Introduction to light shading for real-time rendering

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(Zavie / Ctrl-Alt-Test)

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Introduction

Light, according to Wikipedia:

Light or visible light is electromagnetic radiation that is visible to the human eye, and is responsible for the sense of sight.

Introduction

Les raboteurs de parquet, Gustave Caillebotte, 1875

(some) Physics of light

Physics of light

Properties of light:

- Direction
- Intensity
- Speed
- Wavelength
- Polarization

Physics of light

Speed of light: *c = 299 792 458 m/s* in a vacuum

Thought to be the upper bound of speed in the Universe
(guys at LHC are trying to prove otherwise ;))

Early experiments to measure speed of light:

- 1676, Ole Rømer: 22mn for 2AU (227 000 000 m/s)
- 1849, Hyppolyte Fizeau: 315 300 000 m/s
- 1862, Léon Foucault: 298 000 000 m/s
- 1926, Albert A. Michelson: 299 796 000 m/s
- 1983, Bureau des poids et mesures: ***c***

Physics of light

Visible light is an electromagnetic wave

Wavelength: ~380nm (violet) to ~780nm (red)

Christian Huygens (1629 - 1695)
Thomas Young (1773 - 1829)

Augustin Fresnel (1788 - 1827)



Physics of light

An electromagnetic wave is defined by:

- Its electric field, *E*
- Its magnetic field, *B*

Light being an electromagnetic wave, Maxwell's equations apply

- div E = ρ / ε0
- div B = 0
- B = rot A
- rot E = -∂B / ∂t

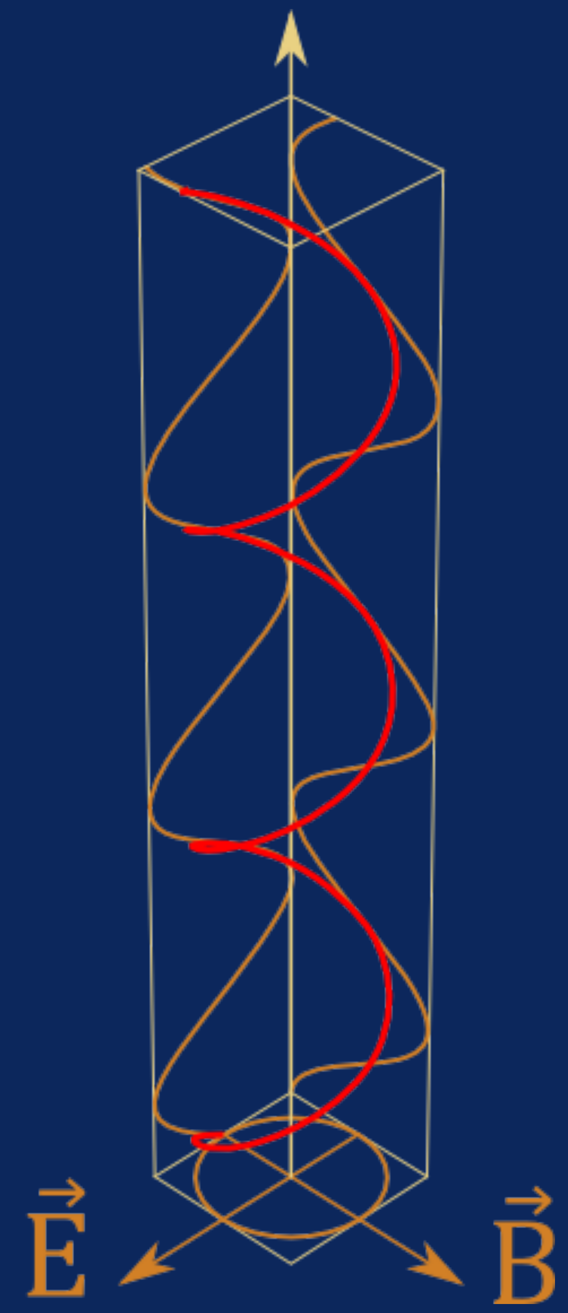
James Maxwell (1831 - 1879)

Physics of light

Phase between *E* and *B* can vary

It defines the polarization

We will not talk about it,
but let's remind it does exist



Physics of light

An electromagnetic wave will interact with matter;
Fresnel equations describe that interaction

From *Eric W. Weisstein's World of Physics*:

The Fresnel equations give the ratio of the reflected and transmitted electric field amplitude to initial electric field for electromagnetic radiation incident on a dielectric.

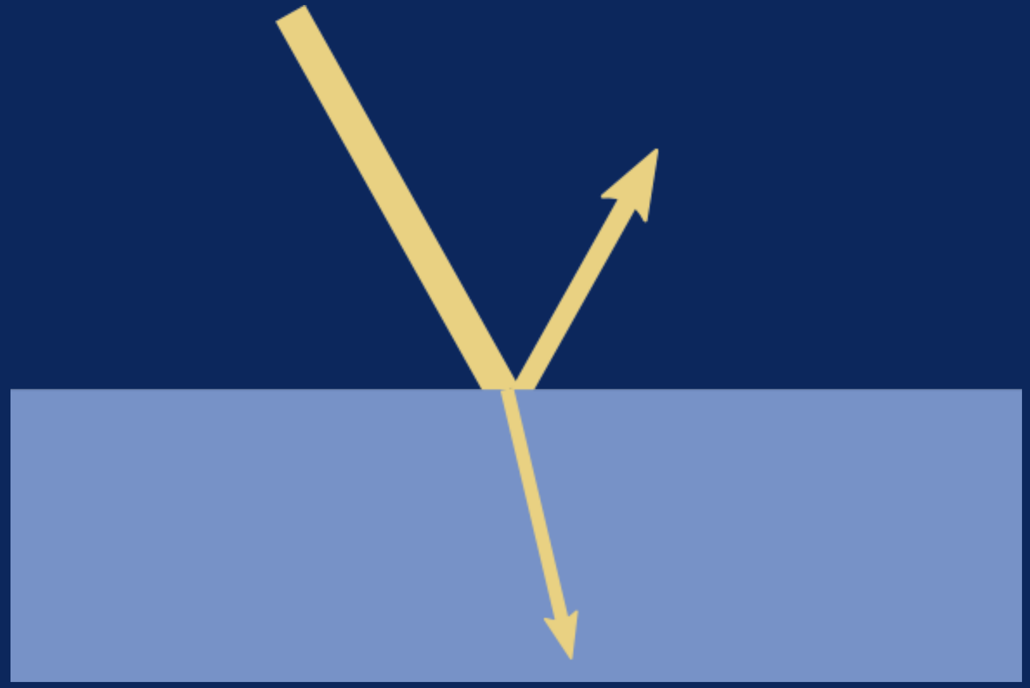
But, what do they mean, really?

Physics of light

In the case of light:

Given an incoming beam of light on a material

- how much of it is reflected?
- how much of it is transmitted?

