

Lecture 7: materials

DHBW, Computer Graphics

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Syllabus

- 3D scene
 - Object
 - Shape
 - **Material**
 - Camera
 - Light
 - Rendering
 - Image and display
- Material
 - Material observation
 - Physics (optics) models for CG
 - Material models in CG
 - Scattering models

Big picture



Materials



<https://www.exp-points.com/asking-the-masters-material-art>



SUBSTANCE
DESIGNER

Material is important for object appearance.
Without material...

Shape and material

- Rendering and creating objects in 3D scene to represent a real world objects requires:
 - Shape representation
- **Shape** is needed for:
 - **Modeling**:
 - Define object form, size, etc.
 - Place object correctly in the scene with respect to other objects
 - **Rendering**:
 - Determine which objects are occluded and areas into which shadow is cast by object → visibility solving



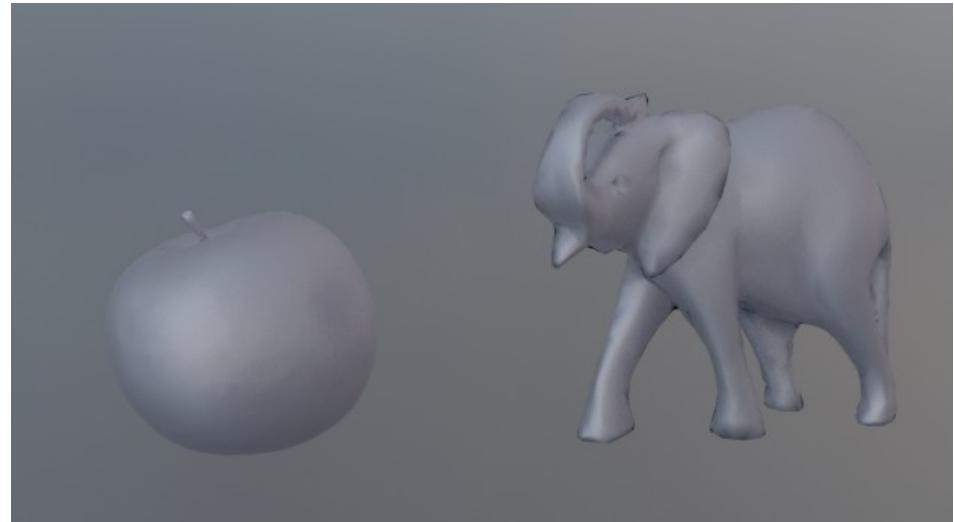
Shape and material

- Rendering and creating objects in 3D scene to represent a real world objects requires:
 - Shape modeling
 - Visual appearance modeling → material
- **Material** is needed for:
 - Modeling: how object will look like
 - Rendering: light-object interaction (shading)



Shape and material

- Material characteristics are independent of shape and position
 - Material is modeled separately
- Enough to model how specific material generally interacts with light
 - This model is then used for arbitrary shape



Aluminum apple and aluminum statue – in both cases aluminum properties are the same. Also, changing position of aluminum apple in space doesn't change aluminum properties.

"Let the form of an object be what it may, - light, shade and perspective will always make it beautiful" – John Constable

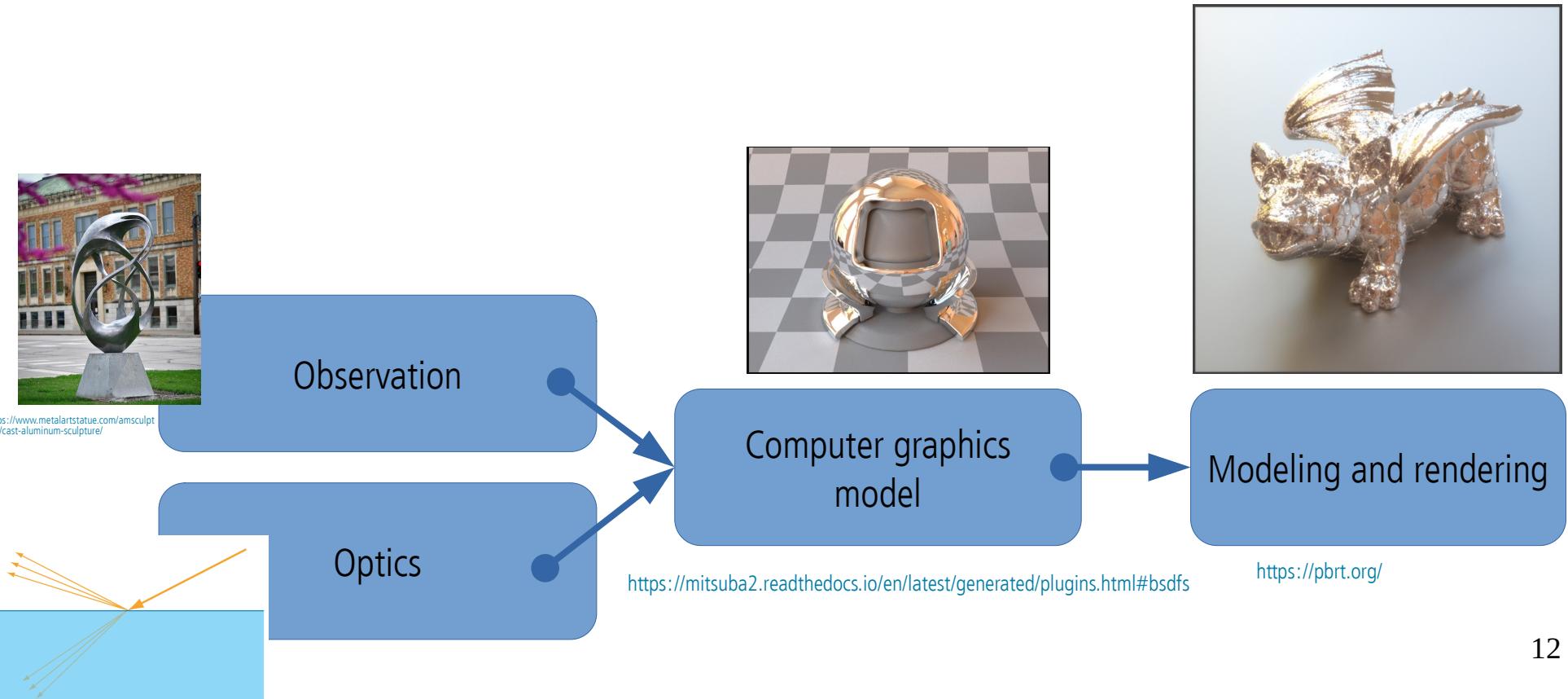
- Importance of material for appearance



- Metal
- Plastic
- Glass
- Wood
- Fabric
- Stone
- Clouds
- Water
- Tree bark
- Leaf
- Plaster
- Paper
- Leather
- Sky
- Etc.

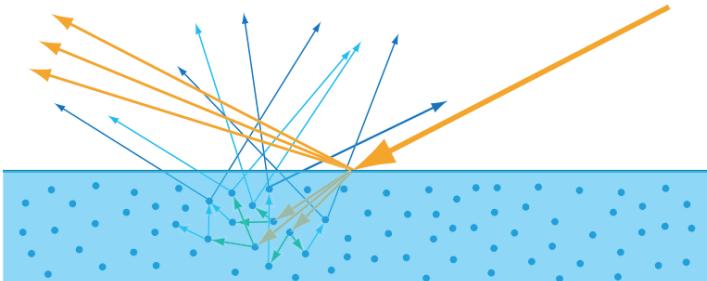


Appearance modeling and rendering

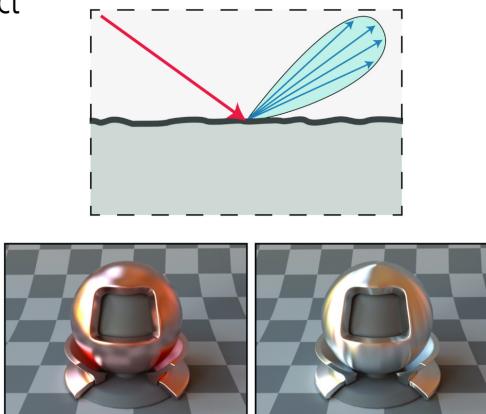


Materials: real world vs models

- Real world materials are very complex are simplified using different **models**:
 - **Physical models**: best description of real world materials
 - Example: geometric optics
 - **Computer graphics models**: simplification for creation and computational purposes
 - Example: separating objects into shape and material
 - **Subjective, artist observation**: based on perception – subjective model of the world
 - Artist draw what they see, not what is physically-correct



Physical model of light scattering



Computer graphics material model



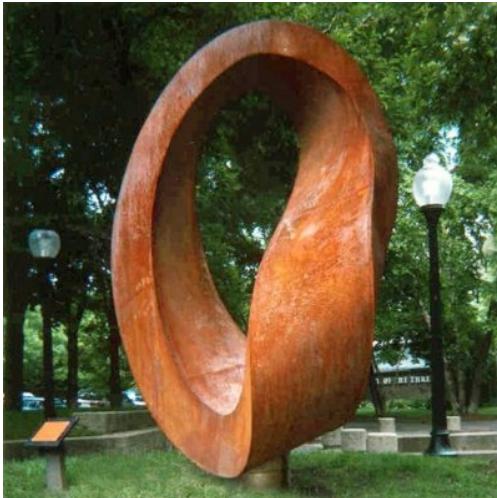
Artist model:
<https://shelleyhannafineart.com/painting-silver-objects/>

Material observation

Modeling begins with **observation**

Observation

- Observation goals:
 - Understand **what makes each material look different** than other materials
 - Observe **characteristics which are responsible for object appearance**



Observation

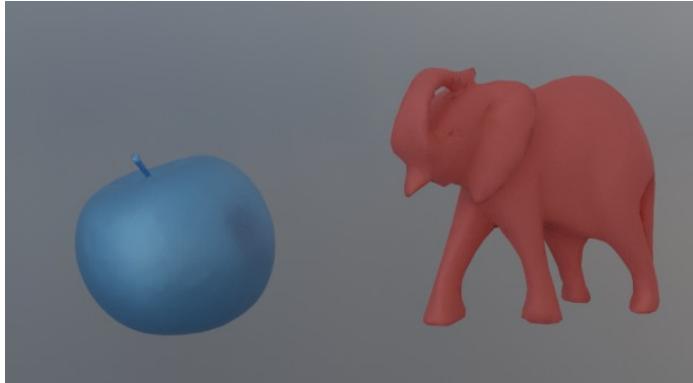
- Characteristics responsible for object appearance:
 - **Shape**: large scale form or geometry of object.
 - **Material**: for computer graphics modeling purposes: fine-scale geometrical variations and substance properties
 - **Illumination**: size, direction, color, etc.
 - **Sensor/Perception**: point of view, camera properties, etc.



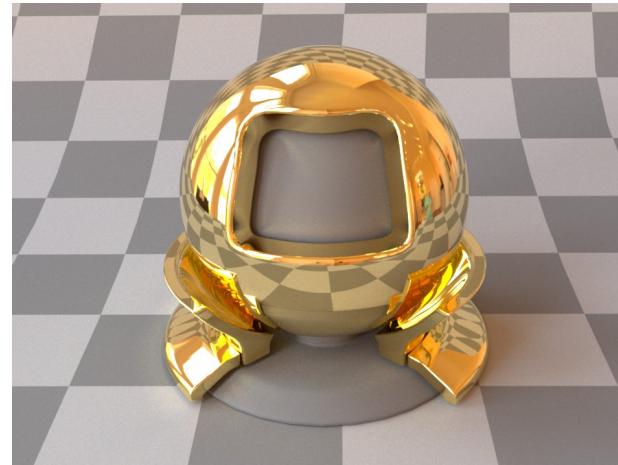
Classifying materials

- Classifying materials enables us to **understand which characteristics are needed to be modeled** in order to obtain required appearance. We can classify any material by following variations:

Spectral: color



Directional

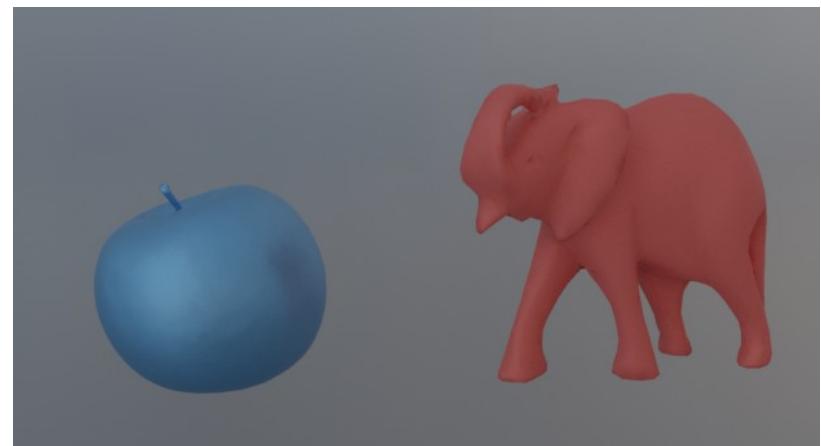
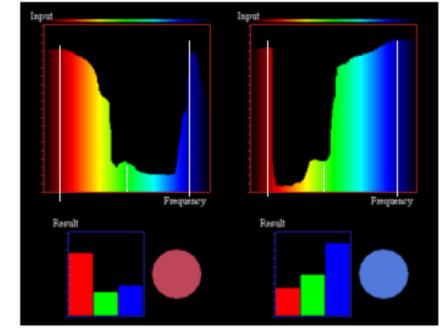
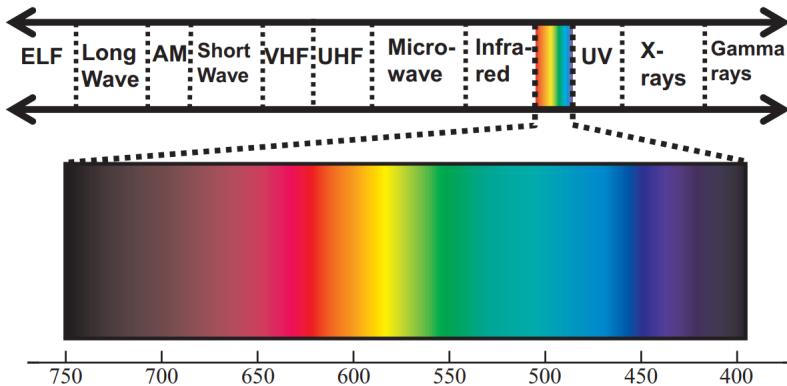


Texture



Spectral/color material characteristic

- Light is a electromagnetic radiation in the spectrum of visible wavelength band 380-780nm
- Light scattered from object surface (its material) is described using:
 - Color is described with red, green and blue floating points (R, G, B) in [0,1]
 - Brightness is floating point value [0, inf]



Directional material characteristic

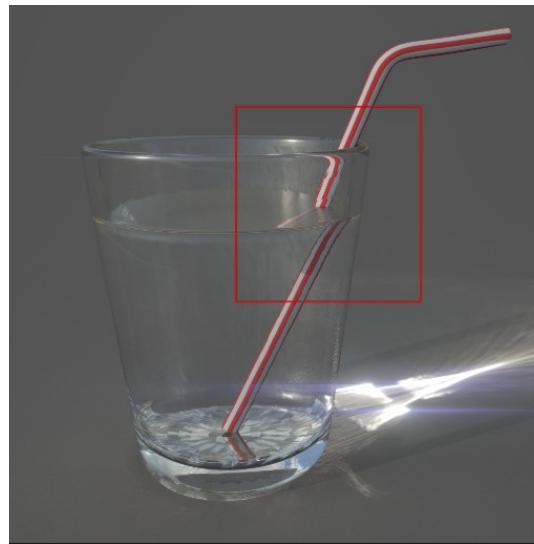
- Direction effects result from **directionality of light scattering** by the object
 - Changes in object appearance as we change view (or light or object position)
- Directional effects are “attached” to object (do not depend on environment)



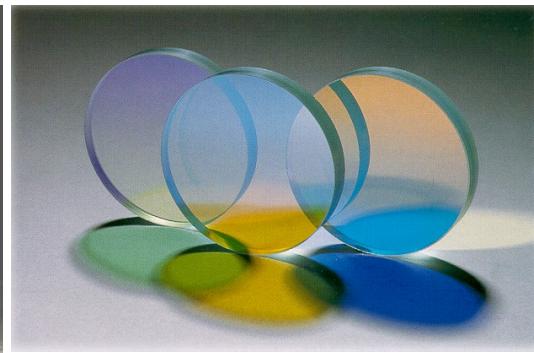
Shiny/glossy



Matte/diffuse



Transparent

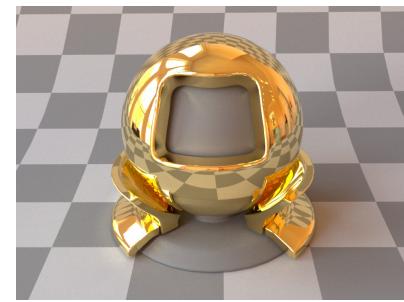


Translucent

<https://substance3d.adobe.com/tutorials/courses/the-pbr-guide-part-1>

<https://polyhaven.com/>

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

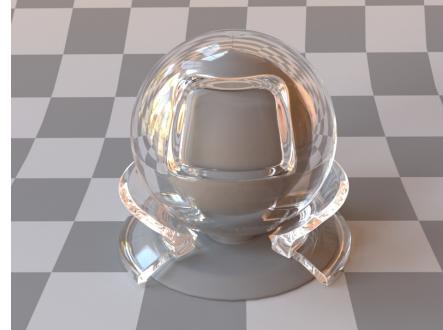


Directional material characteristic

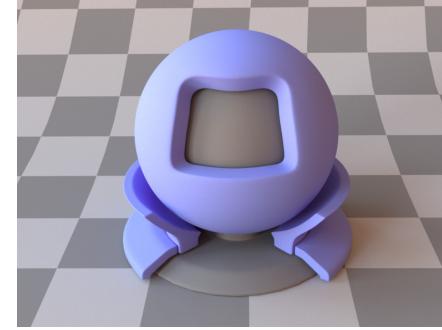
- In computer graphics, higher level description of scattering is used to describe directional – **surface scattering** - characteristics:
 - Reflective
 - Transmissive
 - Specular (mirror)
 - Glossy
 - Lambertian (diffuse)
 - Refractive
 - Retroreflective



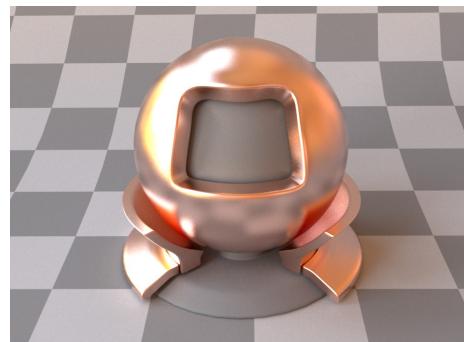
Reflective, specular (conductor, gold)



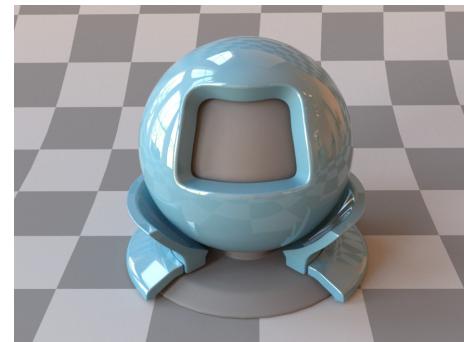
Transmissive, specular (dielectric, glass)



Reflective, Lambertian/diffuse
(dielectric, plastic)



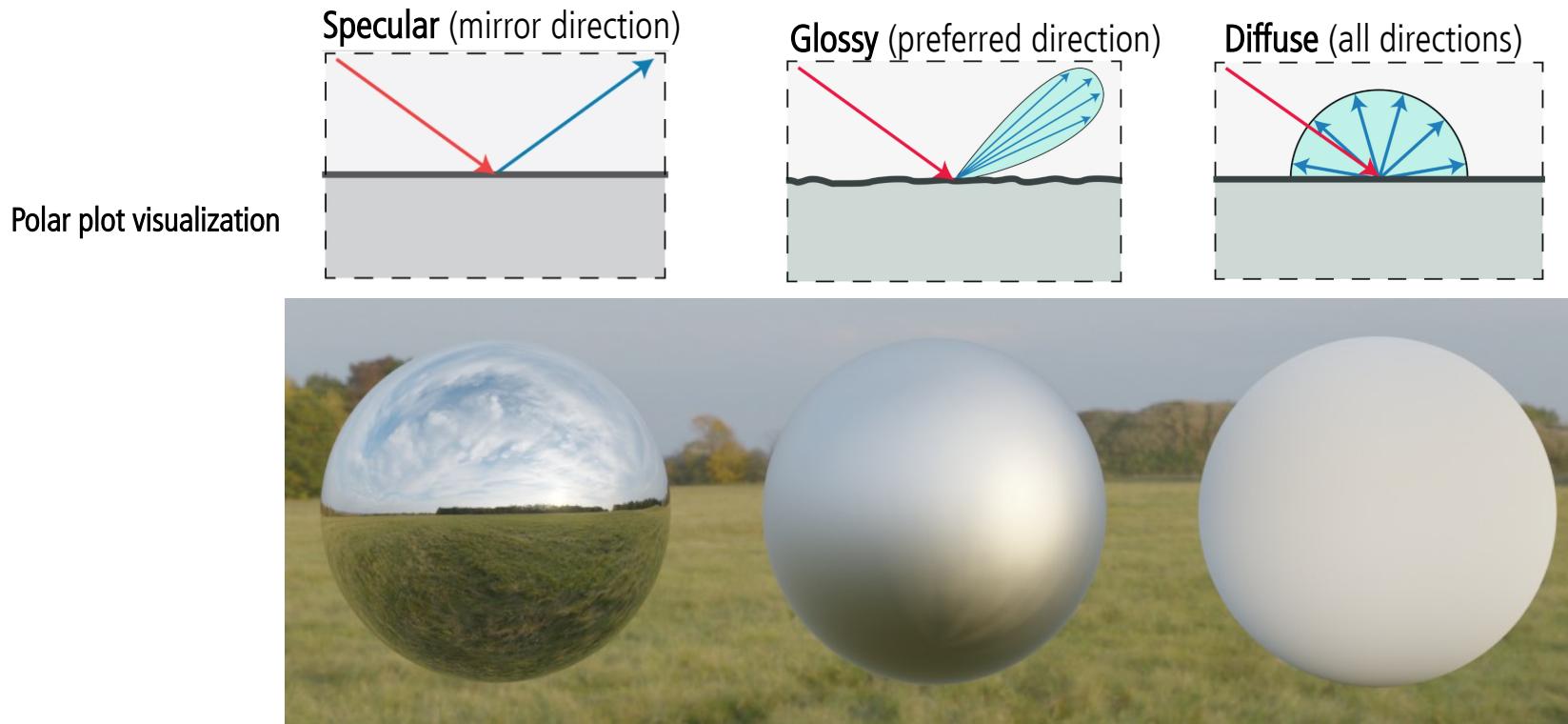
Reflective, glossy



Refractive, glossy (dielectric shiny plastic)

