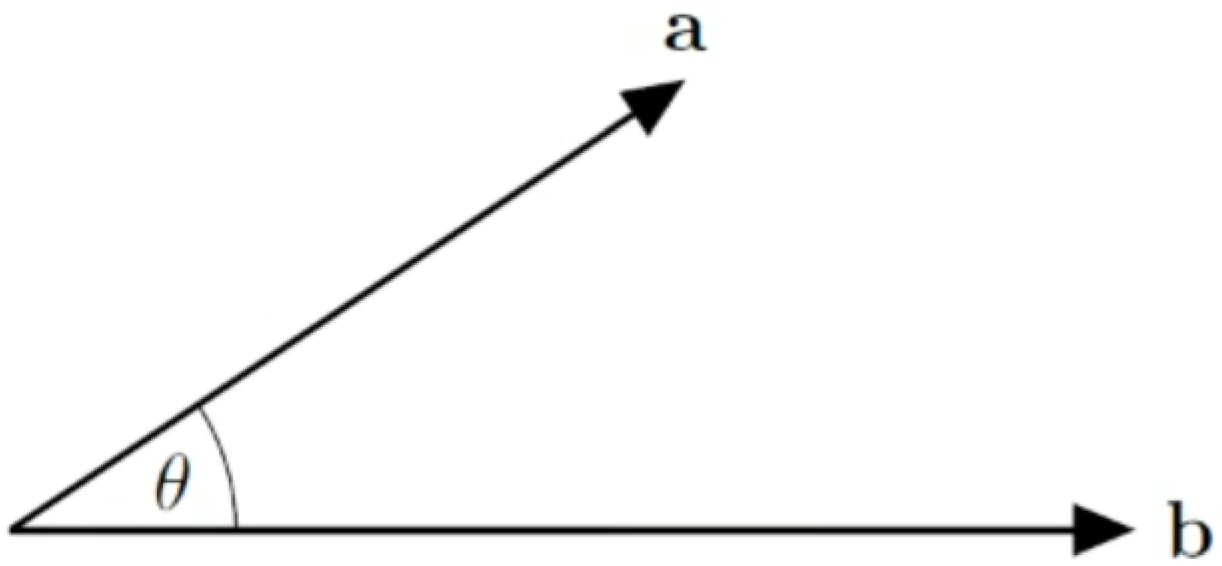
Light reflection



Specular lighting - vectors



Vector projection



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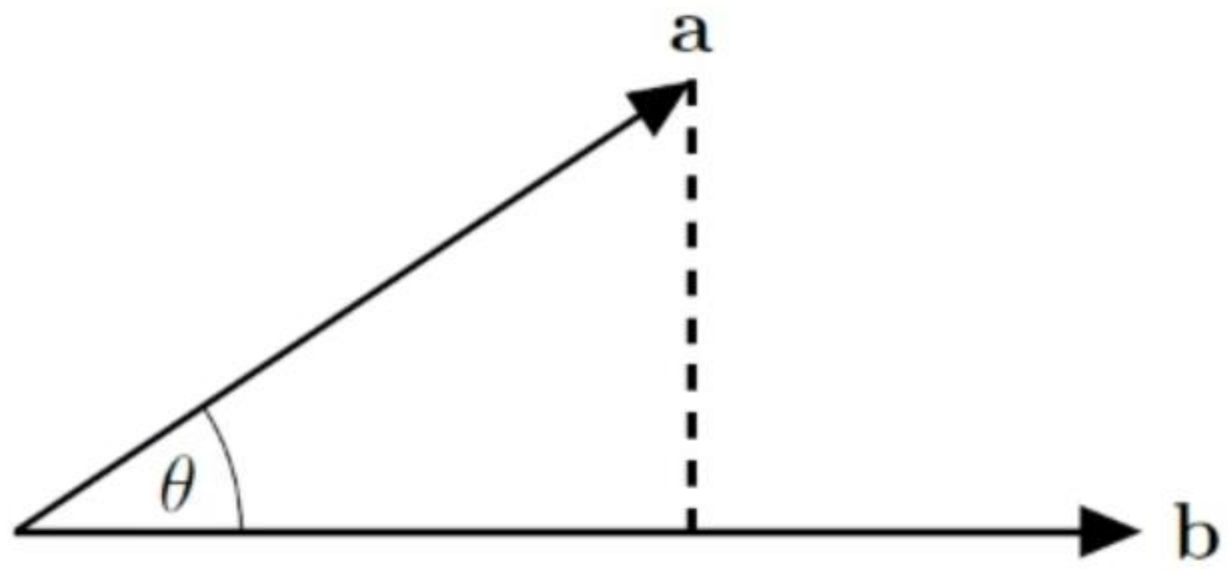
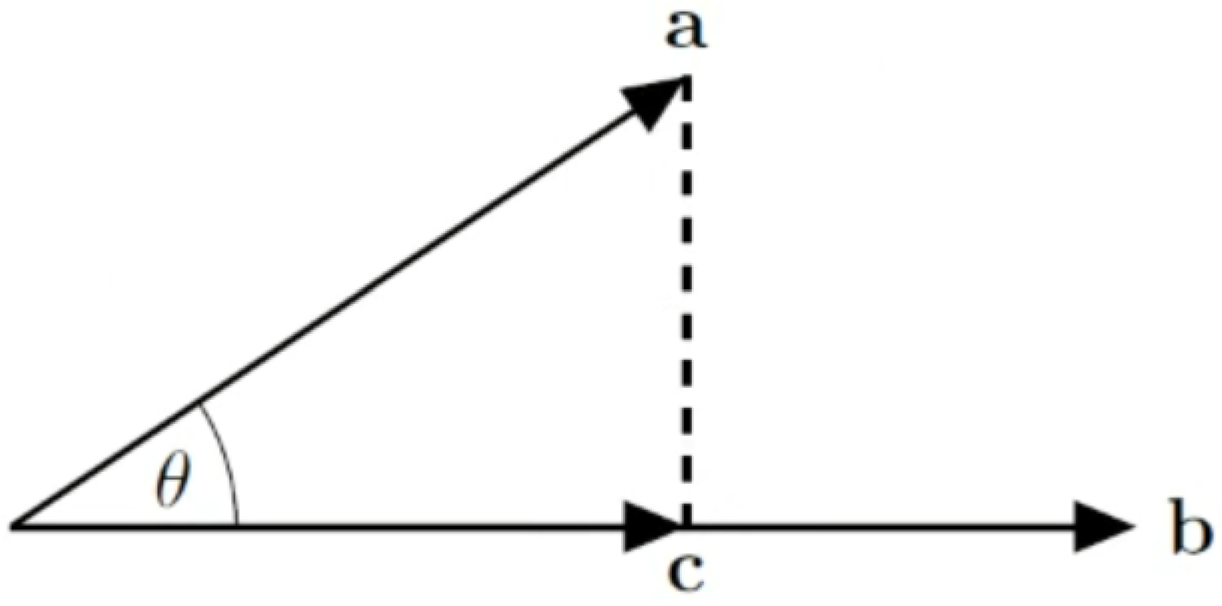
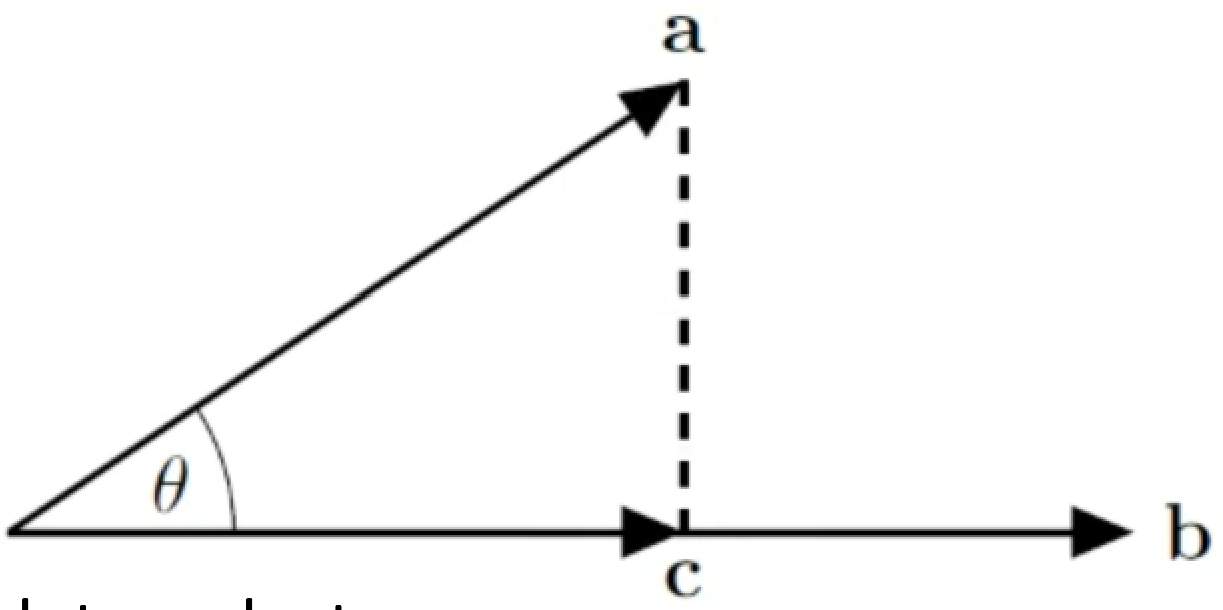
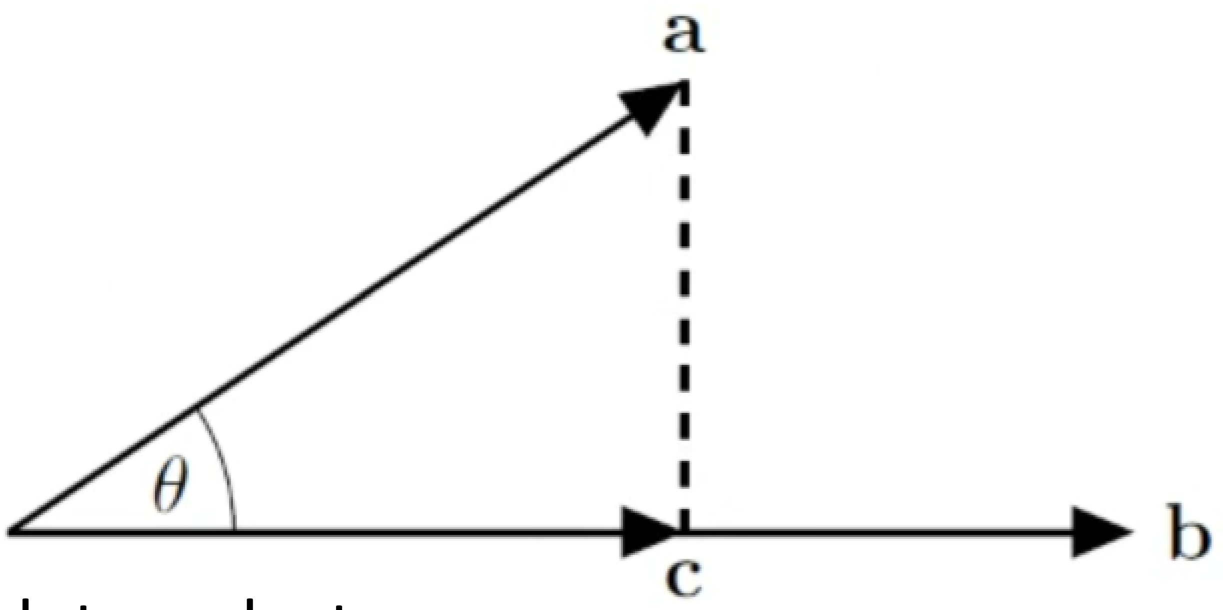


Vector projection





- From the definition of the dot product:
- $a \cdot b = |a||b| \cos(\alpha)$



- From the definition of the dot product:
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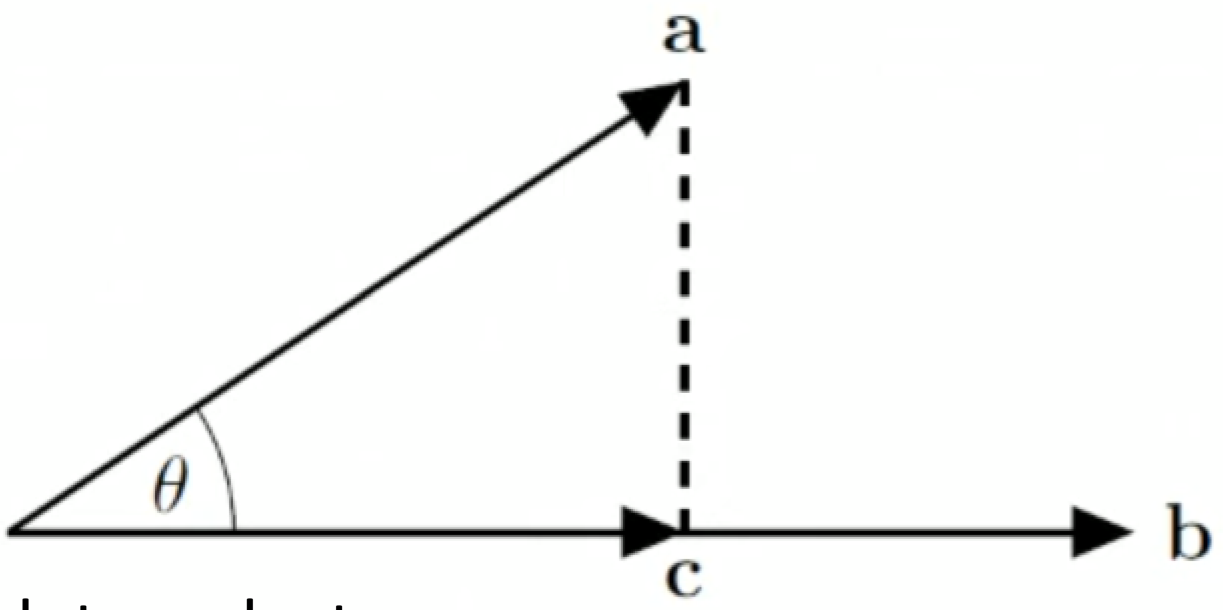