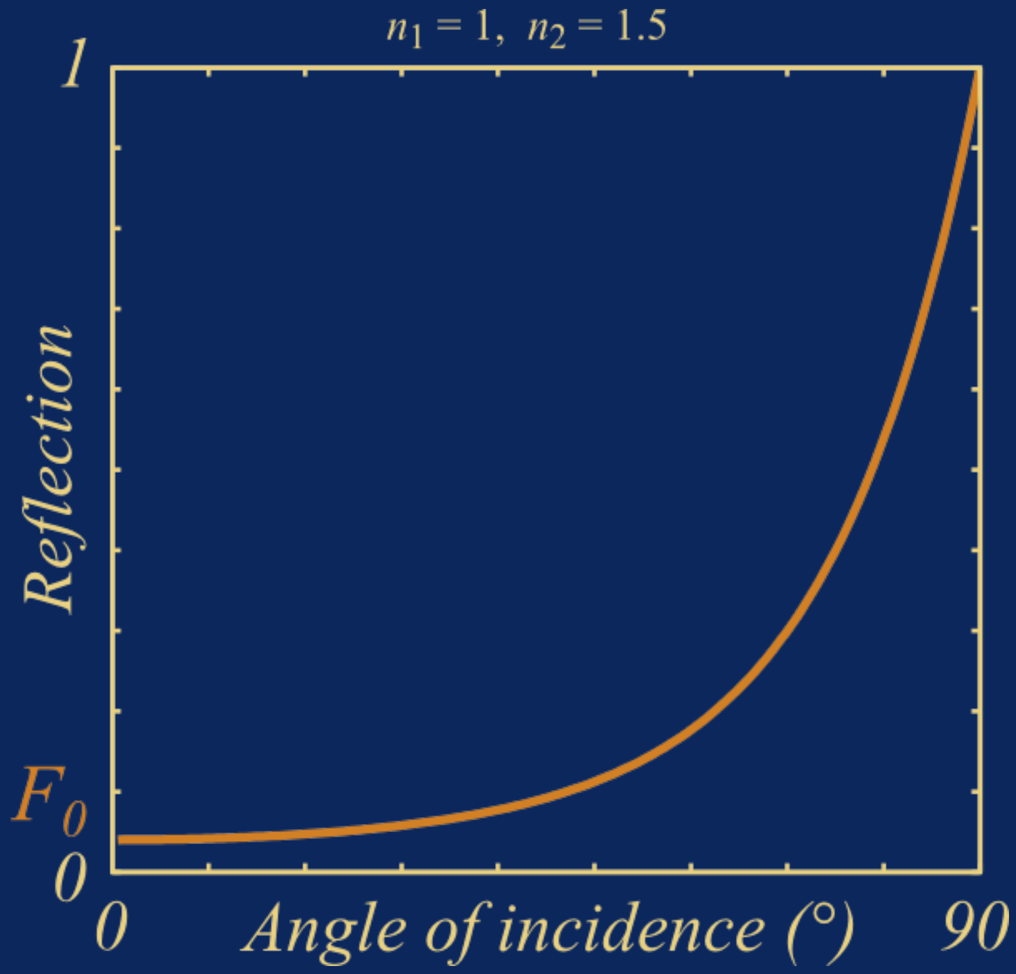


Physics of light

Reflection depends on the refractive indices, wavelength, and angle of incidence

F_0 specific to the material

Reaches 1 at 90° for all materials

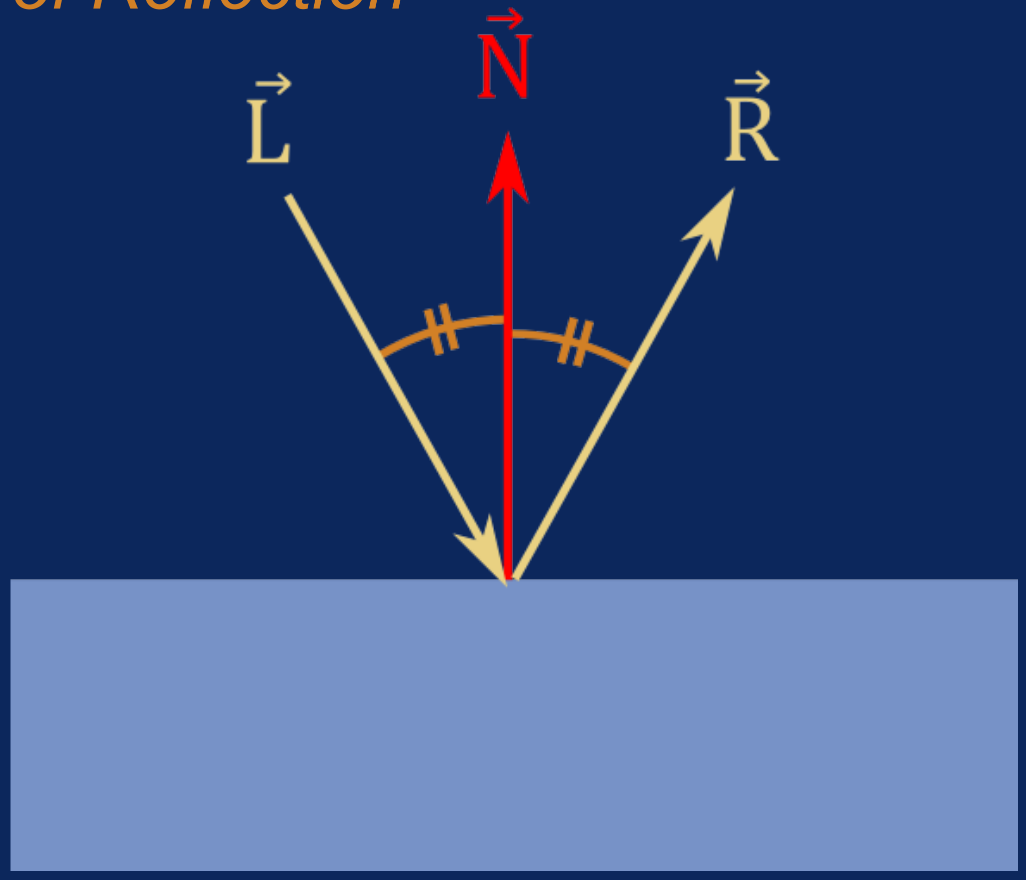


Physics of light

Reflected light bounces off

Direction given by the *Law of Reflection*

angle of incidence
equals
angle of reflection



Physics of light

Reflected light is referred to as the **specular component**

Physics of light

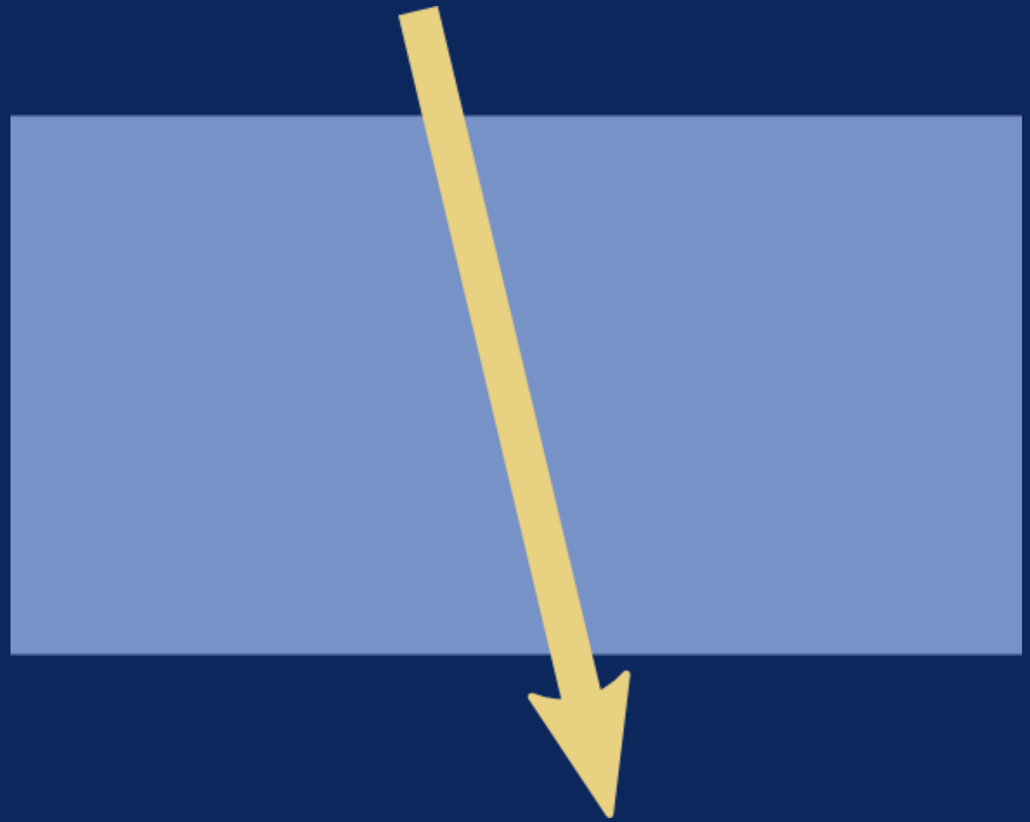
When the surface is not perfectly flat, reflection spreads

Physics of light

Transmitted light may **propagate**

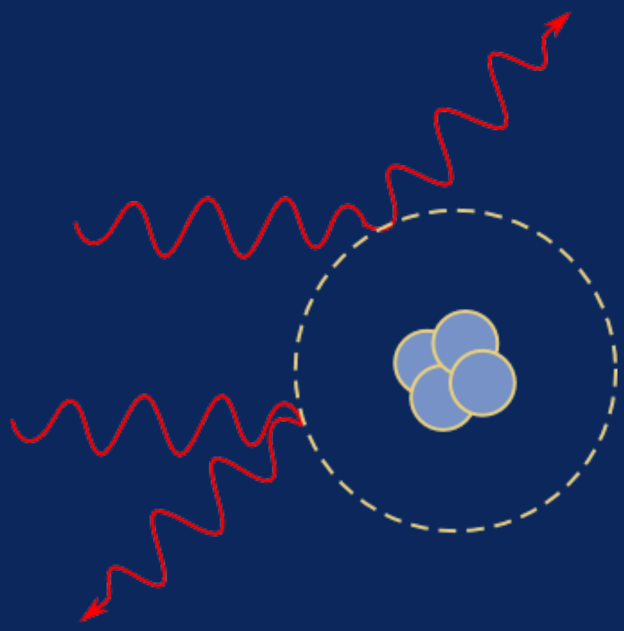
(direction given by Snell's Law, that's refraction)

Water, glass, air...