Surface scattering: scattering function

- Surface directional effects (and color) are modeled using **scattering function**. Most important light scattering models are:



Material characteristics: texture

- Visual variations on the object surface, much smaller scale than size of the object but larger than the wavelength of light - **spatial variations**:
 - Directional or spectral (color)
 - Small scale geometric variations: bumps and pores
- Surfaces with spatial variation are observed as non-uniform: **texture or pattern** can be observed



Color variation



Directional variation

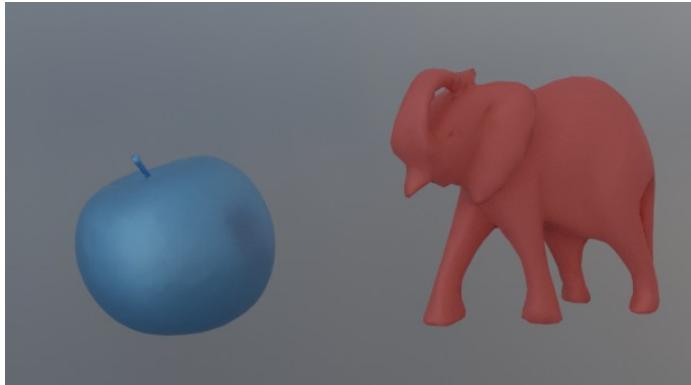


Small scale geometrical variation

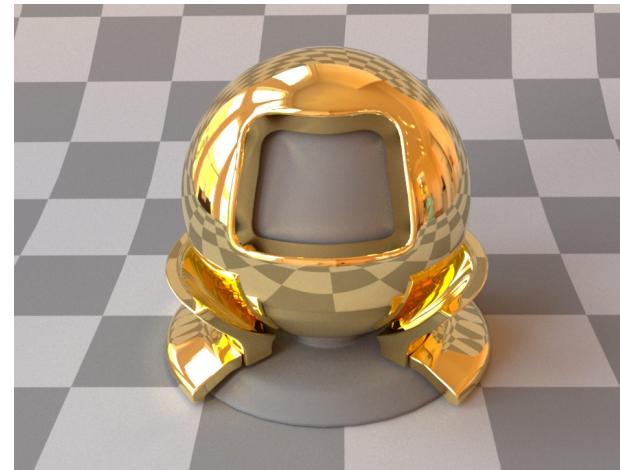
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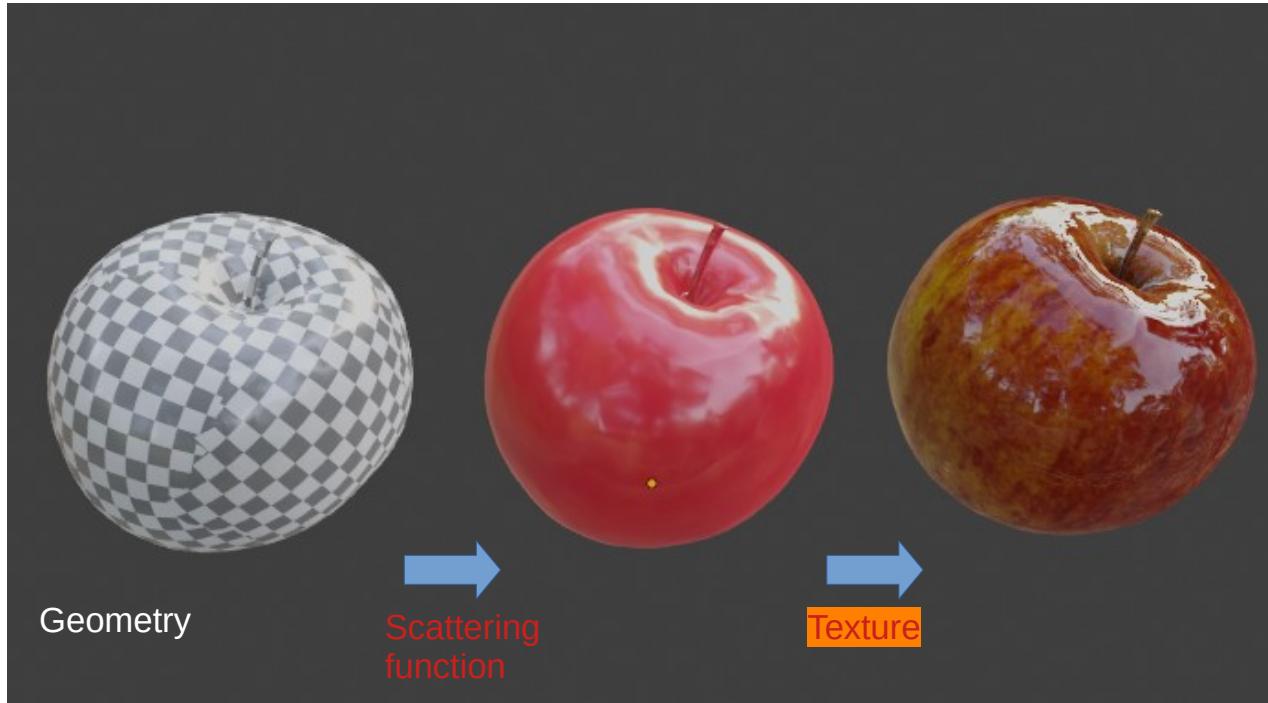
Directional



Texture



Materials in computer graphics



Scattering function

- Directional effects
- Color

Texture

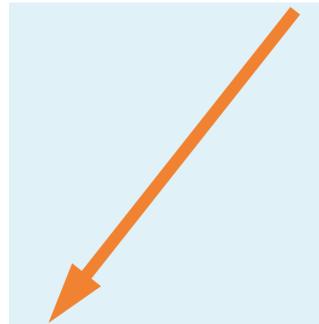
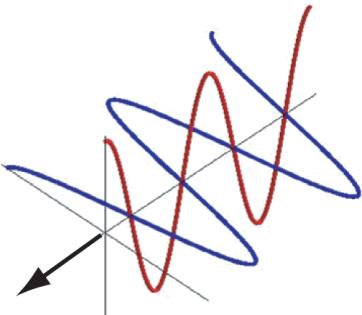
- Surface patterns

Physical models for computer graphics

Modeling is founded on **optics**

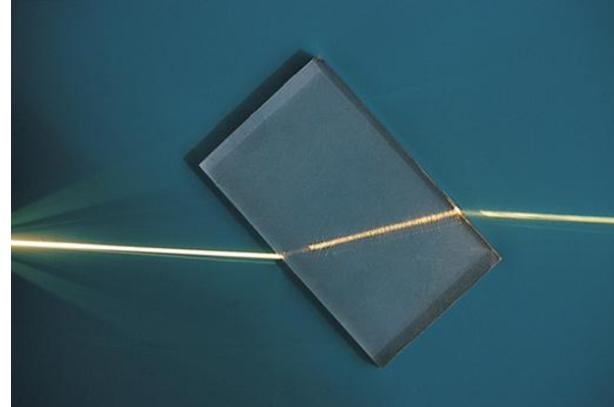
Light-matter interaction

- Light is electromagnetic transverse wave → too complex for CG!
- Geometrical optics
 - Approximates light as rays
 - Describes light-matter interaction via **index of refraction** (IOR) – a complex number:
 - Real part determines speed of light → **scattering**
 - Imaginary part determines **absorption** of light



Light can be represented as ray.

https://ssteinberg.xyz/2022/04/03/practical_plt/



Light scattering due to difference in IOR.

Light-matter interaction

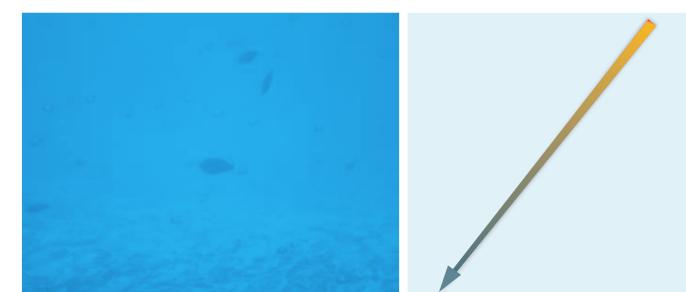
- Simplest light-matter interaction is light propagating through **homogeneous medium**.
 - **Uniform IOR**: light travels on a straight line.
 - It can only be **absorbed**: direction is same, intensity might be attenuated



Transparent media (water): straight line with same intensity (scattering only happens when light crosses air-glass-water homogeneous media since they have different (but constant) IORs.)



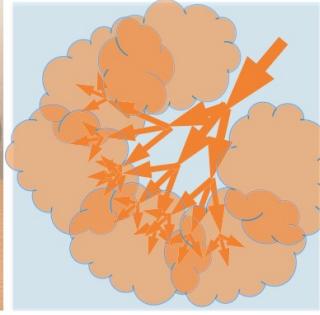
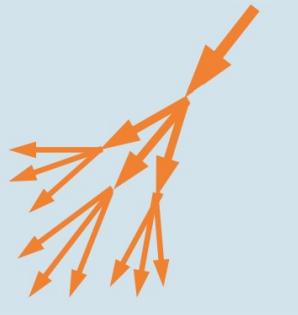
Clear absorbent media (tea): straight line with loss of intensity – selective absorption (color is changed)



Absorption becomes significant with distance.

Light-matter interaction

- In **Heterogeneous medium** IOR varies which causes **light scattering**
 - Direction of light is changed but not the intensity
 - Light can scatter in all directions, mostly non-uniformly: forward or back scattering (in or reverse of incoming direction)



Microscopic particles cause varying of IOR and light to scatter continuously in all possible directions.

Translucent or opaque materials → light is scattered so much that we can not see (clearly) through the object



Longer distances cause more scattering (e.g., clean air)

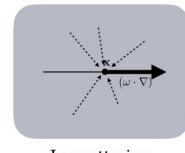
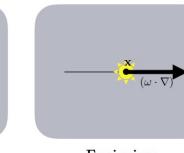
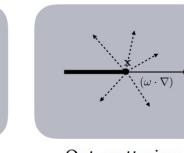
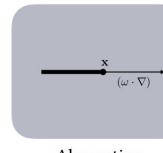
Light-matter interaction: scattering and absorption

- Light traveling through medium, based on **index of refraction** will:
 - Absorb
 - Scatter
- Appearance depends on both scattering and absorption



Participating media*

- Participating media
 - Medium between objects
 - Simplest: vacuum
- Light traveling inside medium in CG is called **volumetric scattering**



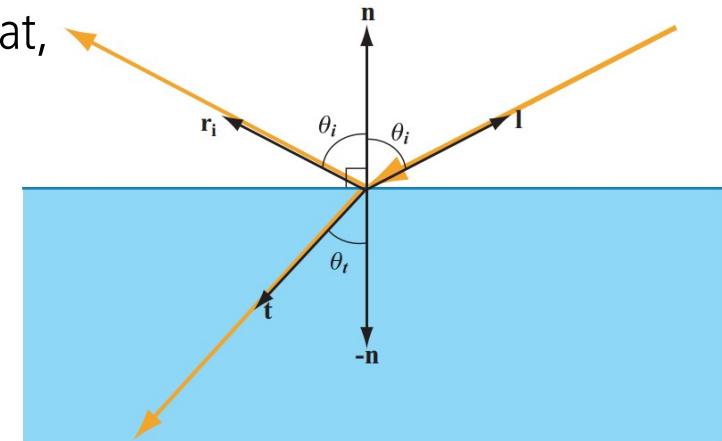
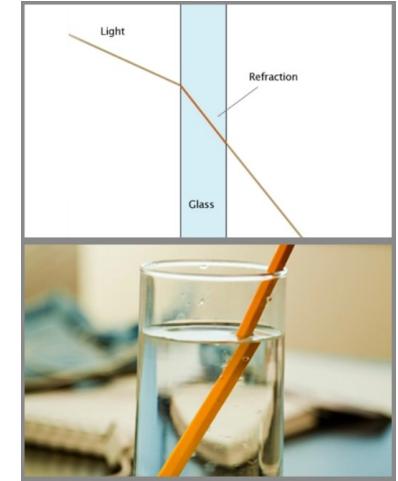
<https://cs.dartmouth.edu/wjarosz/publications/jarosz08radiance.html>

<https://studios.disneyresearch.com/2012/08/05/virtual-ray-lights-for-rendering-scenes-with-participating-media/>

<https://graphics.pixar.com/library/ProductionVolumeRendering/paper.pdf>

Light-surface interaction

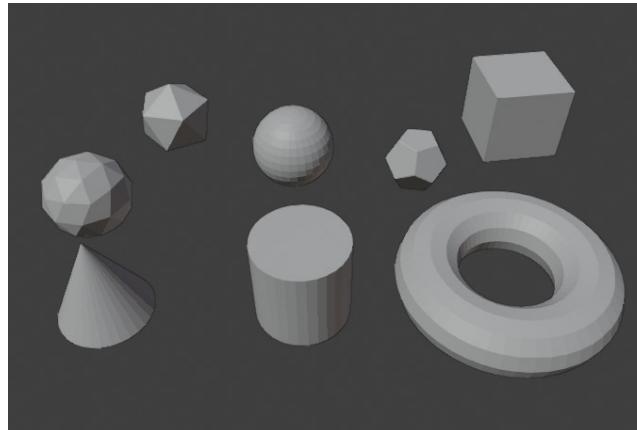
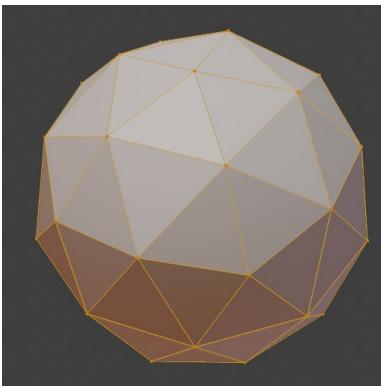
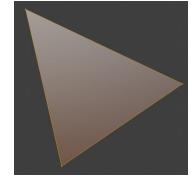
- Light **traveling between media of different index or refraction** - Maxwell's equations – too computationally heavy!
- Simplification and assumptions:
 - Interface between (volumes) media is perfectly (optically) flat, planar boundary* → **object surface**
 - **Geometrical optics**: rays light representation, IOR
- Solution: **Fresnel equations and Snell's law**



* Surface should be infinitely large, but in comparison with wavelength of light, surface real objects can be considered as such.

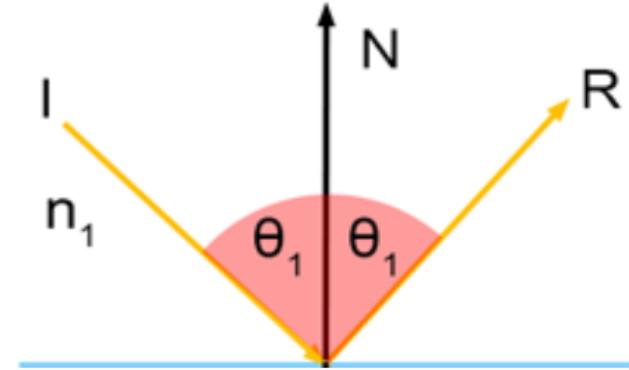
Surface

- Surface: 2D interface separating volumes with different IOR (thin interface between media)
- In CG it is described with **shape representations**, e.g., polygonal mesh
- Behavior of light falling on surface depends on:
 - **Geometry** → surface orientation (normal)
 - **Substance (material)** → IOR



Light-surface interaction: reflection

- Light falling on planar surface can **reflect**
 - **Direction:** law of reflection – angle of reflection is equal to angle of incidence.

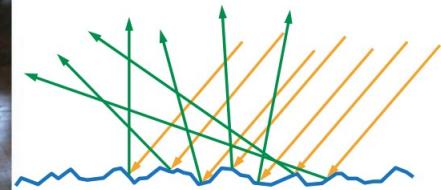
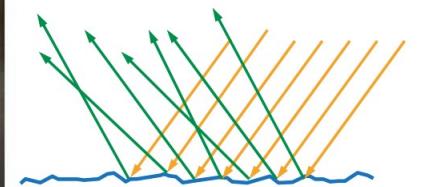


This is property of opaque objects:

- Metals
- Dielectrics (specular reflection)

More physically correct surface reflection

- Real surfaces: small geometrical irregularities not visible by eye affecting reflection
- Surface model: large collection of tiny optically flat surfaces
 - **microfacets**. Final appearance is aggregate result of relevant facets.
 - Smaller deviation of those facets → **mirror-like surface reflection**
 - Larger deviation of those faces → **glossy surface reflection**



Similar shape, different reflection.

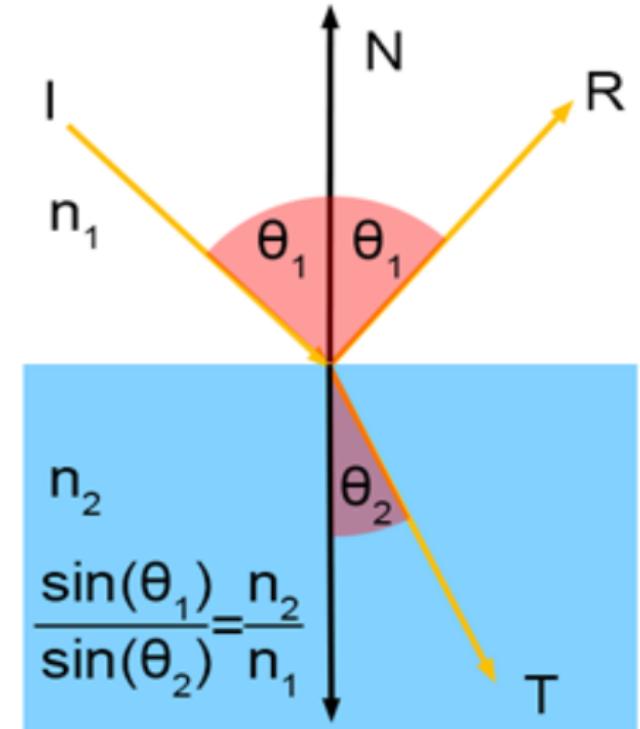
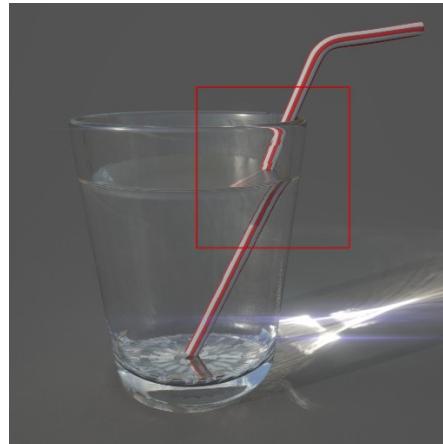
Light-matter interaction: flat surface

- Light falling on planar surface can **refract**:

- Direction of refraction: Snell's law

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}.$$

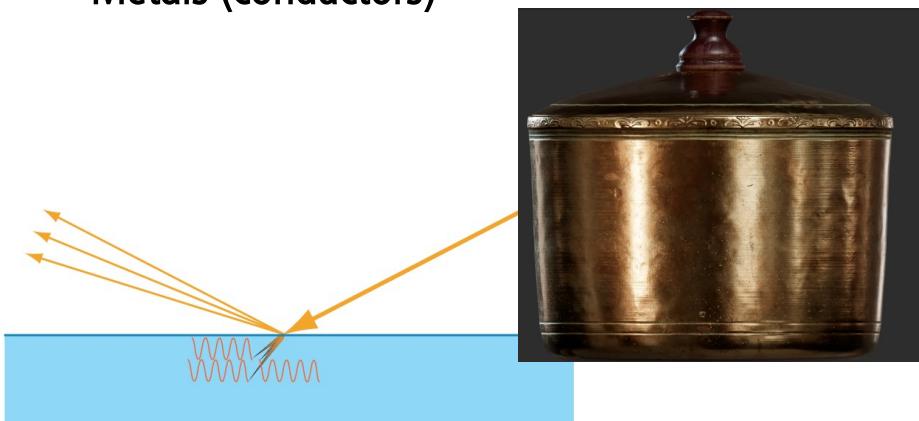
- Characteristic of dielectric objects:
 - Example: glass



Surface refraction

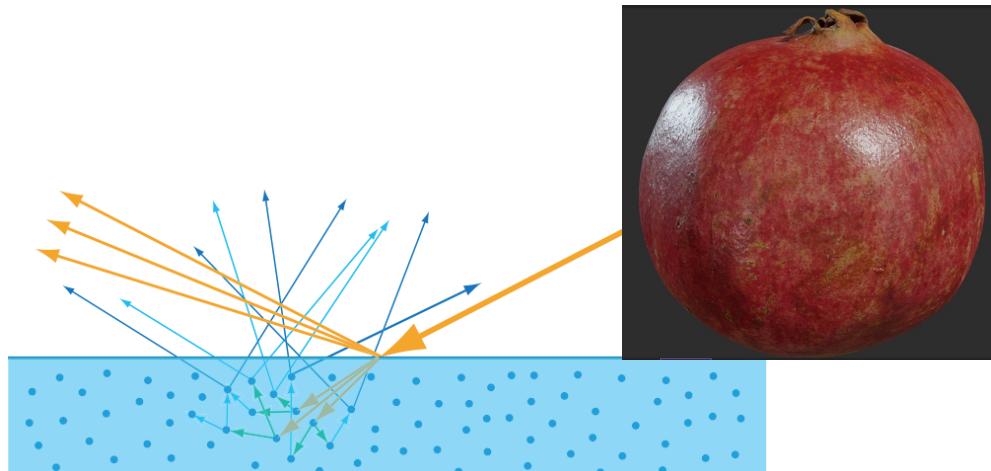
- Amount and direction of refracted light depends on material which we can separate in:

Metals (conductors)



In case of **metals**, most of the light is reflected and rest is immediately absorbed. That is why mirrors are made using metal foundation. Conductors are spectrally selective and thus reflection color may vary

Dielectrics (non-metals)



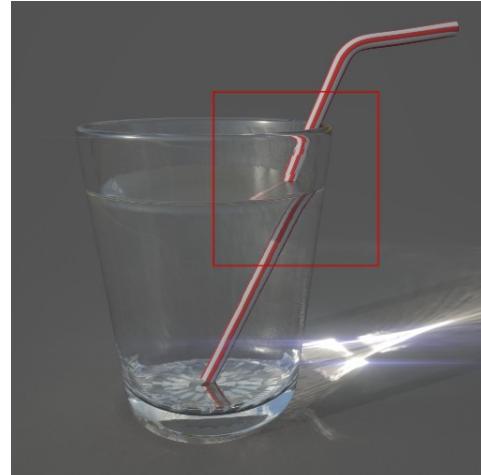
In case of **dielectrics**, light partially reflects and partially refracts. Refracted light is then absorbed and scattered inside surface (**sub-surface scattering (SSS)**) causing **diffuse** reflection.