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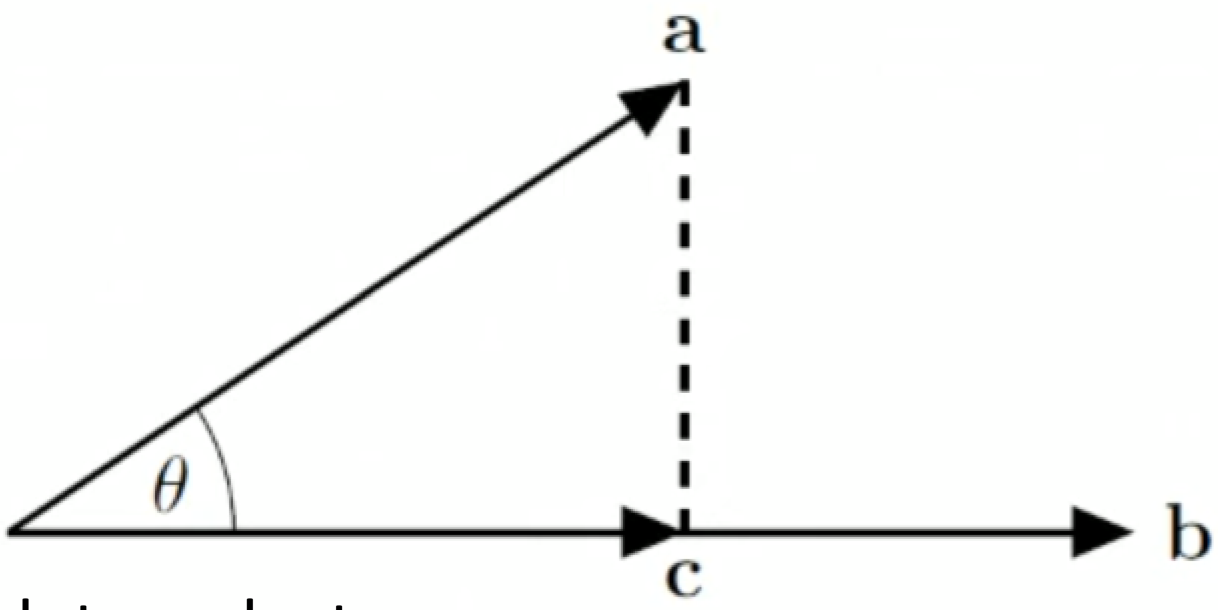

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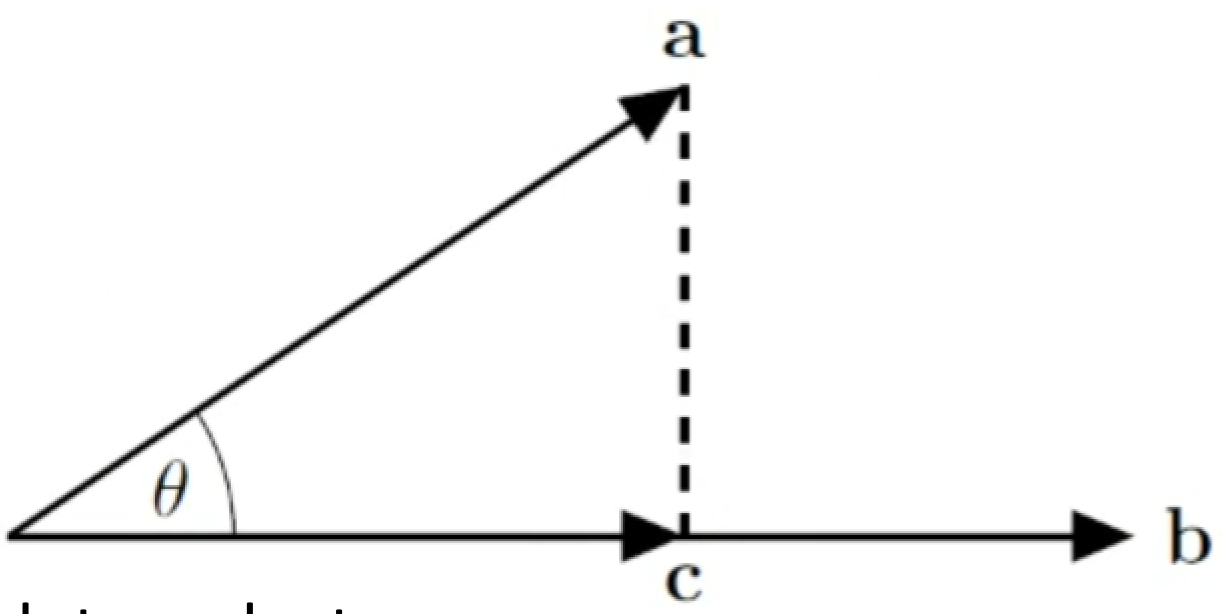

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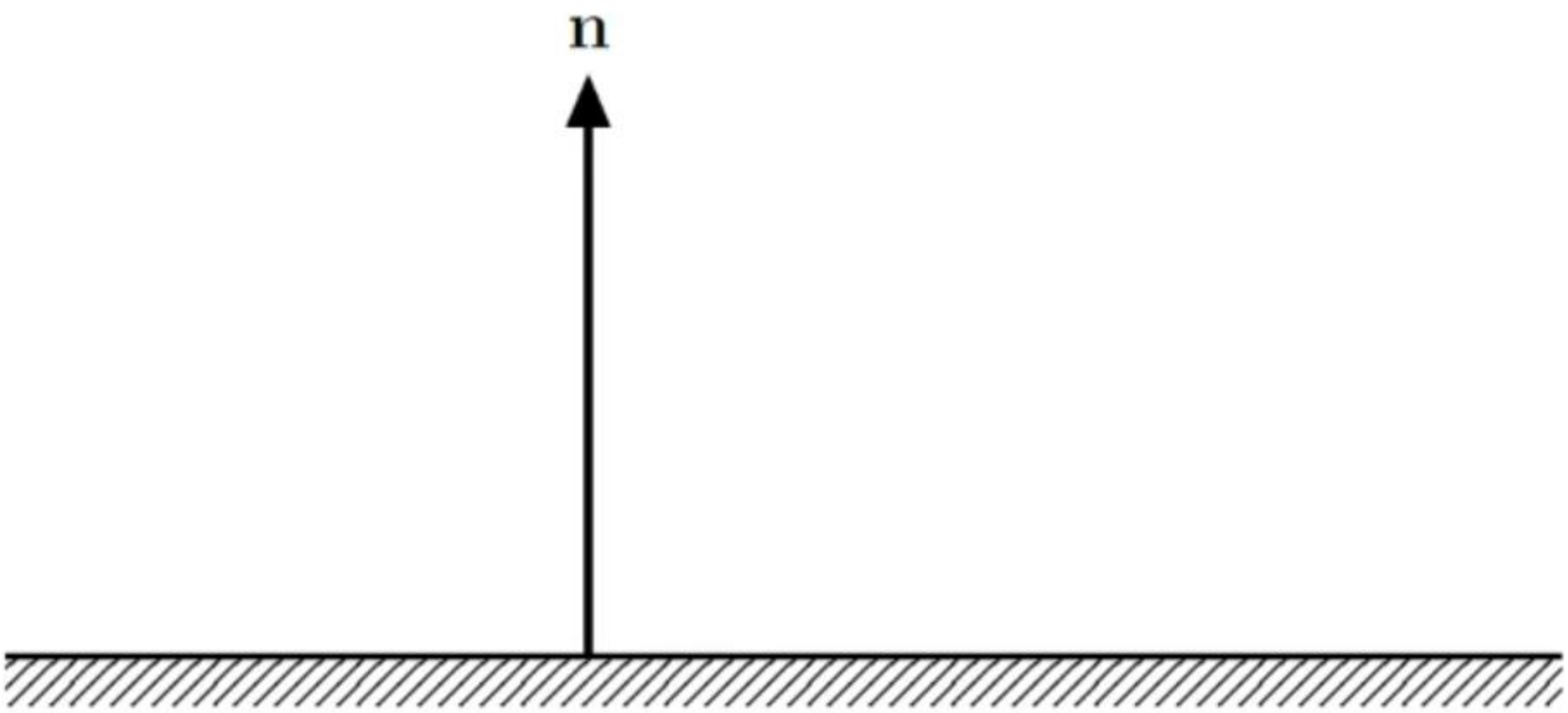
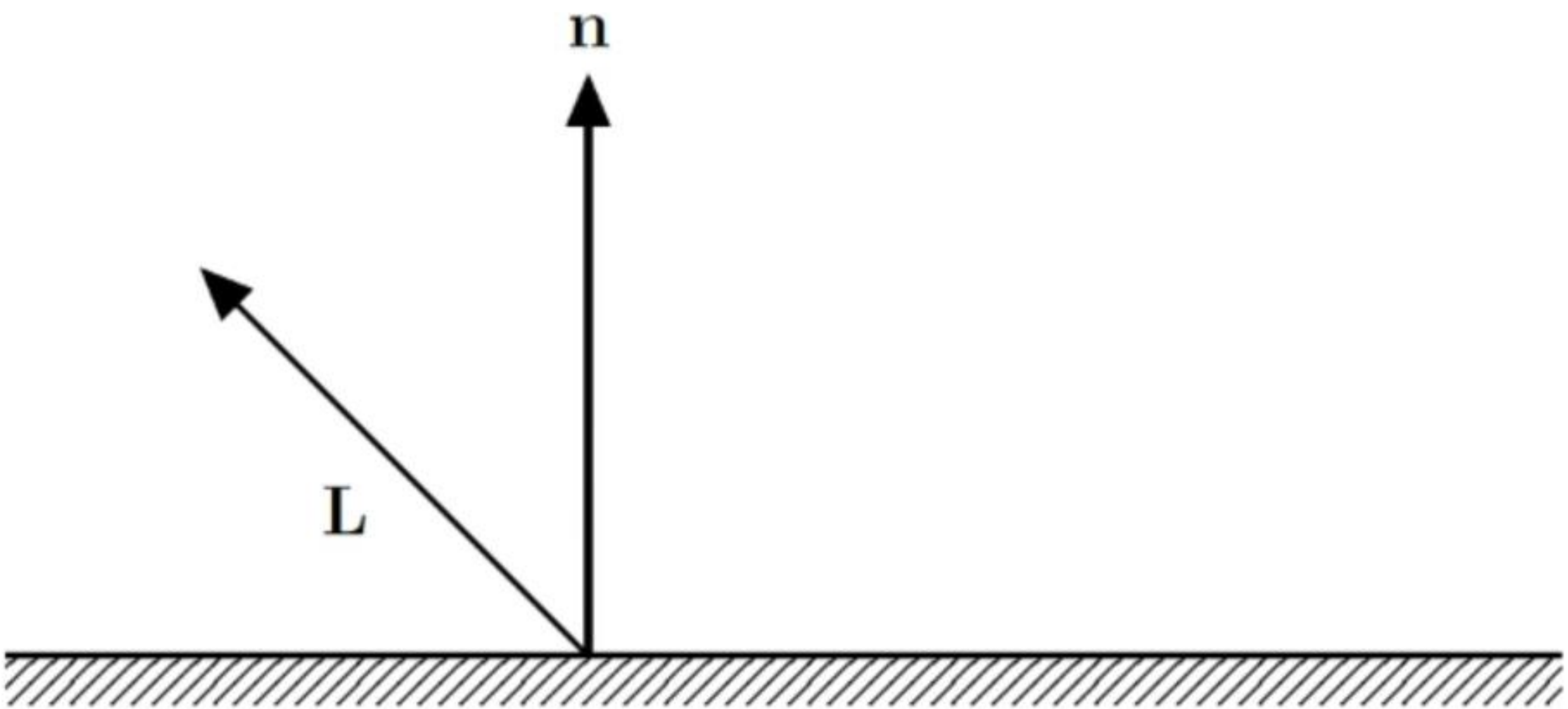
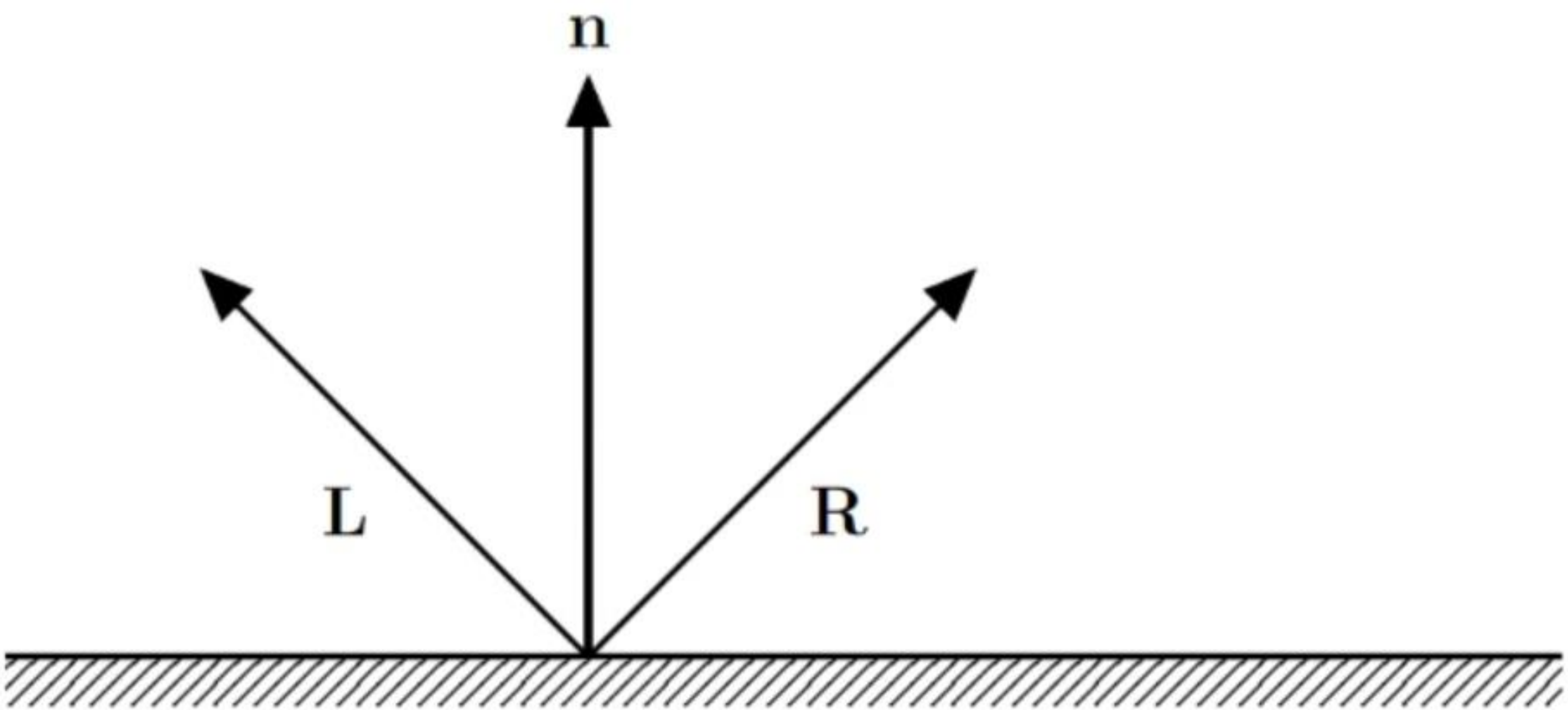
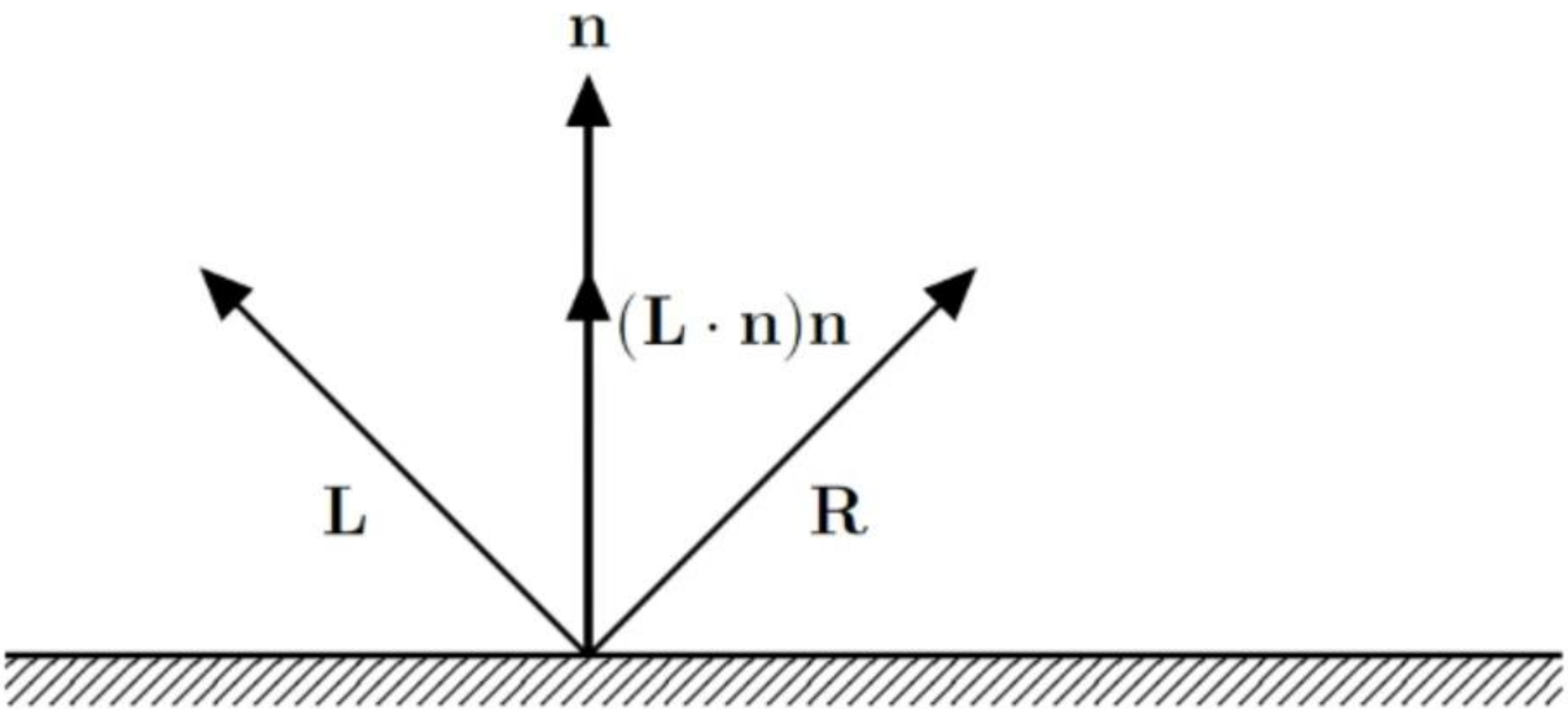
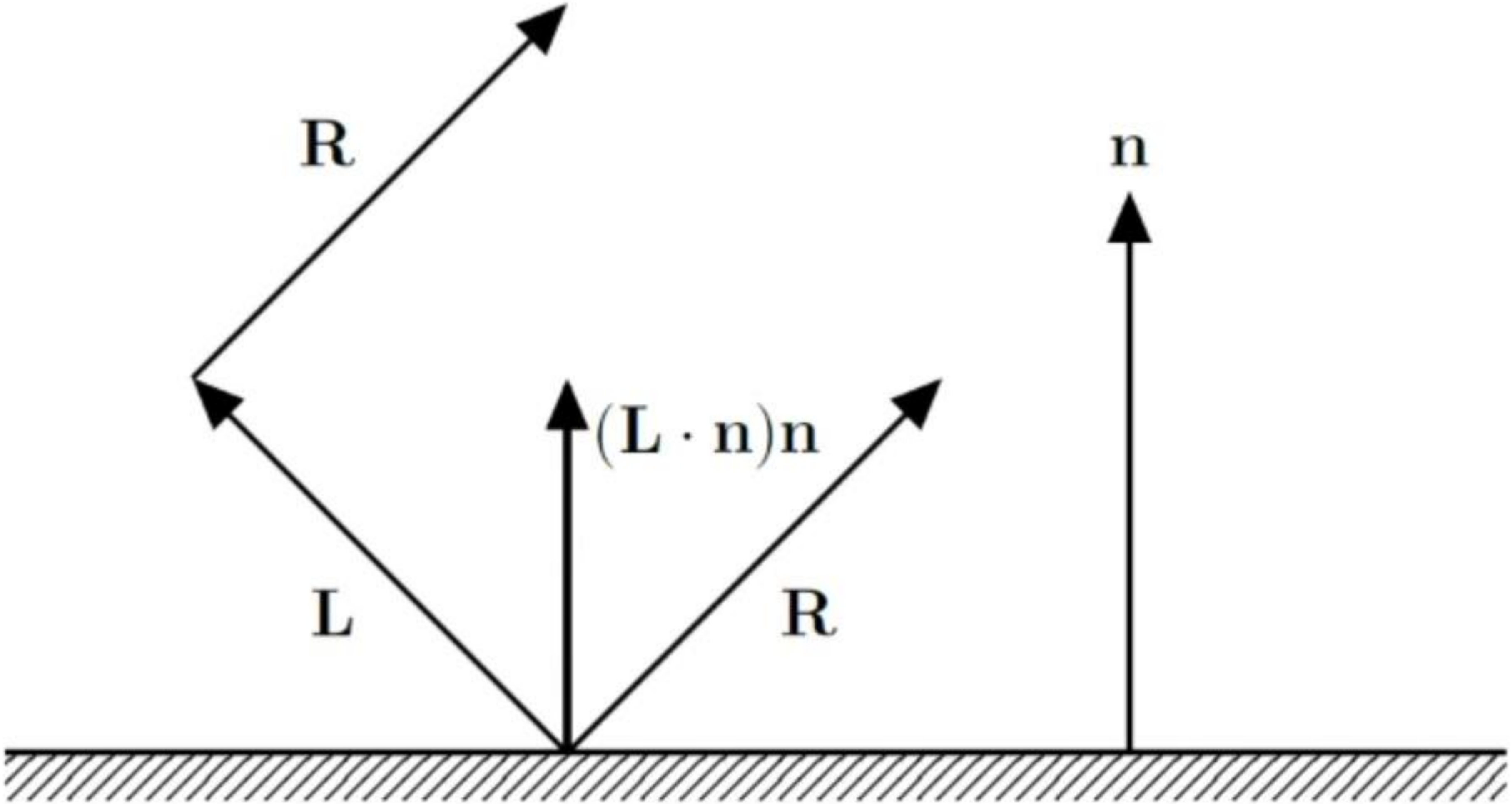
- $a \cdot b = |a||b|\cos(\alpha) = |a||b|\frac{|c|}{|a|} = |b||c|$
- $|c| = \frac{a \cdot b}{|b|}$
- If b is a unit vector $|c| = a \cdot b$ then
- $c = (a \cdot b)b$