Physics of light

Photons may bounce when hitting particles

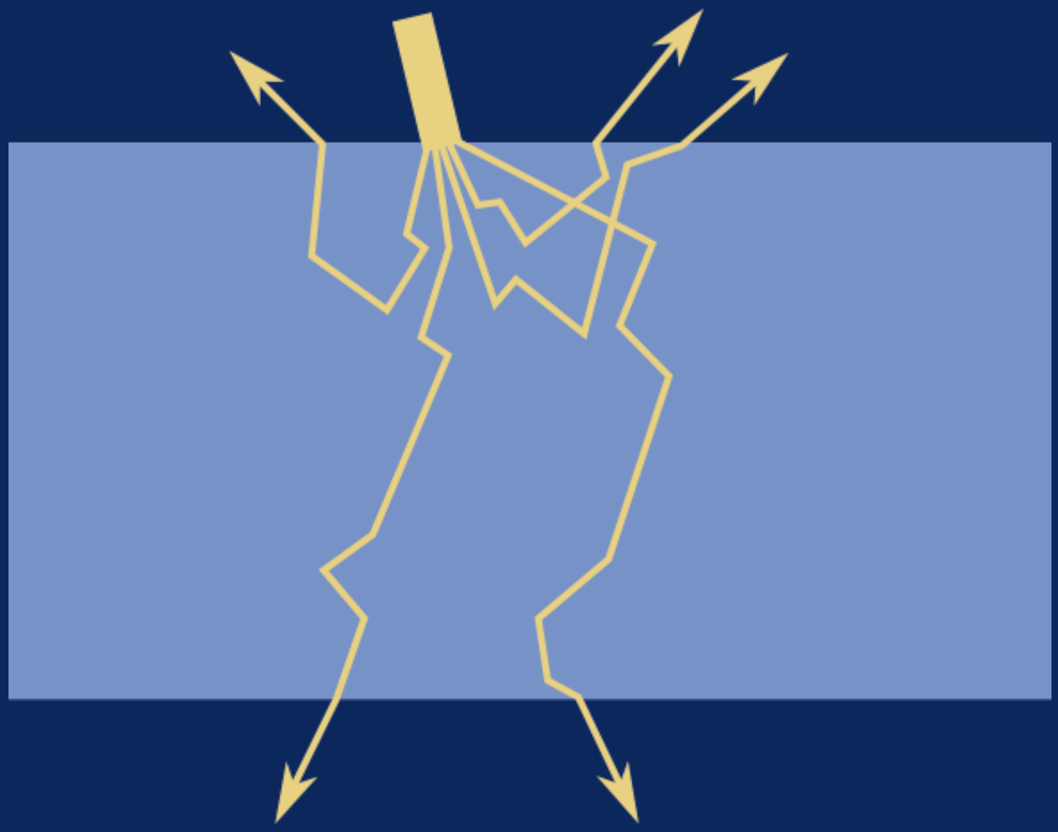


Direction is random, and they can bounce again

Physics of light

Transmitted light may **scatter**

Light gets out in random directions



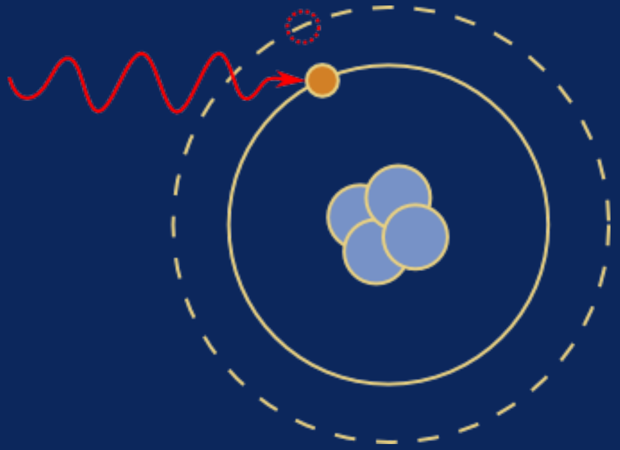
Physics of light

Transmitted light may **scatter**

At macroscopic scale, light re-emerges in all directions

Physics of light

Photons may be absorbed by electrons

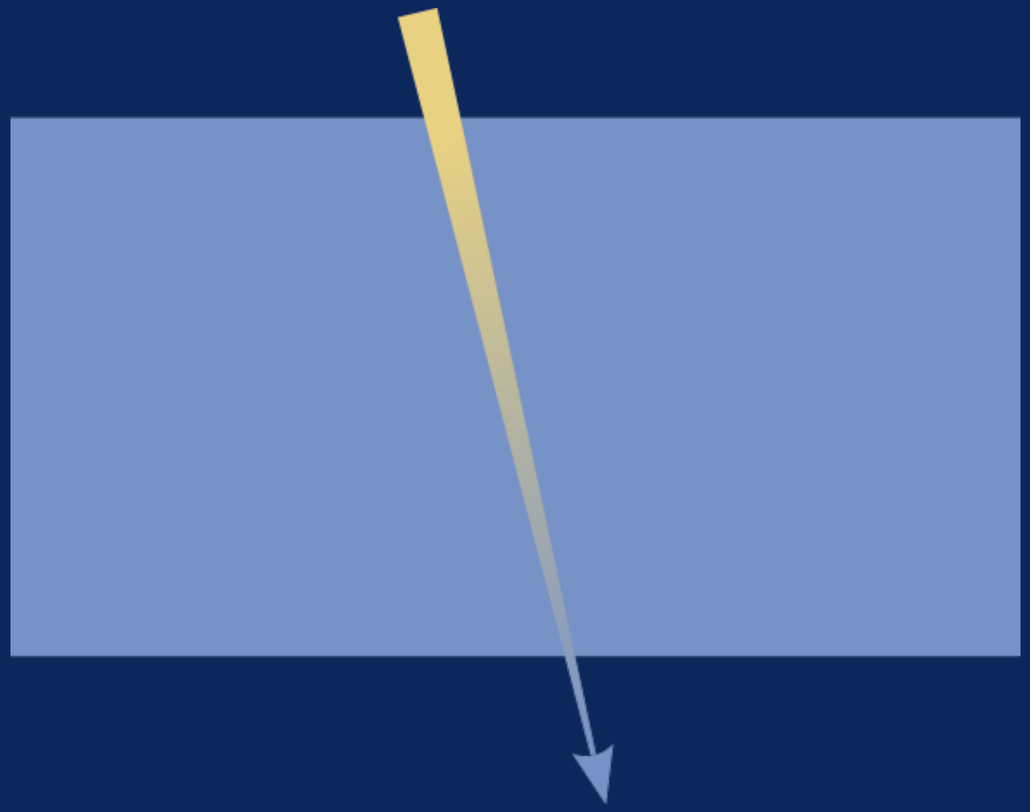


Electrons get elevated to a higher energy state (causing heat)

Physics of light

Transmitted light may **be absorbed**

Colored water, tinted glass...



Physics of light

Transmitted light may scatter, be absorbed, then re-emerge

This re-emerging light is referred to as the **diffuse component**

If distance from entry is short enough, assume point; otherwise this is subsurface scattering

Physics of light

Summary:

Reflected light bounces off
This is the **specular** component

Transmitted light may partly come back
This is the **diffuse** component

Fresnel coefficients give the ratio between them

Physics of light

From Wikipedia:

A piece of highly polished white marble remains white; no amount of polishing will turn it into a mirror.

Physics of light

For metals or semiconductors **all** transmitted light is **absorbed**

Physics of light

For metals or semiconductors **all** transmitted light is **absorbed**

Metals do not have a diffuse component

Physics of light

For metals or semiconductors **all** transmitted light is **absorbed**

Metals do not have a diffuse component

Color of metals is due to specular

Physics of light

So specular really is physically different from diffuse

- Actually specular and diffuses have different polarization
- Specular can be filtered out thanks to polarizing filters
- Photographers do so to reduce reflections

Really <u>all materials do have specular</u>, not only shiny ones

Specular gives visual clue about surface (details, roughness)

Physics of light

Diffuse only:

Specular only:

Article by John Habble:
http://filmicgames.com/archives/233

(some) Shading models

Shading models

Diffuse model:

- Lambert

Specular reflection models:

- Phong
- Blinn-Phong
- Inexpensive anisotropic shading

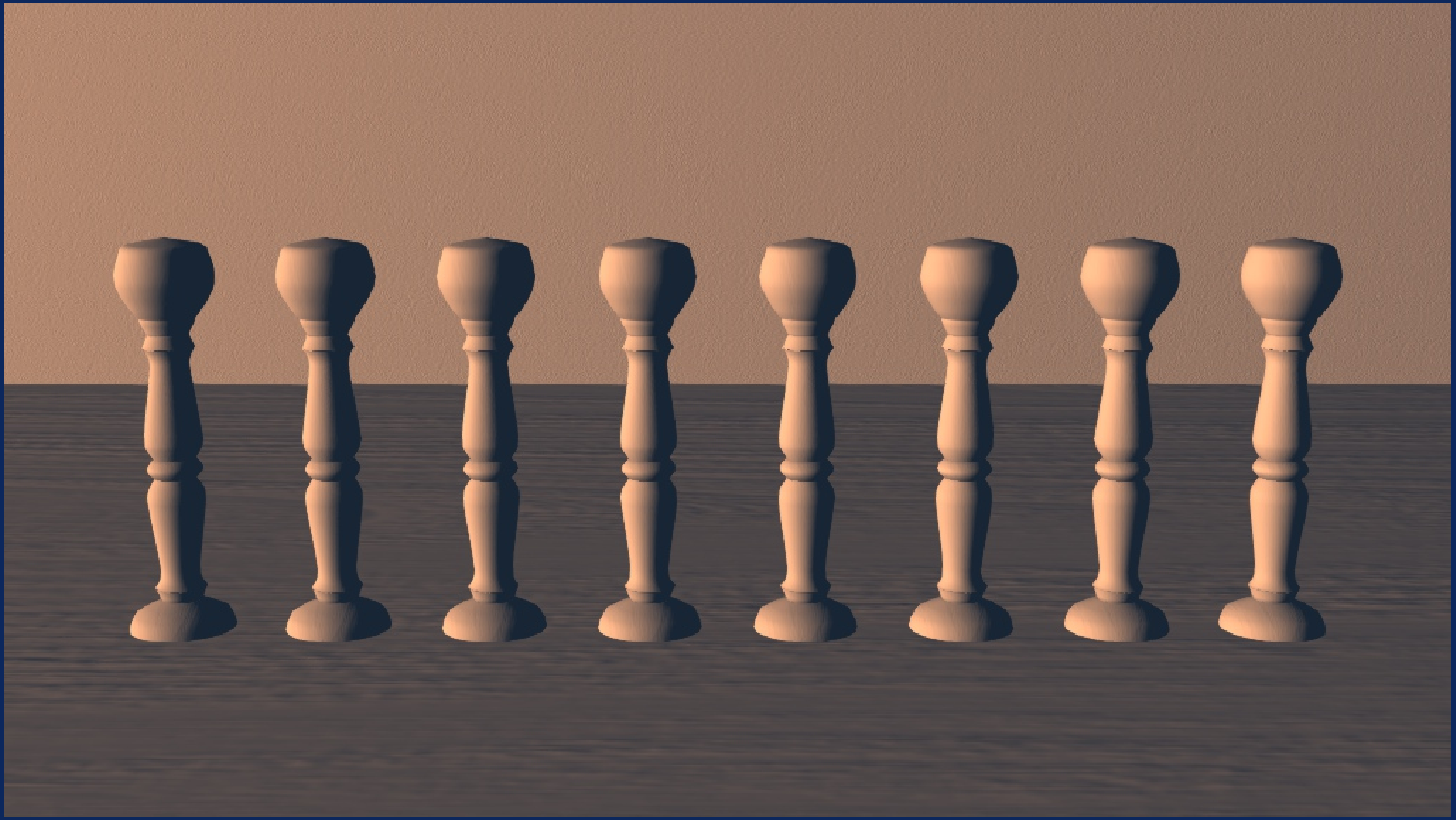
Shading models: Lambert

1760, Johann Heinrich Lambert:
"Photometria"

