3D Models: Material

Syllabus

- 3D scene
  - Object
    - Shape
    - **Material**
  - Camera
  - Light
- Rendering
- Image

- Material
  - Observation
  - Pysics: optics
  - Modeling material
    - Scattering models

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

Material is important for object appearance.
Without material…

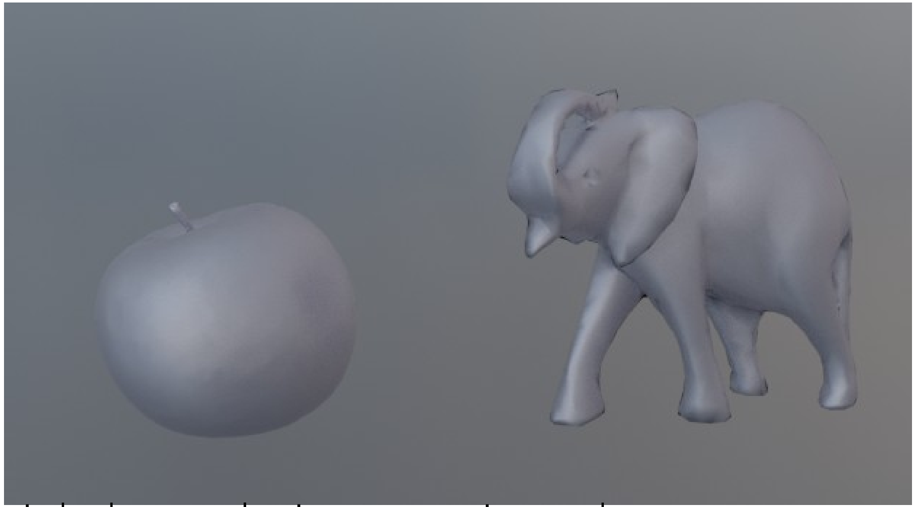
Recap: shape and material

- Rendering and creating objects in 3D scene to represent a real world objects requires:
  - Shape modeling
  - Visual **Appearance** modeling

https://polyhaven.com/a/ship_pinnac
e

Recap: shape and material

- We separated 3D object in shape and material.
  - Material characteristics of object are independent of shape and position.
  - This enables us to model material separately from shape and its position, since it is enough to model how one tiny bit of material interacts with light, we reuse this model for arbitrary shape.



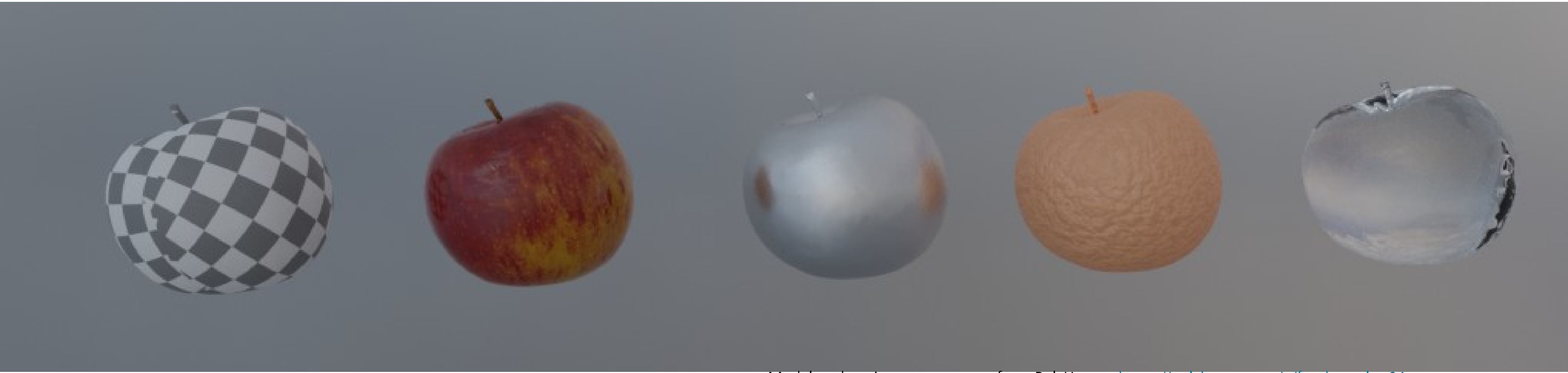
Aluminum apple and aluminum statue – in both cases aluminum properties are the same.
Also, changing position of aluminum apple in space doesn't change aluminum properties.

Appearance of 3D object

Material representation

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

- To takeaway: modeling of shape of an object and material can be separated



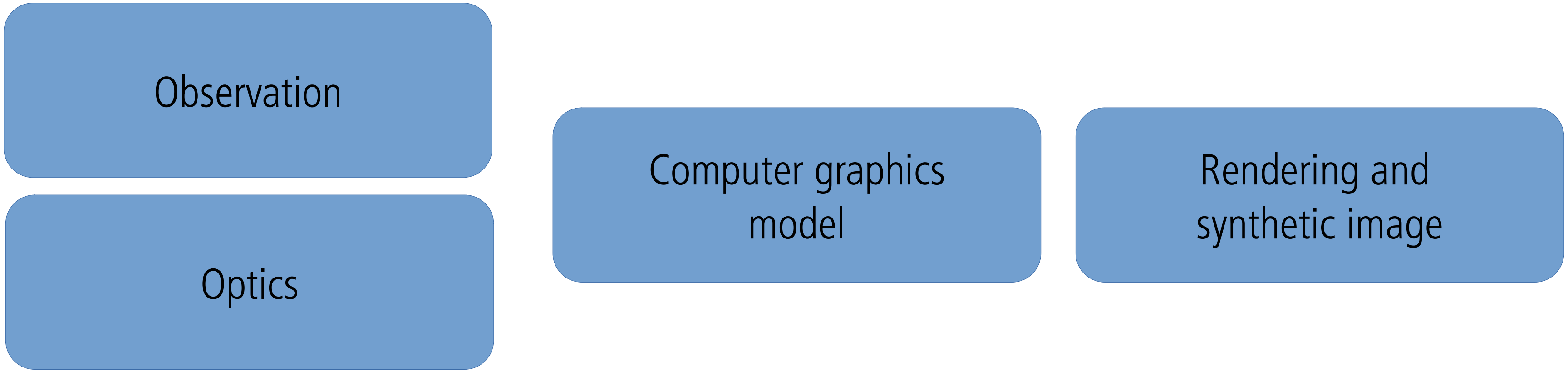
Model and environment texture from PolyHaven: https://polyhaven.com/a/food_apple_01

Real-world phenomena

- Examples of various real-world objects that we would like to represent
  - Metals
  - Plastics
  - Glass
  - Wood
  - Fabric
  - Stone
  - Clouds
  - seas