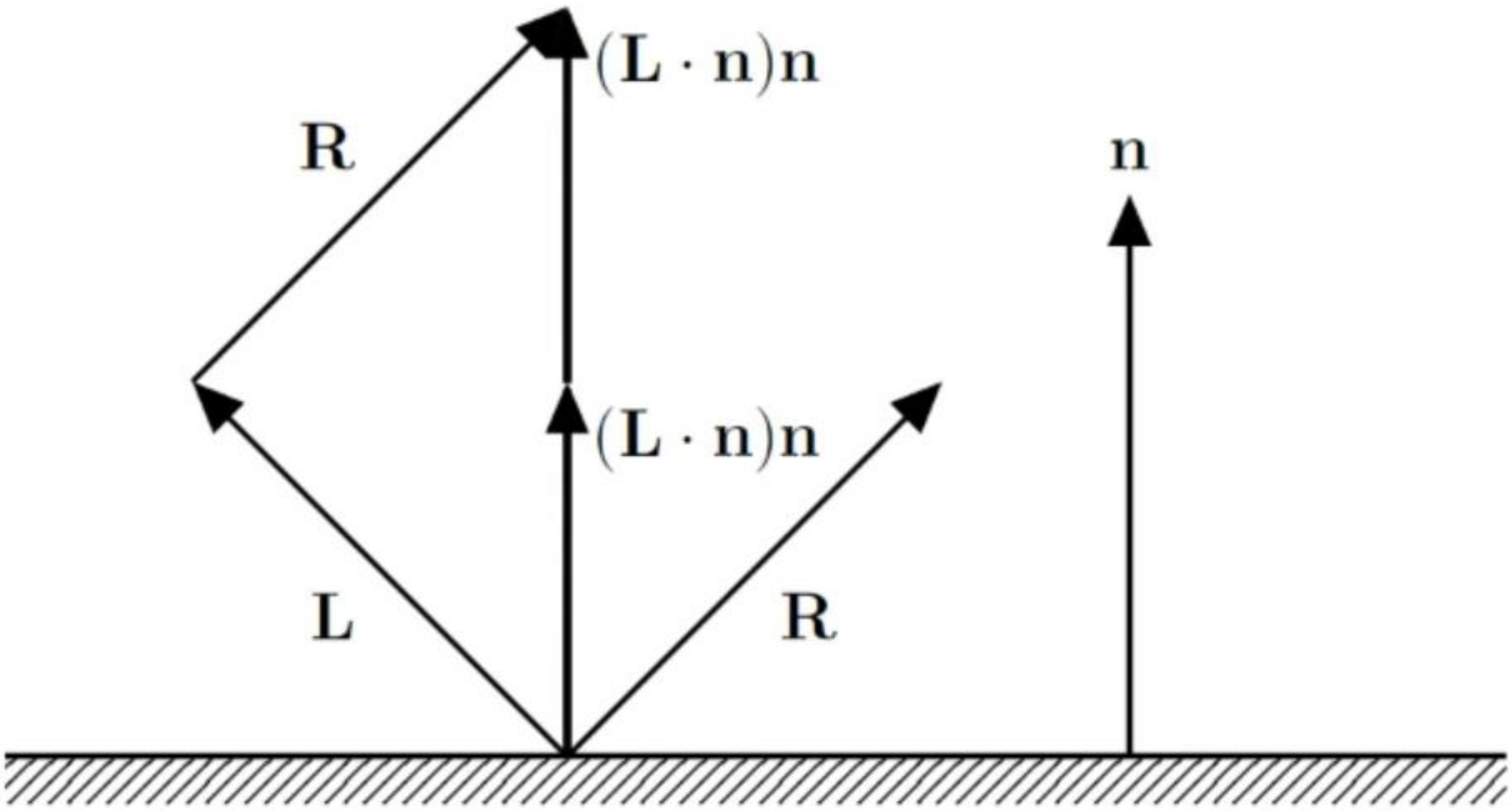

n


n
L


n
L
R


n
(L · n)n
L
R


R
n
$(\mathbf{L} \cdot \mathbf{n})\mathbf{n}$
L
R


(L · n)n
R
n
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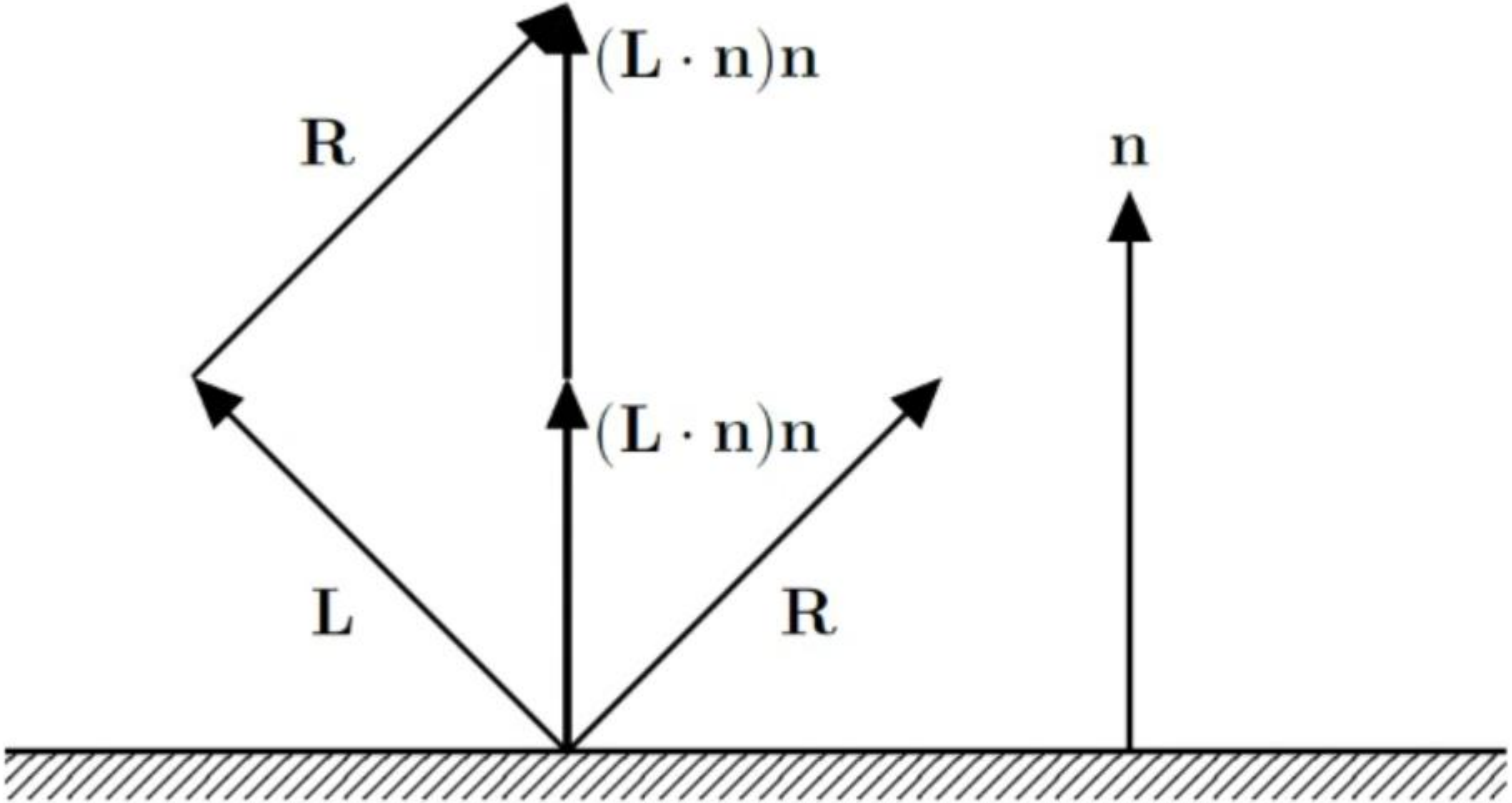
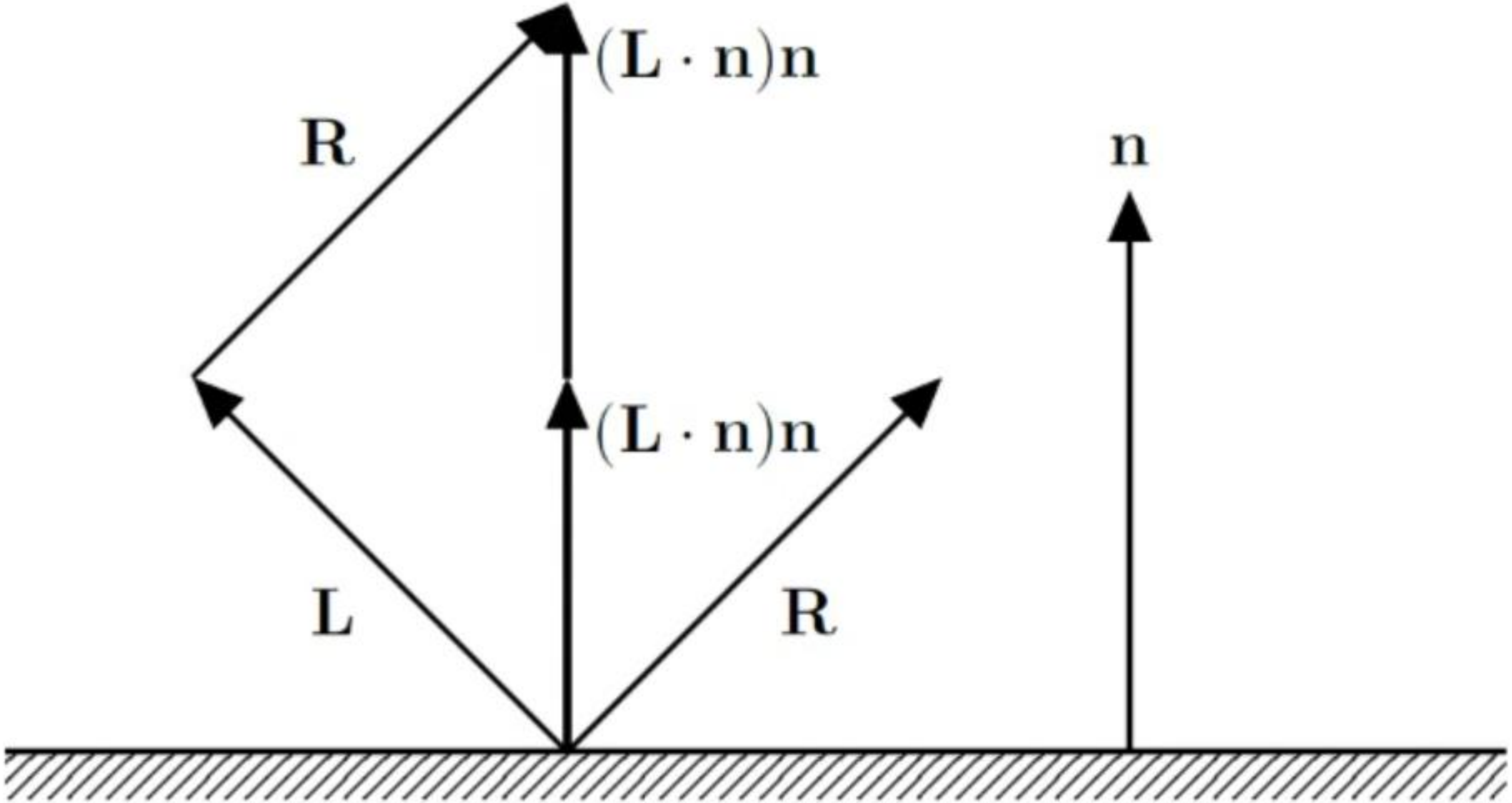
L
R



$$\mathbf{L} + \mathbf{R} = 2(\mathbf{L} \cdot \mathbf{n})\mathbf{n}$$



$$\mathbf{L} + \mathbf{R} = 2(\mathbf{L} \cdot \mathbf{n})\mathbf{n}$$

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

GLSL

r = reflect(I, n)

Name

reflect — calculate the reflection direction for an incident vector

Declaration

```
genType reflect( genType I,
                 genType N);

genDType reflect( genDType I,
                  genDType N);
```

Parameters

I

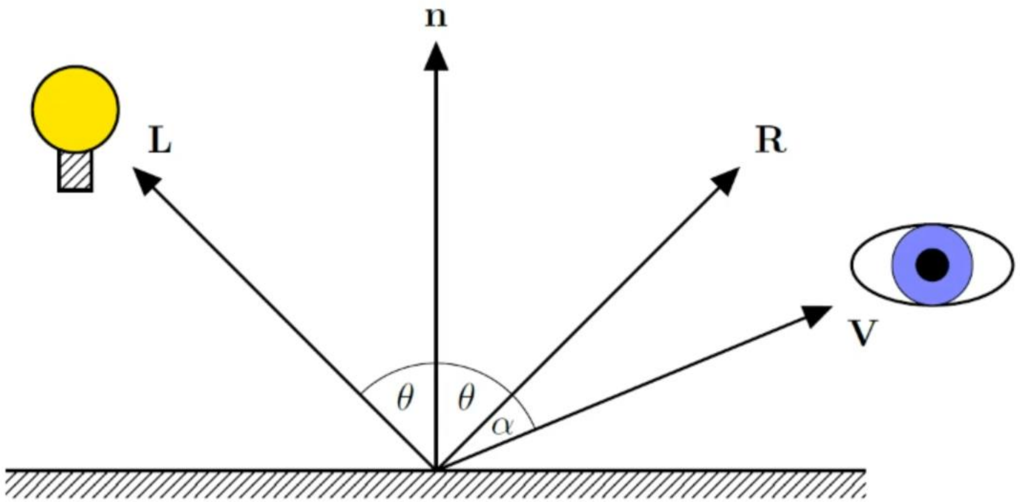
Specifies the incident vector.

N

Specifies the normal vector.

Specular lighting - vectors

- The Phong model of specular lighting is:
- $S = I_p k_s cos^n(\alpha) = I_p k_s (V \cdot R)^n$



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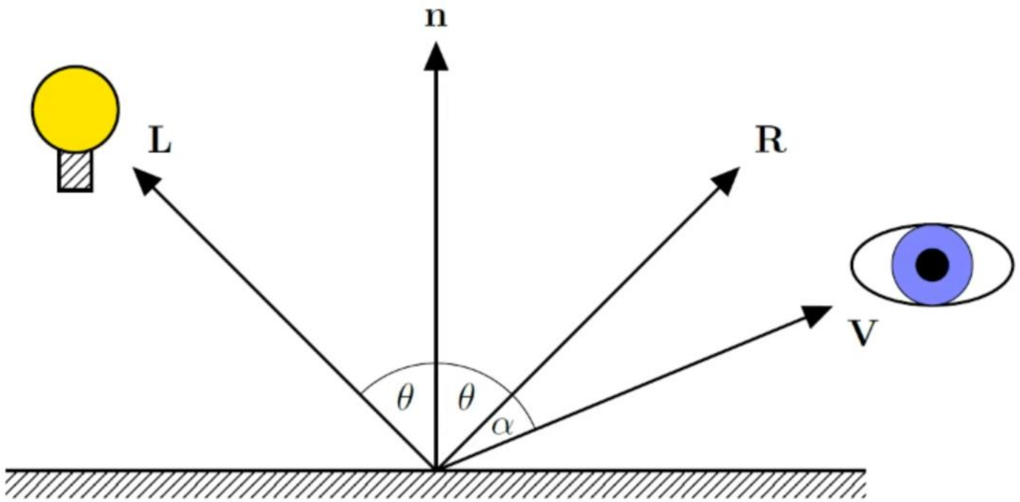
- $\boldsymbol{S = I_p k_s cos^n(\alpha) = I_p k_s (V \cdot R)^n}$
- Where
  - $k_s \in [0, 1]$ is the specular lighting coefficient
  - n is the specular lighting exponent
  - α is the angle between R and V



Specular lighting - vectors

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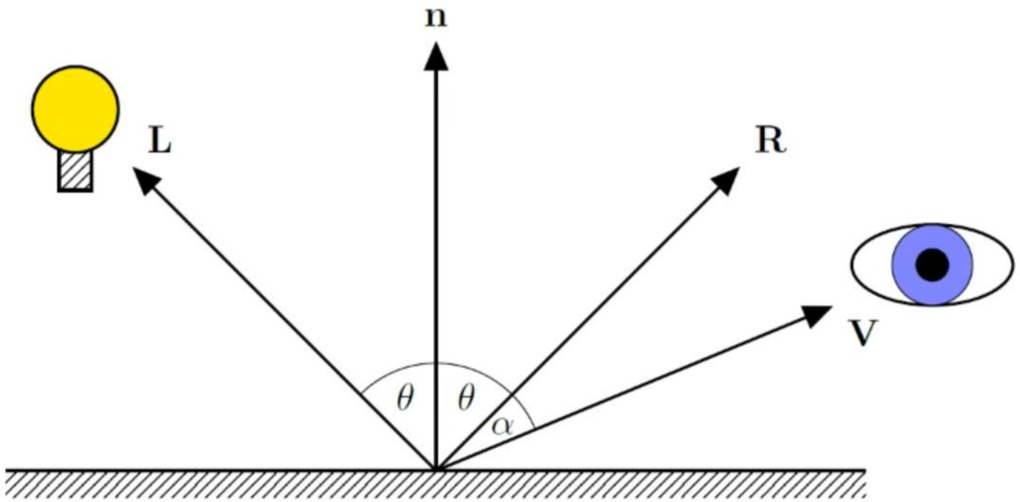
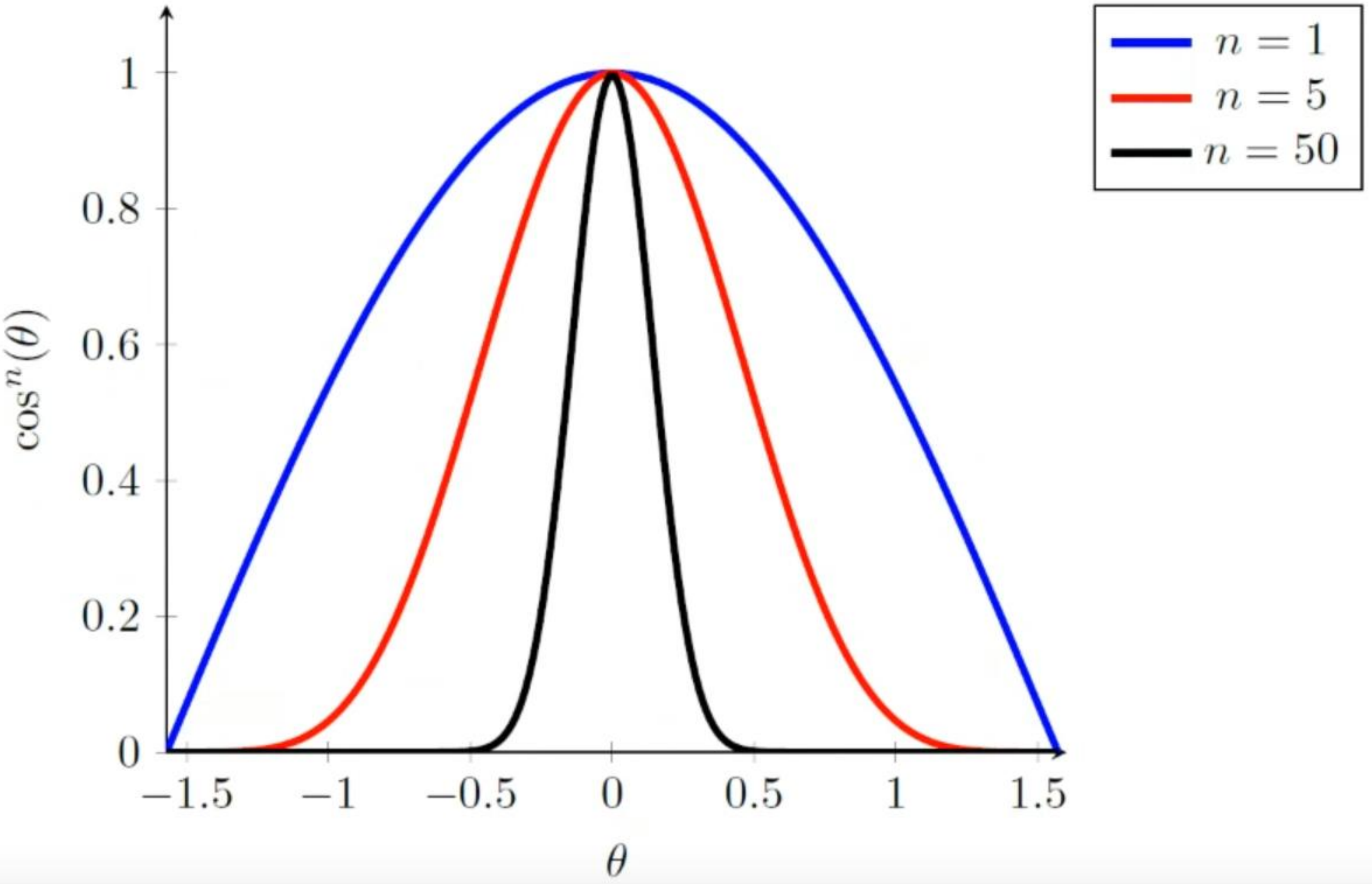
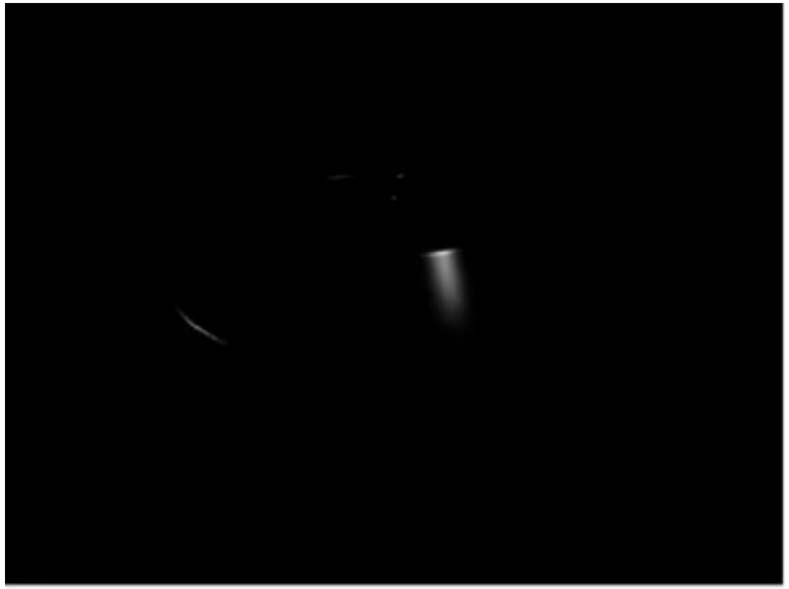
- $\boldsymbol{S} = \boldsymbol{I_p k_s cos^n(\alpha)} = \boldsymbol{I_p k_s (V \cdot R)^n}$
- Where
  - $k_s \in [0, 1]$ is the specular lighting coefficient
  - n is the specular lighting exponent
  - α is the angle between R and V
- $cos^n(\alpha)$ determines how much light is reflected by a given material