- *Lambertian reflectance :* ***d = N·L***
- Models an ideal diffuse material
- Assume light to be evenly reflected in all directions
- Reflection does not depend on direction of the viewer
- Simple, intuitive, cheap

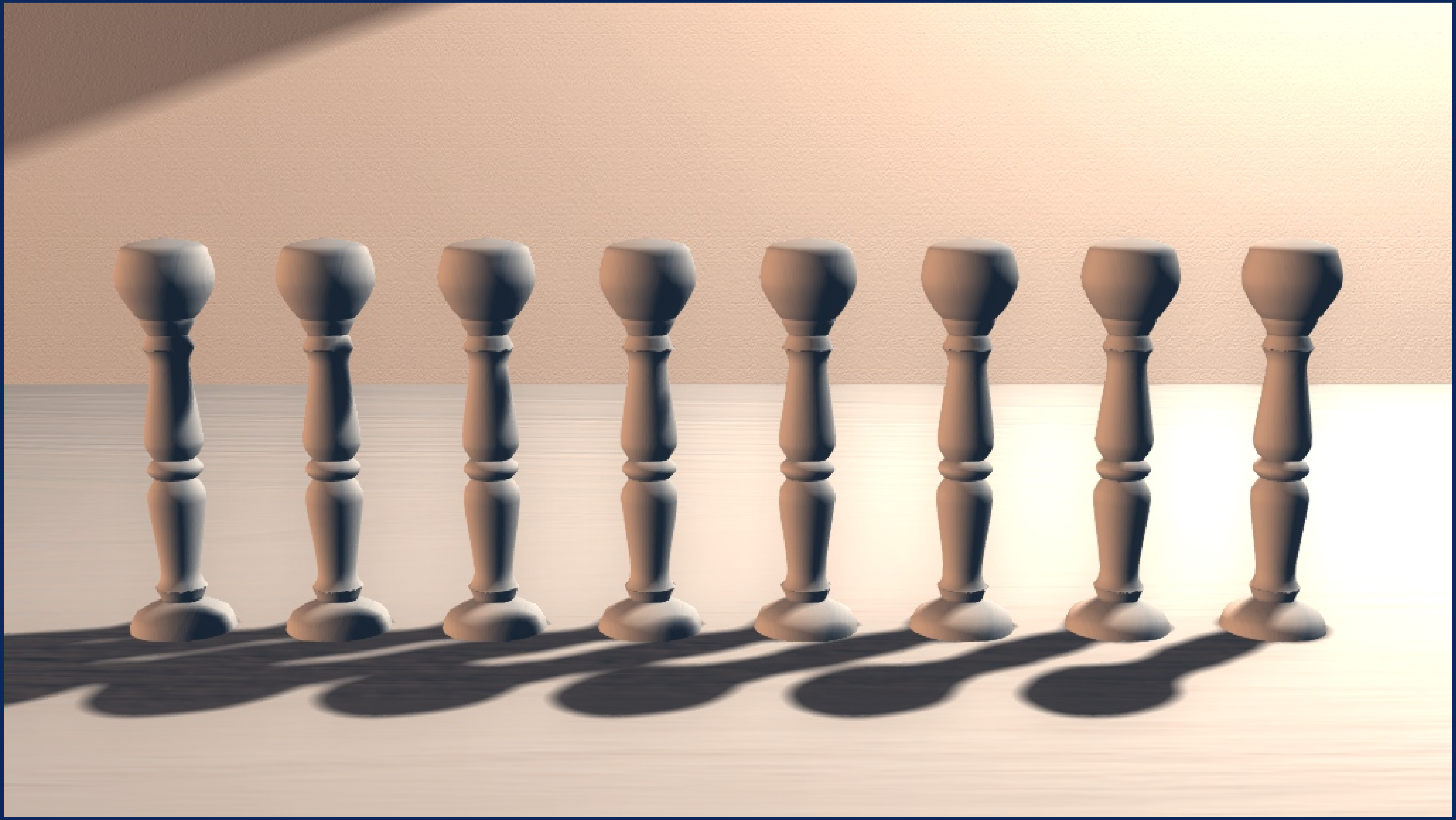
Shading models: Lambert

Lambert diffuse:



Shading models: Lambert

Lambert diffuse, two lights:



Shading models: Lambert

Lambert diffuse, two lights + albedo:

Shading models: Lambert

In reality, materials are not ideal diffuse

Lambertian reflectance is often close enough though

A good example of non Lambertian object: the Moon

Some papers propose more advanced models

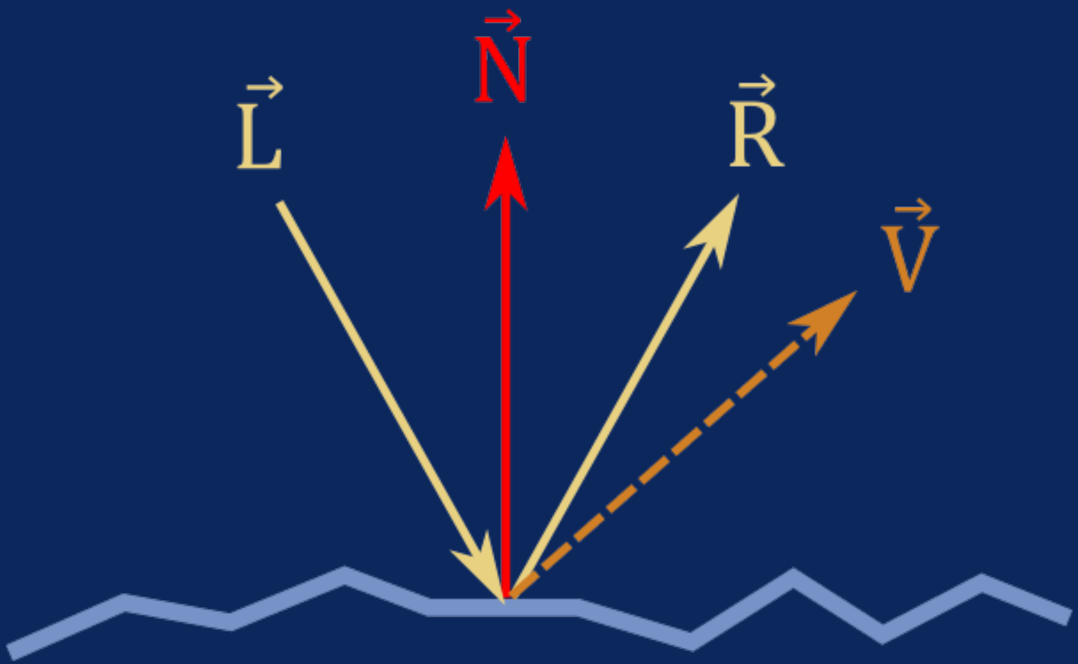
Shading models: Phong

1973, Bui-Tong Phong:
"Illumination for Computer Generated Pictures"

- Empirical model
- Simple
- Somewhat convincing
- Not physically plausible

Shading models: Phong

L : incoming light beam
R : reflected beam for an ideal surface
V : toward viewer



How much light goes in direction *V* ?