Prior to appearance modeling

- Two main disciplines influence modeling:
  - Observation
  - Physics - optics



Understanding appearance

Modeling begins with **observation**

Observation

- Understand **what makes each material look different** than other materials
- Observe **characteristics which are responsible for object appearance**:
  - Shape: large scale form or geometry of object. Shape is needed to place object correctly in the scene with respect to other objects, to determine which objects are occluded and areas into which shadow is cast by object
  - Material: for computer graphics modeling purposes this are fine-scale geometrical variations and substance properties
  - Illumination
  - Sensor/Perception
  - **Material**

<EXAMPLES: CHARACTERISTICS RESPONSIBLE FOR APPEARANCE>

Note: real world and models

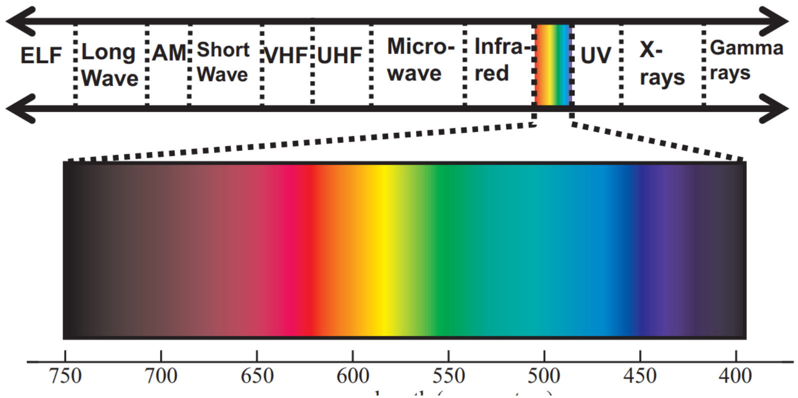
- Real world objects are very complex phenomena which have to be simplified using a **model** for desired application.
- Best description of real world is physics which again describes a world using models – simplifications
  - Geometric optics
- Computer graphics takes step further into simplification for creation and computational purposes
  - Separation of objects into shape and material
- Finally, artists who create based on real world use their perception – subjective model of the world – they draw what they see, not necessary what is true and correct.

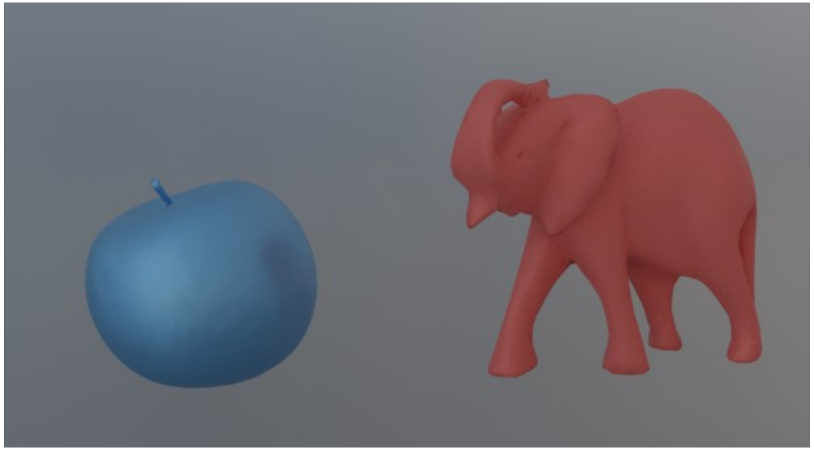
Classifying materials

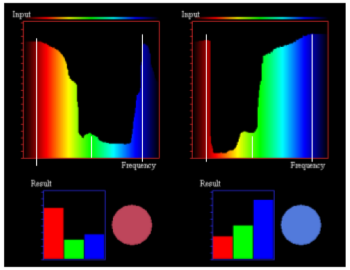
- Classifying materials enables us to **understand which characteristics are needed to be modeled** in order to obtain required appearance. We can classify any material by following variations:
  - Spectral: color
  - Directional
  - Spatial

Material characteristics: color

- Light is a electromagnetic wave, thus characterized by wavelength. Small part of wavelengths are interesting for material modeling
- Light scattering from object surface (its material) is described using color and brightness
  - Applications concerned with color reproduction: photography, print and television
- Color is described with red, green and blue floating points (R, G, B) in [0,1]
- Brightness is floating point value [0, inf]



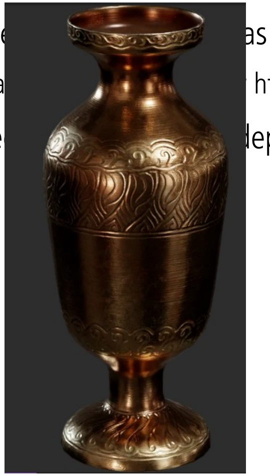




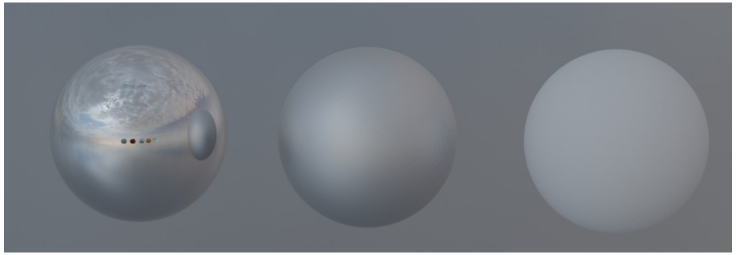
https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf
https://www.researchgate.net/publication/234814482_Digital_modeling_of_the_appearance_of_materials

Material characteristics: directional

- Object appearance that results from **directional of scattering of light** by the object
- **Directional effects:** whether we see ... as we change view
  - Those effects are due to structures a ... htan ... ves ... sider flat by looking at it)
- Directional effects that are attache ... depen
  - Shiny
  - Hazy
  - Glossy
  - Matte
  - Dull
  - Translucent
  - Transparent



- Directional effects are modeled using **scattering function.** There are many perceptual dimensions of material types. Most important light scattering models are:
  - Specular (mirror direction)
  - Glossy (preferred direction)
  - Diffuse (all directions)

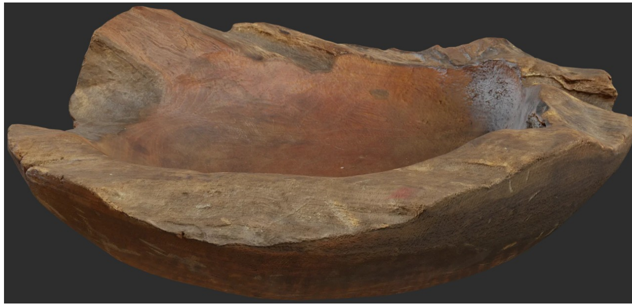


Material characteristics: texture

- 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

Understanding appearance

Modeling is founded on **optics**

Light-matter interaction

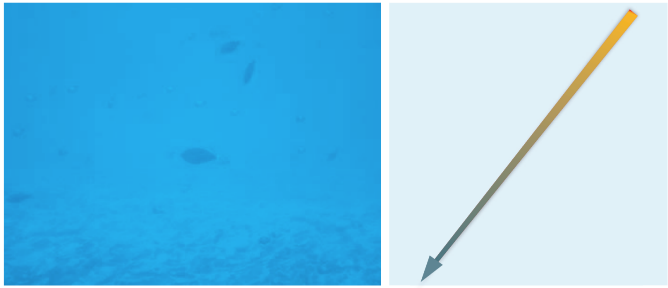
- Effect that material has on light is defined by property called **index of refraction** (IOR) **–** complex number
  - Light is electromagnetic wave.
  - We use **geometrical optics** model which approximates light as rays and materials with index of refraction:
    - Real part of IOR determines speed of light
    - Imaginary part if IOR determines absorption of light

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**, meaning that direction is same, but intensity might be attenuated
  - Examples: transparent materials; glass or water.