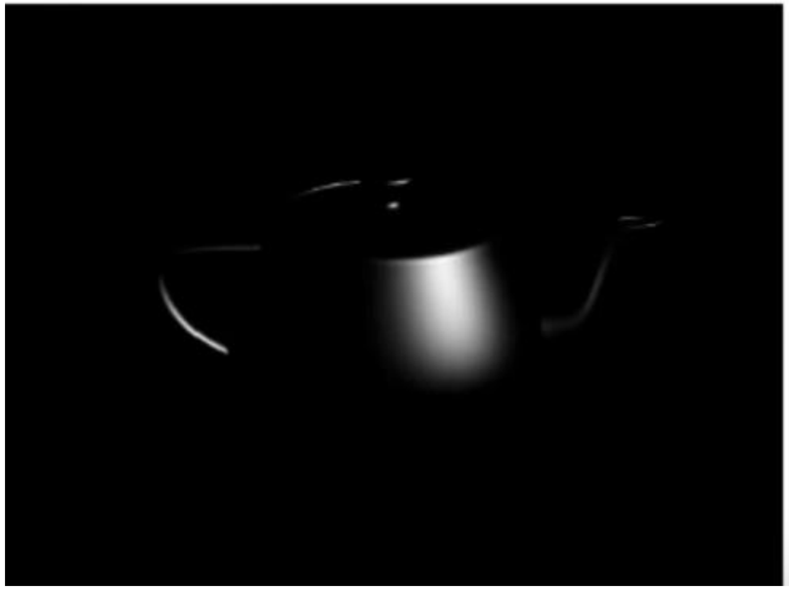
Specular lighting coefficient





n = 50

n = 20

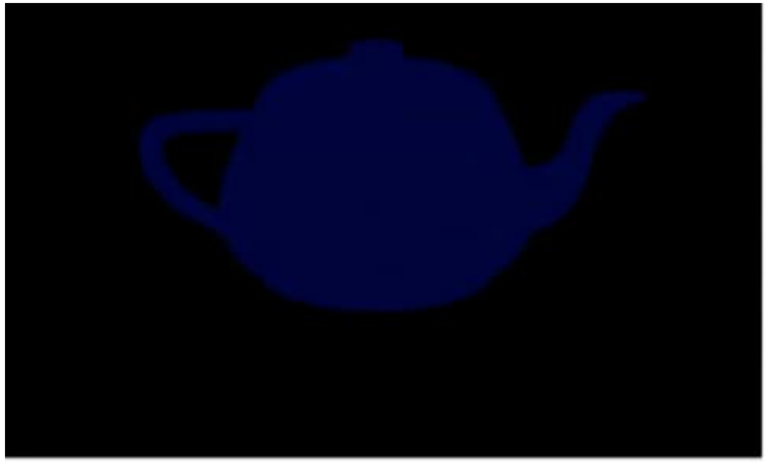


n = 5

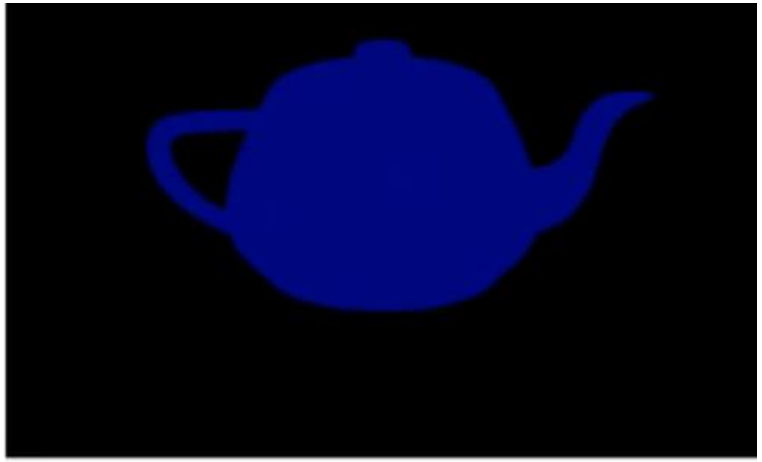
n = 1

Ambient lighting

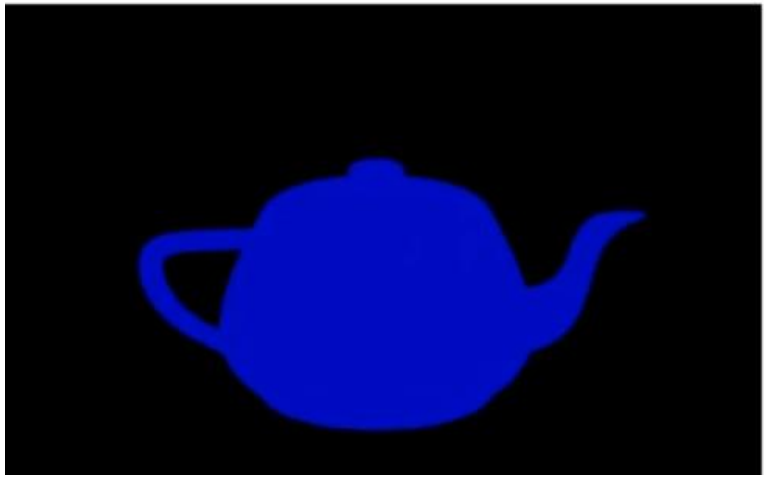
- Ambient lighting, is the reflected light not coming directly from the light source
- $\boldsymbol{A = \ I_a k_a}$
- Where I_a denotes light intensity $k_a \in [0, 1]$ is the coefficient of the environment
- k_a allows to specify a minimum amount of light available for all objects in a scene, n.p. $k_a \to 1$ for bright $k_a \to 0$ for dark scenes



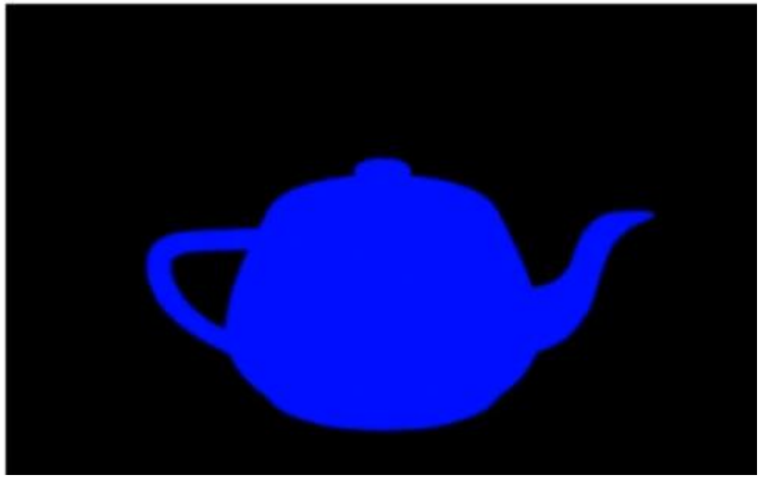
$k_a = 0.25$



$k_a = 0.5$



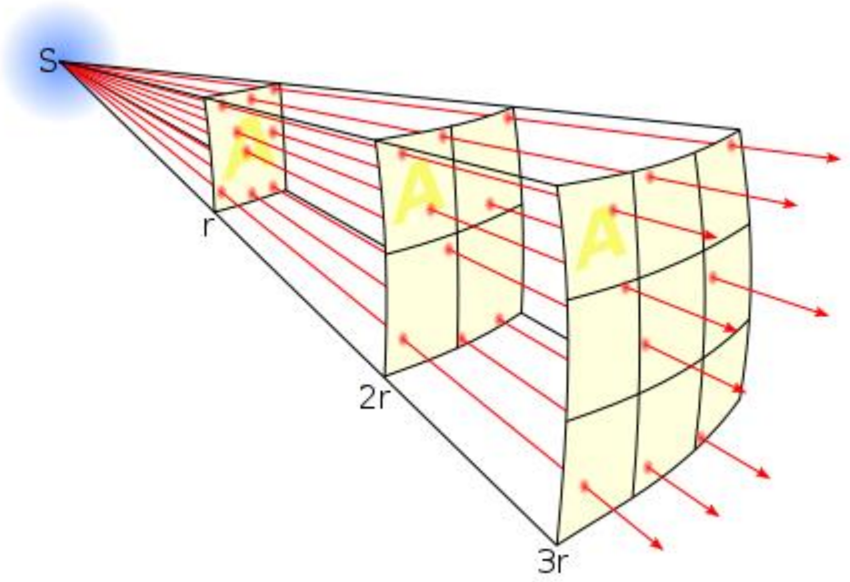
$k_a = 0.75$



$k_a = 1.0$

Attenuation

- Attenuation describes the diminishing of light energy in space
- In the Phong model the coefficient f_{att} models this phenomenon
- Physically-based models propose the following relation
- $f_{att} \sim \frac{1}{d^2}$



Attenuation

- Because the Phong model is a direct lighting model not accounting for reflected light rays usually too much light would be removed using the physically-based formulation. Instead, the following relation is used:
- $f_{att} = 1 - (\frac{d}{r})^2$
- Where r is the radius of the sphere surrounding the light source that represents the furthest possible light

Attenuation

- Adding all the individual parts of the Phong model gives the full Phong light reflectance model
- $I = I_a k_a + \boldsymbol{f_{att}} I_p k_d \max[L \cdot n, 0] + \boldsymbol{f_{att}} I_p k_s (V \cdot R)^n$

Attenuation

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- For scenes with more than one light source, the individual intensities are simply added together
- $I = I_a k_a + \sum_{i=1}^{m} \boldsymbol{f_{att}} I_{p,i} [k_d \max(L_i \cdot n, 0) + k_s (V \cdot R_i)^n]$

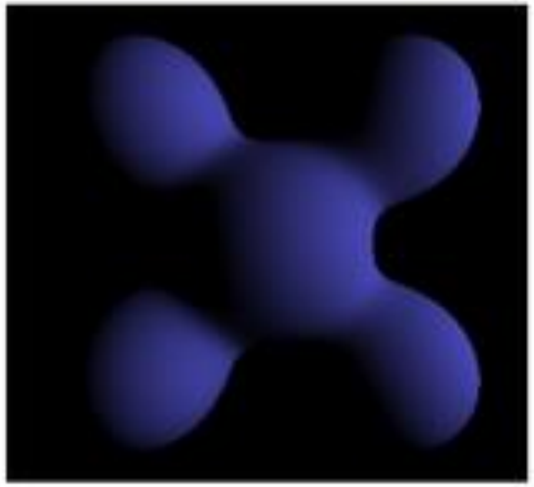
Light intensity and RGB colors

- We can simply scale the **color vectors** in the fragment shader: $v_{new} = v \cdot I$

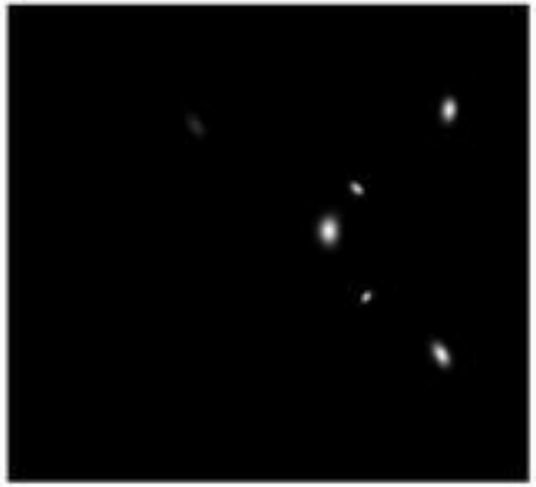
- For example: the red color $v =$(1, 0, 0) with 50% intensity becomes $v_{new} =$ (0.5, 0, 0)