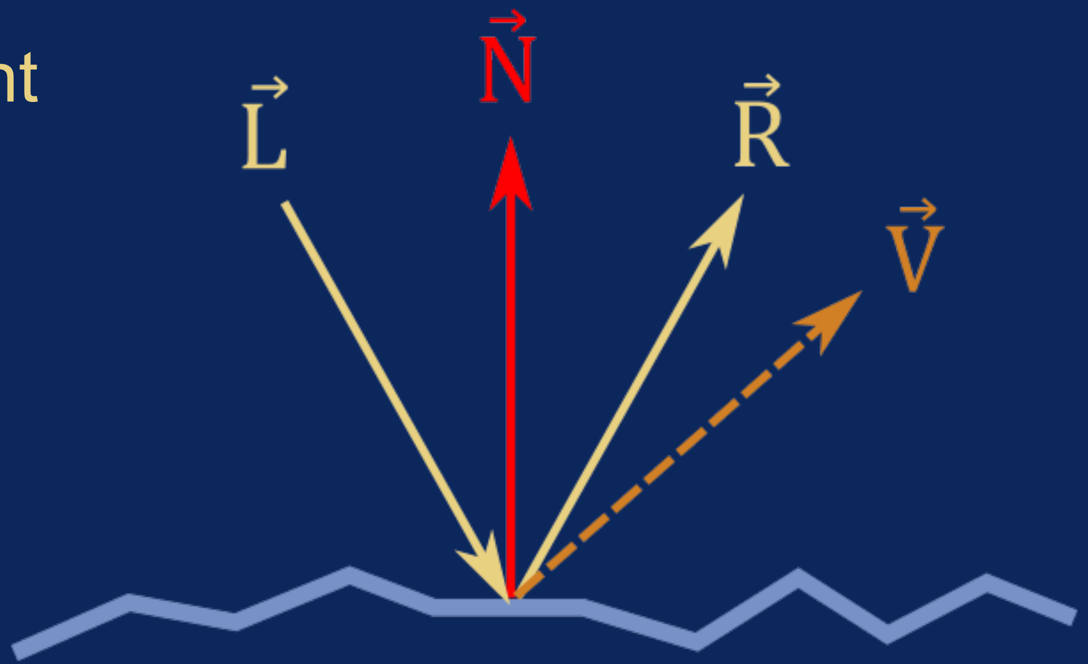
Shading models: Phong

"Closeness" of V and R: V·R

- 1 if V = R
- 0 if V ⊥ R

"Narrow" with an exponent

$s = (\underline{V \cdot R})^n$



Shading models: Phong

Diffuse only:

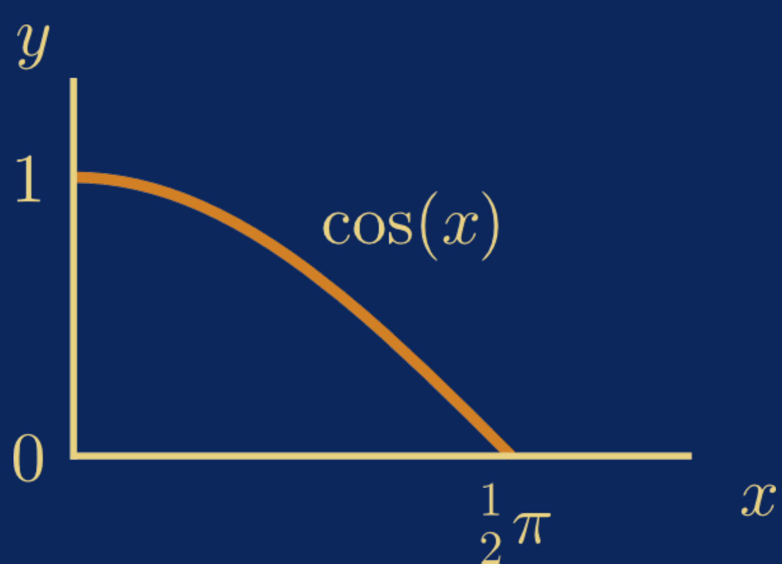
Shading models: Phong

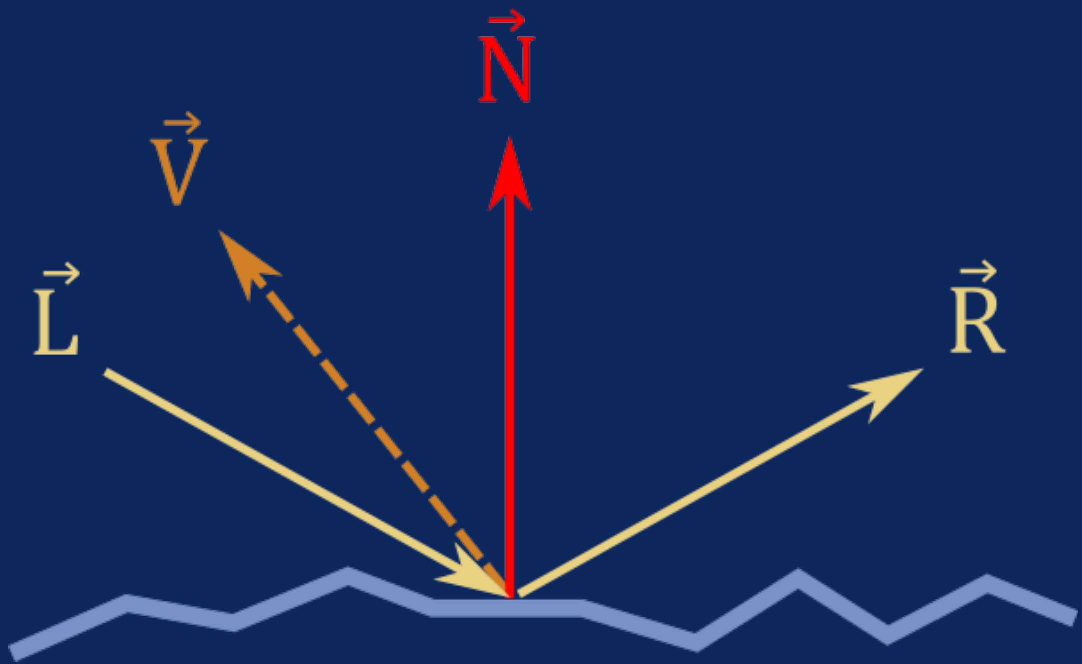
Diffuse + Phong specular:

Shading models: Phong

Dot product is the cosinus of the angle between two vectors

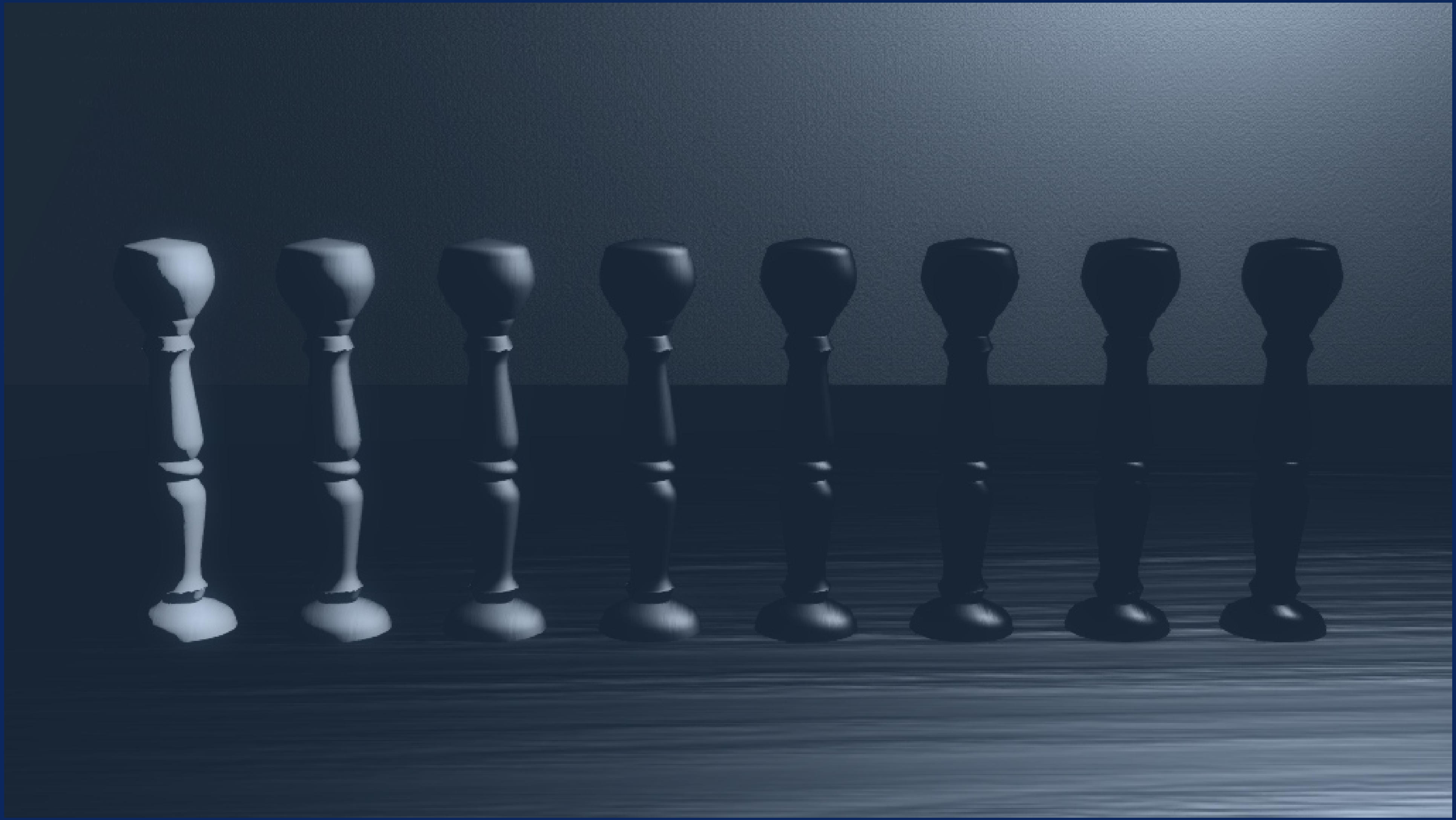
What happens when *angle(V, R) > 90°* ?