Surface refraction

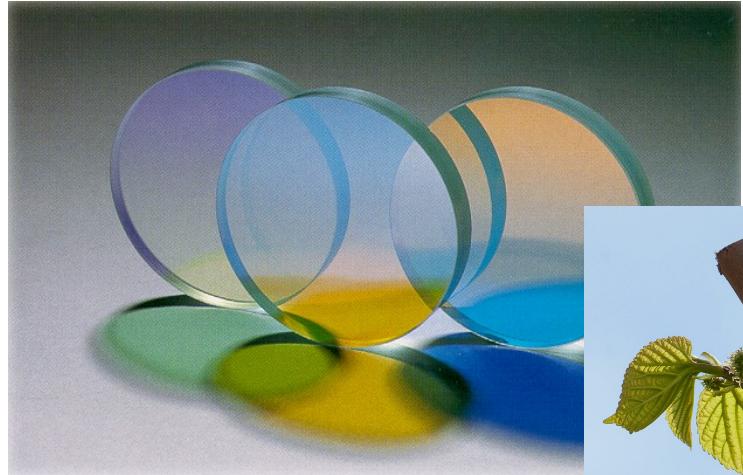
- Refracted light on **dielectric surface** can:
 - Sub-surface scatter, absorb and re-emit: **opaque** objects
 - Transmit; pass through object: **transparent** objects
 - Sub-surface scatter, absorb, re-emit and transmit: **translucent** objects



Opaque



Transparent



Translucent

<https://www.hippopx.com/en/query?q=translucent>



Light-matter interaction: flat surface

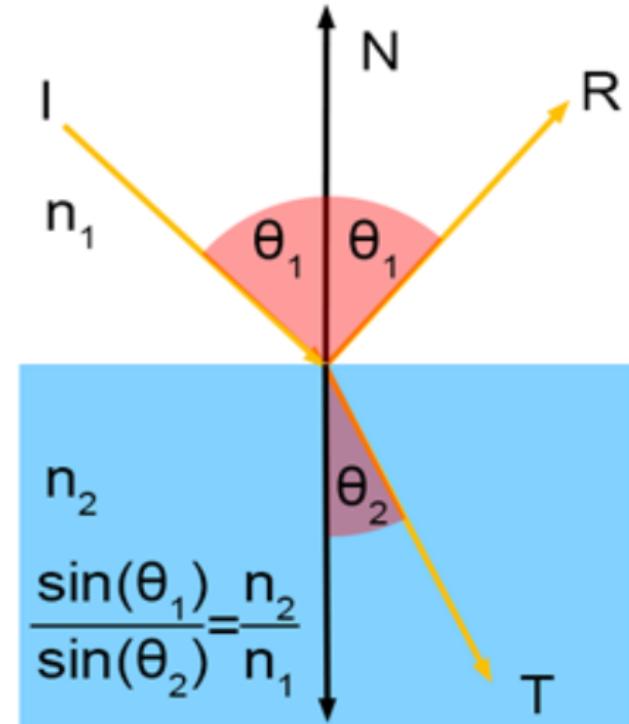
- Amount of light reflected/refracted (transmitted) is described with **Fresnel's equations**

$$F_{R\parallel} = \left(\frac{\eta_2 \cos \theta_1 - \eta_1 \cos \theta_2}{\eta_2 \cos \theta_1 + \eta_1 \cos \theta_2} \right)^2,$$

$$F_{R\perp} = \left(\frac{\eta_1 \cos \theta_2 - \eta_2 \cos \theta_1}{\eta_1 \cos \theta_2 + \eta_2 \cos \theta_1} \right)^2.$$

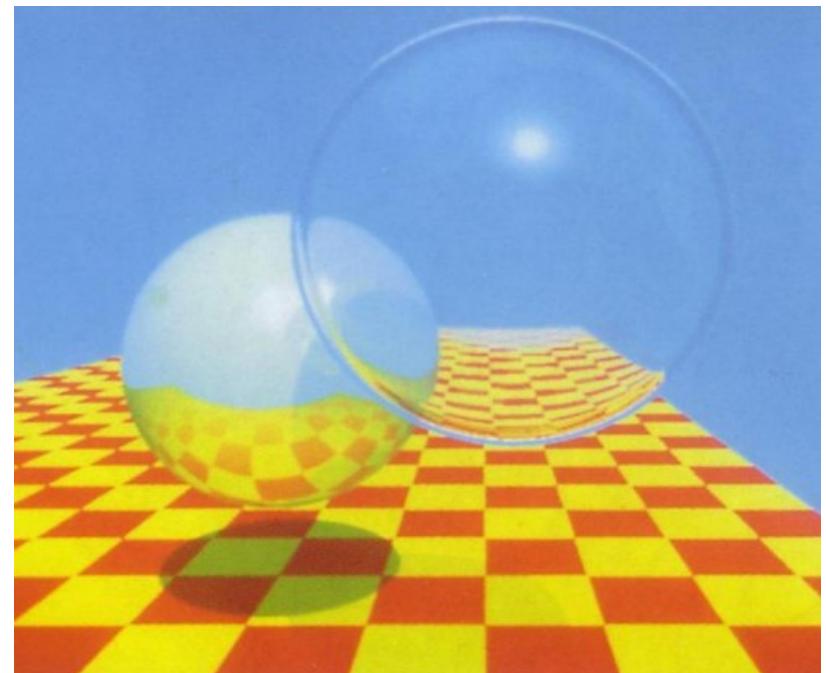
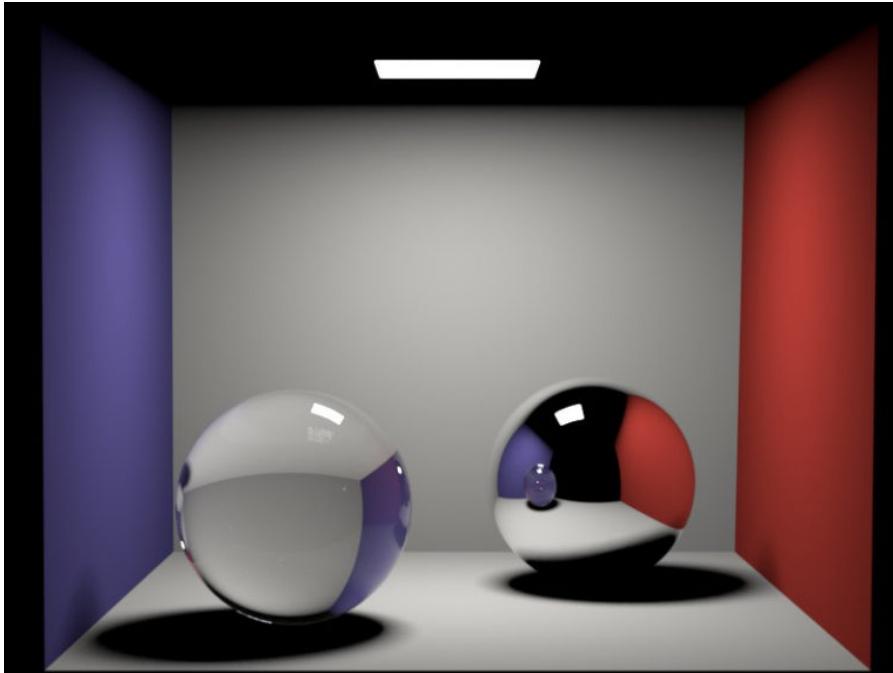
Amount of reflected light $\rightarrow F_R = \frac{1}{2}(F_{R\parallel} + F_{R\perp}).$

Amount of refracted light $\rightarrow F_T = 1 - F_R.$



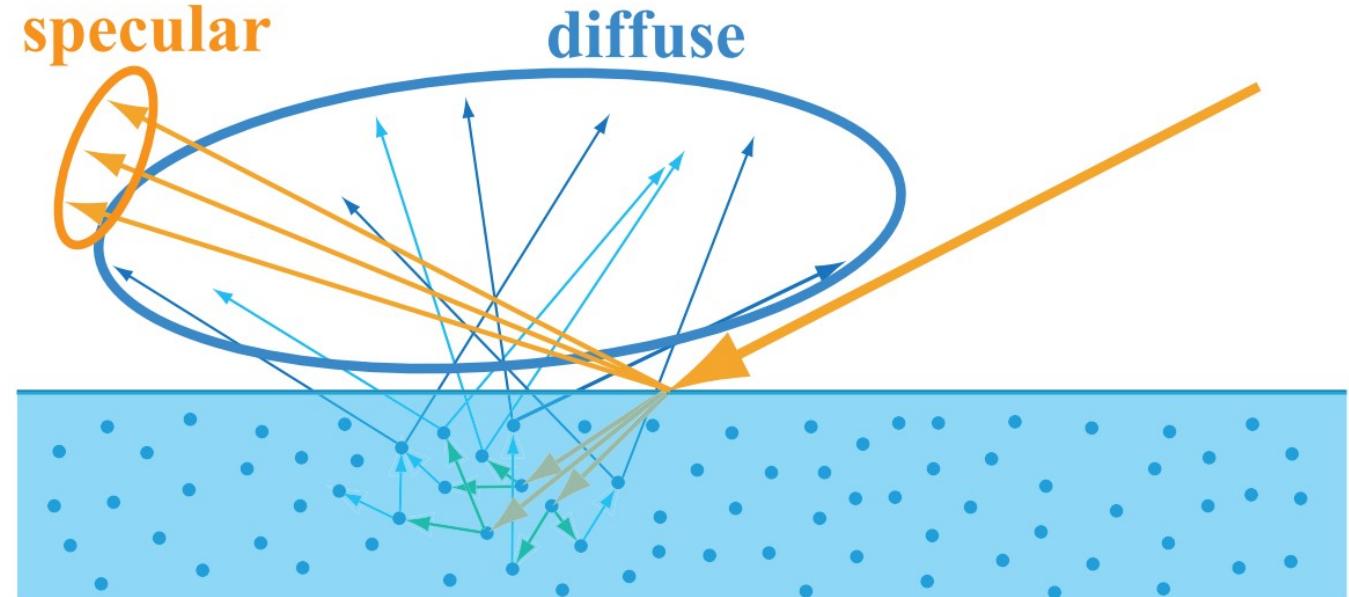
Light-matter interaction: flat surface

- Surface reflection and refraction is crucial for realistic synthesis
 - Whitted ray-tracing for realistic image synthesis



Diffuse and specular reflection

- Two fundamental **light-surface** scattering processes:
 - **Diffuse**: incoming light is distributed in all directions
 - **Specular/glossy**: incoming light is reflected into single or preferred direction



Light-matter interaction: summary

simplify

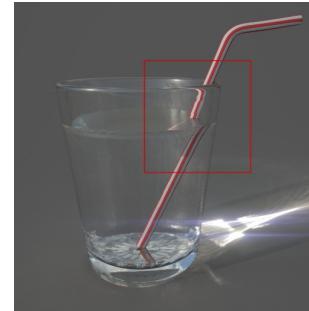
- Light traveling between objects can be scattered/absorbed
 - **Volumetric scattering** in participating media
- Light falling on object surface – **surface scattering**:
 - **Reflect** (metals and dielectrics)
 - **Refract** (only dielectrics)
- Depending on dielectric material, refracted light can:
 - **Transmit** (transparent, translucent surfaces)
 - **Sub-surface scatter and absorb** (opaque and translucent object volume) → **volumetric scattering**



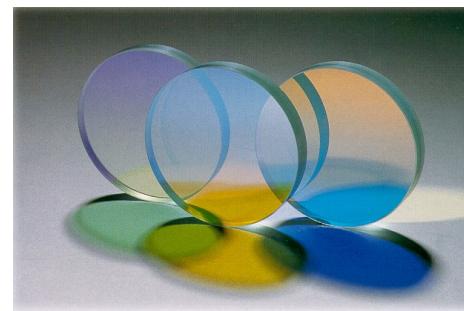
Participating media



Opaque dielectric: reflect + refract → SSS/diffuse



Transparent dielectric: reflect + refract → transmit



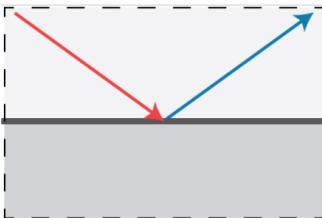
Translucent dielectric: reflect + refract → transmit



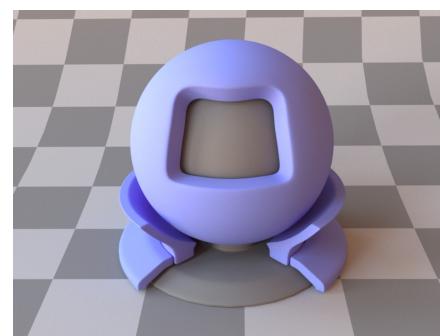
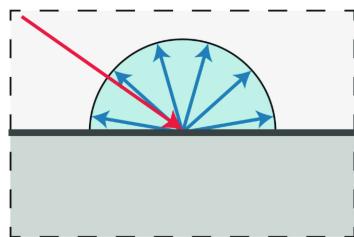
Metal: reflect

Material modeling

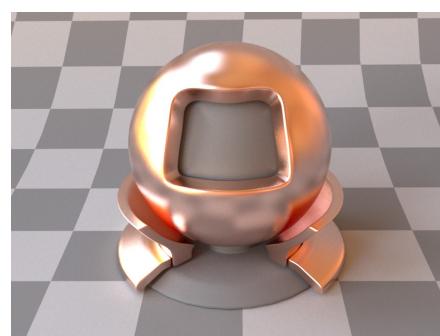
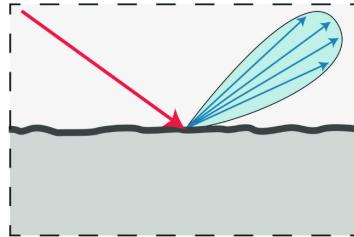
- Four scattering models for this lecture: local surface models



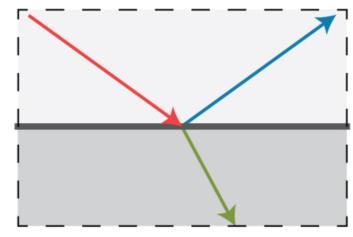
Perfect specular reflection.
Light is reflected into only
one direction.



Diffuse reflection.
Light is reflected into all
directions equally.



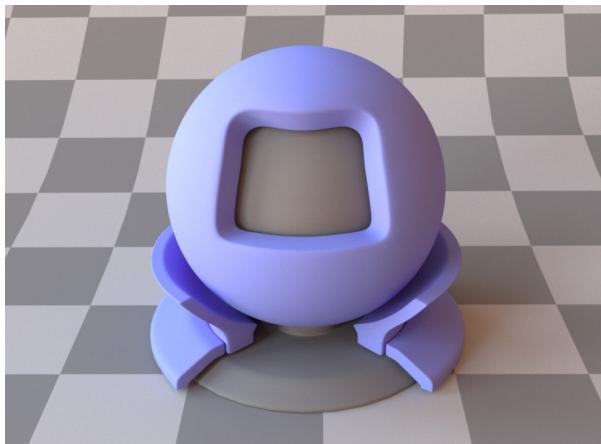
Glossy reflection.
Light is reflected into
preferred direction.



Perfect specular reflection and
transmission.

Modeling material characteristics

- Small scale light behavior is described with **scattering model**:
 - Directional effects, light scattering
 - Color, light absorption
- Larger scale variations visible by eye described with **Texture**:
 - Varying scattering models or their parameters over surface



Modeling only scattering function (small scale) can represent different but uniform directional and color characteristics → smooth surfaces.

Varying scattering model parameters⁴⁵ results in textured objects

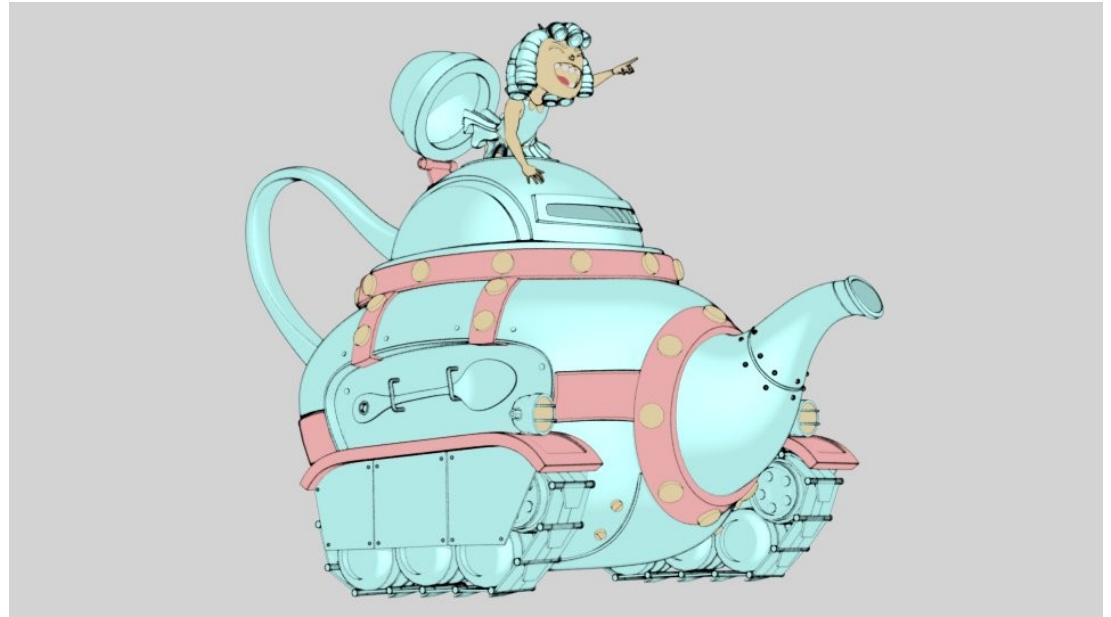
Modeling appearance

Diversity of appearance models

- Appearance models, depending on application, can range from **photo-real** to **stylized**.



<https://www.artstation.com/artwork/rANRe5>

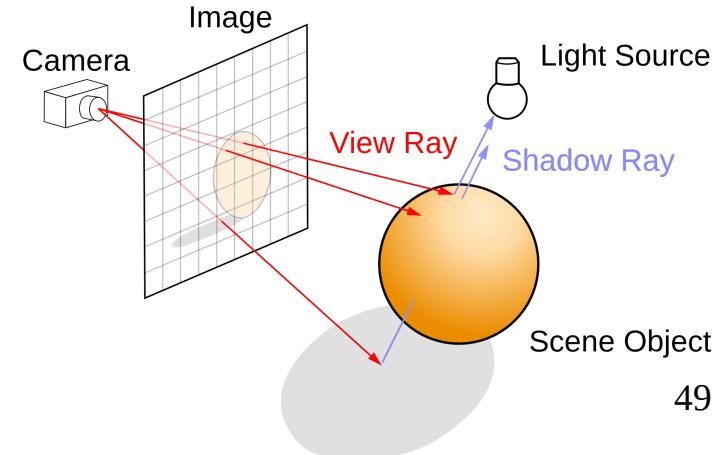


"Rolling Teapot" - Model by Brice Laville, concept by Tom Robinson, render by Esteban Tovagliari - RenderMan 'Rolling Teapot' Art Challenge:

<https://appleseedhq.net/gallery.html#https%3A%2F%2Fappleseedhq.net%2Fimg%2Frenders%2Frolling-teapot.jpg>

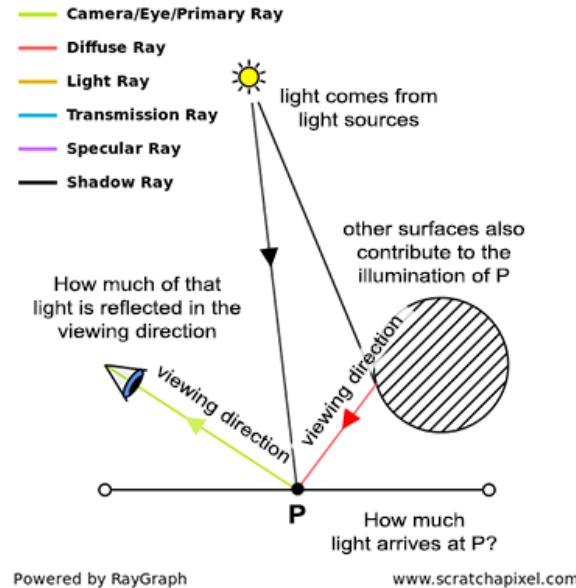
Material and rendering

- Rendering: computing **intensity** and **color** of pixels of virtual image plane in virtual camera
- For each pixel of virtual image plane, **camera (viewing) ray** is generated and traced into scene
 - This simulates light entering the camera along set rays
- **View rays are tested for intersection** with objects in the scene
 - Closest intersected object surface is found → **shading point**
 - Ignore participating media for now
- Compute intensity and color of the surface intersected by viewing ray → **shading**



Materials and shading

- Shading uses:
 - Material model
 - Viewing position
 - Object shape
 - Light information
- Final color of surface is calculated by:
 - Summing all **incoming light** that falls onto surface
 - Light transport – also uses material information
 - Calculating color and intensity of light reflected into camera using **material description** - shading

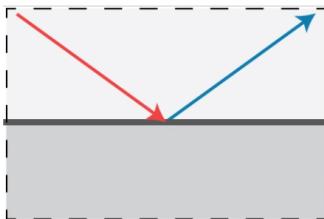


Powered by RayGraph

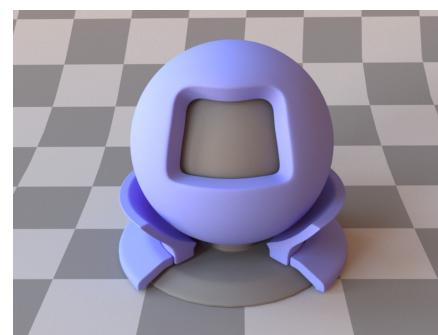
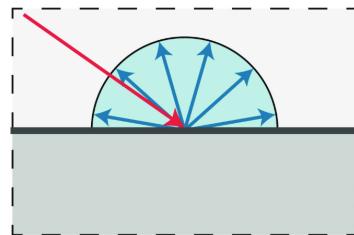
www.scratchapixel.com

Material modeling

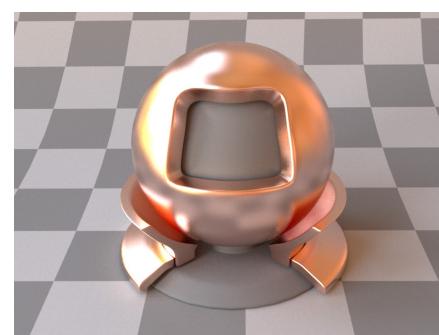
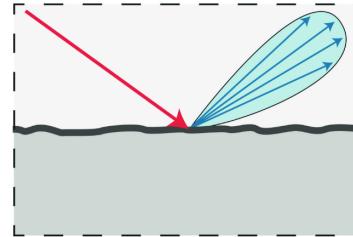
- Model interaction of light in shading point → **scattering model**.
 - Four scattering models for this lecture: local and surface-related



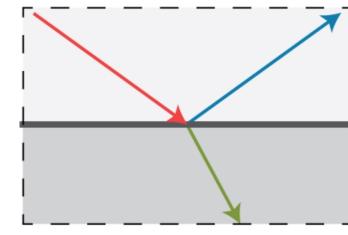
Perfect specular reflection.
Light is reflected into only one direction.