Result

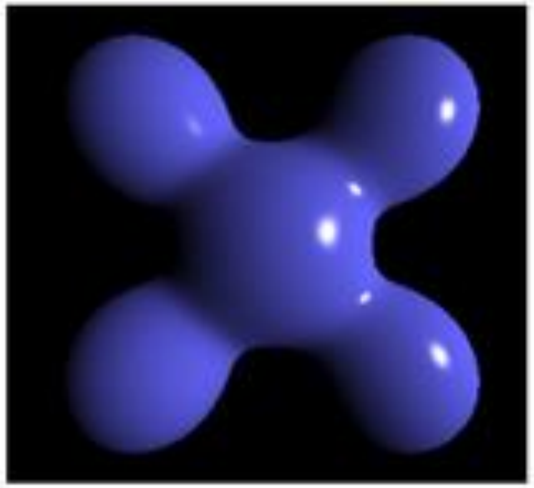
Ambient light



Diffuse light



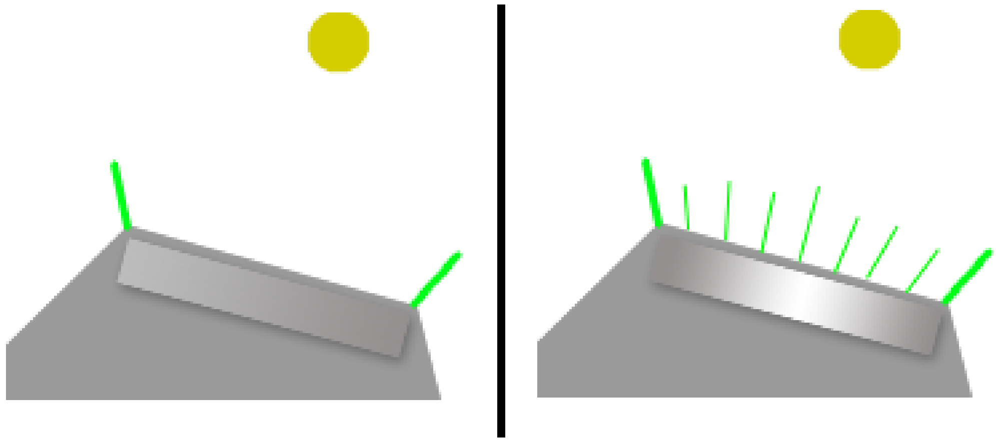
Specular light



Phong lighting model

Shading

- The Phong lighting model calculates light intensity using the surface normal of an object



Shading

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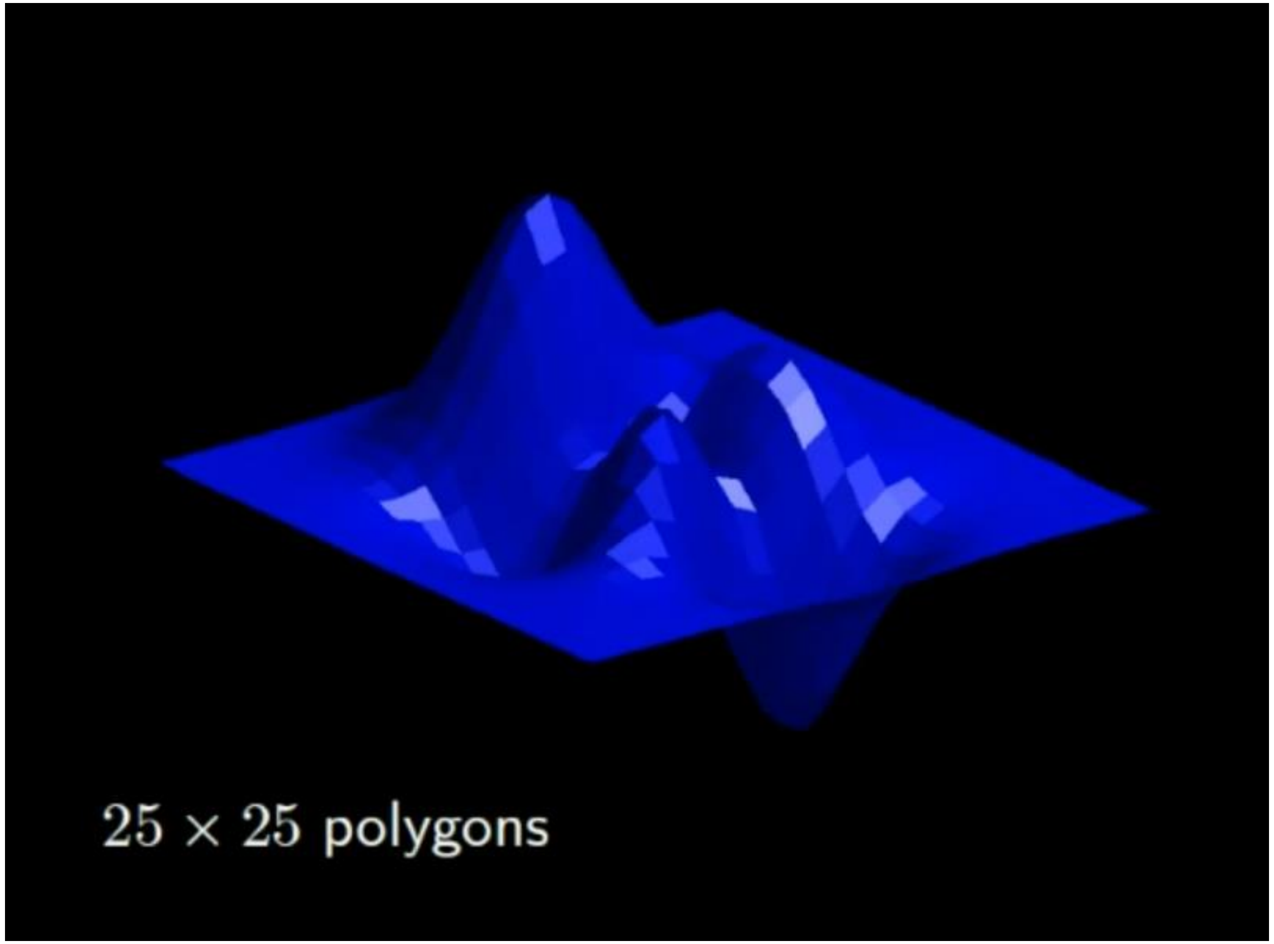
- The calculation of lighting for a whole triangle is called shading

Shading

- The Phong lighting model calculates light intensity using the surface normal of an object
- The calculation of lighting for a whole triangle is called shading
- Basic shading methods:
  - Lambert shading
  - Gouraud shading
  - Phong shading

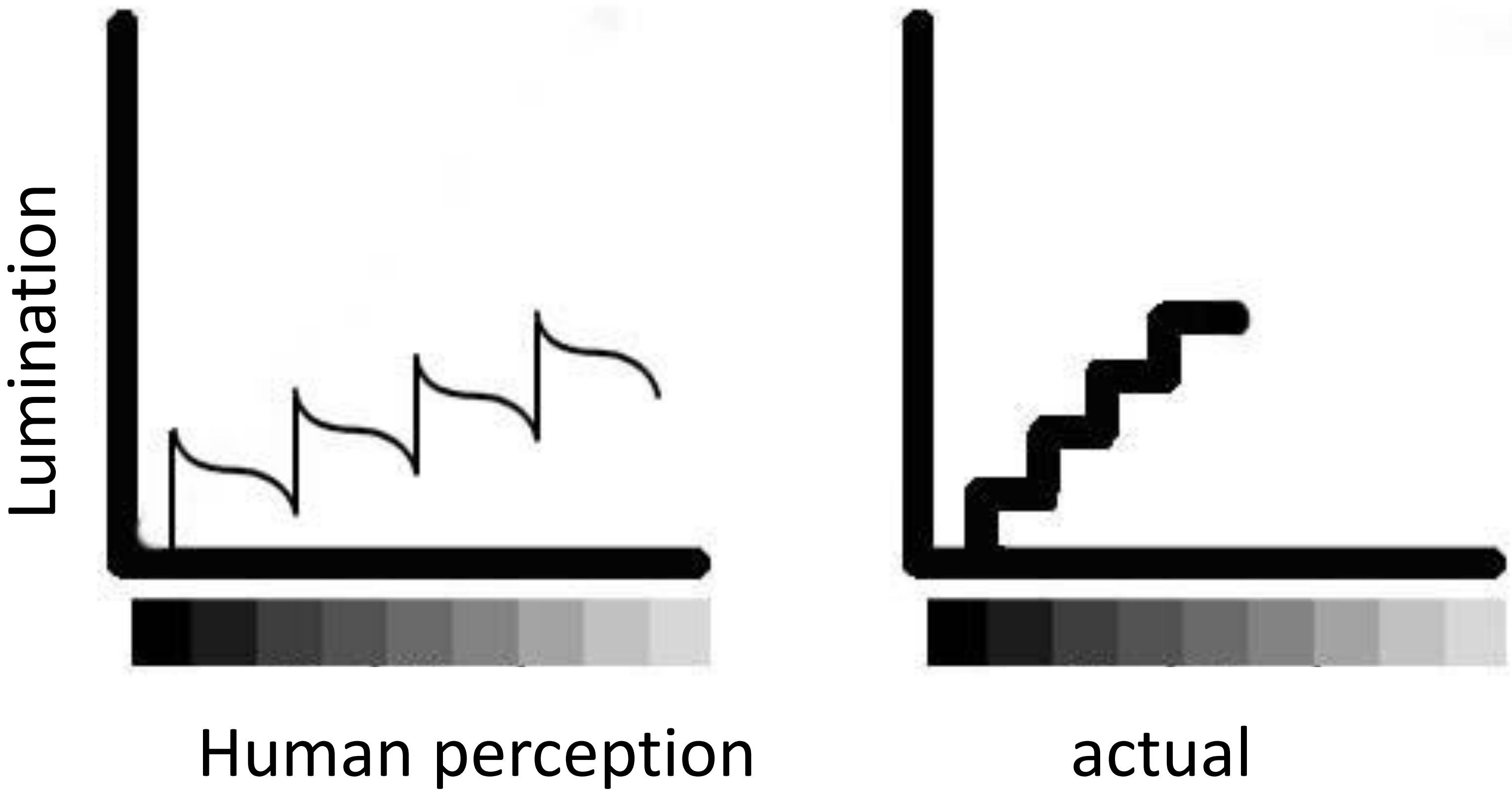
Lambert shading (flat shading)