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

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

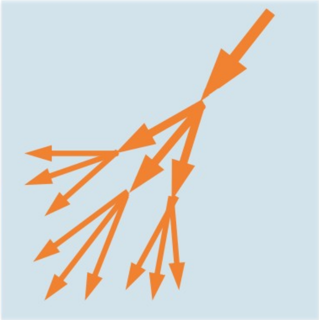


Slight absorption becomes significant with distance

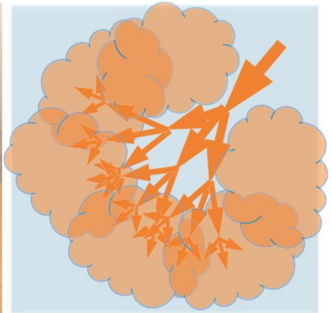
https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf

Light-matter interaction

- In **Heterogeneous medium** IOR varies which cause **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)

https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf

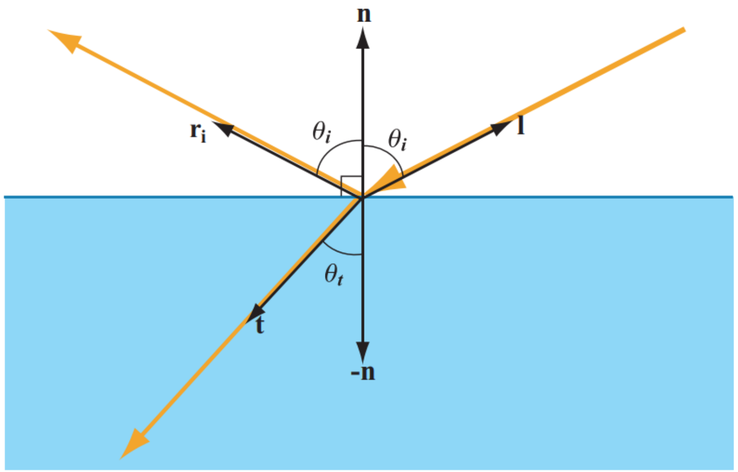
Light-matter interaction: scattering and absorption

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

https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf

Light-matter interaction: between media

- We have discussed how **light propagates through a medium**.
- Behavior of light when **propagating between media of different index or refraction** is defined with Maxwell's equations
- Those equations are too heavy for computer graphics thus, we:
  - Utilize geometrical optics approximations: rays light representation and IOR
  - Assume that interface between (volumes) media is perfectly (optically) flat, planar boundary* → **object surface**
  - On the one side is IOR of air and on the other IOR of object
- Solution for such surface is called **Fresnel equations**
- For such surfaces, light can **reflect** and **refract** where amount and direction depends on IOR.

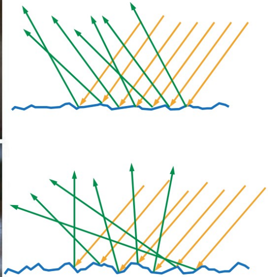


* Surface should be infinetly large, but in comparison with wavelenght of light, surface real objects can be considered as such.

https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf

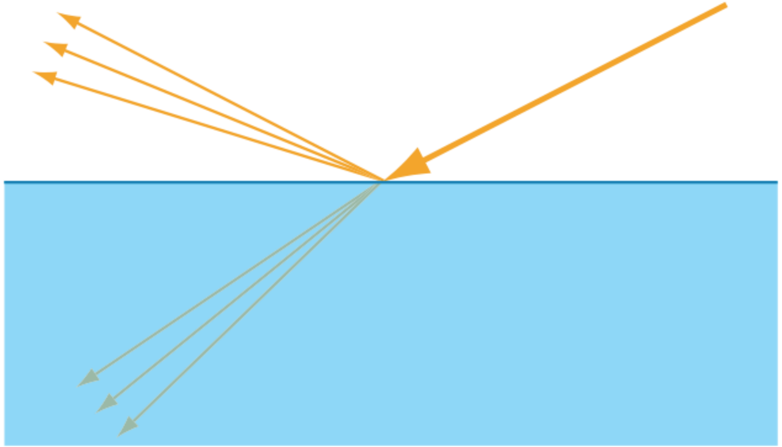
Light-matter interaction: reflection

- Real surfaces are not optically flat.
- Often, irregularities are present – larger than wavelength (causing light to reflect differently) and too small to render since this interaction happens under one pixel.
- In this case, we model such surface as a large collection of tiny optically flat surfaces – facets. Final appearance is aggregate result of relevant facets.
  - Smaller deviation of those facets cause more **mirror-like surface reflection** (small roughness)
  - Larger deviation of those faces causes more **blurred surface reflection** (glossy, high roughness)



Both surfaces look smooth but surface on bottom is rougher. Roughness difference is on microscopic scale - **microgeometry**.

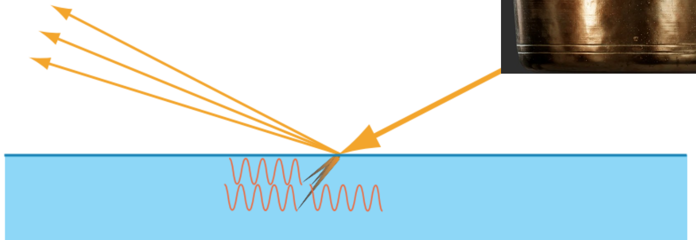
https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf



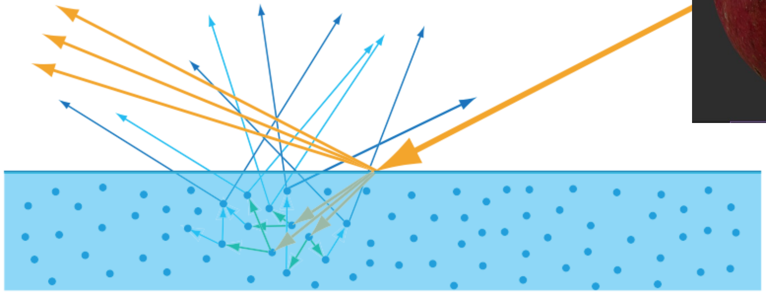
Macroscopically, non-optically flat surface can be treated as reflecting with multiple directions