Diffuse reflection.
Light is reflected into all directions equally.



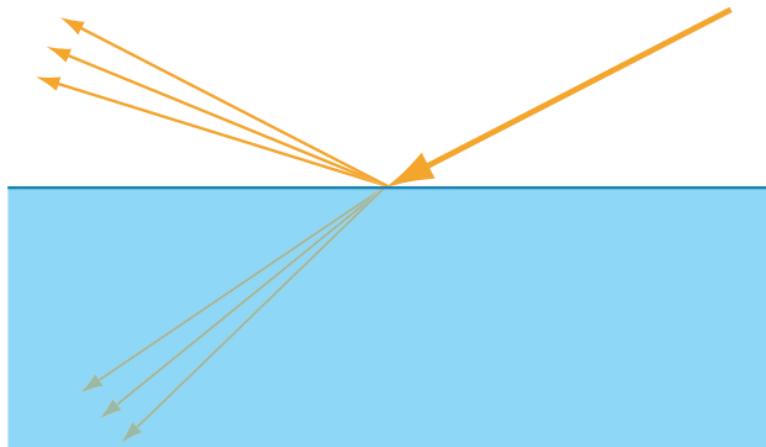
Glossy reflection.
Light is reflected into preferred direction.



Perfect specular reflection and transmission.

Local scattering models

- Local (direct) models: describe what happens when light falls on one point and scatters from that one point.
- Surface scattering can be well described (approximated) with local models.

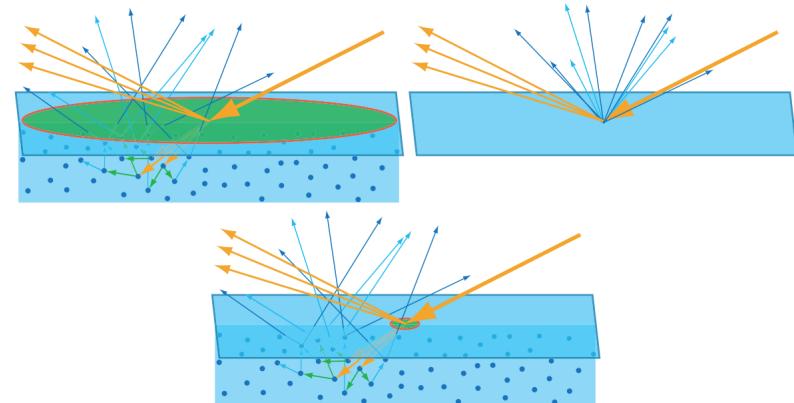


Local models describe what happens at one point of intersection with object surface

Macroscopically, non-optically flat surface can be treated as flat surfaces reflecting with multiple directions

Global scattering models

- Volumetric scattering phenomena requires **global scattering model**
- Can be approximated with local model (e.g., SSS with diffuse model)



Volumetric scattering inside surface (SSS) or in participating media requires global models: light path is not exiting the same point where it entered.

Material modeling: texture

- Same parameters of scattering model in each point of 3D surface results in **homogeneous surface material**: smooth surface
- Scattering model parameters are varied using **texture**.



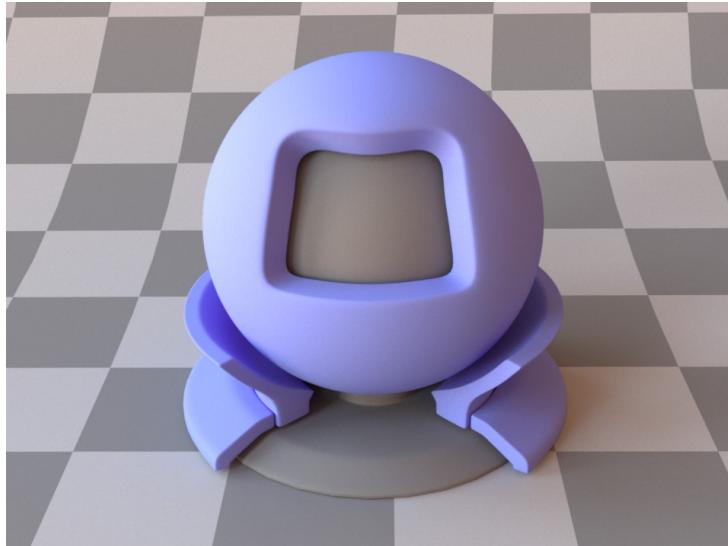
Homogeneous material: scattering model has the same parameters in all points of the surface.



In CG texture is used to vary scattering parameters over surface

Elements of material model

- Material modeling in computer graphics is separated into:
 - **Scattering** → description of light-matter interaction at a point (directional effects and color)
 - **Texture** → variation of small-scale geometry and scattering properties across 3D object surface



Diffuse scattering model only.



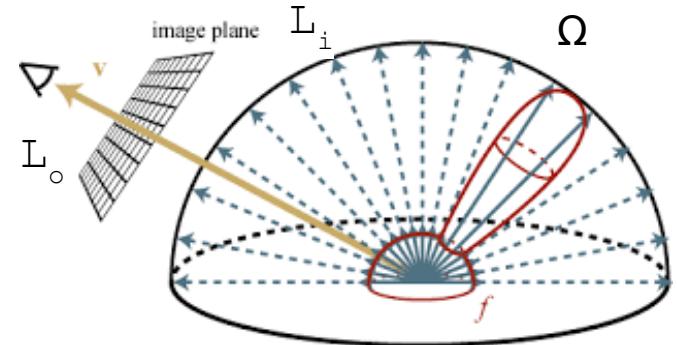
Diffuse scattering model with texture.

Shading and light

- Rendering equation – basis for physically based rendering
 - Describes global illumination

$$L_o(p, \omega_o) = L_e(p, \omega_o) + \int_{\Omega} f(p, \omega_o, \omega_i) L_i(p, \omega_i) (\omega_i \cdot n) d\omega_i$$

| | | | | |
|--|--|------------------|--|---|
| Outgoing light in point p in direction ω_o . | Emitted light in point p (only if light source) | Scattering model | Incoming light in point p from light direction ω_i . Calculated using light transport | Attenuation (cosine) factor: surface orientation towards light |
|--|--|------------------|--|---|



For case when camera ray intersects the surface then:

- L_o is shading results, a color
- ω_o is equal to view direction
- ω_i is equal to light direction

Note that this is recursive equation and for each light direction direction this equation must be evaluated again.

Shading and light

- Reflectance equation. Special case of rendering equation.
 - Describes global illumination but only for reflective surfaces.
- Shading “collects” all incoming light and shading point and multiplies it with scattering model.

$$L_o(p, v) = \int_{l \in \Omega} f(l, n, v) L(p, l) (n \cdot l)^+ dl$$

Collect light over whole hemisphere above shading point, placed on normal in shading point

Incoming light at shading point

Color in shading point.

Scattering model

Light attenuation due to surface orientation (cosine factor)

Shading and light

- Simplification: **direct illumination** – take in account only light coming from light sources (e.g., point lights).

$$c_{shaded(p,v)} = \sum^n f(l_i, n, v) c_{light_i}(n \cdot l_i)^+$$

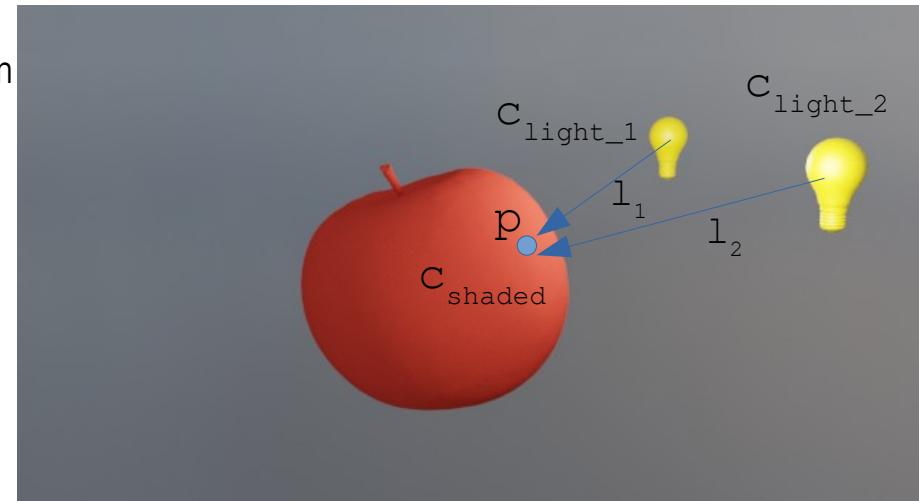
Color in
shading
point

Sum over all
lights in 3D
scene

Scattering model

Current light color

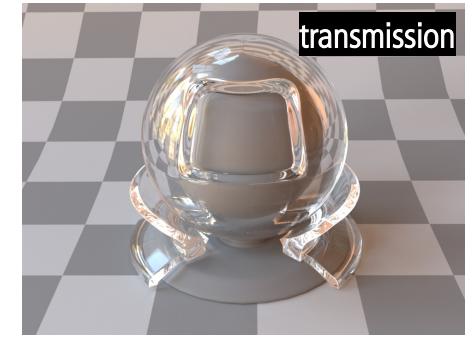
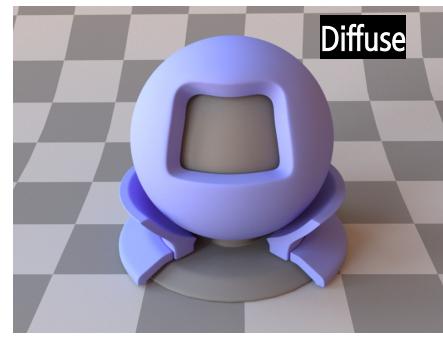
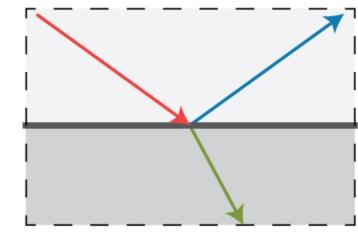
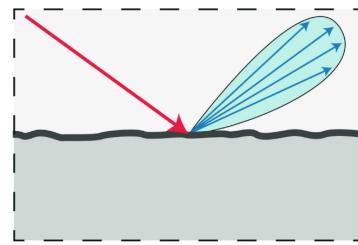
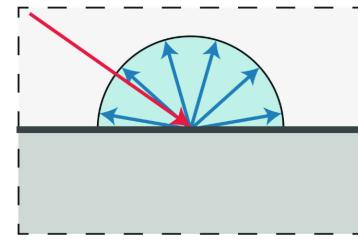
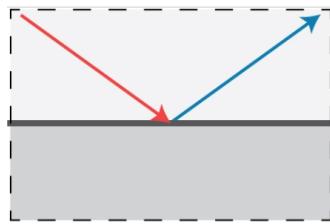
Attenuation



Scattering models

Surface scattering:

Reflection and transmission



Shape and brightness

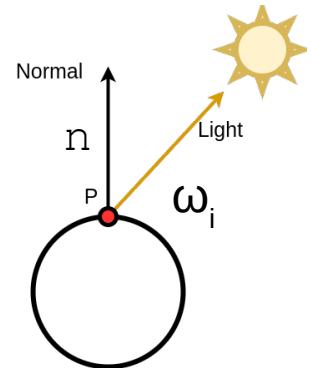
Amount of light falling on surface depends on:

- Shape
- Light position/direction:

Alignment of surface normal towards light determines amount of surface brightness

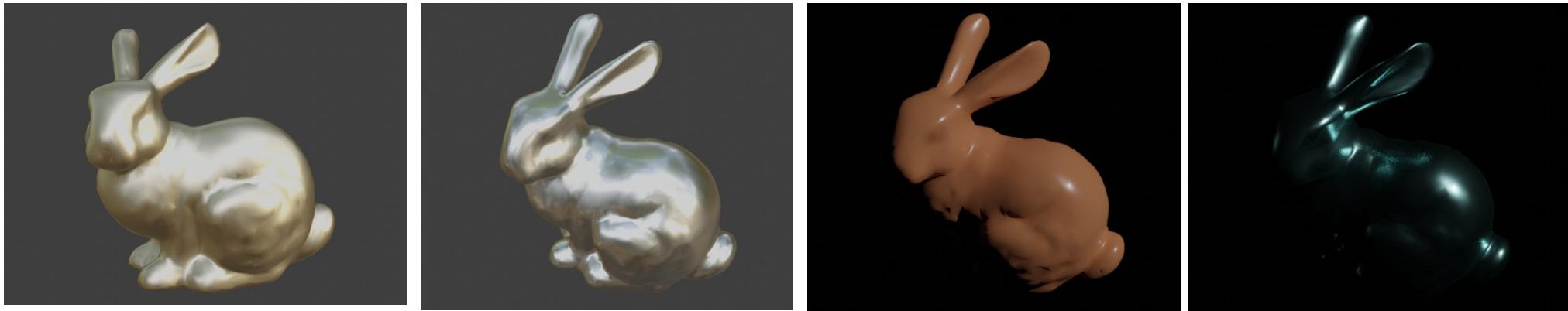
- Light attenuation (cosine factor)

$$(\omega_i \cdot n)$$



Scattering model

- Observing objects we can see that they have different appearance, although similar in shape
 - This particular look of objects is defined by how light scatters when it falls on surface point.
 - This behavior is defined by **surface scattering function** - surface response to light



Surface scattering function

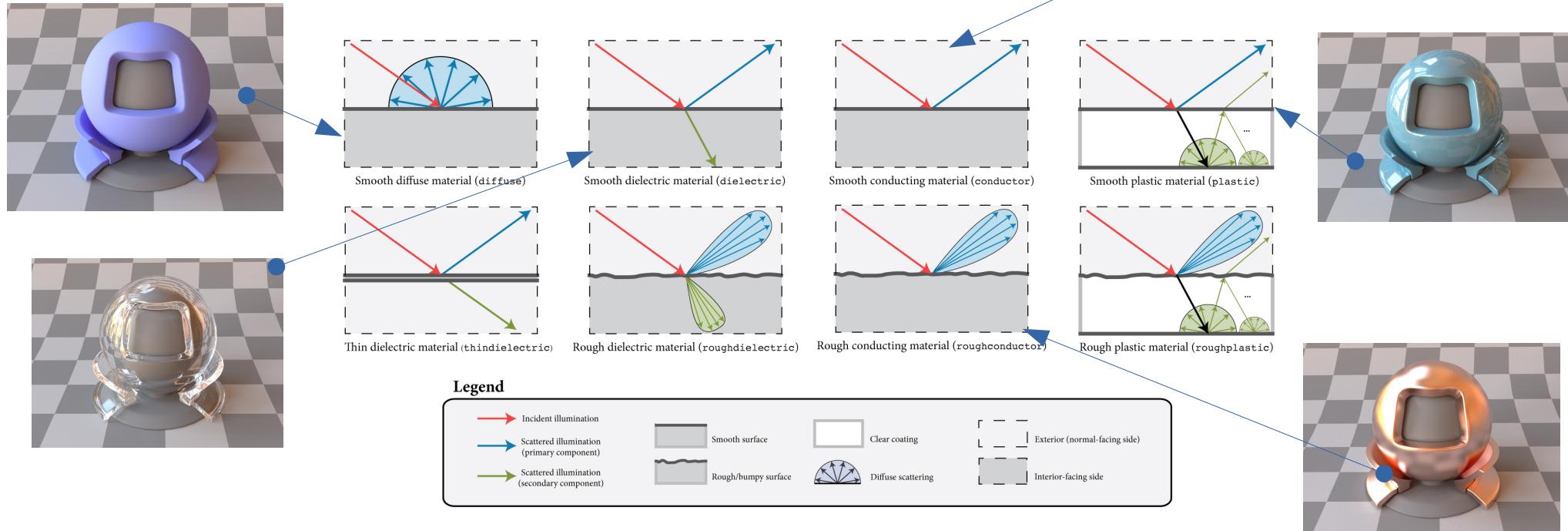
- Scattering function can be separated in reflection and transmission
 - Model describing reflection is called “bidirectional **reflectance** distribution function” – **BRDF**.
 - Model describing transmission is called “bidirectional **transmission** distribution function” – **BTDF**.
 - Model describing both reflectance and transmission is called “bidirectional **scattering** distribution function” – **BSDF**.



- **Reflective** – all light is scattered above surface
- **Transmissive** – all light is scattered below surface
 - Refractive – special case of transmissive

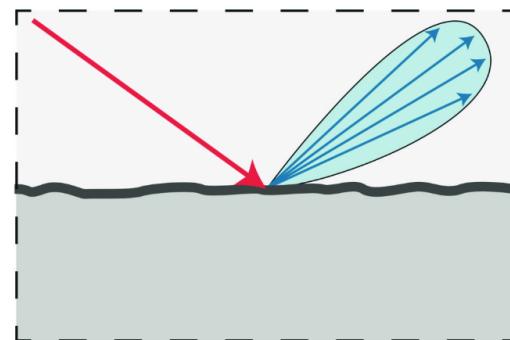
Visualizing BRDF/BTDF

- The way surface reflects light can be visualized using **lobes – polar plot**
 - Given incident light direction, describes surface light reflection



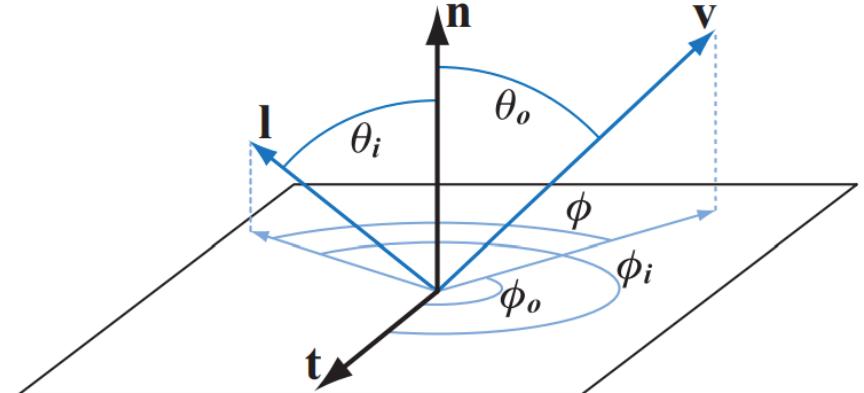
BRDF

- Describes reflectance phenomena: redirection of light hitting surface (shading point) back outward
- Mathematical approximation of light interaction and microscopic structure of material:
 - Surface reflection
 - Local sub-surface scattering (e.g., diffuse model)
- BRDF is evaluated at shading point



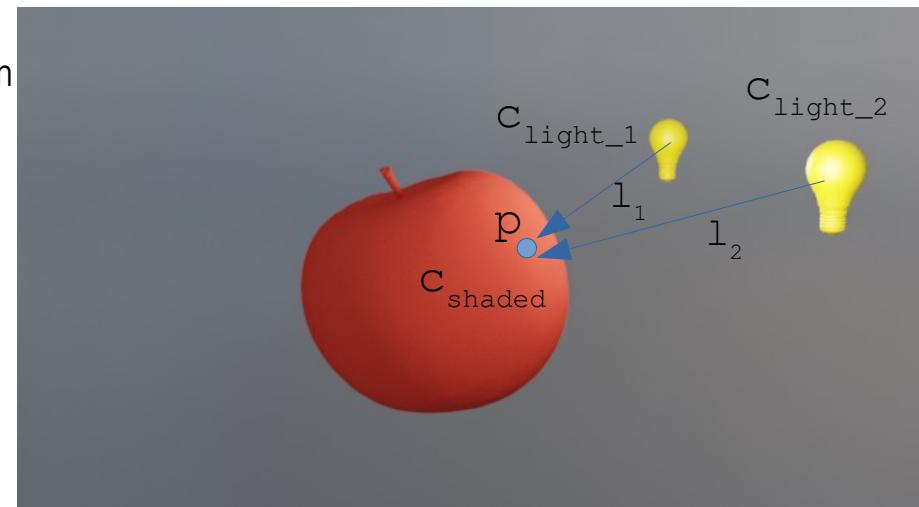
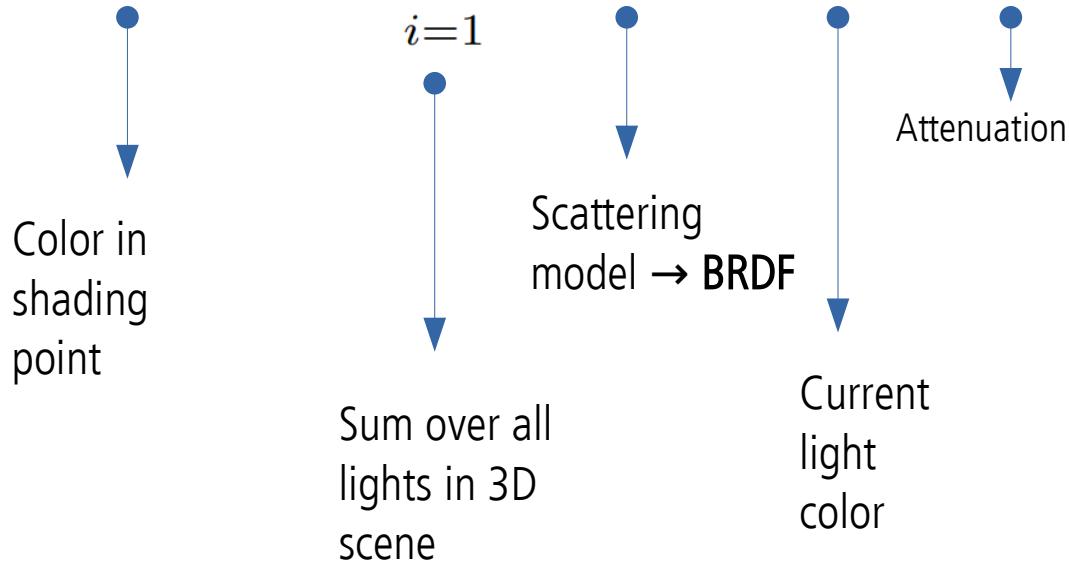
BRDF notation