- Flat shading assumes that all triangle pixels are shaded with the same color

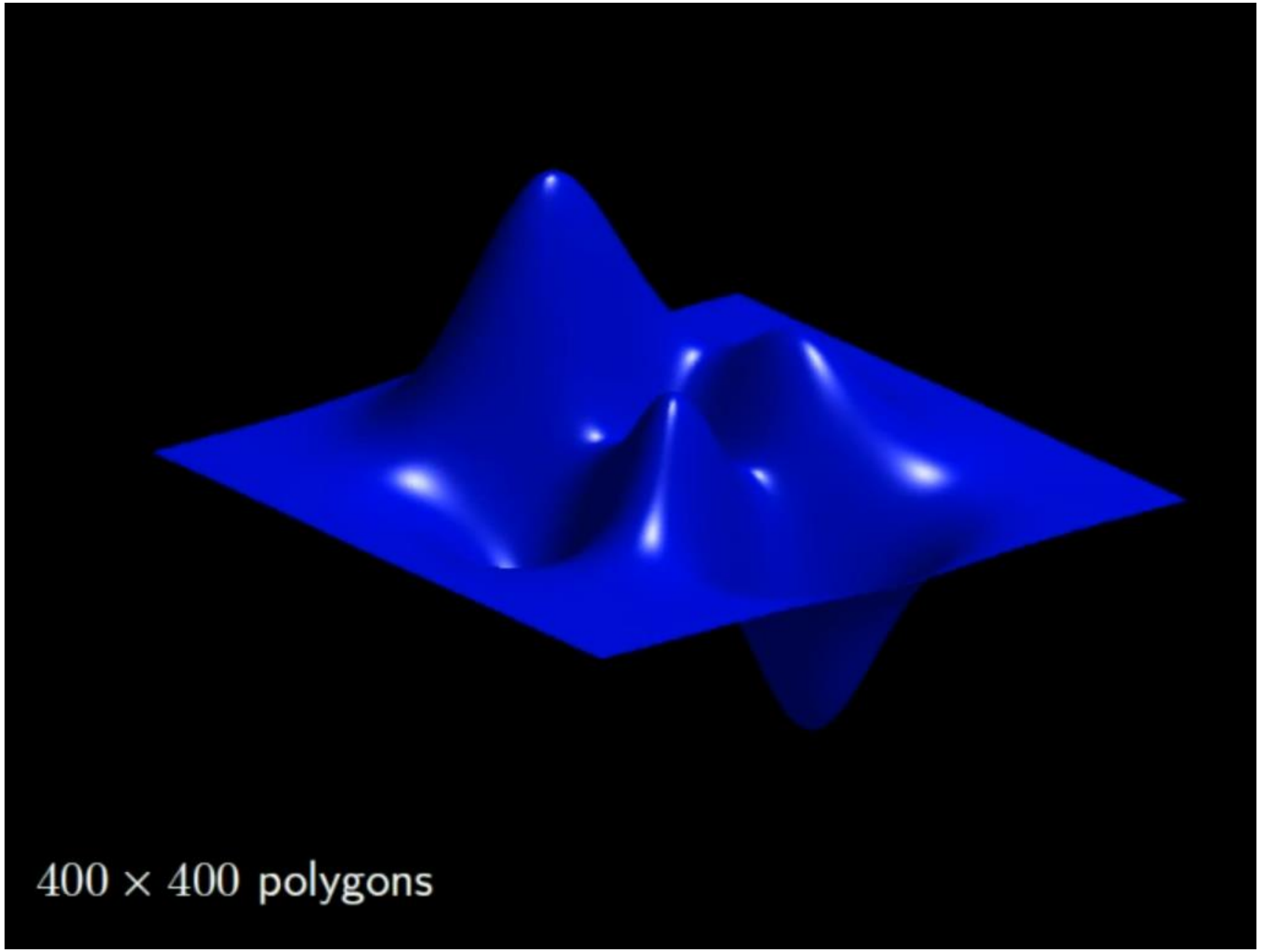


Mach bands optical illusion

Mach bands optical illusion

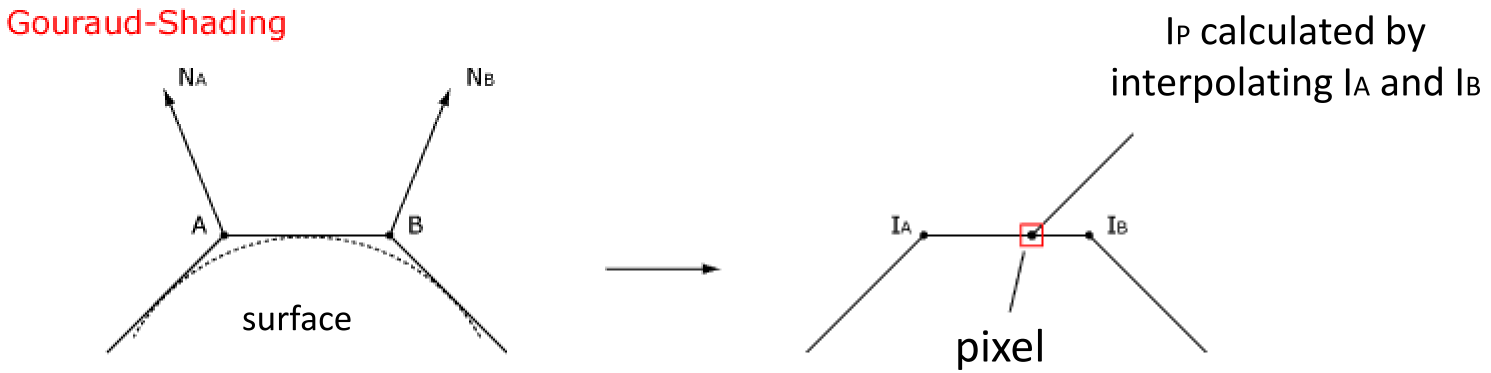


Solution: more polygons



Gouraud shading

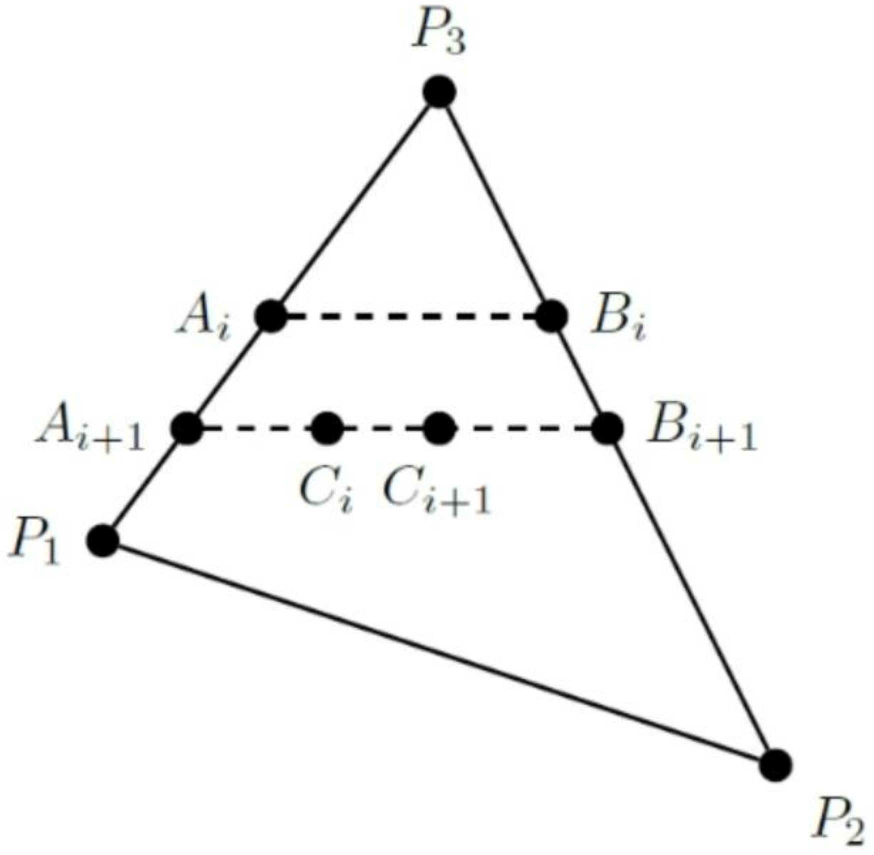
- Gouraud shading calculates lighting for **vertices** of a polygon and linearly interpolate light intensity values of all polygon pixels



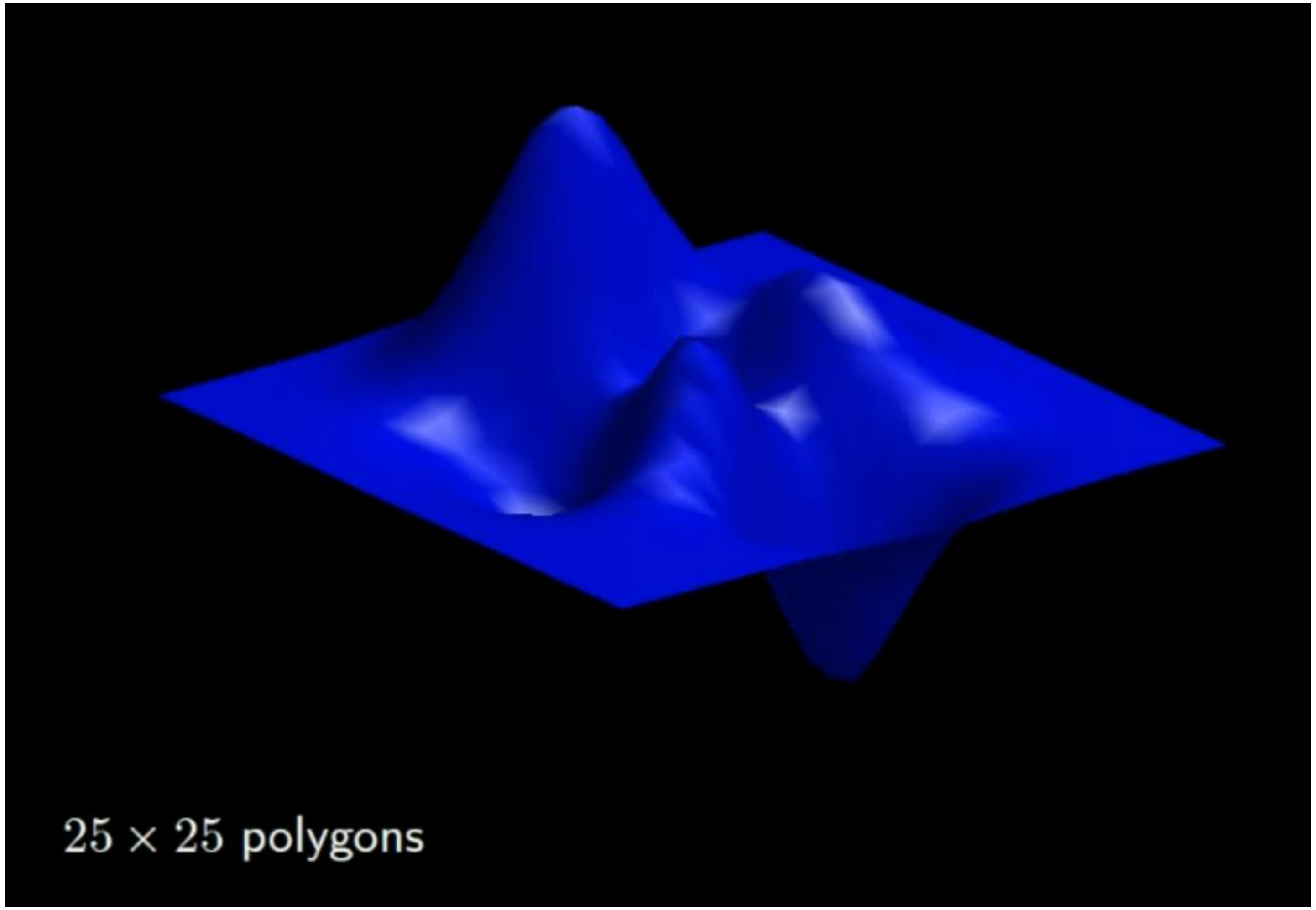
Interpolating intensities

- If *I* is the **light intensity** in a given point P:
- $I_{A,i+1} = I_{A,i} - \Delta I_A$
- $I_{B,i+1} = I_{B,i} - \Delta I_B$
- $I_{C,i+1} = I_{C,i} - \Delta I_C$

- Where
- $I_A = \frac{I_3 - I_1}{y_3 - y_1}, I_B = \frac{I_3 - I_2}{y_3 - y_2}, I_C = \frac{x_B - x_A}{I_B - I_A}$

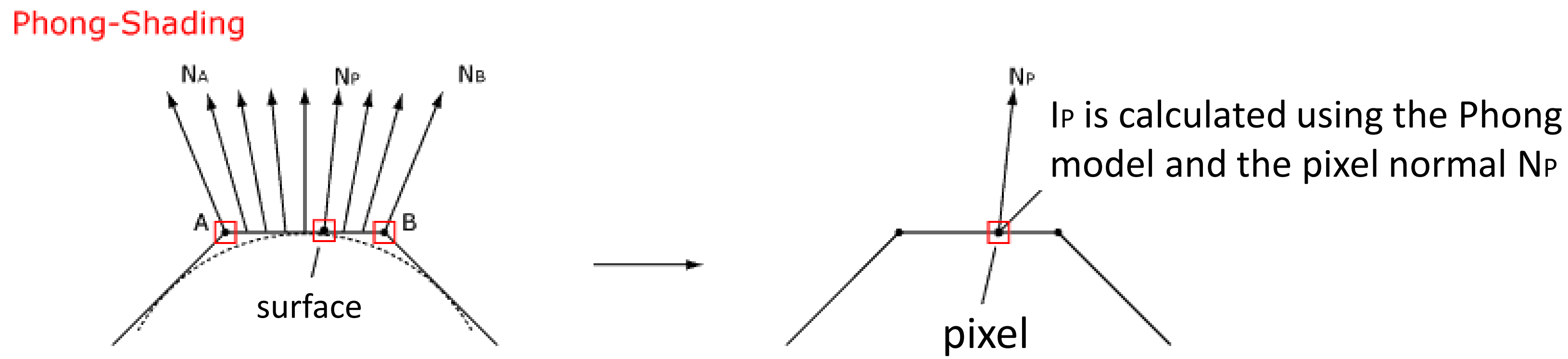


Gouraud shading



Phong shading

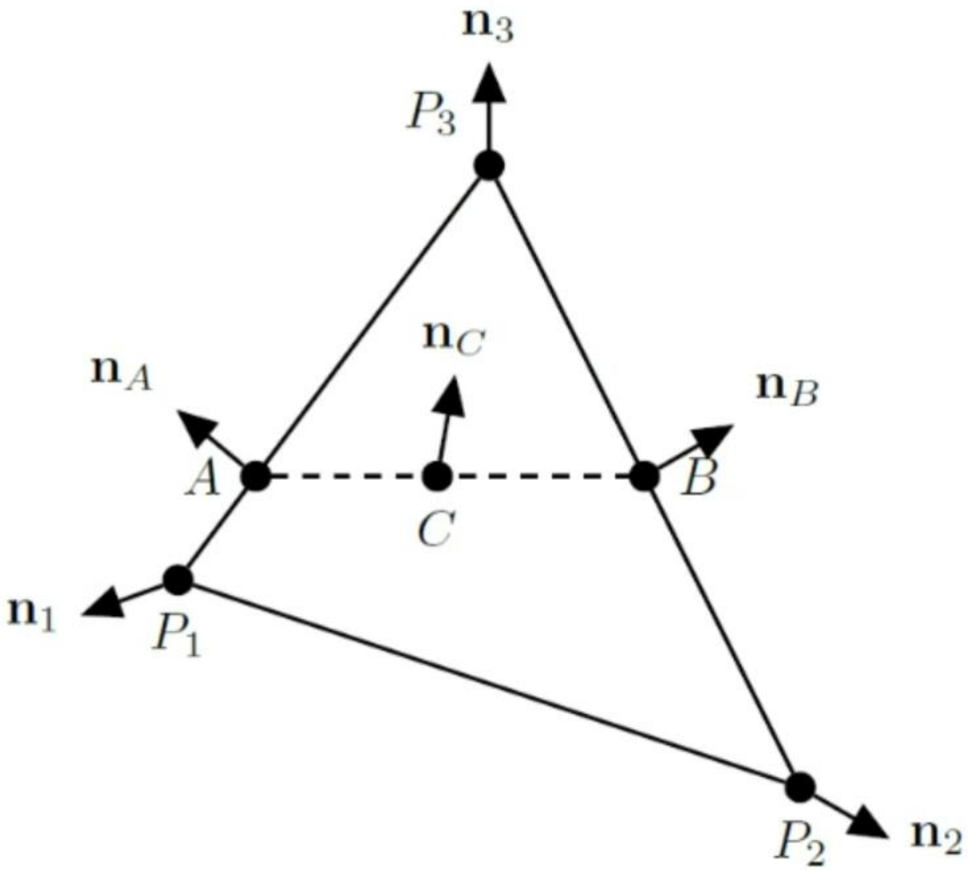
- Phong shading interpolates normal vectors of all pixels of a polygon



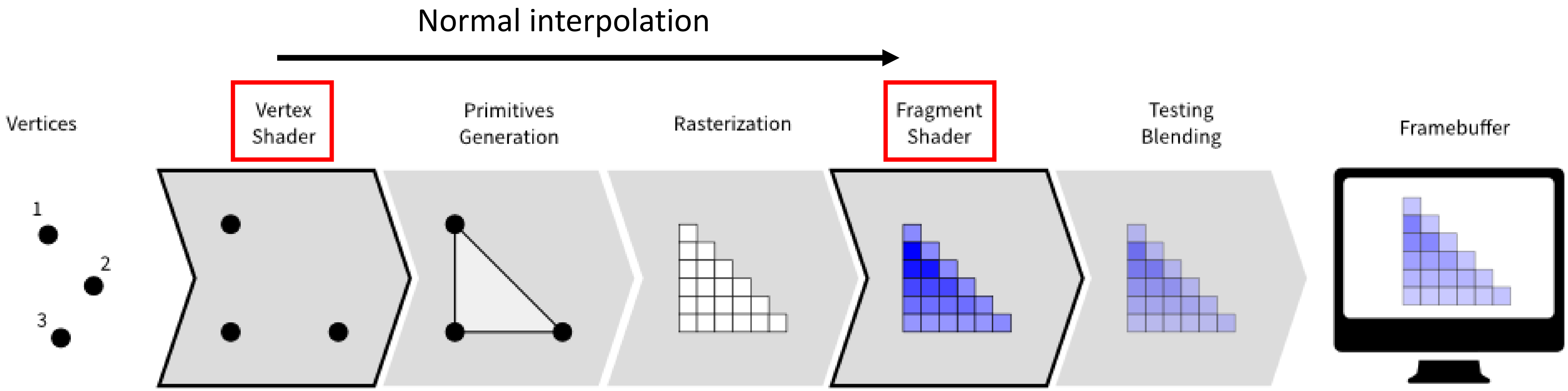
Normal interpolation

- If **n** is a normal vector of a vertex P:
- $\mathbf{n}_{A,i+1} = \mathbf{n}_{A,i} - \Delta\mathbf{n}_A$
- $\mathbf{n}_{B,i+1} = \mathbf{n}_{B,i} - \Delta\mathbf{n}_B$
- $\mathbf{n}_{C,i+1} = \mathbf{n}_{C,i} - \Delta\mathbf{n}_C$