Light-matter interaction: refraction

- Besides of reflection on surface, light can also **refract**.
- Amount and direction of refracted light depends on material which we can separate in:
  - **Metals**
  - **Dielectrics**



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

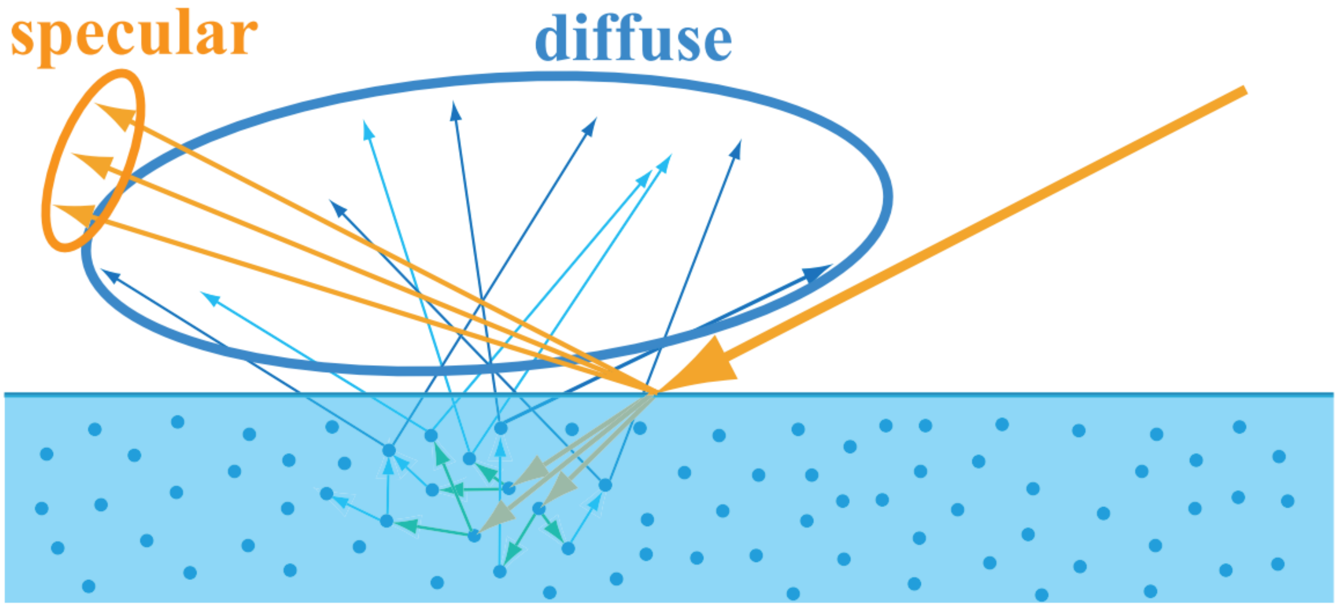


In case of **dielectrics**, light partially reflects and partially refracts. Refracted light is then absorbed and scattered inside surface (**sub-surface scattering (SSS)***). Some of the light can also be re-emitted – causing **diffuse** reflection.

* Note that in this case, light is not exiting from the same point where it has entered, thus we need more than local information for calculating light behavior. Therefore, this is one of more complex effects that require advanced rendering methods or approximation methods.

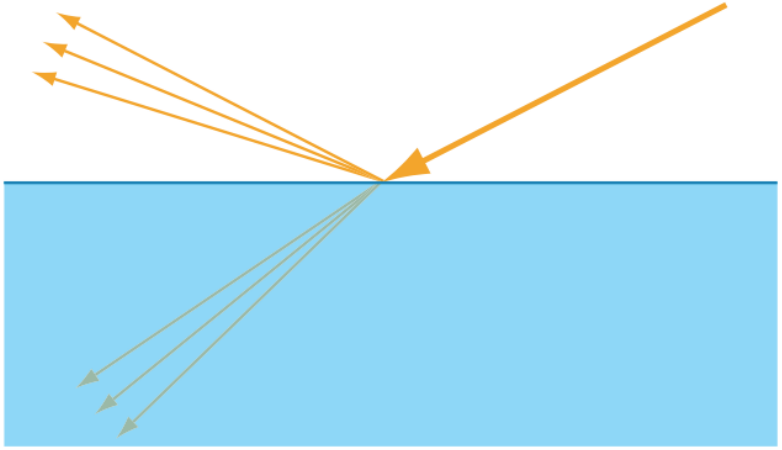
Diffuse and specular reflection

- With these considerations we can understand two foundamental light scattering processes:
  - Diffuse
  - Specular

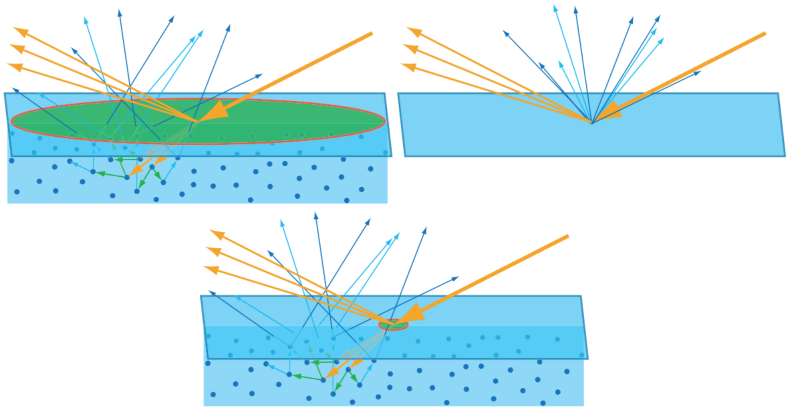


Local models and complexity of SSS

- We will discuss local models: describing what happens when light falls on one point
- SSS is a complex scattering phenomena requiring global model which we will approximate with local model.



We will be focusing on local models which describes what happens at one point/pixel



SSS can be approximated with local model: diffuse scattering.

- With physical considerations we have looked at small scale and gave foundations to:
  - Directional effects and scattering
  - Color
- Larger scale variations visible by eye are simulated by varying scattering model

Modeling appearance

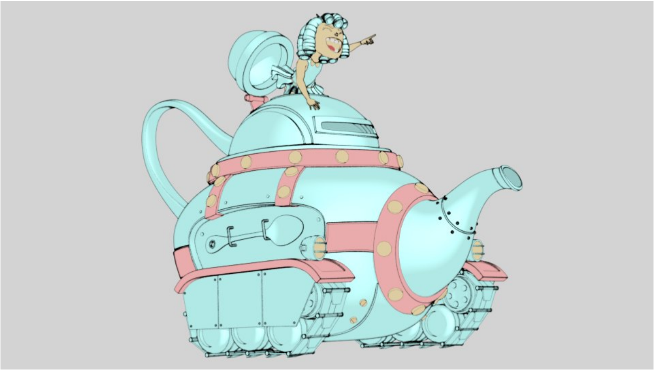
Towards material modeling

- With material in CG we describe light-matter interaction - **shading**
- Material in CG can is decomposed to describe:
  - Color
  - Directional effects
  - Spatial variation:
    - Of color and directional effects
    - **Small-scale geometrical information** that is too small to represent explicitly by geometry/shape.