- BRDF $f(v, n, l)$ describes surface response which depends on:
 - Incoming – unit length vector - **light direction** (l)
 - Outgoing – unit length vector - **view direction** (v)
 - **Shading point normal** (n)
- Incoming (l) and outgoing (v) directions have 2 degrees of freedom, two angles relative to surface normal:
 - Elevation (θ)
 - Azimuth (ϕ)
- Dimensionality of BRDF: 4

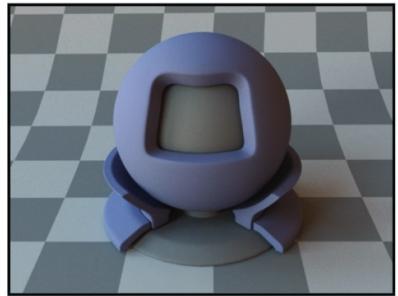
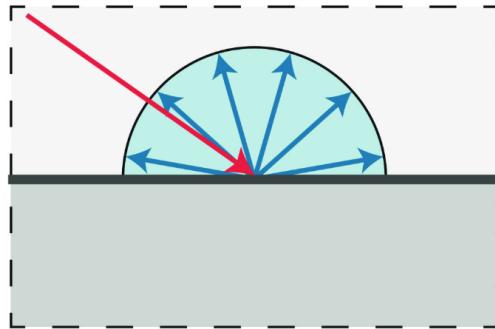


BRDF in shading

$$c_{shaded}(p, v) = \sum_{i=1}^n f(l_i, n, v) c_{light_i} (n \cdot l_i)^+$$

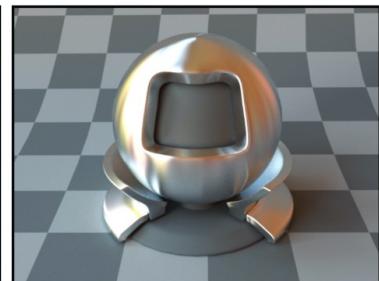
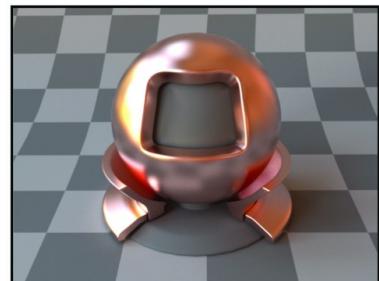
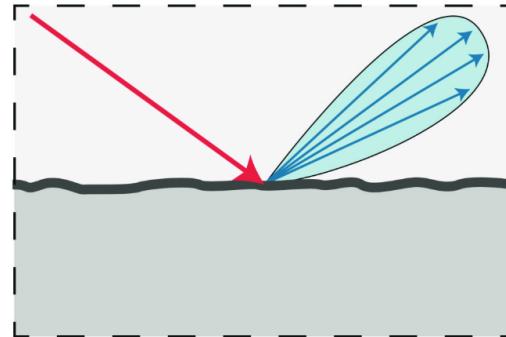


Common BRDFs



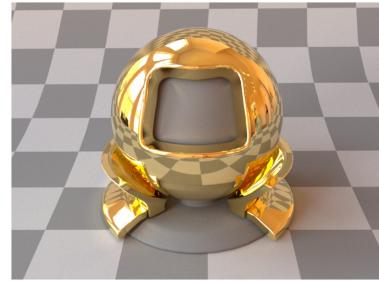
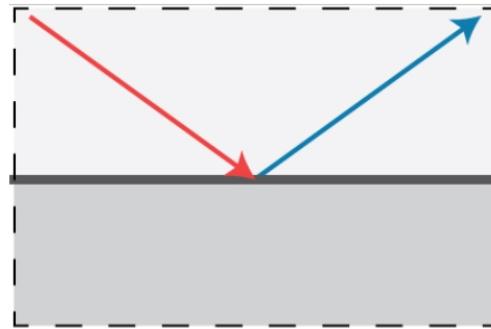
Diffuse, Diffuse textured.

Light is scattered in all possible directions.
Independent of viewing direction. Equally
bright from all directions.



Glossy: Copper, Aluminium.

Scattered light is concentrated around
particular direction (lobe). Appears blurred.
Dependent of viewing direction.

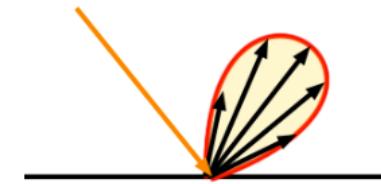


Specular (gold)

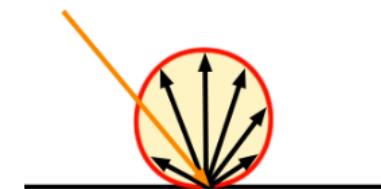
Light is scattered in single
direction (mirror-reflection
direction). Perfectly sharp.
Dependent of viewing
direction.

BRDF reflection

- Real materials have complex lobes
- While modeling, several lobes are combined with different weights and parameters
- Wide range of materials can be described with these three basic reflection types:
 - Specular
 - Diffuse
 - Glossy (rough specular)



specular reflection



diffuse reflection



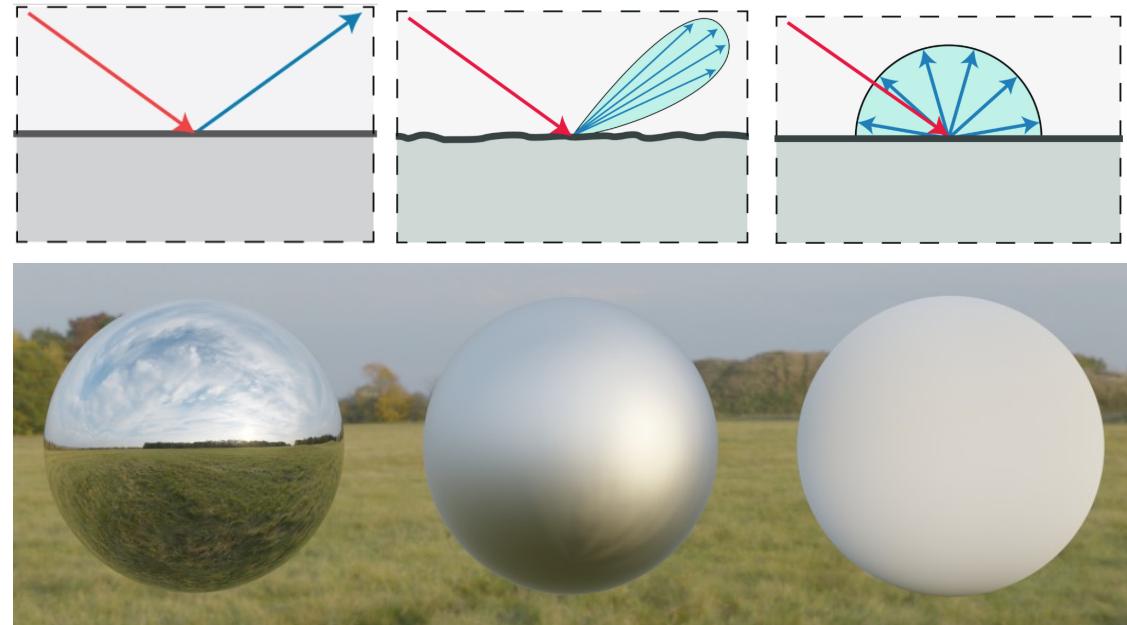
diffuse + specular

Scattering models

- Modeling approaches:
 - **Empirical**
 - Simulate observed scattering phenomena
 - **Data-based**
 - Scattering is measured from real world and stored in tables
 - **Physically-based**
 - Based on physical interaction of light with matter

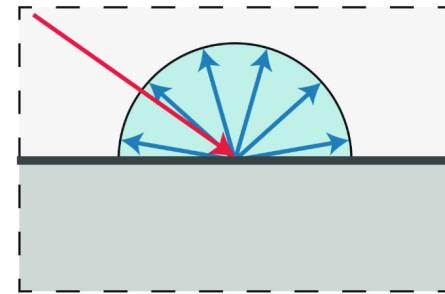
Empirical models

- Models based on **observation** of scattering phenomena rather than physical correctness
- **Phenomenological models**: describe the quantitative properties of real-world surfaces by mimicking them
- Easy to implement and use
- Types:
 - **Lambertian** → diffuse
 - **Specular** → mirror
 - **Phong and Blinn-Phong** → glossy



Lambertian (diffuse) model

- Reflected light is equal in all directions and linearly depends on incoming light
- Simplest BRDF model:
 - Doesn't depend view direction
 - Note that surface orientation will attenuate or increase incoming light making surface darker or brighter (**attenuation factor**)
 - Constant reflectance value: **diffuse color (albedo)**: (R, G, B)
- **Local model** can be used to approximate sub-surface scattering
- The basis for more complex models



$$f(v, l) = \frac{\text{albedo}}{\pi}$$



Lamberitan in shading

$$c_{shaded}(p,v) = \sum_{i=1}^n \frac{albedo}{\pi} c_{light_i} (n \cdot l_i)^+$$

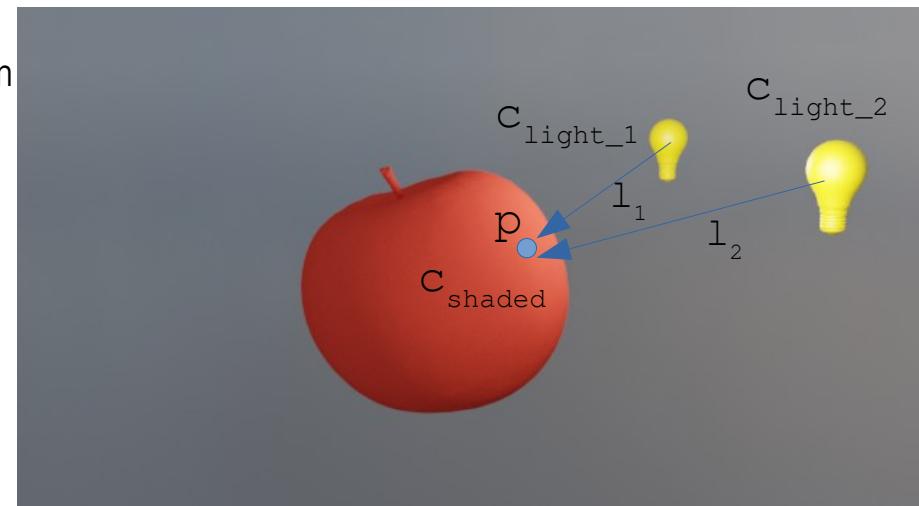
Color in shading point

Lambertian scattering model

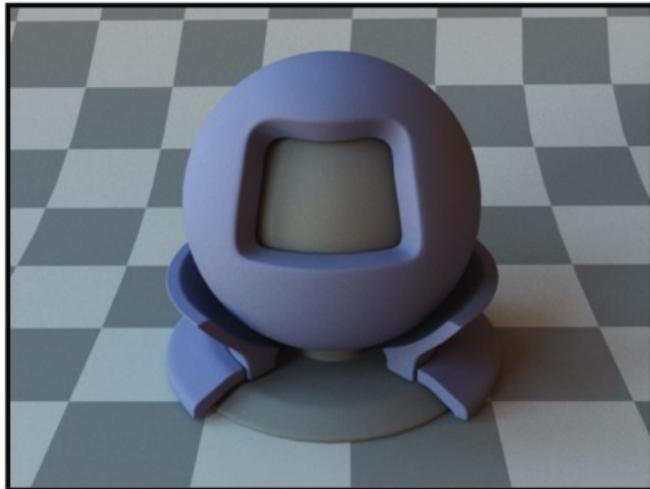
Sum over all lights in 3D scene

Current light color

Attenuation

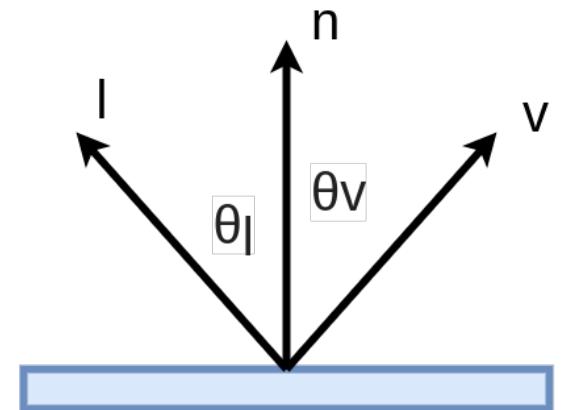
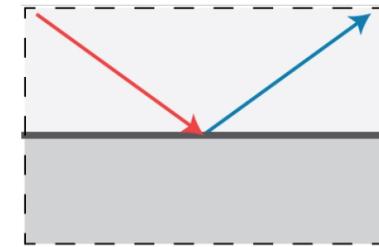


Lambertian (diffuse) model examples



Specular (mirror) model

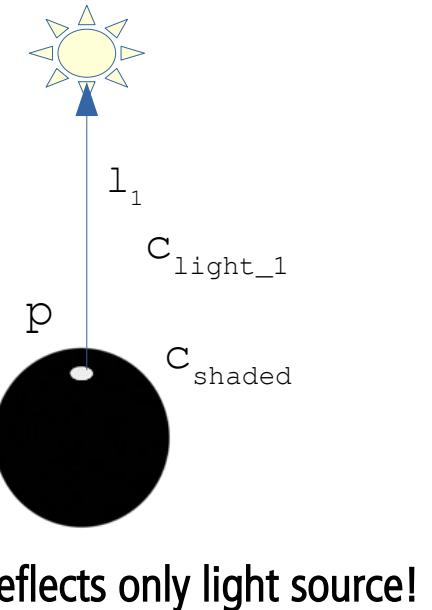
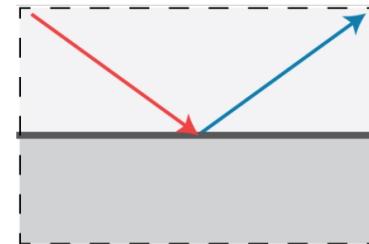
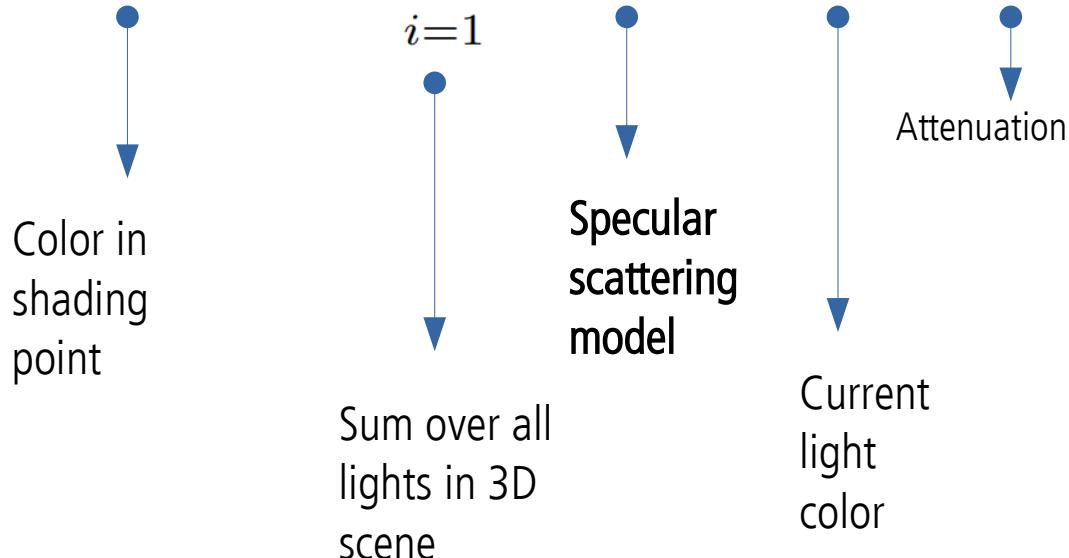
- Ideal reflection where incoming light is reflected completely in a single outgoing direction
 - Mirror reflectance direction $\rightarrow \theta_l = \theta_v$
- Depends on view and light directions
- Single parameter: **reflectivity** – a constant (R,G,B)



$$f(v, l) = \begin{cases} \text{reflectivity if } v = l - 2(l \cdot n)n \\ 0 \quad \text{otherwise} \end{cases}$$

Specular in shading

$$c_{shaded}(p, v) = \sum_{i=1}^n f(l_i, n, v) c_{light_i} (n \cdot l_i)^+$$



$$f(v, l) = \begin{cases} reflectivity & \text{if } v = l - 2(l \cdot n)n \\ 0 & \text{otherwise} \end{cases}$$

Specular in shading

$$c_{shaded}(p, v) = \sum_{i=1}^n f(l_i, n, v) c_{light_i} (n \cdot l_i)^+ +$$

Color in shading point

Specular scattering model

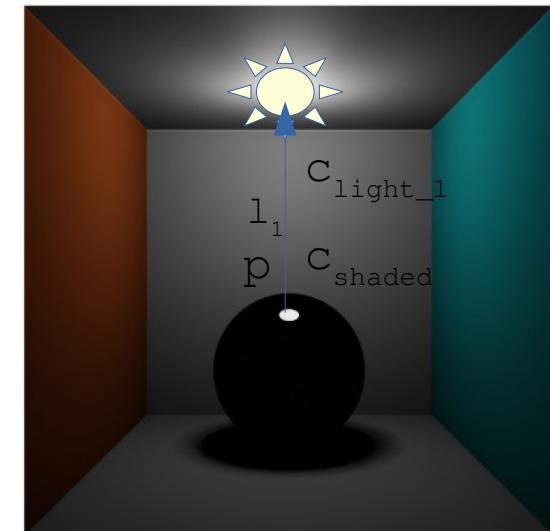
Sum over all lights in 3D scene

Current light color

Attenuation

$$f(v, l) = \begin{cases} \text{reflectivity if } & v = l - 2(l \cdot n)n \\ 0 & \text{otherwise} \end{cases}$$

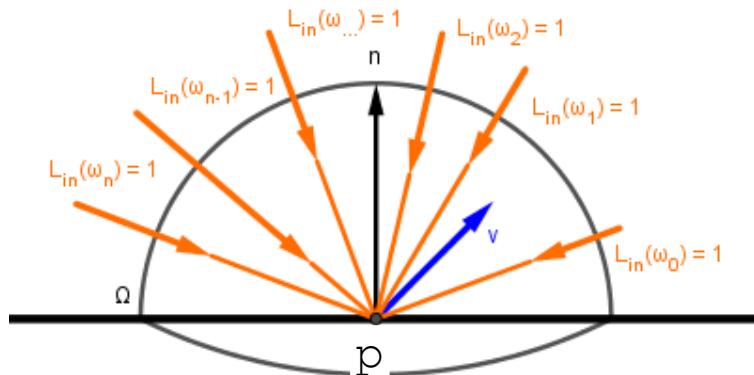
Drawback of direct illumination



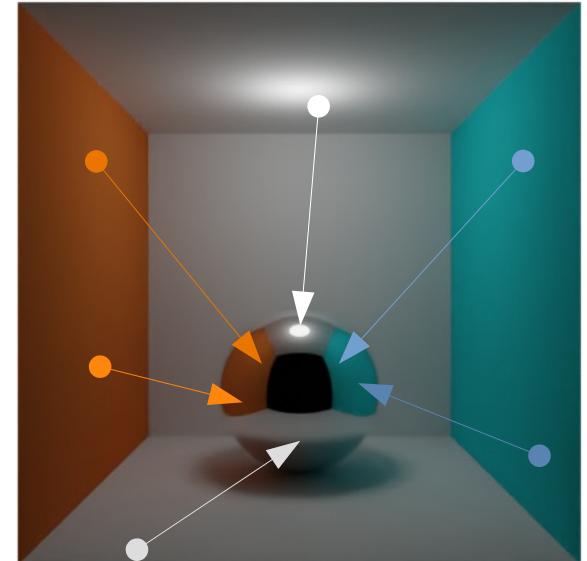
Specular in shading

- Ideal reflection where incoming light is reflected completely in a single outgoing direction – **mirror reflectance direction**
 - Light has to be gathered from all surfaces in 3D scene → reflectance equation

$$L_o(p, v) = \int_{l \in \Omega} f(l, n, v) L(p, l) (n \cdot l)^+ dl$$



- Global illumination:
- direct illumination
 - indirect illumination



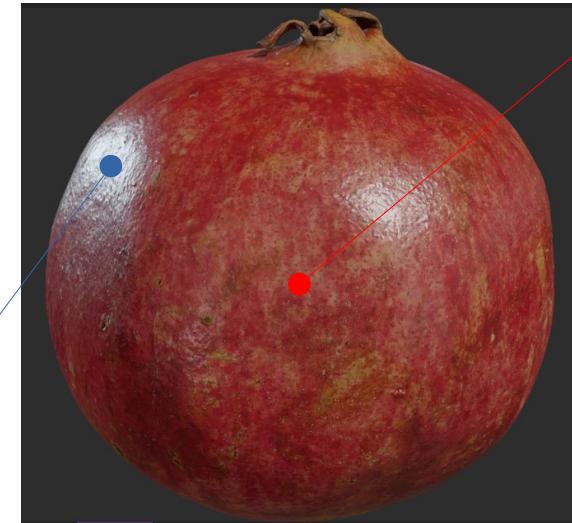
Specular and diffuse reflection examples

- Specular reflectivity parameter determines color for metals (conductors)
 - Metals have colored specular reflection due to spectral selectivity



Metals reflect almost all specularly

Metals: colored specular highlight



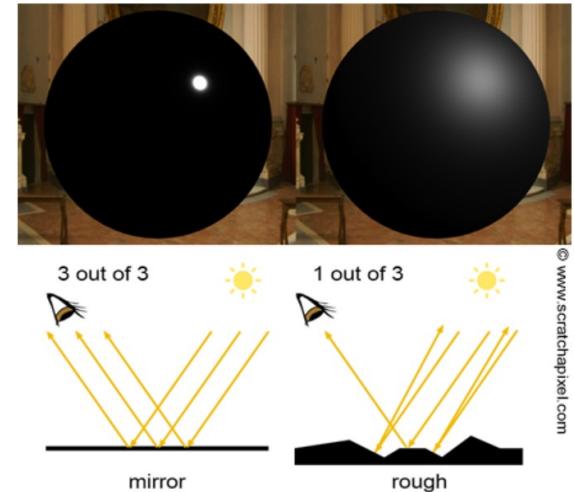
Specular highlight.
Dielectrics: specular highlight the same as light source color

Diffuse reflection gives color to the dielectric materials.

It is a result of re-emitted light which entered surface and partially absorbed.