- Where
- $\mathbf{n}_A = \frac{\mathbf{n}_3 - \mathbf{n}_1}{y_3 - y_1}, \mathbf{n}_B = \frac{\mathbf{n}_3 - \mathbf{n}_2}{y_3 - y_2}, \mathbf{n}_C = \frac{\mathbf{n}_B - \mathbf{n}_A}{x_B - x_A}$

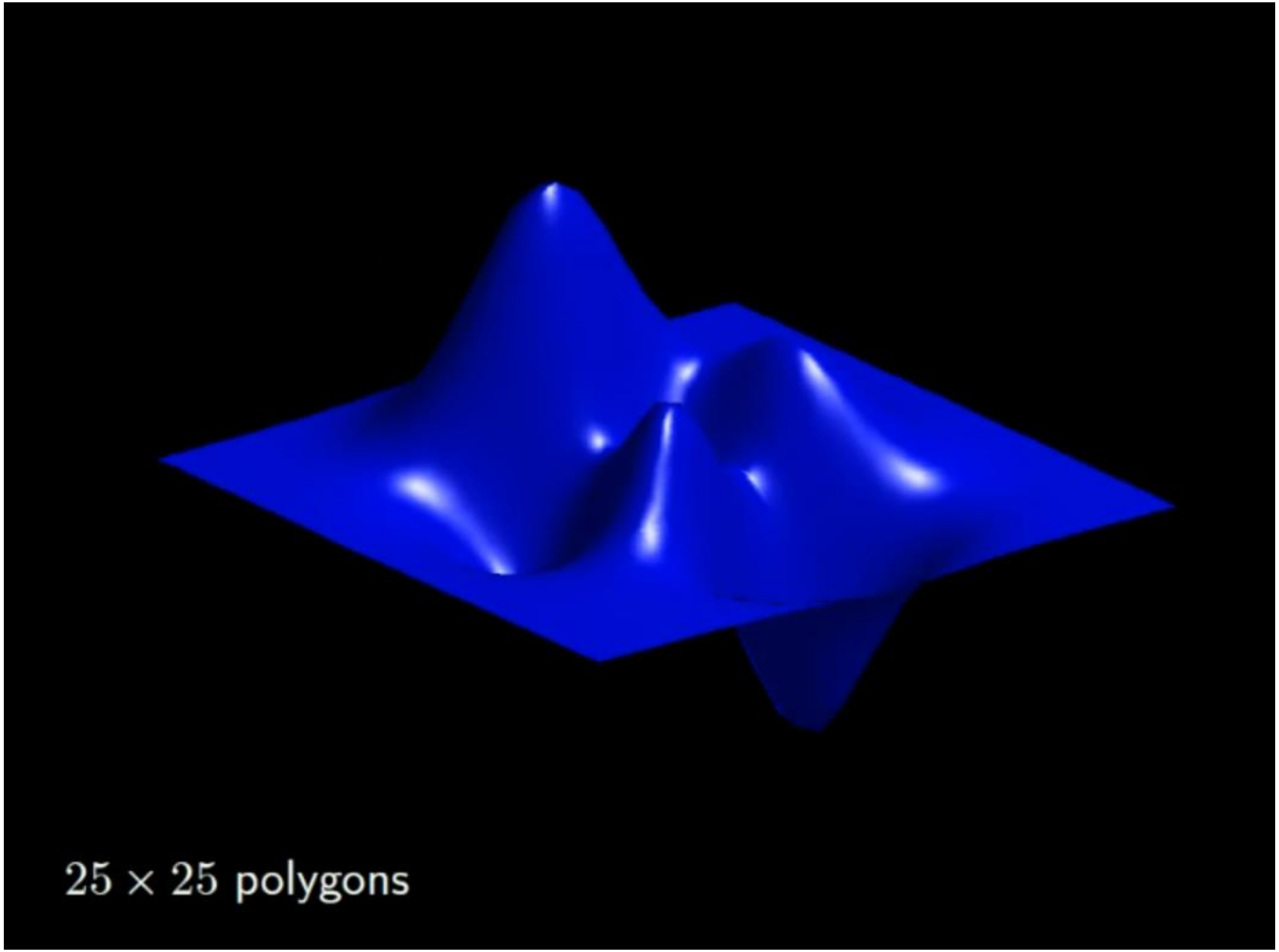


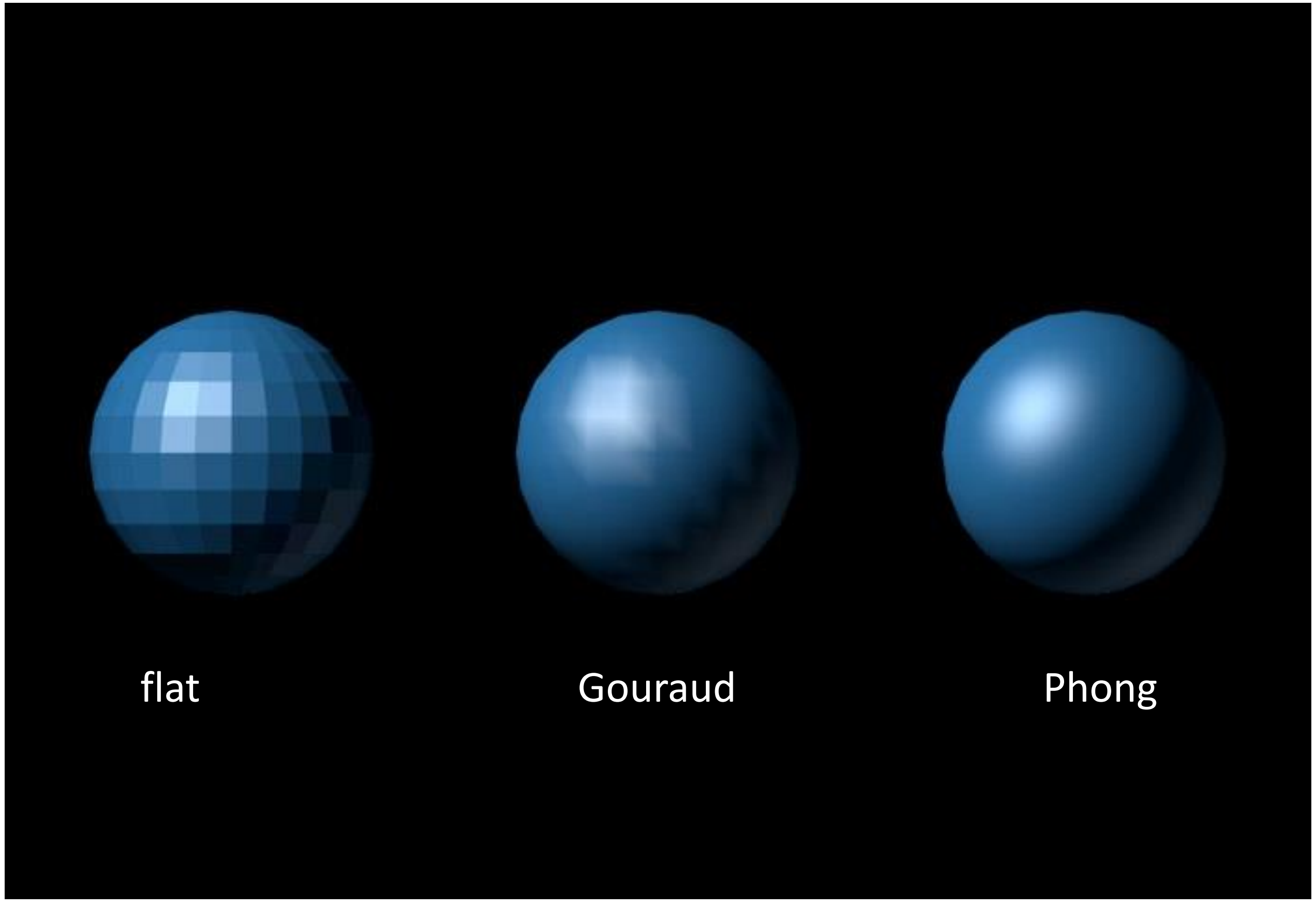
OpenGL



Normal interpolation
Vertices
1
2
3
Vertex Shader
Primitives Generation
Rasterization
Fragment Shader
Testing Blending
Framebuffer

Normal Map Visualized with RGB Model


25 × 25 polygons

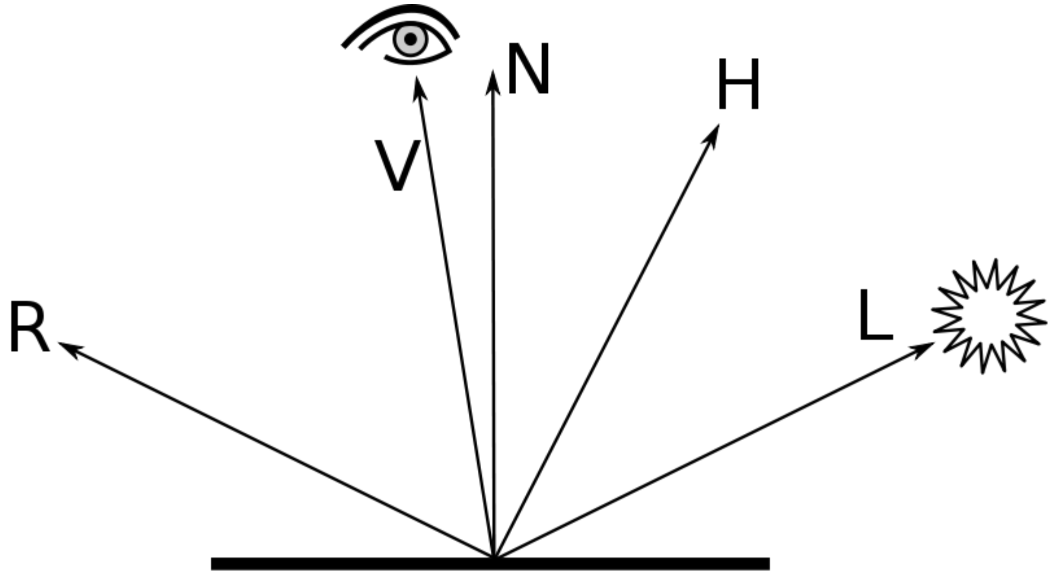

flat
Gouraud
Phong

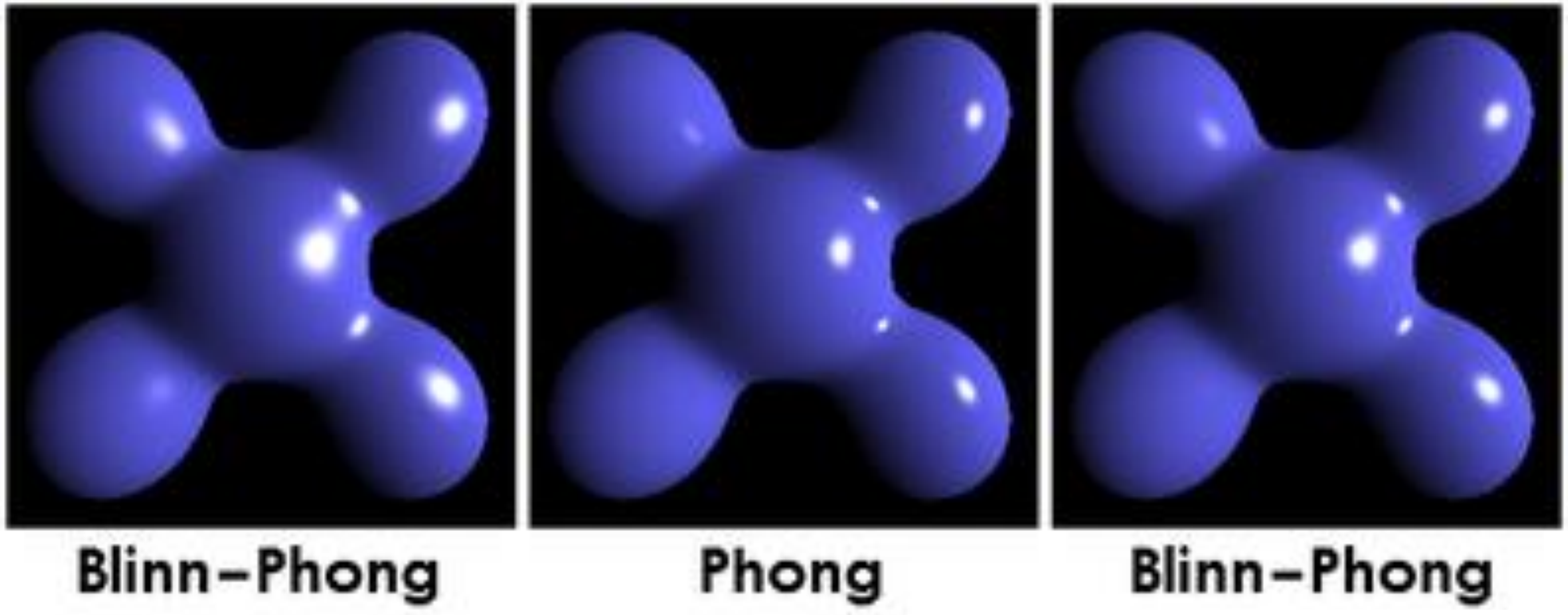
Blinn-Phong

- A popular variation of the Phong model implemented in OpenGL and Direct3D
- Instead of calculating vector R we define a unit vector exactly half-way between light vector L and the view vector V

- $\boldsymbol{I_p k_s (N \cdot H)^n}$, where $\boldsymbol{H} = \frac{\boldsymbol{L+V}}{|\boldsymbol{L+V}|}$

- Calculation of H is more efficient than R





Higher exponent

https://en.wikipedia.org/wiki/Blinn%E2%80%93Phong_shading_model