Diversity of appearance models

- Appearance models, depending on application, can range:
  - Photorealism
  - Stylized
- Note: Stylized is based on photoreal with exaggeration

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

Materials and rendering

- Appearance in real world depends on material, shape, illumination and camera position
- Appearance of simulated object also depends on material description
- Shading step in rendering uses material model, alongside with viewing position, object shape and light to calculate the object color
- Final color of surface is calculated by:
  - summing all incoming light that falls onto surface – light transport
  - Calculating color and intensity of light reflected into camera using material description - shading
  - <comparison>

Scattering models: intuition

- Rendering comes down to computing **intensity** and **color** of light – RGB values* - entering the camera along set of **viewing rays.**
- Viewing rays are intersecting objects in the scene. Thus, intensity and color of viewing ray comes from **closest intersected object surface**
  - We will ignore **participating media** for now – medium between objects
- Therefore, our goal is to **compute intensity and color of the surface intersected by viewing ray**
  - <image of big picture: camera object and light>
- For this purposes we use **scattering function.**

* Physically-based color and intensity of light is called radiance but we work with RGB rendering which is simplification of spectral rendering

Material modeling: scattering

- Material modeling describe how light behaves when interacts with objects:
  - Light-surface interaction
  - Light-volume interaction
- Description of light interaction with surface, when considered locally, is called scattering.

Material modeling: texture

- Same description of material for each point of the 3D object, results in homogeneous material: smooth surface
- Once we have a scattering model, we can parameterize it and vary its properties over the surface.
- Therefore, we create parameterized material models and associate some parameters to each point of the surface. For example, this way, we can model marble which has color variation over surface.

Elements of material model

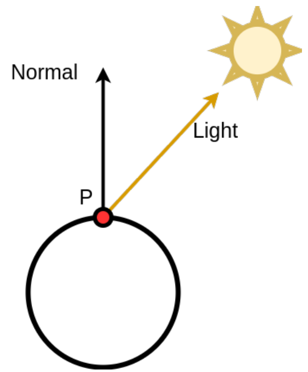
- Material modeling is separated into:
  - **Scattering** → description of light-matter interaction in a point
  - **Texture** → variation of scattering function properties across 3D object surface

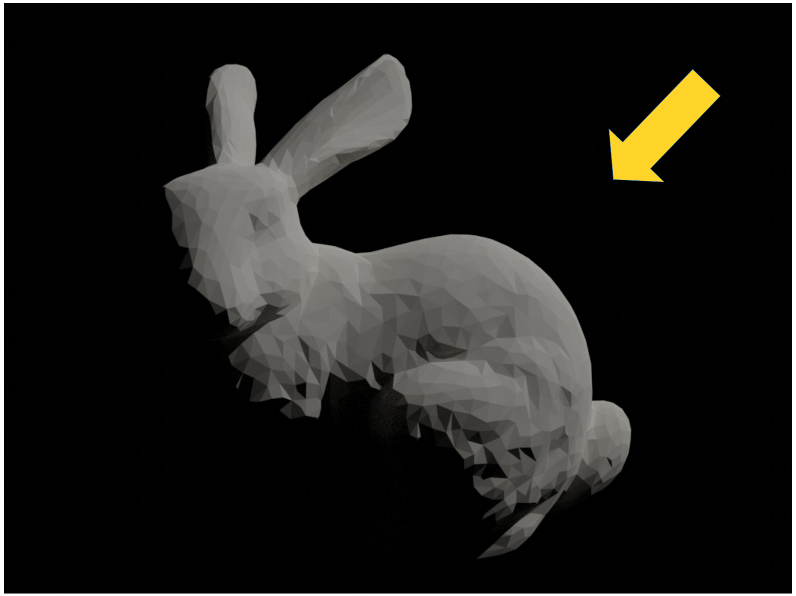
Scattering models

Scattering model

By now we know that amount of light falling on surface depends on shape and light:

- Surface normal in point is crucial for determining how much the surface is oriented towards light

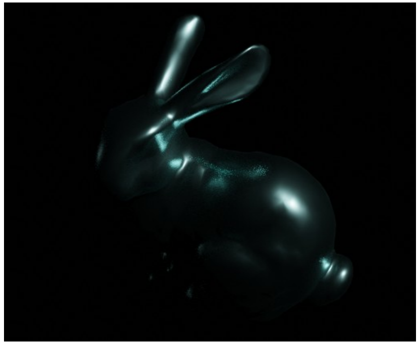




Scattering model

- 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 **scattering function** - surface response to light



Scattering function

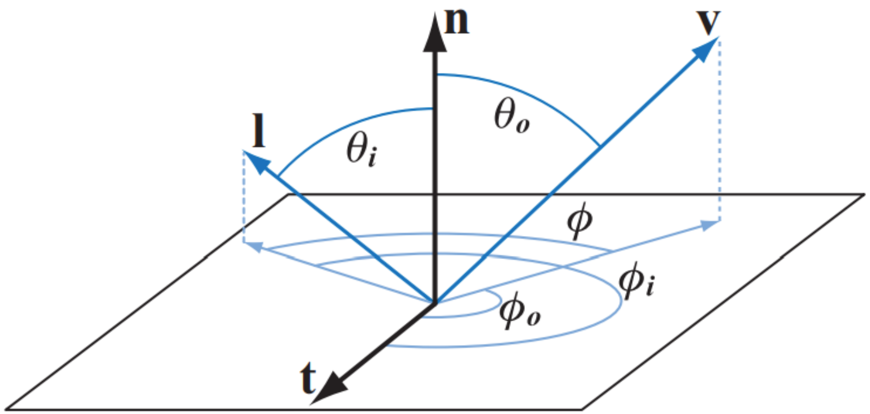
- Scattering function can be separated in reflection and transmission
  - Model describing reflection is called “bidirectional **reflectance** distribution function” – **BRDF**.
  - Model describing transmission is called “bidirectional **transmission** distribution function” – **BTDF**.