Phong model

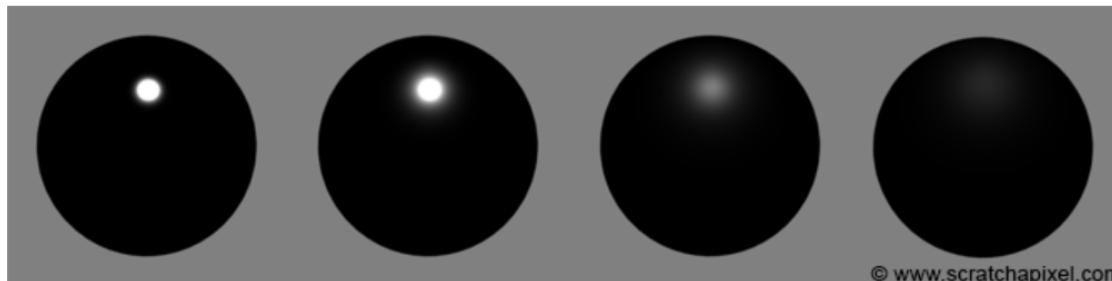
- Idea: wide range of materials can be described with **diffuse** and **specular** component:
 - $\text{surface_color} = \text{diffuse}() * K_d + \text{specular}() * K_s$
- Some surfaces exhibit **glossy** highlights: reflection of light source (or another object) on object surface
 - Compared to perfect specular mirror reflection, glossy is blurred and broken up
 - This kind of rough surface acts like “broken mirror” and it is modeled as collection of small mirrors → **micro-facets**



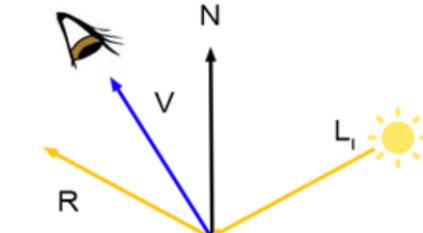
- Only fraction of light rays are reflected in eye direction by rough surface causing dimmer/blurred light reflection
- Brightness of glossy reflection decreases as angle between view and ideal reflection increases – number of microfacets reflecting in eye decreases

Phong model: glossy observations

- Maximum reflection is when viewer (V) aligns with reflection (R)
- Reflection decreases as angle between viewer (V) and reflection (R) distance increases
 - Light source reflection spreads across larger area
 - Highlight brightness decreases as distance of object points from original reflected light position increases



$$R = \text{reflect}(L_i, N)$$
$$\text{specular} = (V \cdot R)^n$$



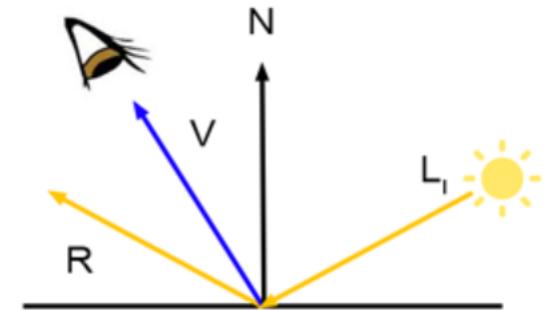
© www.scratchapixel.com

Phong model: specular component

- Phong observation: glossy surface can be simulated by:
 - Computing ideal specular reflection (R) of incident light ray (L)
 - Computing dot product between reflected ray and view direction
 - Raising dot product to power of n

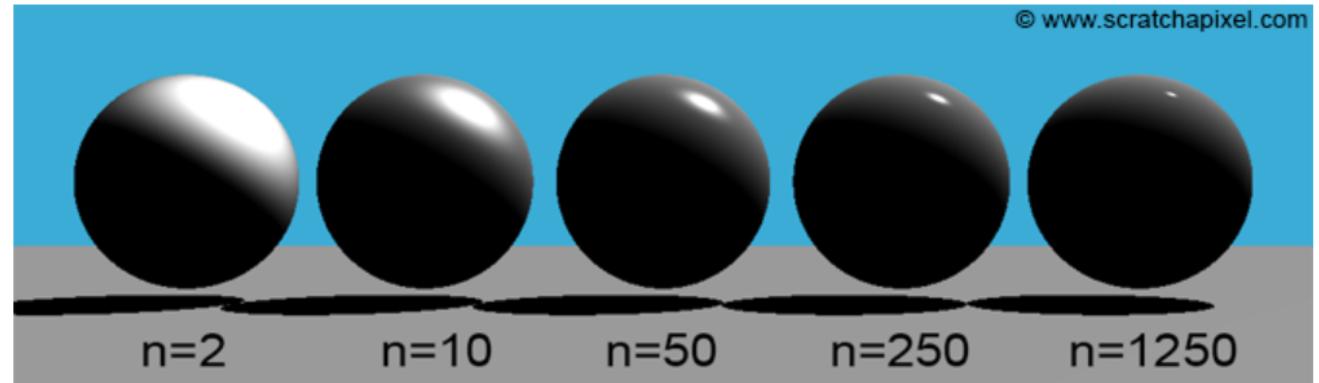
$$\text{Specular} \approx (V \cdot R)^n.$$

$$R = \text{reflect}(L, N)$$
$$\text{specular} = (V \cdot R)^n$$



© www.scratchapixel.com

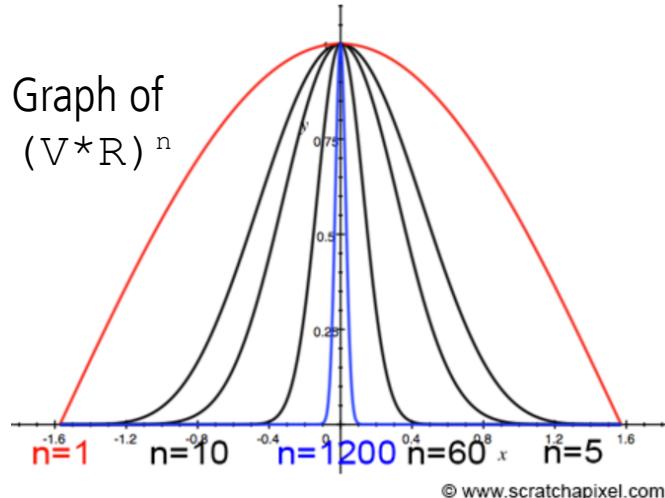
$$R = 2(N \cdot L)N - L.$$



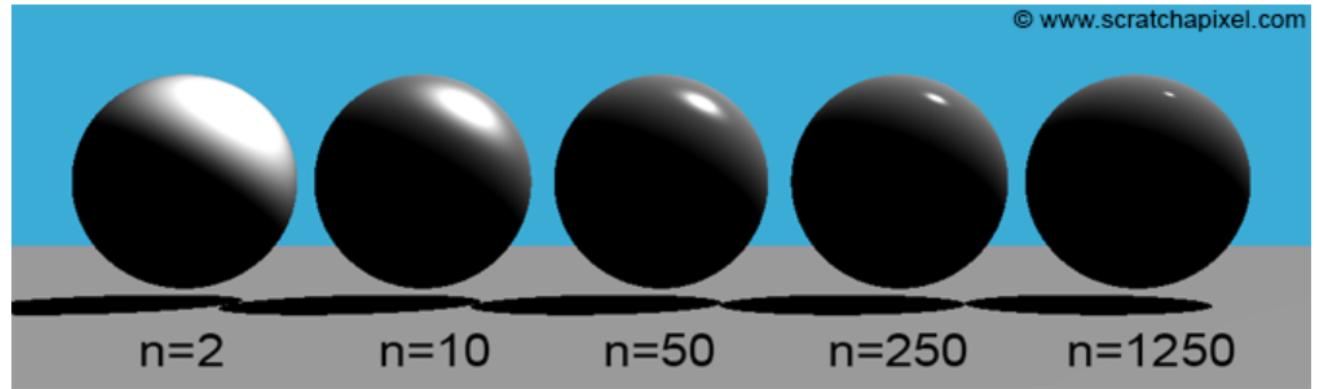
© www.scratchapixel.com

Phong model: specular component

- Empirical model: parameters doesn't have physical meaning
 - Parameters are tweaked by artist/user until desired appearance is achieved
 - Specular highlights become “sharper” as n grows
- Physically based models build on this concept and provide physically-based parameters

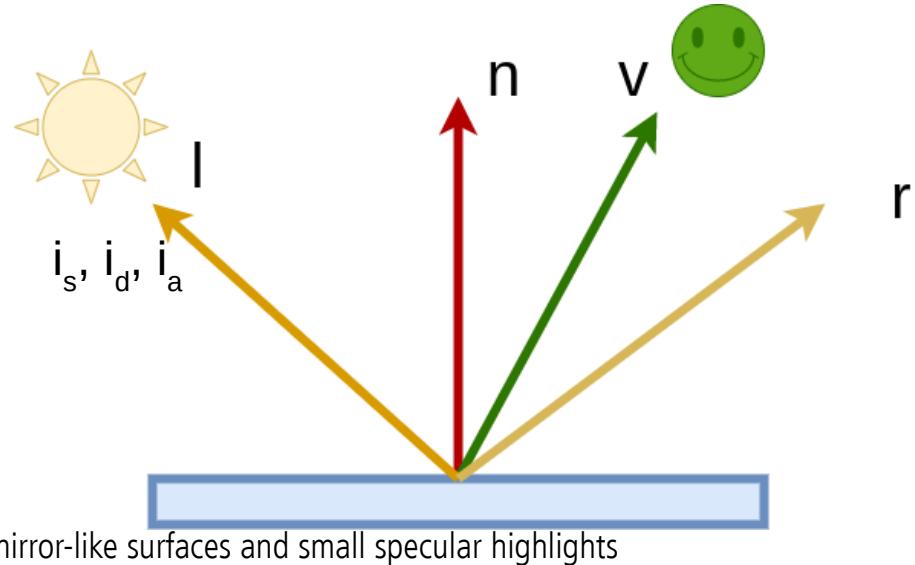


$$\text{Specular} \approx (V \cdot R)^n.$$

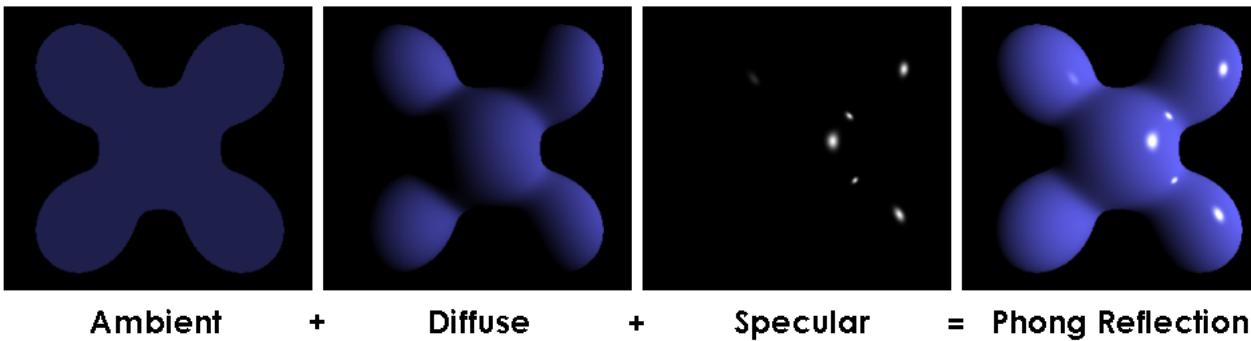


Phong illumination model

- Describes local shading (direct illumination)
- Lambertian diffuse reflection: rough surfaces, large highlights
 - Parameter: k_d – ratio of reflection of the diffuse term of incoming light
- Specular reflection: shiny surfaces, small highlights
 - Parameter: k_s – ratio of reflection of the specular term of incoming light
 - Additional parameter: alpha – shininess constant: larger for smooth and mirror-like surfaces and small specular highlights
- Ambient term: small amount of light that comes from around the scene
 - Parameter: k_a – ratio of reflection of the ambient term for all points on the surface

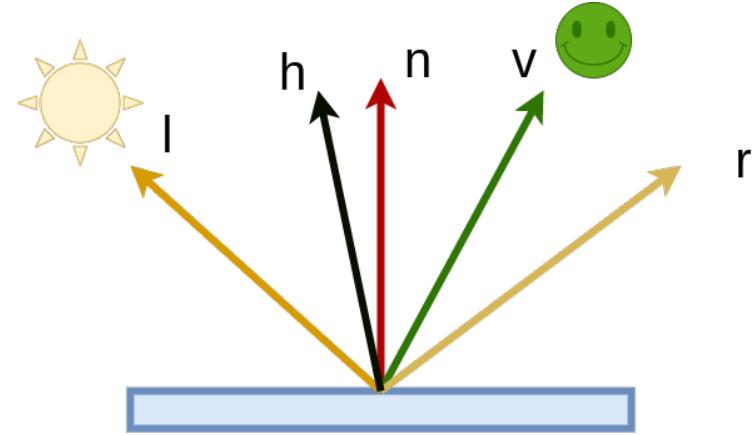


$$L_o = k_a i_a + \sum_j^n (k_d(l_j \cdot n) i_{j,d} + k_s(r_j \cdot v)^\alpha i_{j,s})$$



Blinn-Phong reflection model

- Modification of Phong model
- Introducing **half vector (h)** between light and view vectors
 - Maximum reflection: $V = R \rightarrow N = H$
 - Reflection decreases when angle between N and H increases
- Parameters:
 - **Lambertian** (k_L), range: [0,1]
 - **Glossy** (k_G), range: [0,1]
- Energy conserving if $k_L + k_G \leq 1$

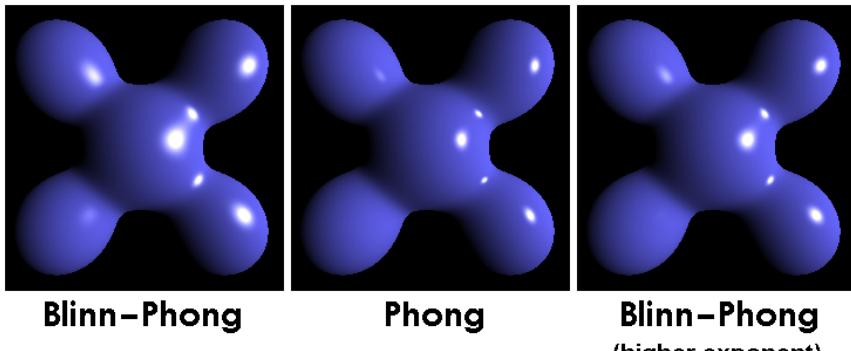


$$f(v, l) = \frac{k_L}{\pi} + k_G \frac{8 + s}{8\pi} z^2$$

$$z = \max(0, h \cdot n)$$

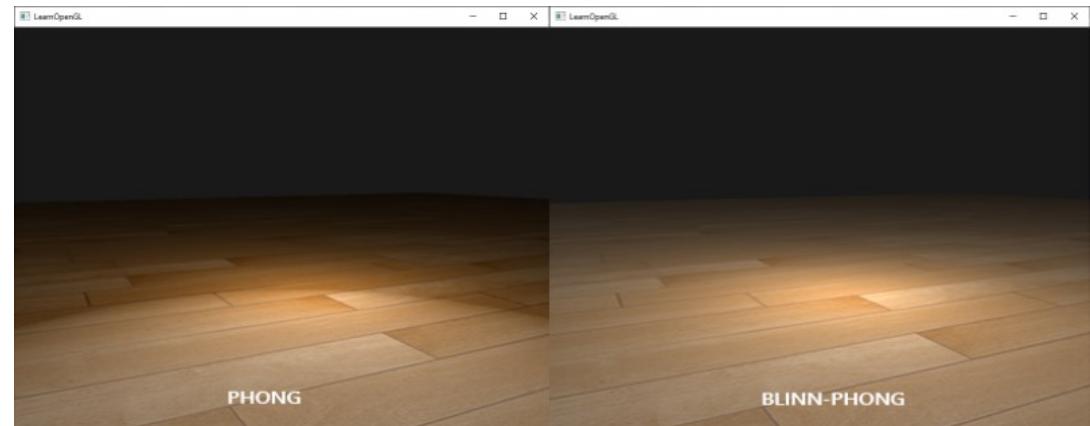
$$h = \frac{v + l}{\|v + l\|}$$

Blinn-Phong reflection model



https://en.wikipedia.org/wiki/Blinn%20Phong_reflection_model

- Phong and Blinn-Phong models are often perceived as “plastic”.
- Physically-based microfacet models solve this problem

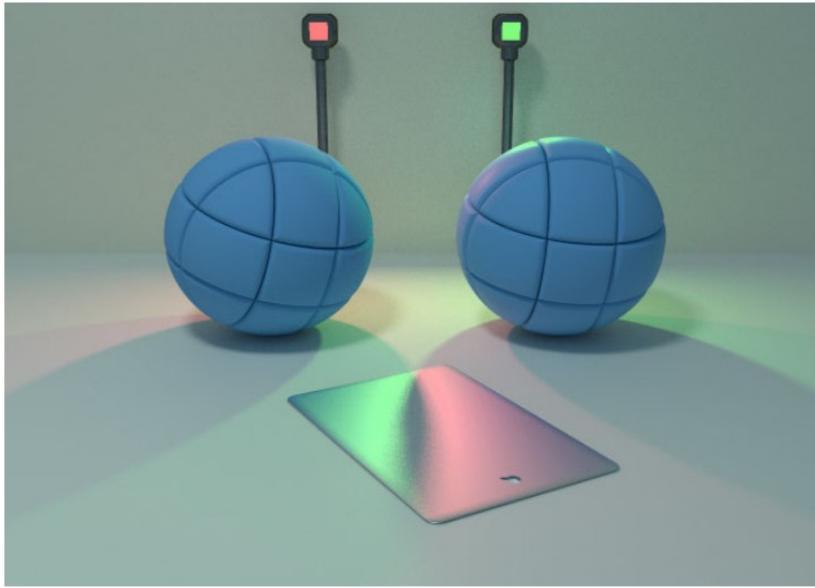


Example in OpenGL:

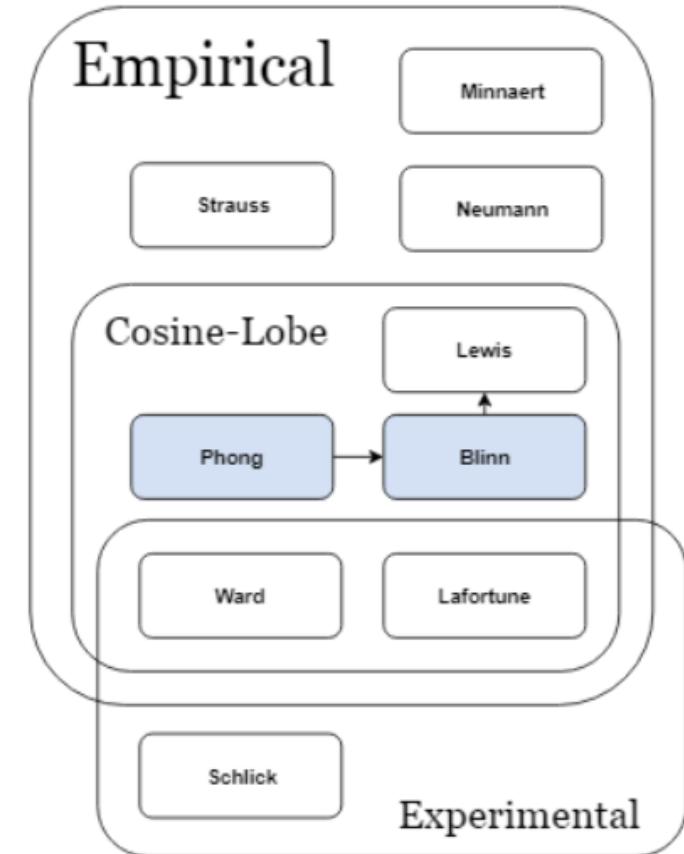
<https://learnopengl.com/Advanced-Lighting/Advanced-Lighting>

Other empirical models

- Lafourture model
 - Generalization of Phong's model
 - Richer appearance with multiple lobes



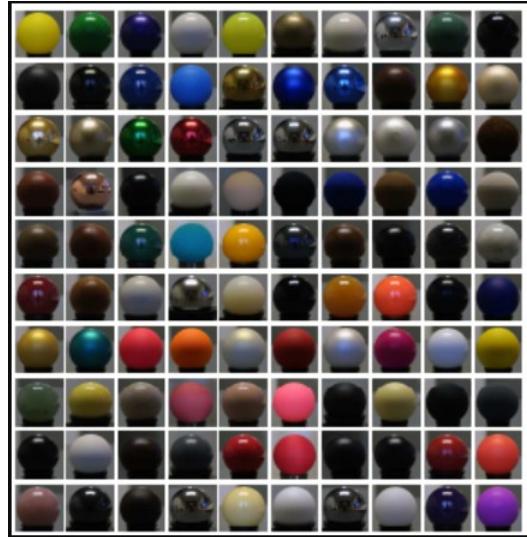
Lafourture model. http://people.csail.mit.edu/addy/research/ngan05_brdf_eval_ppt.pdf



<https://cglearn.eu/pub/advanced-computer-graphics/physically-based-shading>

Data-based models

- BRDF measurement → **gonioreflectometer**
 - Measurements are stored in table on which lookup with view and light direction is performed
- BRDF measurement of real-world can be used for:
 - Evaluation of phenomenological and physically based models
 - Modeling of material
- Different real-world materials have been measured:
 - Isotropic BRDFs
 - Anisotropic BRDFs
 - Texture characteristics
 - Sub-surface scattering
- Problems:
 - Costly for rendering
 - Memory



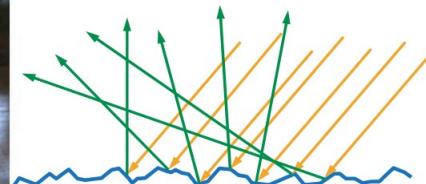
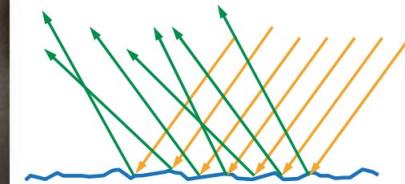
Isotropic materials: <https://www.merl.com/brdf/>



Anisotropic materials: Brushed
aluminium, Yellow satin, Purple satin, Red velvet
<http://people.csail.mit.edu/addy/research/brdf/>

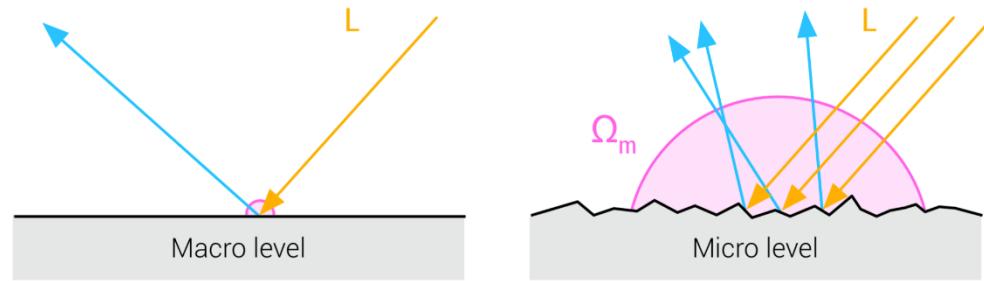
Physically-based models

- Real-world surfaces have geometrical detail on multiple and thus **very small scales**
- Small scale geometry is invisible to the eye directly, but its cumulative response is visible.
 - Micro-facet theory



Microfacet-based models

- Small-scale surface irregularities (smaller than a pixel) can not be modeled explicitly, therefore this is modeled using BRDF
 - Geometric optics assumption: these irregularities are much smaller than light wavelength (they have no effect of appearance) or much larger than light wavelength (they cause light redirection). Wave optics describes phenomena in between.
- Small scale irregularities are represented as optically-flat facets with **microsurface normals** → microfacet-based models.