Shading models: Phong

Phong specular discontinuity:



Shading models: Blinn-Phong

1977, Jim Blinn:
"Models of light reflection for computer synthesized pictures"

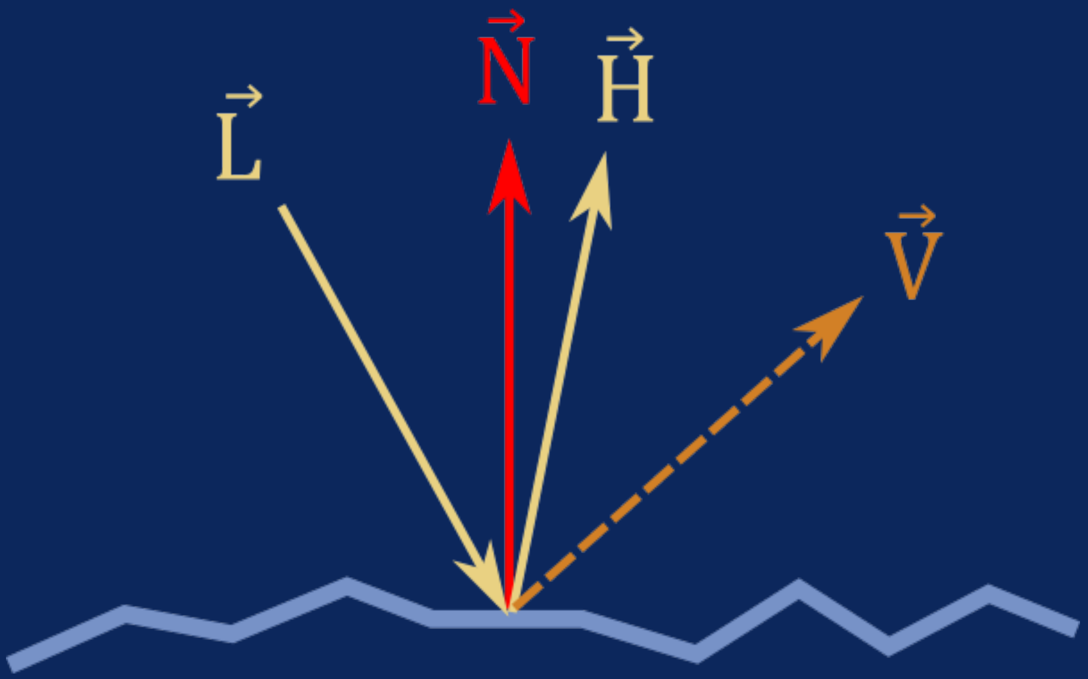
- Improves over Phong model
- Still empirical model
- Takes reality into account
- Still not physically plausible

Shading models: Blinn-Phong

L : incoming light beam
V : toward viewer

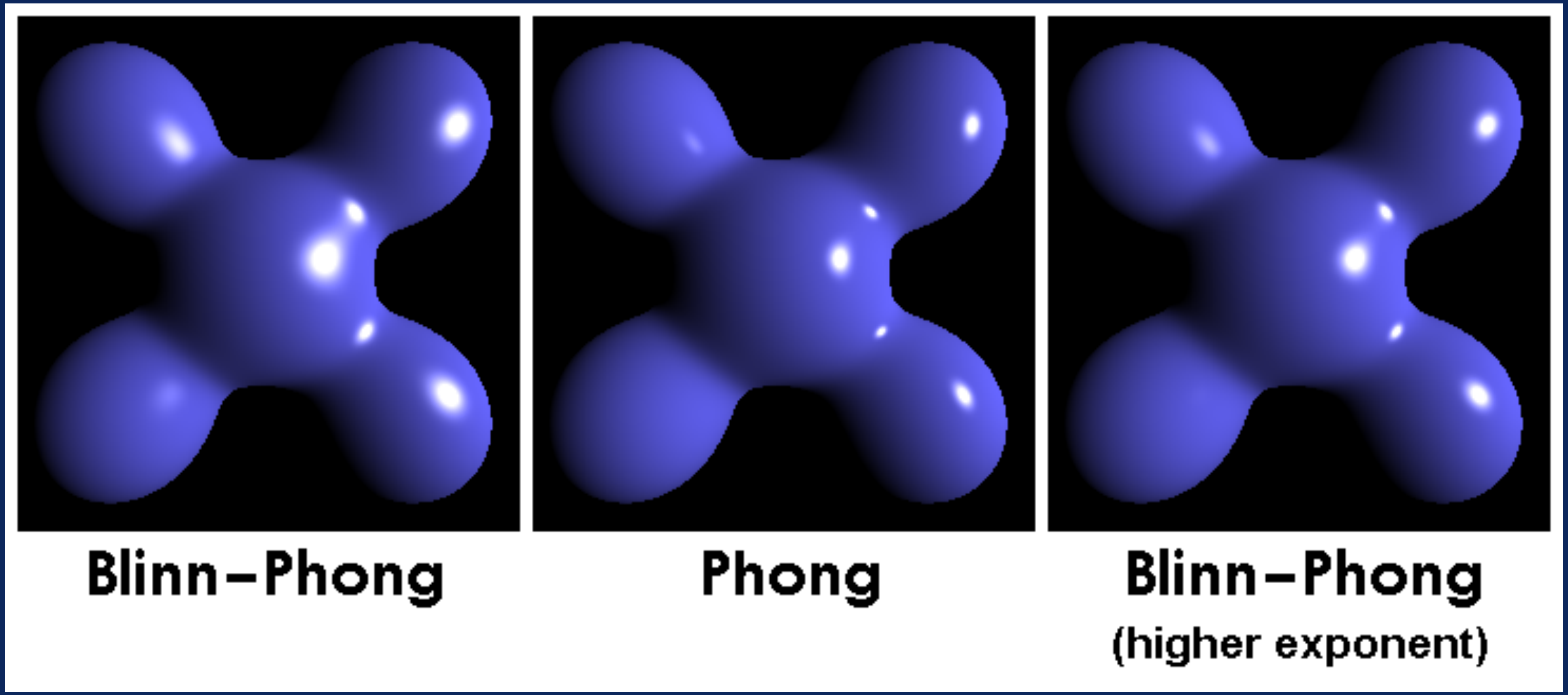
No more *R*

Introduce *H = (-L+V) / 2*
halfway between *L* and *V*



Shading models: Blinn-Phong

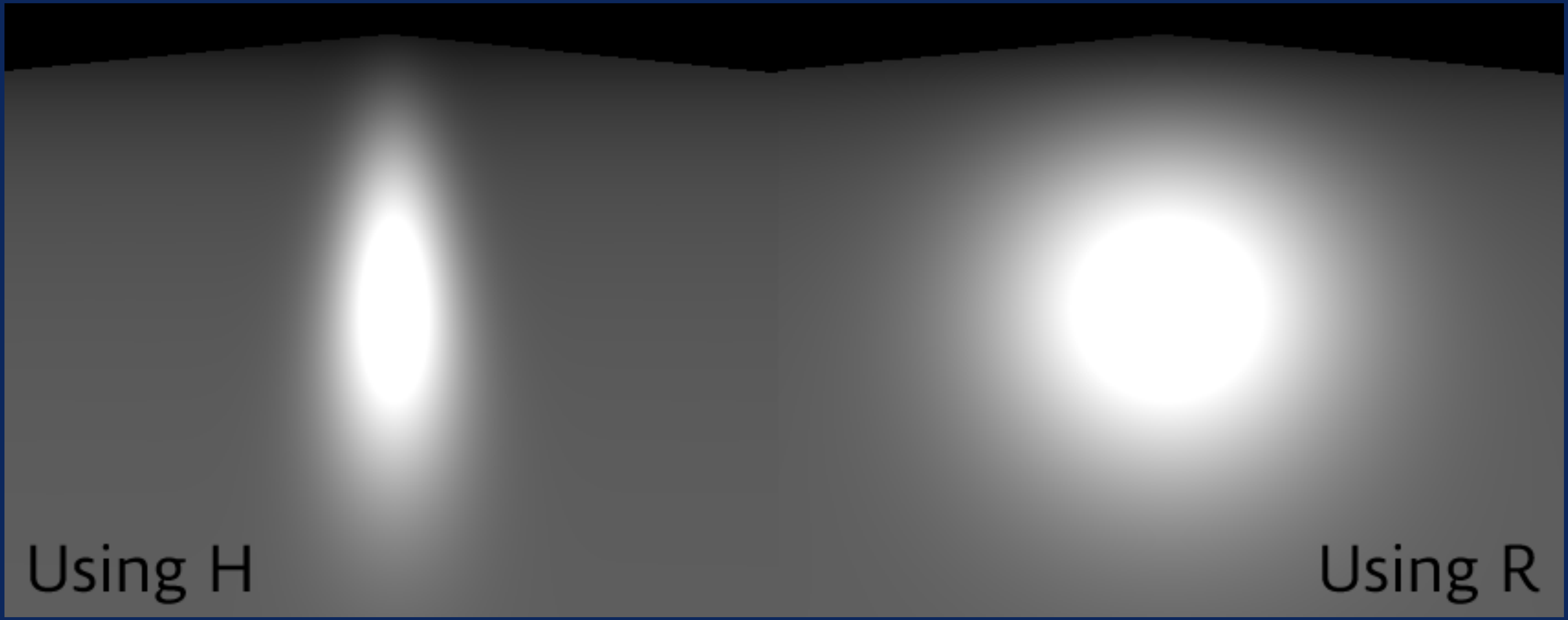
Image from the Wikipedia article:



...obvious, isn't it?

Shading models: Blinn-Phong

A different example:



Shading models: Blinn-Phong

...looks familiar?