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

https://www.pbr-book.org/3ed-2018/Reflection_Models/Specular_Reflection_and_Transmission

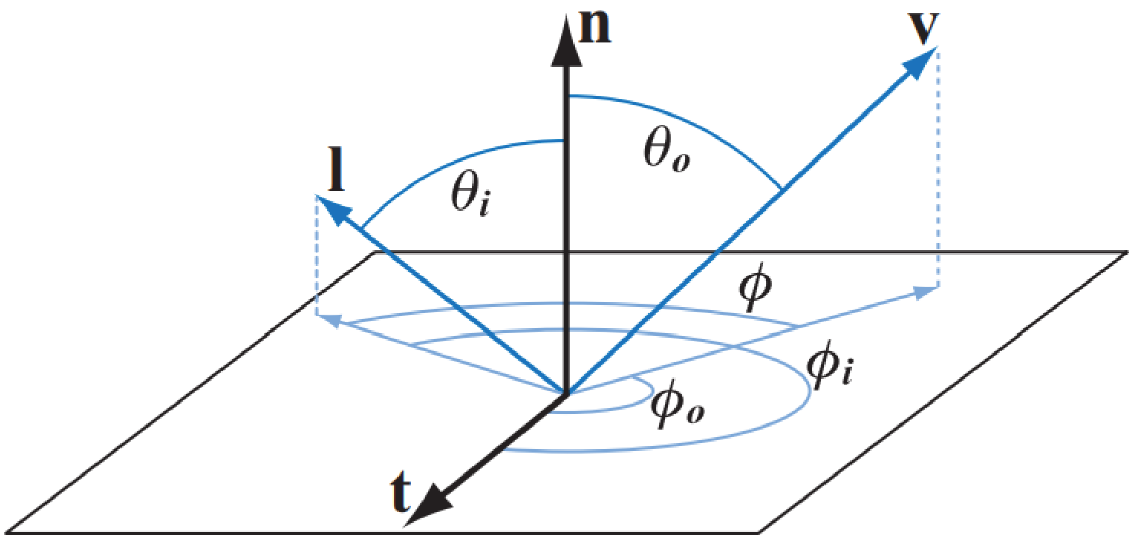
BRDF

- Description of how the light is **reflected** when light falls on **opaque** surface
- Describes **local interactions:** how reflects from a surface point
- BRDF f(v,l) describes surface response which depends on:
  - Incoming – unit length vector - light directior
  - Outgoing – unit length vector - view directioi



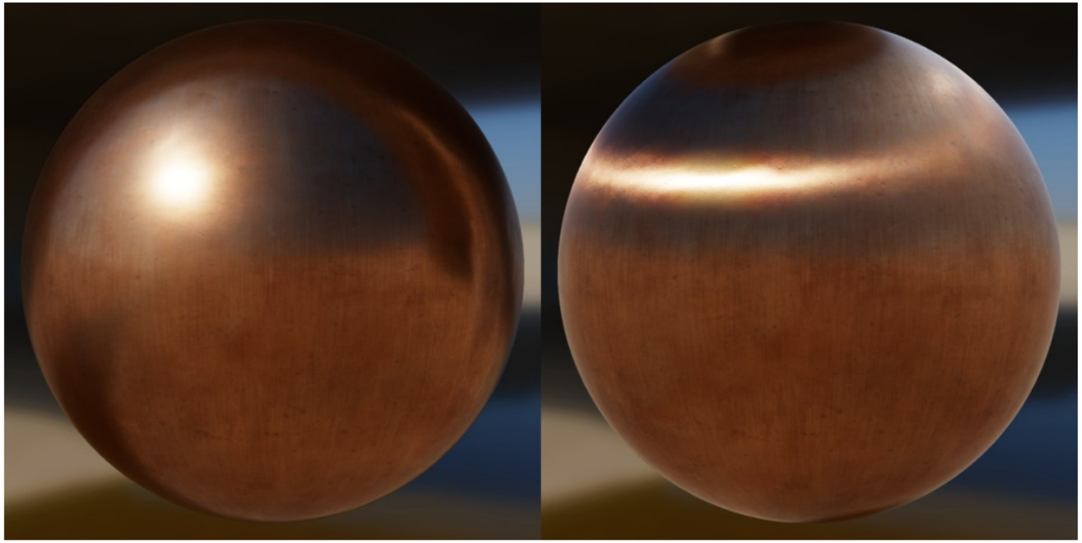
BRDF

- Incoming (l) and outgoing (v) directions have 2 degrees of freedom, two angles relative to surface normal:
  - Elevation (θ)
  - Azimuth (Φ)
  - Dimensionality of



Isotropic and anisotropic BRDF

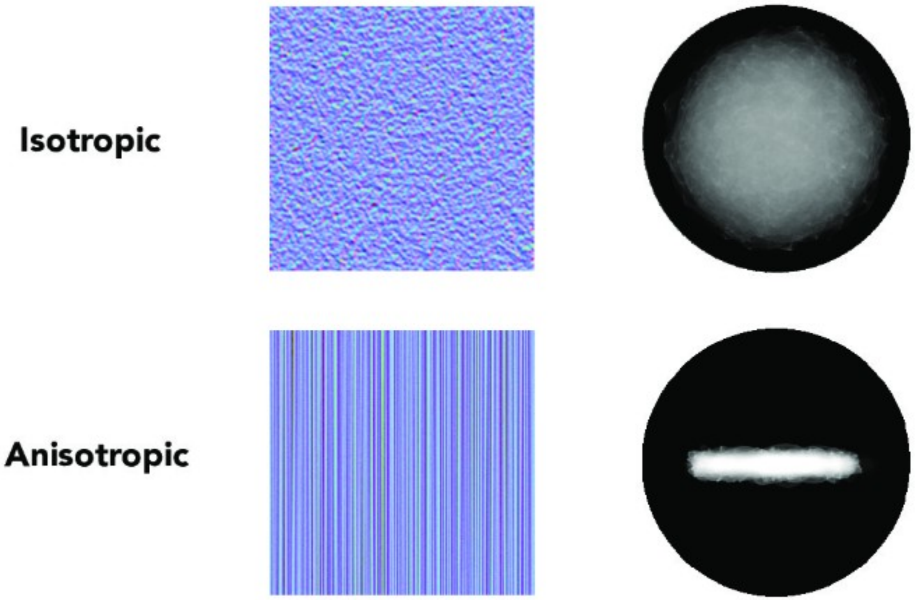
- **Isotropic BRDF**: rotating light and view directions around the surface normal does not affect the BRDF.
  - Incoming and outgoing directions have the same relative angles between them: such BRDF can be parameterized with three angles.
- **Anisoptropic BRDF**: reflection behavior changes when light and view vectors are rotated around normal



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

Isotropic and anisotropic BRDF

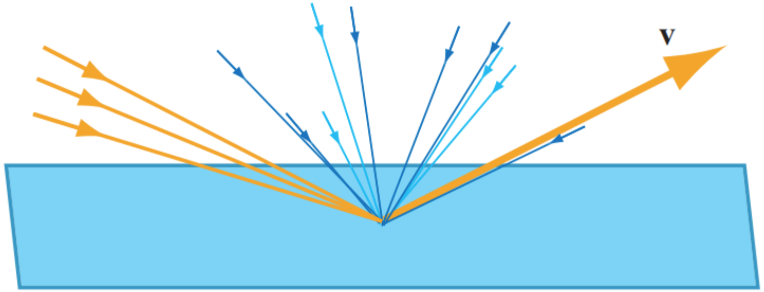
- **Anisoptropic behavior** is present due to underlying surface sturcture which is directional