<https://google.github.io/filament/Filament.html>

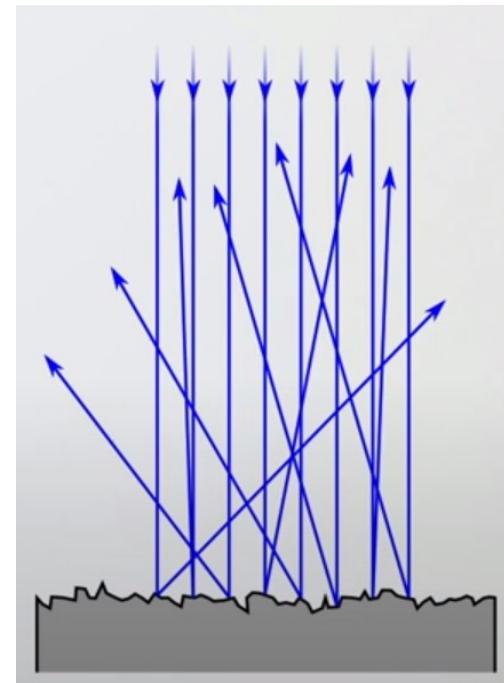
Microfacet-based models

- **Cook-Torrance reflection model:** model surface statistically as large number of microfacets

$$R_{Cook-Torrance} = R_s + R_d$$

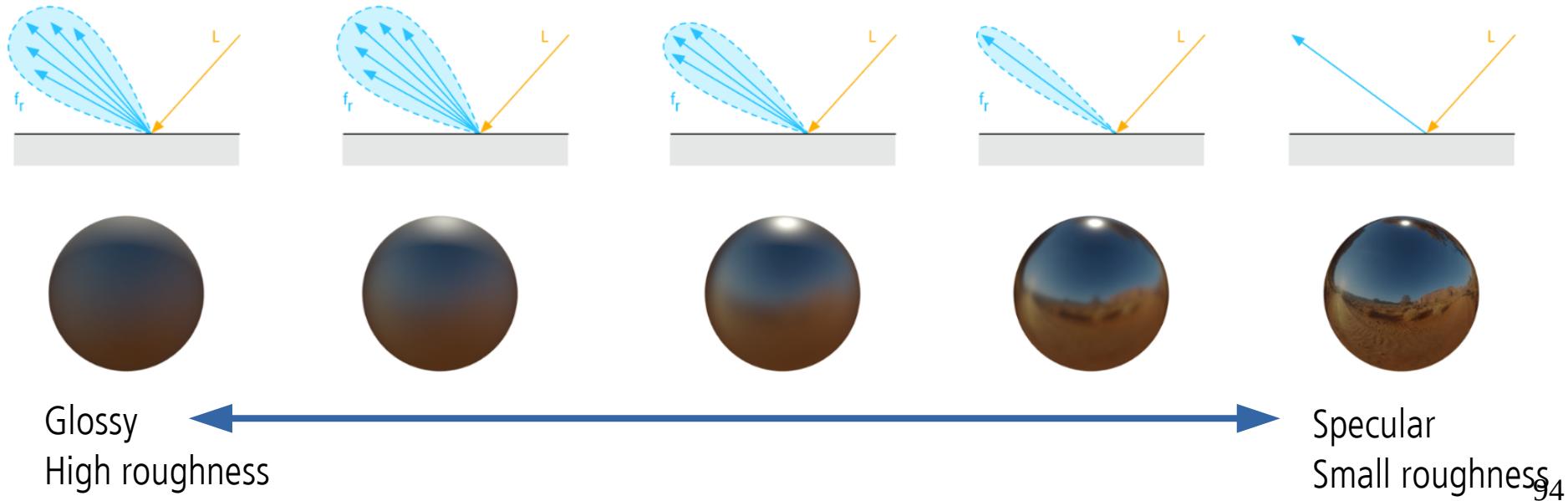
$$R_s = \frac{D \cdot G \cdot F}{dot(N, V) \cdot dot(N, L)}$$

- D – distribution of microfacet normals
- F – Fresnel
- G – geometry term: masking-shadowing
- R_d – Lamberitan reflection model



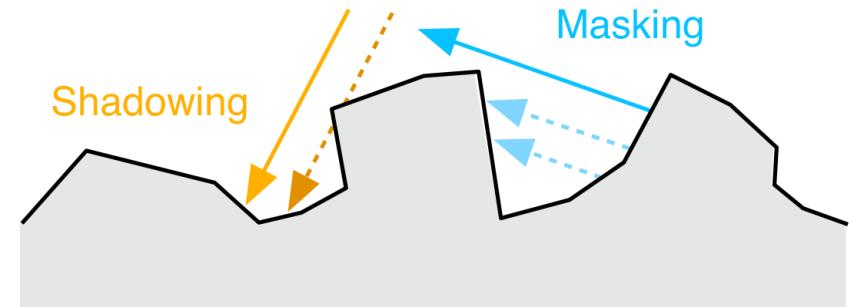
D – distribution of microfacet normals

- Statistical distribution of microfacet normal orientation. Distributions: Gaussian, Beckmann, GGX
- Spread of this distribution is called **roughness** and it determines the regularity of microfacets
 - Higher roughness → more blurred surface since micronormals will be more spread (**glossy-diffuse**).
 - Small roughness → mirror-like surface (**specular**).



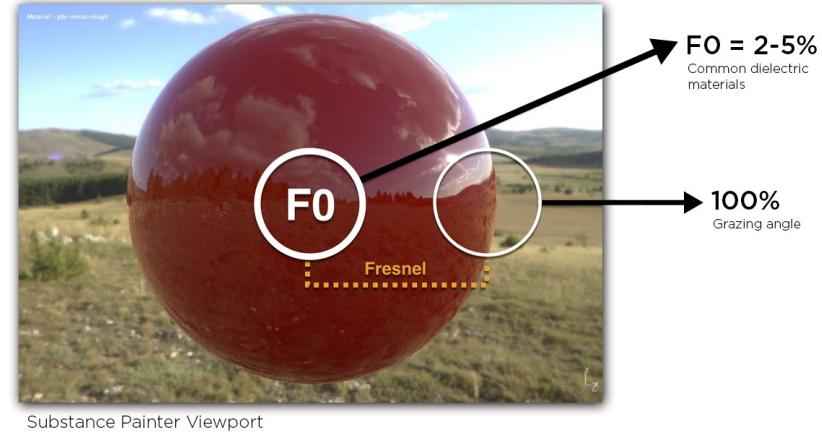
G – geometry term

- Statistically describes attenuation at microfacet level
 - Microfacets can shadow or mask one another
 - Gives probability for such event
- Depends on distribution of microfacet normals D
 - Often Smith's model is used.



F – Fresnel term

- Determines amount of reflected vs transmitted light
- Depends on:
 - Index of refraction
 - Incident angle
- Specular reflection is increased at grazing angles



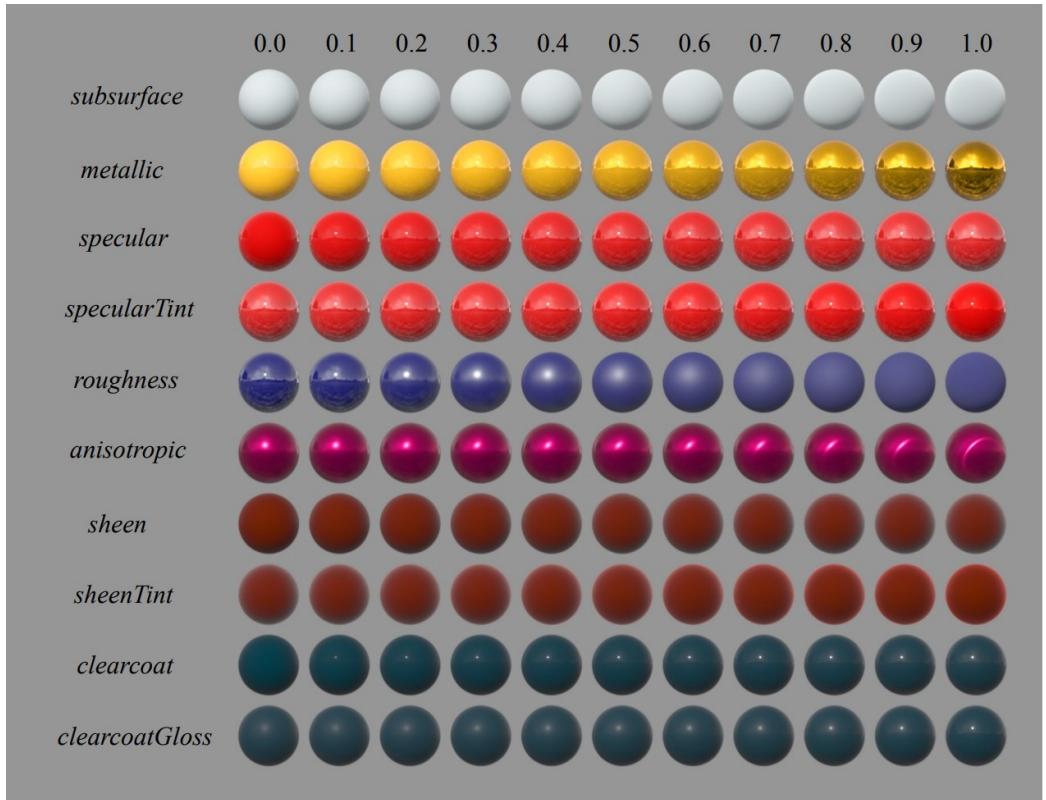
Microfacet-based models

- Microfacet-based BRDFs are state of the art reflectance models using in professional modeling and rendering software.
- Fundamental models are:
 - **Torrance–Sparrow, Cook-Torrance** for glossy surfaces
 - **Oren-Nayar** better approximation of diffuse reflection than Lambertian model



Physically-based models

- Disney BRDF
 - Universal BRDF with few parameters
 - Blender:
https://docs.blender.org/manual/en/last/render/shader_nodes/shader/principled.html

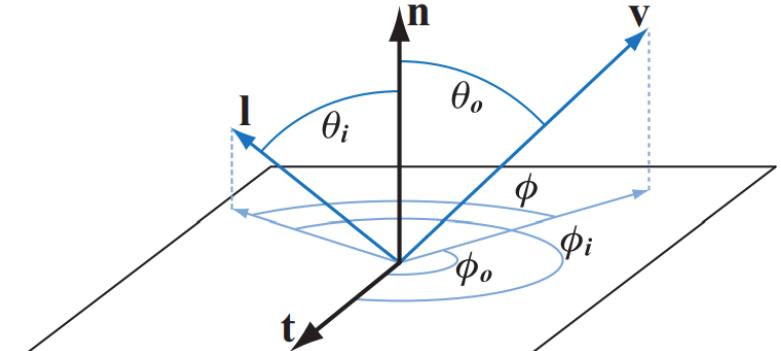
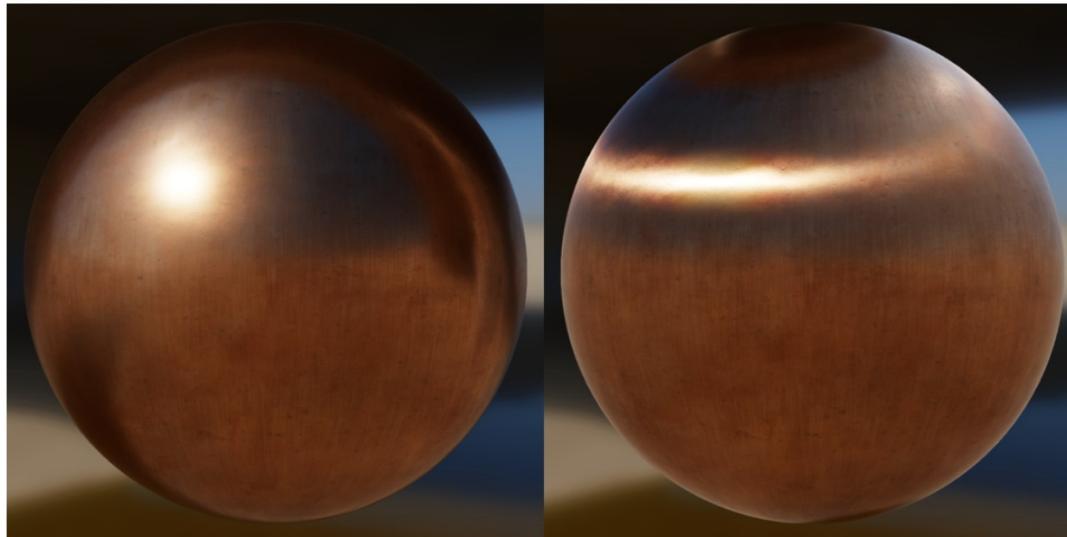


Disney BRDF:

https://media.disneyanimation.com/uploads/production/publication_asset/48/asset/s2012_pbs_disney_brdf_notes_v3.pdf

Isotropic and anisotropic BRDF

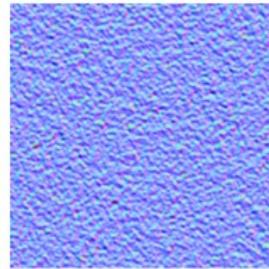
- **Isotropic BRDF:** rotating light and view directions around the surface normal does not affect the BRDF.
 - Incoming and outgoing directions have the same relative angles between them: such BRDF can be parameterized with three angles.
- **Anisotropic BRDF:** reflection behavior changes when light and view vectors are rotated around normal
 - Ward anisotropic BRDF: good for modeling surfaces with anisotropic structure, e.g., hair, grooves in metals



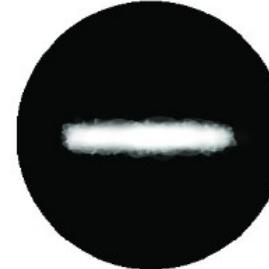
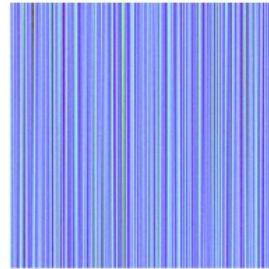
Isotropic and anisotropic BRDF

- Anisotropic behavior is present due to underlying surface structure which is directional

Isotropic



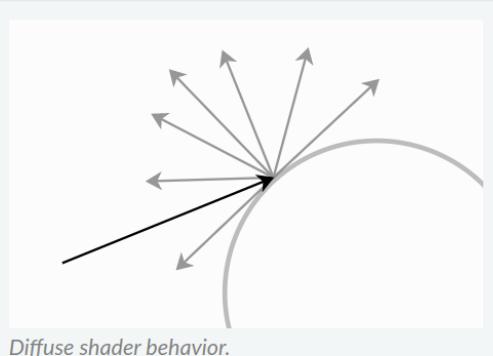
Anisotropic



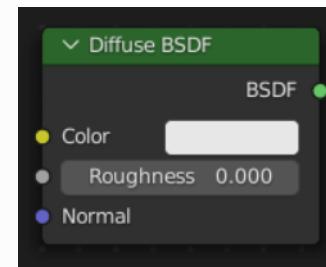
Blender is our friend



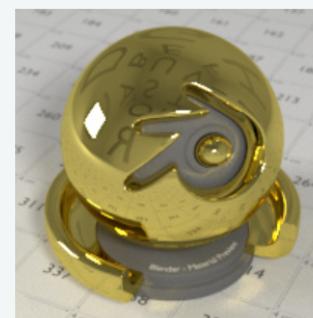
Lambertian reflection.



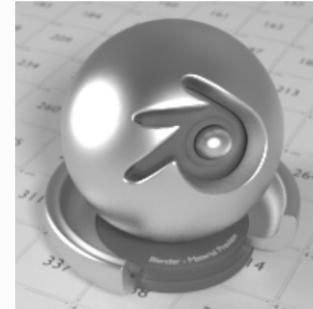
Oren-Nayar reflection.



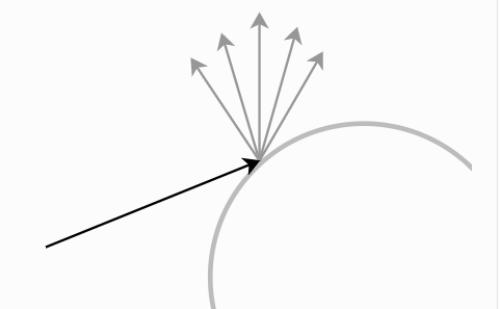
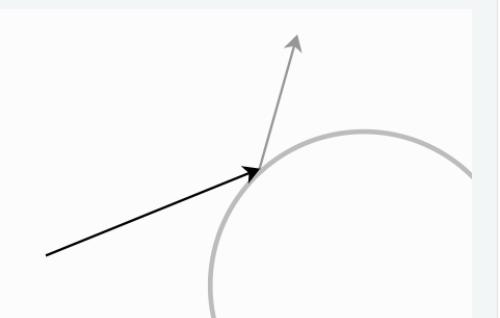
- https://docs.blender.org/manual/en/latest/render/shader_nodes/shader/diffuse.html
- https://docs.blender.org/manual/en/latest/render/shader_nodes/shader/glossy.html
- https://docs.blender.org/manual/fr/2.79/render/blender_render/materials/properties/diffuse_shaders.html?highlight=diffuse%20shaders



Sharp Glossy example.

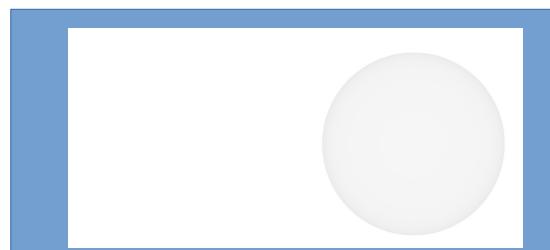


Rough Glossy example.



Physically-based models

- Physically based rendering imposes two laws:
 - **Helmholz reciprocity:** $f(l, v) = f(v, l)$ – input and output can be switched and the function value will stay the same
 - **Conservation of energy***: outgoing energy can not be greater than incoming energy. BRDF which significantly violates this property leads to too bright and thus not realistic surfaces.
 - Note that BRDF can have arbitrary large values in certain directions if the distribution it describes is highly non-uniform. An example are highly reflective surfaces with highlights.



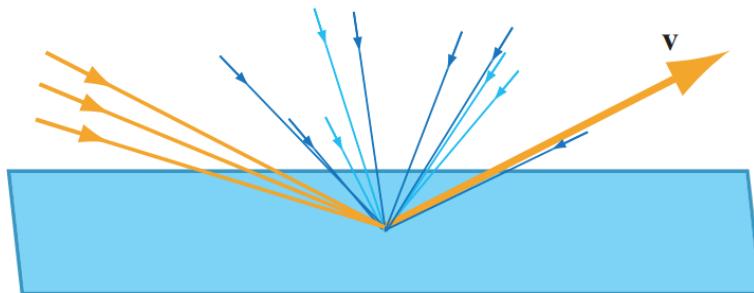
White furnace test: white sphere is illuminated with white light from all directions. If energy conserving is satisfied, the sphere will disappear in white background

<https://boksajak.github.io/files/CrashCourseBRDF.pdf>

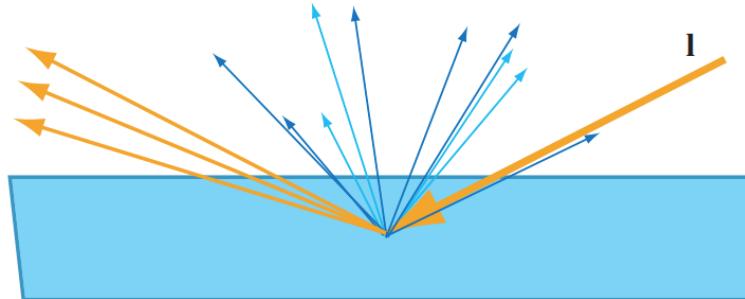
* Energy conservation is measured with directional-hemispherical reflectance $R(l)$. It measures amount of light coming from given direction that is reflected into any outgoing direction in the hemisphere around normal – it measures energy loss for a given incoming direction. If BRDF is reciprocal then hemispherical-directional reflectance can be calculated as well giving the same value. Term for both reflectance and directional albedo. The value must be in $[0,1]$ to satisfy energy conservation: 0 is completely absorbed, 1 is completely reflected. Note that this restriction doesn't apply to BRDF since it can have arbitrarily large values in certain direction (e.g., highlight direction).

Note: bidirectionality of BRDF

- “Bidirectional” in BRDF means that given incoming and outgoing direction, we can compute **amount of reflected light** in outgoing direction.
- Further, **bidirectionality** can be used for:
 - Given outgoing (view) direction, it specifies the relative contributions of incoming light
 - Given incoming light direction, it specifies distribution of outgoing light



Contributions of incoming light given view direction



Distribution of outgoing light directions given incoming light direction

BTDF

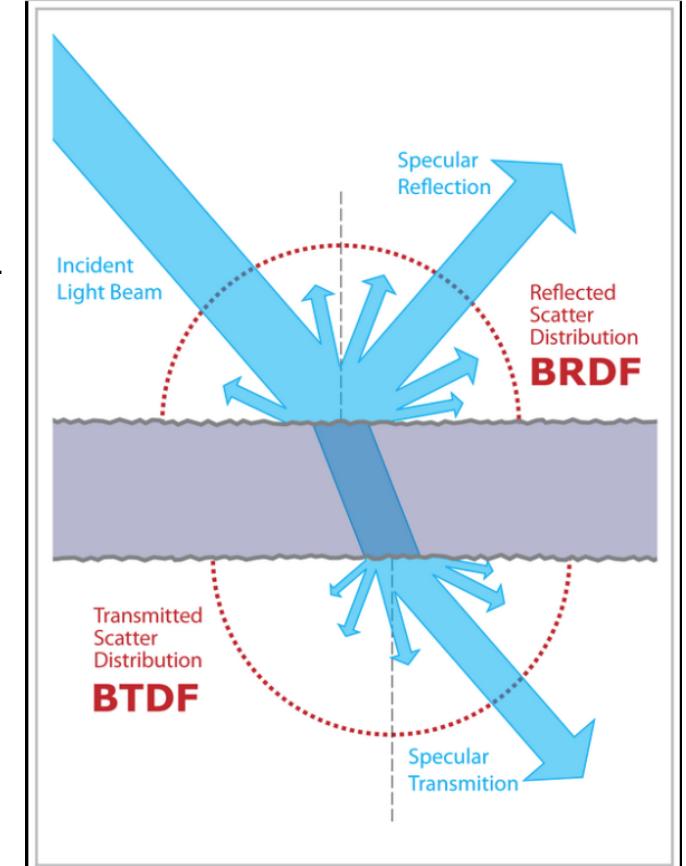
- Scattering function can be separated in reflection and transmission
 - Model describing reflection is called “bidirectional **reflectance** distribution function” – **BRDF**.
 - Model describing transmission is called “bidirectional **transmission** distribution function” – **BTDF**.