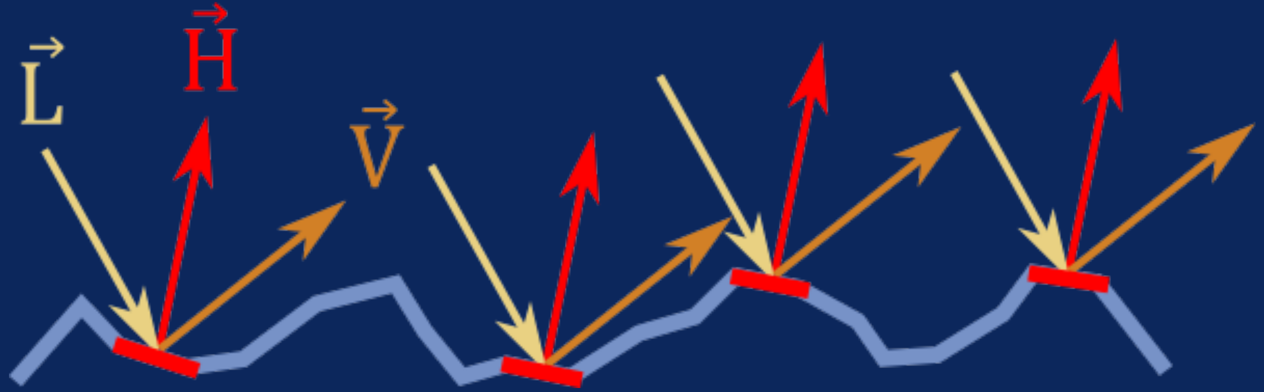
Photo: Golden Charles of Praha, by Éole

Shading models: Blinn-Phong

Consider the material surface made of microscopic facets

Suppose some facets reflect light toward viewer

The normal of those facets would be... *H*



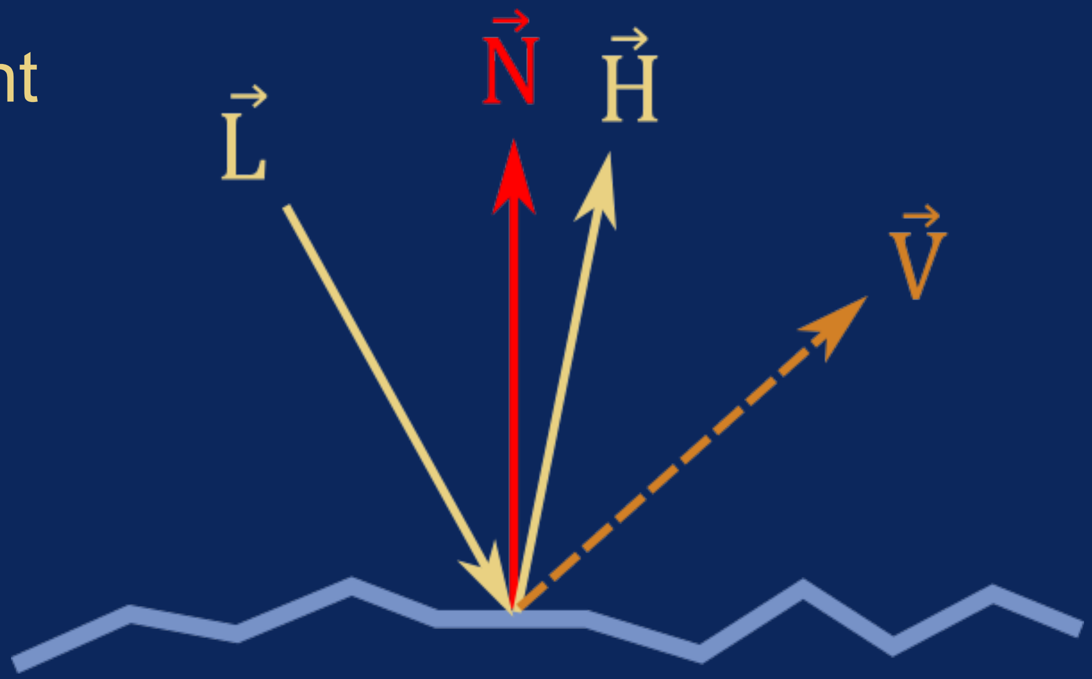
Shading models: Blinn-Phong

How likely is it to have facets with normal *H* ?

"Closeness" of *N* and *H*: *N·H*

"Narrow" with an exponent

$$s = (\underline{N \cdot H})^n$$



Shading models: Blinn-Phong

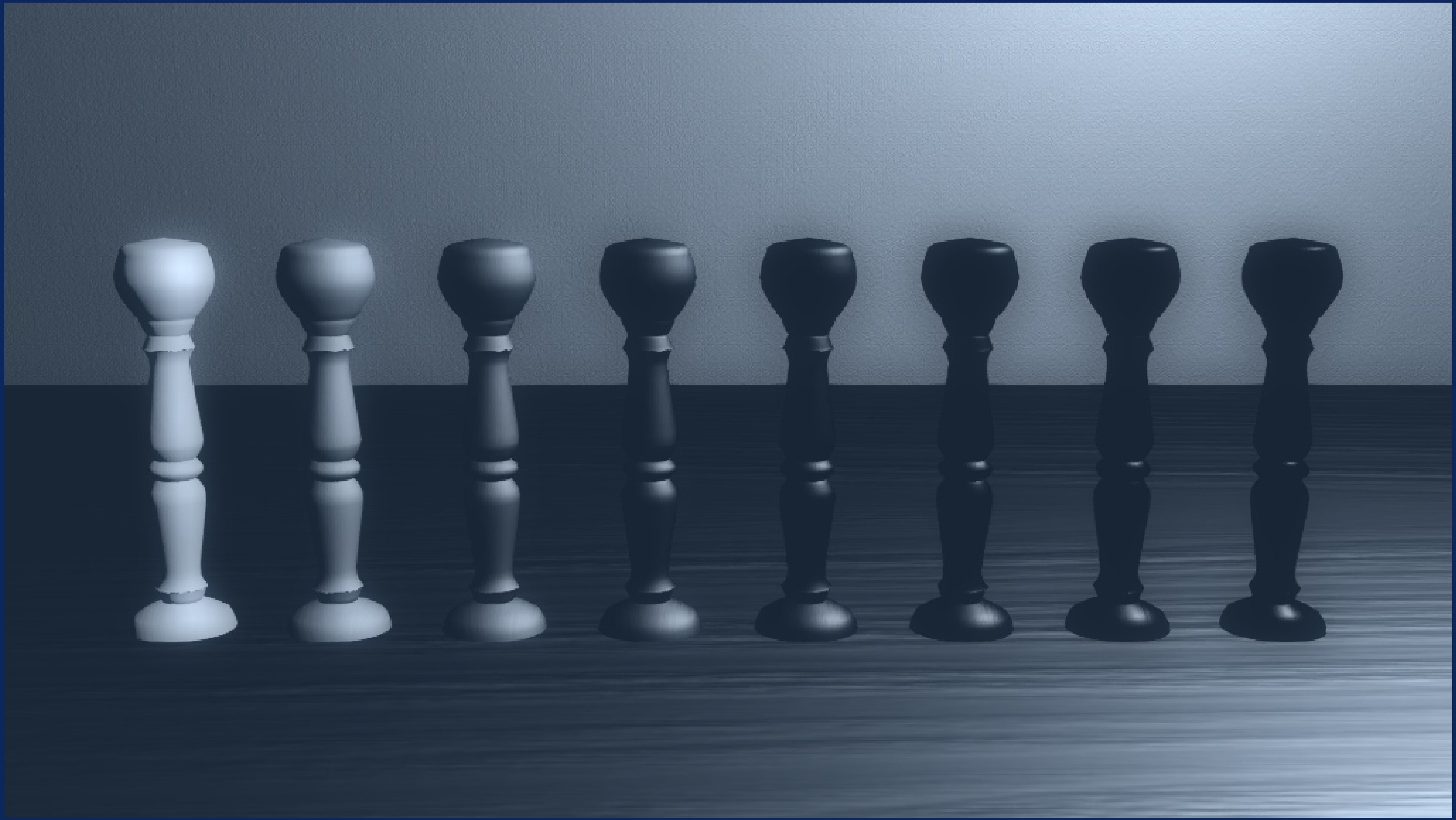
Diffuse + Phong specular:

Shading models: Blinn-Phong

Diffuse + Blinn-Phong specular:

Shading models: Blinn-Phong

No discontinuity:



Shading models: anisotropic lighting

So far we assumed lighting is direction independent

That is, **isotropic**

What if facets are direction biased?
Grooves, brushed metal, etc.