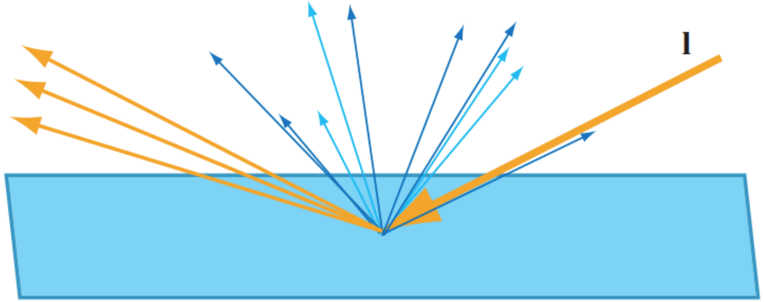
https://cs184.eecs.berkeley.edu/sp22/lecture/14-29/material-modeling

Note: bidirectionality of BRDF

- "**bidirectional**" in BRDF means that given 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

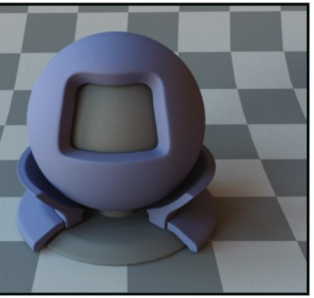


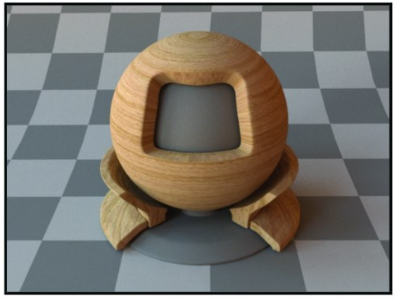
Distribution of outgoing light directions given incoming light direction

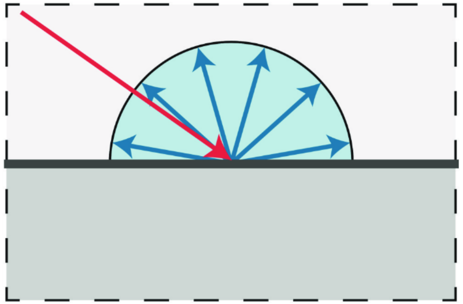
https://blog.selfshadow.com/publications/s2013-shading-course/hoffman/s2013_pbs_physics_math_notes.pdf

https://mitsuba2.readthedocs.io/en/latest/generated/plugins.html#bsdfs

BRDF reflection types

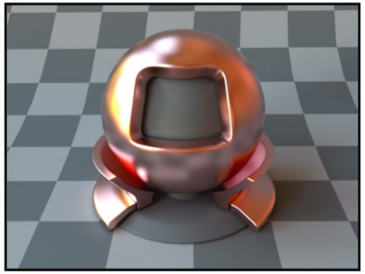


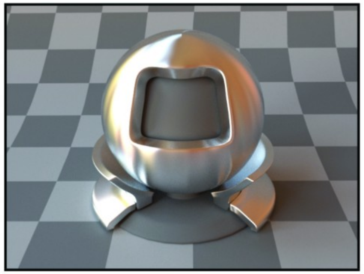




Diffuse, Diffuse textured

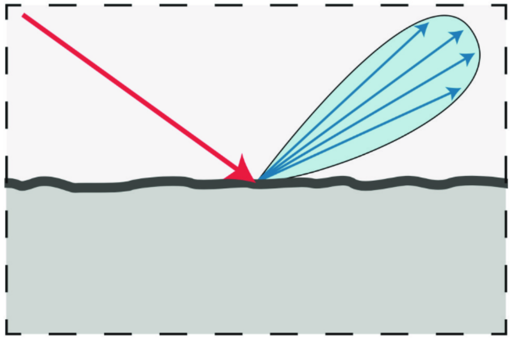
Light is scattered in all possible directions. Independent of viewing direction. Equally bright from all directions.

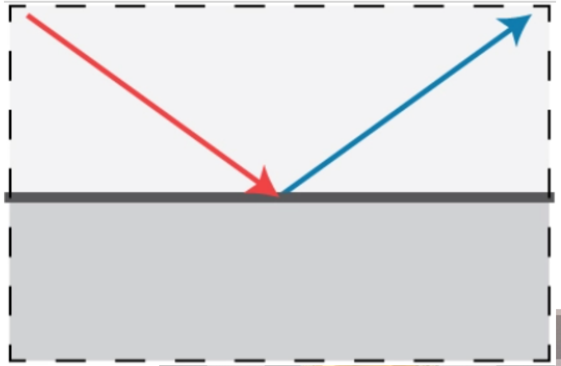


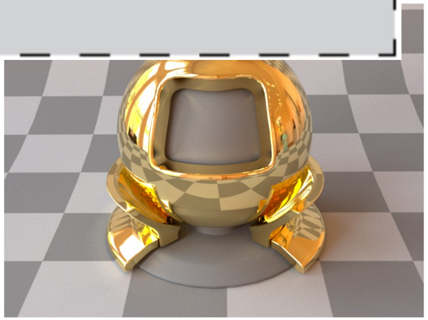


Glossy: Copper, Aluminium

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.

Generally, impulse scattering is term when light is scattered in single direction, but not necessary mirror-reflection direction

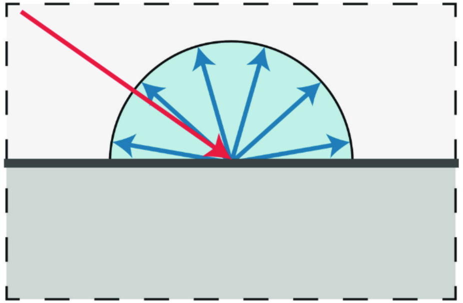
Scattering models

- Main types are:
  - **Empirical**
    - Created to simulate observed scattering phenomena
  - **Data-based**
    - Scattering is measured from real world and stored in tables on which lookup with direction (li, lo) is peformed
  - **Physical-based**
    - Based on physical interaction of light with matter

Empirical models

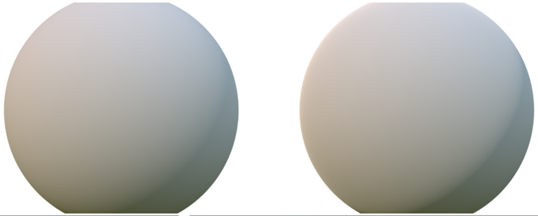
- Models based on observation of scattering phenomena
- Phenomenological models: describe the quantitative properties of real-world surfaces by mimicking them
- Easy to implement and use
- Types:
  - Lambertian
  - Mirror
  - Phong and Blinn-Phong