Reflection

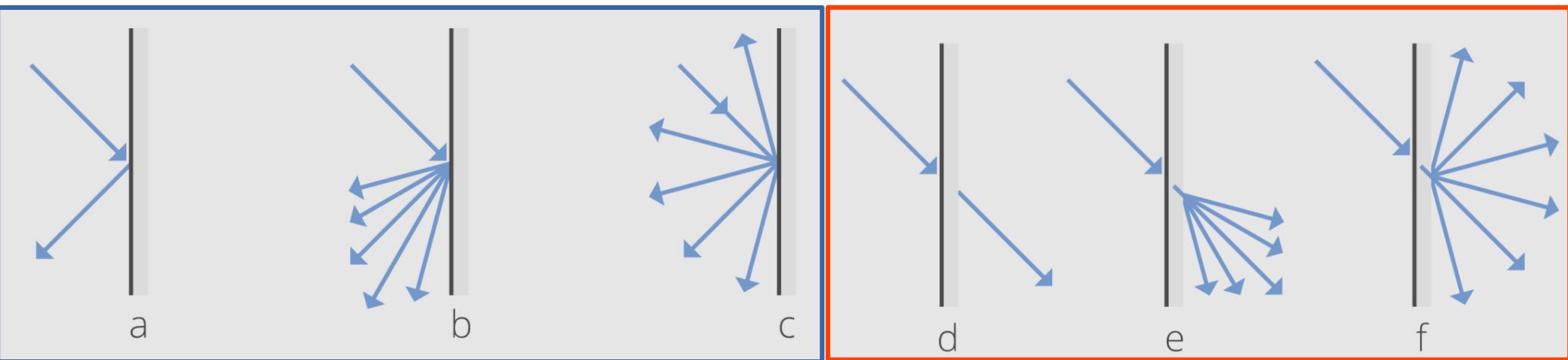


Transmission

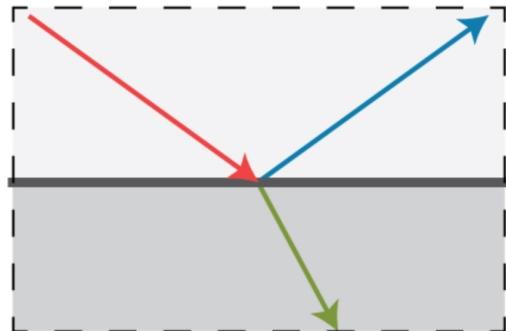


Surface reflection and refraction

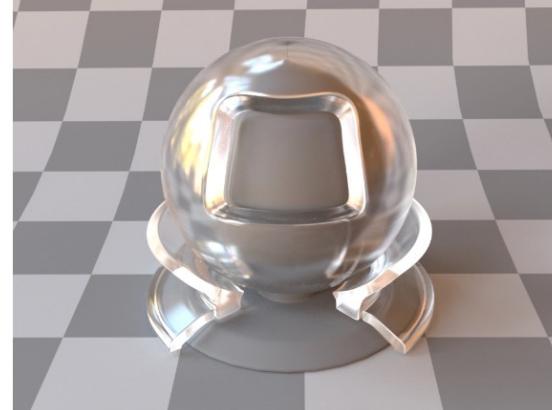
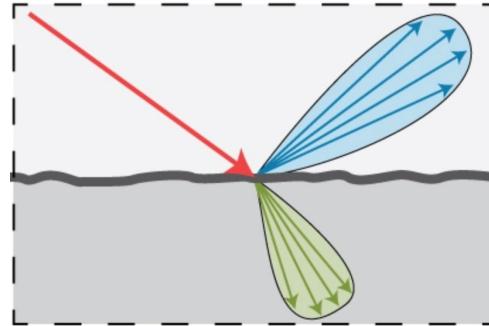
- Specular, glossy and diffuse surface **reflection** models are similar for **refraction**.



Common BTDF types



Perfect specular transmission.
Smooth dielectric.



Glossy transmission.
Rough dielectric

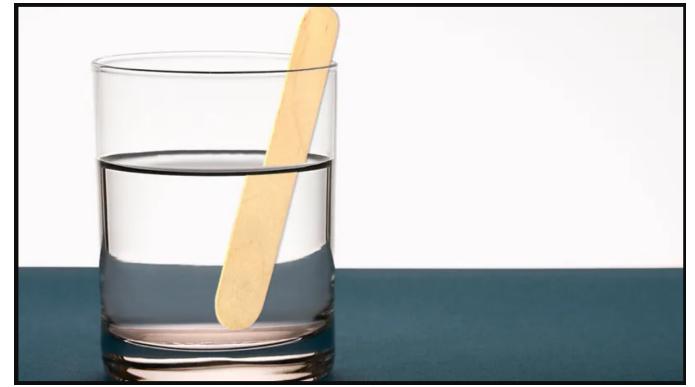
BTDF: specular transmission

- Light passing from one transparent to another transparent medium with different IOR
 - Refraction – light changes direction – illusion of disproportional/broken object
- New - transmission - direction depends on:
 - IOR η
 - Incident direction
- Snell's law: refracted angle
- Refraction/transmission direction: $T = \eta I + (\eta c_1 - c_2)N.$

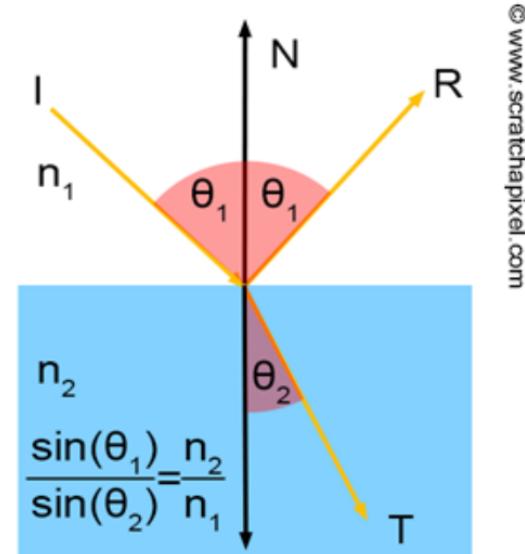
$$\eta = \frac{\eta_1}{\eta_2},$$

$$c_1 = \cos(\theta_1) = N \cdot I,$$

$$c_2 = \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 \sin^2(\theta_1)} \rightarrow \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 (1 - \cos^2(\theta_1))}$$

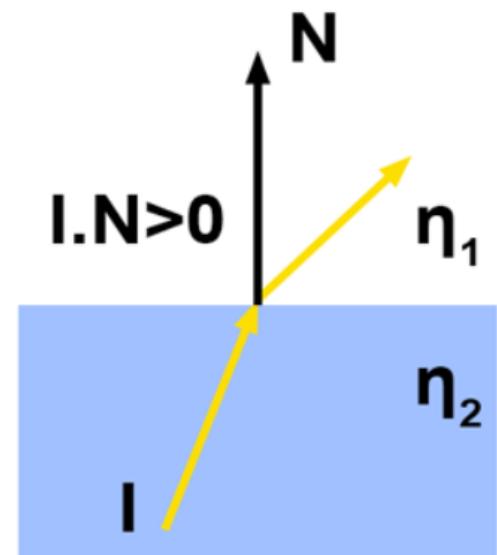
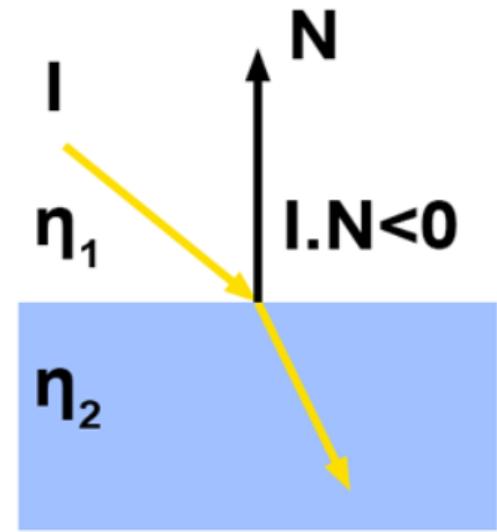


<https://www.britannica.com/science/refraction>



BTDF: specular transmission

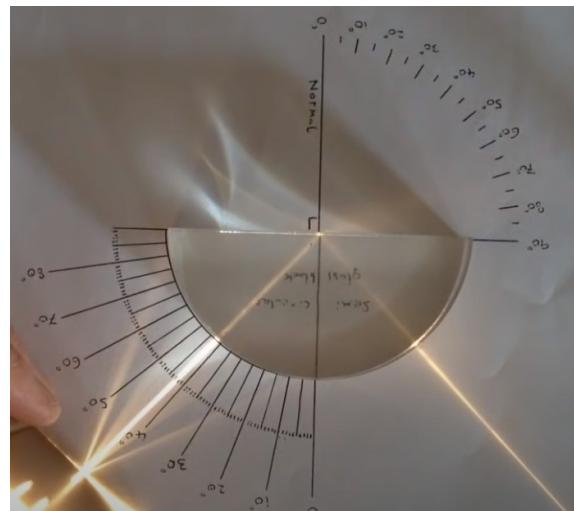
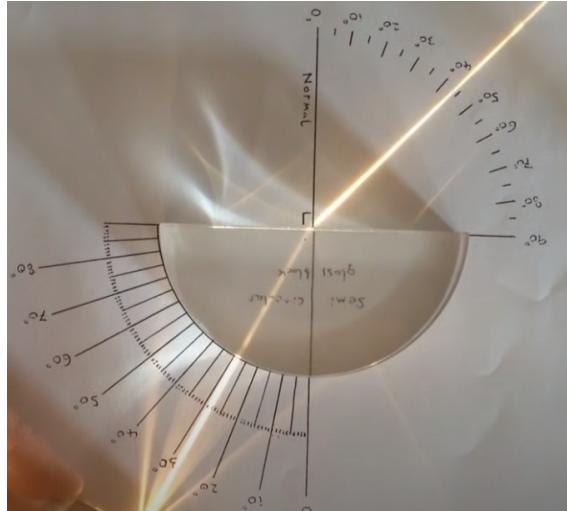
- 3D objects represent surfaces encapsulating media with different IOR
- Space around 3D objects is often considered vacuum → lowest IOR
- Light can travel:
 - From lower to higher IOR medium, e.g., light hitting surface from outside
 - From higher to lower IOR medium, e.g., light leaves volume of water
- If light travels from inside object (from higher to lower IOR) then normal direction must be flipped and then used for computing normal direction
 - Check the sign of dot product between incident ray direction and normal



BTDF: specular transmission

- When angle of incidence is larger than critical angle, then 100% of the light is reflected
 - Happens when light ray passes from higher to lower IOR (e.g., glass-water)
 - **Total internal reflection**
 - Check: term under square root is negative $c_2 = \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 (1 - \cos^2(\theta_1))}$

$$\theta_{critical} = \arcsin\left(\frac{n_1}{n_2}\right)$$



https://www.youtube.com/watch?v=NAaHPRsveJk&ab_channel=QuantumBoffin

BRDF and BTDF

- How much light is reflected and refracted?
 - Fresnel equations
 - Approximation: Schlick equation
- Amount of reflected/refracted light depends on:
 - Media IOR
 - Angle of incidence → amount of transmitted light increases when angle of incidence decreases
- Amount of reflected/transmitted light (in case when total internal reflection doesn't occurs)

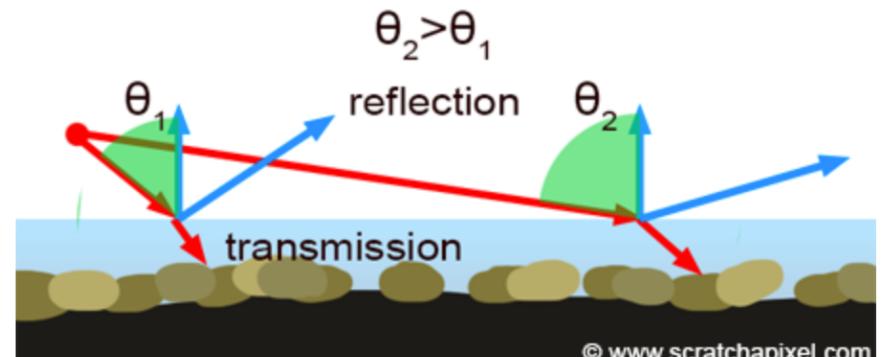
$$F_{R\parallel} = \left(\frac{\eta_2 \cos \theta_1 - \eta_1 \cos \theta_2}{\eta_2 \cos \theta_1 + \eta_1 \cos \theta_2} \right)^2,$$

$$F_{R\perp} = \left(\frac{\eta_1 \cos \theta_2 - \eta_2 \cos \theta_1}{\eta_1 \cos \theta_2 + \eta_2 \cos \theta_1} \right)^2.$$

$$F_R = \frac{1}{2}(F_{R\parallel} + F_{R\perp}). \quad F_T = 1 - F_R.$$



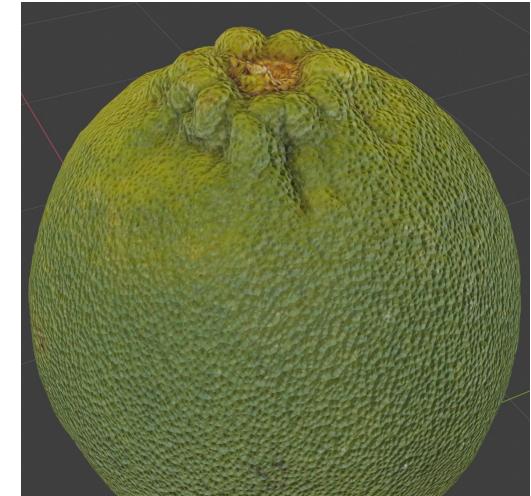
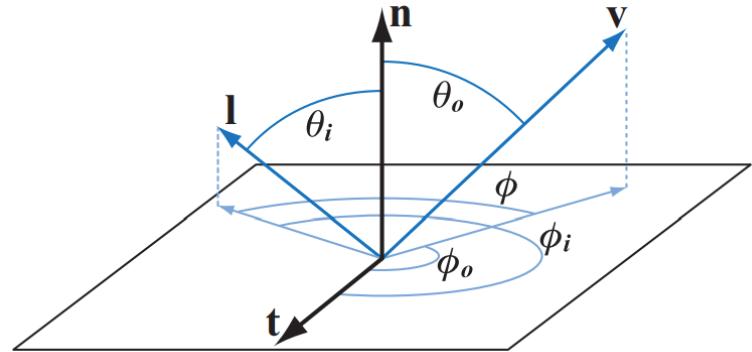
<https://shanesimmsart.wordpress.com/2018/03/29/fresnel-reflection/>



© www.scratchapixel.com

Normal and BRDF (BTDF)

- BRDF evaluation depends on surface normal
 - Normal defines so called **basis**
- Note that **perturbing the normal**, would tilt the basis and reflected light would be different!
- This enables modeling small **scale geometrical details**
- Variation of surface normal is task for **texturing**.



Scattering models parameters

- Scattering models are parameterized: color, roughness, etc.
- **Uniform parameters** result in overly smooth and perfect surface – not realistic.
- If BRDF depends on position on which is evaluated then it is called spatially varying BRDF
 - Variation of parameters over surface is done using **texturing**



Scattering models: practical tip

- In graphics, **various scattering models have been developed** (and still are!) to represent surface even more correctly or efficiently.
- Choice of the model depends on application and desired appearance.
- Practical tips:
 - When modeling a material in DCC Tool, you will be often offered with multiple implementations of basic (or more advanced) models that you further combine to achieve desired material description. In this case, it is good that you are familiar with how they work and their parameters because a lot of time is actually spent on “tweaking” parameters to achieve desired appearance. Understanding parameters of scattering models help very much with upcoming topic: texturing. This is huge and important topic.
 - If you are more interested in **developing your own scattering models** to achieve different appearance (not necessary photorealistic, rather non-photorealistic which will be discussed later) then understanding of existing scattering models is great foundation to build on: you will see that advancements of scattering models just added more complexity to basic ones.

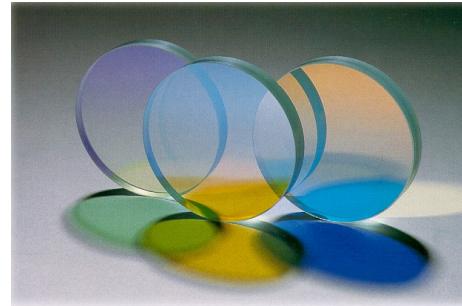
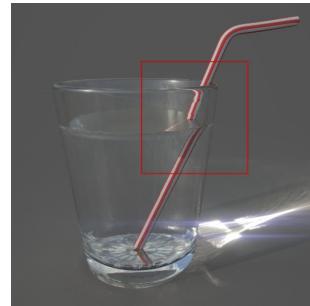
Exploring BSDFs

- Various BSDFs are available in modeling tools for material creation. Core scattering models are deeply integrated into renderer source code and user is provided with an interface to those for combining and creation of complex material.
 - Cycles/EEVEE (Blender): https://docs.blender.org/manual/en/latest/render/shader_nodes/shader/index.html
 - Appleseed: <https://appleseed.readthedocs.io/projects/appleseed-maya/en/master/shaders/shaders.html#materials>
- Similarly as for object shape (e.g., mesh), materials are meant to be transferable between applications. Note that it is up to applications renderer which scattering models are supported. Therefore, it is often a case that material defined in one modeling tool can not be easily fully and exactly transferred to another application.
 - This requires matching supported scattering functions between applications. Example is Blender to Unity
- In order enable easier communication and transfer, standardized BSDF is created and supported by different applications.
 - Principled BSDF: Blender to Godot: https://docs.godotengine.org/en/3.0/tutorials/3d/spatial_material.html
- Tendency is towards integrations of material modeling tool standards into game engines for easier transfer
 - Example: <https://substance3d.adobe.com/plugins/substance-in-unreal-engine/>

Volumetric scattering

Light-matter interaction: summary

- Light traveling to/between objects can be scattered/absorbed → **volumetric scattering**
- Light falling on object surface – **surface scattering** - can:
 - Reflect (metals and dielectrics)
 - Refract (only dielectrics)
- Depending on material, refracted light can:
 - Transmit (transparent surfaces)
 - Sub-surface scatter (opaque and translucent object volume) → **volumetric scattering**



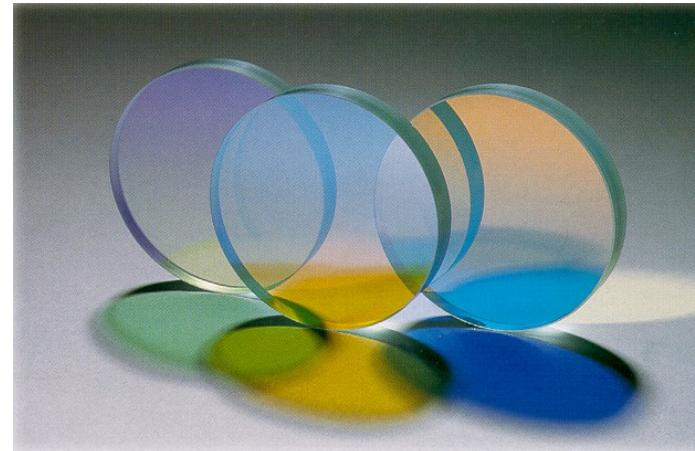
Participating media

- Light traveling to or between objects can be attenuated by **participating media**
 - Atmosphere, clouds, fog, smoke, etc.



Sub-surface scattering

- Light which is not reflected from surface (of dielectric) is scattering inside surface: **sub-surface scattering**.
 - Translucent objects: wax, skin, leafs, etc.



Volumetric scattering

- Complex topic which can not be described with direct (local) models
 - When it comes to shading, advanced light transport must be utilized to capture volumetric effects
- Often, for real-time applications, volumetric scattering can be simulated to look correct, without physically-based computation

Light-matter interaction

- Ratio of light that gets through medium over certain distance is given by **Beer-Lambert Law**
- Simple volumetric fog effect can be simulated using Beer-Lambert Law:

$$F = e^{-(d * z)}, \quad d - \text{medium density}, \quad z - \text{medium depth}$$

To remember

- Material observation
 - Directional effects
 - Color
 - Spatial variation
- Optics for material
 - Scattering and absorption
 - Surface scattering
- Material model
 - BRDF
 - Scattering parameters

More into topic

- Note that BSDFs describe interaction of light with surface (opaque or transparent)
- Other objects have specific appearance due to sub-surface scattering. Example for such material is wax. Such material is not transparent, but it is important what happens under surface since some light scatters outside and influences appearance – such material is called **translucent** and requires **BSSRDF***.
 - For simpler applications these materials can be approximated with diffuse BRDF (note that diffuse scattering is actually a result of sub-surface scattering and re-emitting as well as surface roughness)
 - Different approaches take phenomenological approach where they model what we observe in reality. They result in realistic appearance but are not physically correct:
<https://www.ea.com/frostbite/news/approximating-translucency-for-a-fast-cheap-and-convincing-subsurface-scattering-look>
 - Finally, physically based approaches model actual scattering of light inside of surface and its absorption, reflection and re-emission.
- Next to translucent surfaces, there are many phenomena for which it is important to model light scattering inside a volume. These are called **volumetric rendering** approaches and they rely both on scattering function and light transport.
 - Volumetric rendering is highly researched and developed field:
<http://advances.realtimerendering.com/s2015/The%20Real-time%20Volumetric%20Cloudscapes%20of%20Horizon%20-%20Zero%20Dawn%20-%20ARTR.pdf>
- Often cloth is important material to render. **BRDF for cloth** (e.g., sheen BRDF) are developed and investigated.
- <https://www.realtimerendering.com/#visapp>

* https://www.pbr-book.org/3ed-2018/Volume_Scattering/The_BSSRDF

More into topic

- We discussed light scattering on geometric optics. **Wave optics** is active research area.
 - Required if physical simulation of wave-effects such as diffraction is needed.
 - Color is then not described with RBG triplets rather using spectral representation and wavelength dependence
 - More information: https://ssteinberg.xyz/2022/04/03/practical_plt/

Summary questions

- https://github.com/lorentzo/IntroductionToComputerGraphics/tree/main/lectures/7_material

Literature

- <https://github.com/lorentzo/IntroductionToComputerGraphics/wiki>