Lighting will be **anisotropic**

Shading models: anisotropic lighting

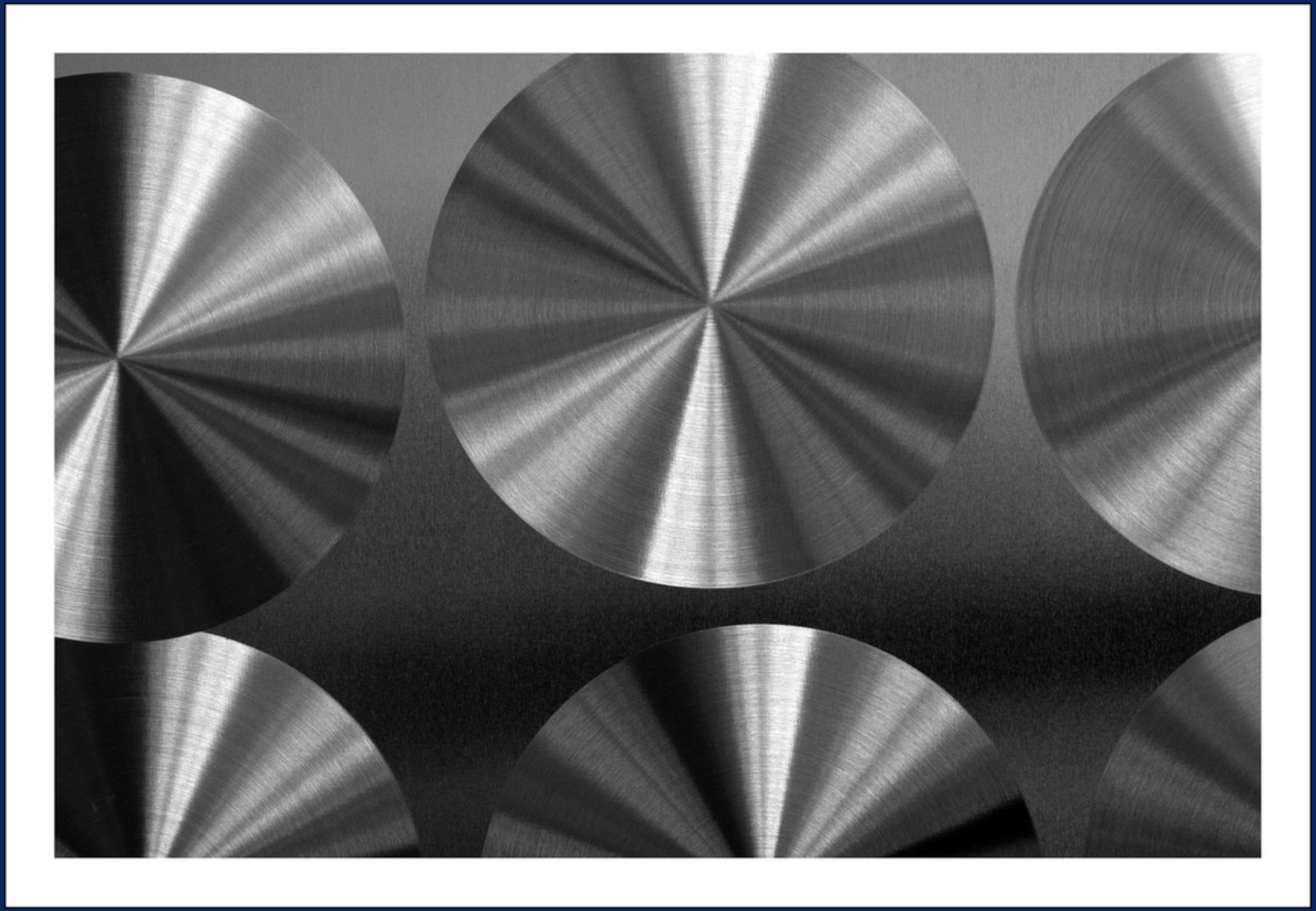


Photo: Brushed metal, by Brett Oliver

Shading models: anisotropic lighting

1998, Wolfgang Heidrich and Hans-Peter Seidel:
"Efficient Rendering of Anisotropic Surfaces Using Computer Graphics Hardware"

- Assume surface to be made of strands
- Simple implementation
- Convincing result

Shading models: anisotropic lighting

A strand has an infinity of normals

Instead of integrating, assume most significant reflection to come from one normal

L: incoming ray of light
N: most significant normal
T: strand tangent

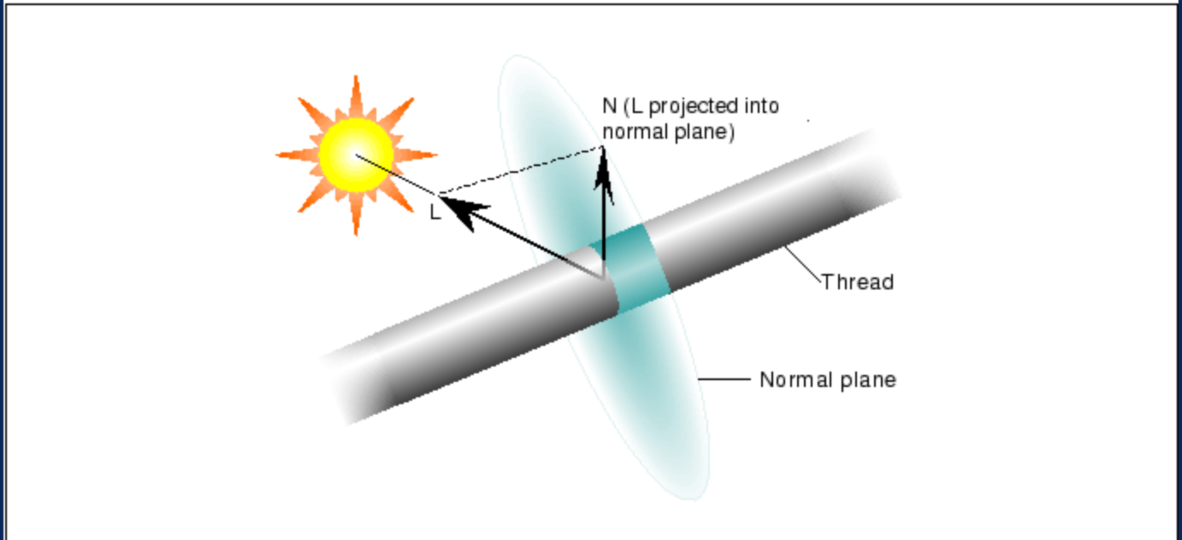


Figure 51. Projecting Light Vector to Maximize Lighting Contribution

Specular: $s = RV =$

$$L \cdot T \times V \cdot T - \mathrm{sqrt}(1 - L \cdot T^2) \times \mathrm{sqrt}(1 - V \cdot T^2)$$

Shading models: anisotropic lighting

Anisotropic specular:

(toward) Physically based shading

Physically based shading

Many models are not physically correct

Experimental approach, ad hoc formulas

Visual result more important than correctness

Some shading models are not even plausible

For example, material reflecting more light than it received

Physically based shading

Artists can achieve intended result via tweaking

Visual result can get convincing

But values get (very) disconnected from reality

Change one parameter (lighting conditions, material)...

...and it falls apart

Physically based shading

With physically based shading:

- Implementation makes more sense, and is easier to modify
- Less values to tweak, more physically correct values
- Physically based shading gives more robust result
- As a coder, it reduces the artistic needs
- In the end: *Better Looking Result*

PBS: normalization

Switch to an energy conserving model

- A material should not reflect more light than it receives
- The used light equation should reflect that

- Integrate the equation over the hemisphere
- Deduce a *normalization factor*
- Apply it to the equation

PBS: normalized Phong

Normalized Phong model:

- Original equation: $s = (V \cdot R)^n$
- Normalization factor: $(n + 1) / 2\pi$
- Normalized version: $\boldsymbol{s = (V \cdot R)^n \times (n + 1) / 2}$

PBS: normalized Phong

Original Phong specular:

PBS: normalized Phong

Normalized Phong specular:

PBS: normalized Blinn-Phong

Normalized Blinn-Phong model:

- Original equation: $s = (N \cdot H)^n$
- Normalization factor: $(n + 2)(n + 4) / (8\pi \times (2^{-n/2} + n))$
- Approximation (bounds): $(n + 2) / 8\pi$; $(n + 4) / 8\pi$
- Normalized version: $\boldsymbol{s = (N \cdot H)^n \times (n + 4) / 8}$

PBS: normalized Blinn-Phong

Original Blinn-Phong specular:

PBS: normalized Blinn-Phong

Normalized Blinn-Phong specular:

PBS: a word on microfacet BRDF

BRDF: *Bidirectional Reflectance Distribution Function*

Describes the reflectance of a material over the hemisphere

Usual form of microfacet BRDF:

$$f(L, V) = \frac{F(L, H) \times G(L, V, H) \times D(H)}{4 \times N \cdot L \times N \cdot V}$$

PBS: a word on microfacet BRDF

$$f(L, V) = \frac{F(L, H) \times G(L, V, H) \times D(H)}{4 \times N \cdot L \times N \cdot V}$$

- F(L, H): Fresnel reflectance
- D(H): normal distribution
- G(L, V, H): geometry factor (self occlusion, etc.)

D and G independent, choose as you see fit

"New BRDF" models usually really introduce a new D or G

PBS: Schlick's approximation

1994, Christophe Schlick:
"An inexpensive BRDF model for physically-based rendering"

- Ad hoc models are cheap but unrealistic
- Physically correct models are expensive
- Precision of physically correct models is overkill
- Propose approximations with limited error

PBS: Schlick's approximation

Schlick proposed approximations for the different parts of the Cook-Torrance BRDF model

Schlick's approximation refers to the Fresnel term one:

$$F(\theta) = F_0 + (1 - F_0)(1 - \cos\theta)^5$$

$$\mathbf{F(L, H) = F_0 + (1 - F_0)(1 - L \cdot H)^5}$$

Imaginary part assumed to be 0, leading to significant error for metals; some models improve over this one

PBS: Schlick's approximation

Normalized Blinn-Phong specular, fudge factor (0.2):

PBS: Schlick's approximation

Normalized Blinn-Phong specular, Fresnel term factor:

References

Naty Hoffman's course at SIGGRAPH:
http://renderwonk.com/publications/s2010-shading-course/
Reflectance functions:
http://odforce.net/wiki/index.php/ReflectanceFunctions
Learning Modern 3D Graphics Programming:
http://www.arcsynthesis.org/gltut/

Blog, Light is beautiful:
http://lousodrome.net/blog/light/

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Thank you!

These slides to be found at:
http://lousodrome.net/resources/