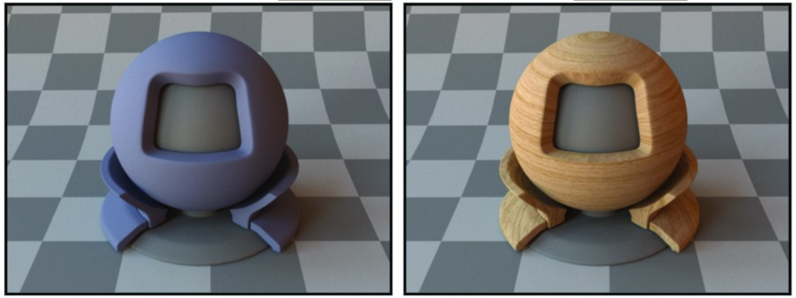
Lambertian model



- Scattered amount of light in all directions is the same and linearly depend on incoming light
- Simplest BRDF model:
  - Doesn’t depend on surface or view direction but note that surface orientation will attenuate or increase incoming light making surface darker or brighter
  - **Constant reflectance value: diffuse color** or **albedo: (**R, G, B) value
- Often used as cheap approximation for sub-surface scatterir
- Although simple, it forms the basis for more complex model

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





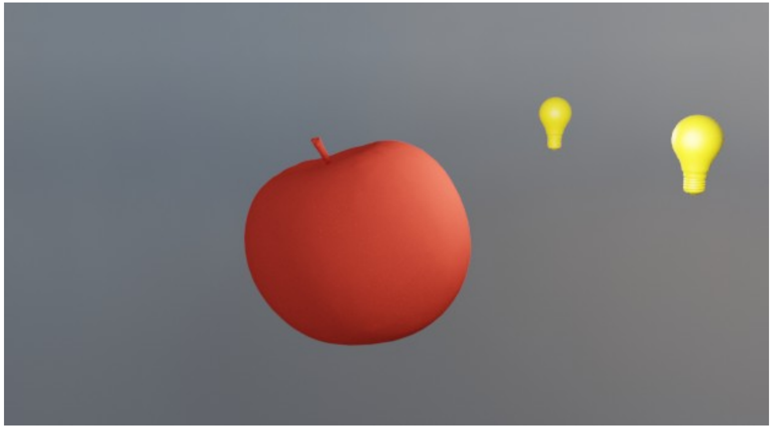
https://google.github.io/filament/Filament.html

Digression: where is light?

- BRDF is used in shading step of rendering.
- Shading "collects" all incoming light and multiplies it with BRDF – reflectance equation:

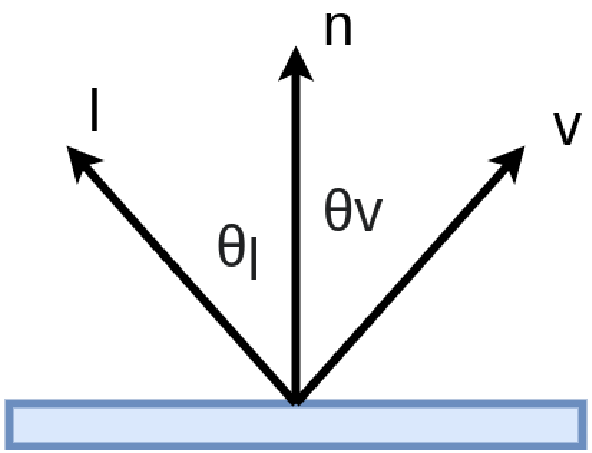
$$L_o = \sum_{l}^{n} L(l) \cdot f(v,l) \cdot (n \cdot l)$$

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



Mirror (specular) model

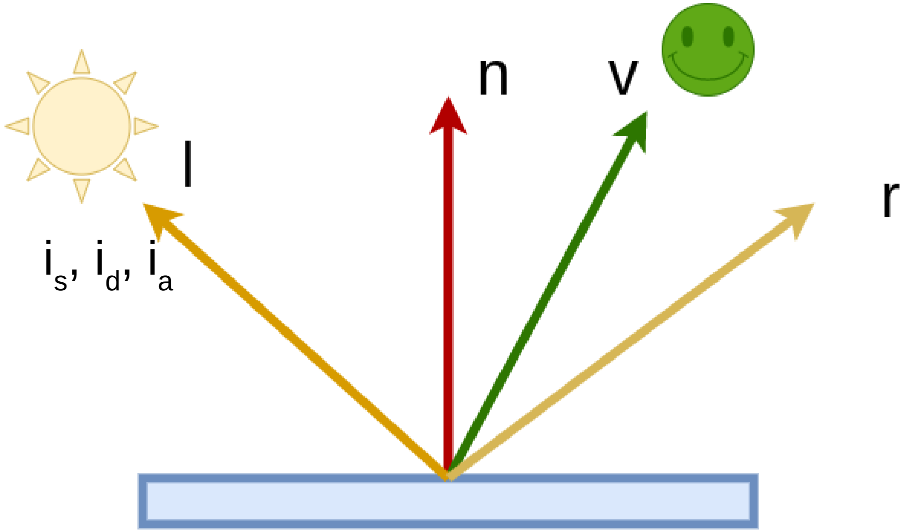
- Ideal reflection where incoming light is reflected completely in a single outgoing direction
- Reflects only in mirror reflectance direction:
  - Depends on view and light directions
- Single parameter: **reflectivity** – a constant (R,G,B)
  - Conductors have colored reflection due to spectral selectiv



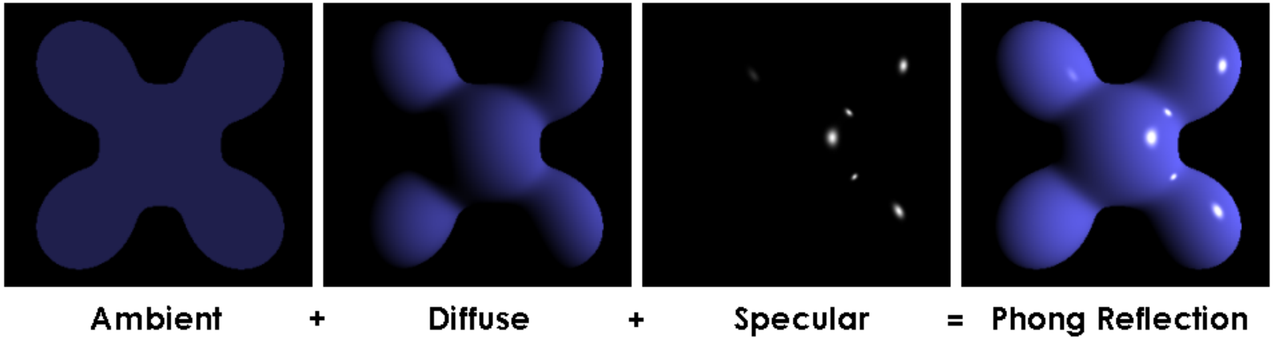
$$f(v,l) = \begin{cases} reflectivity \text{ if} & v = l - 2(l \cdot n)n \\ 0 & otherwise \end{cases}$$

Phong model

- Rather than BRDF, Phong model is a complete reflection model
- A phenomenological model using:
  - **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

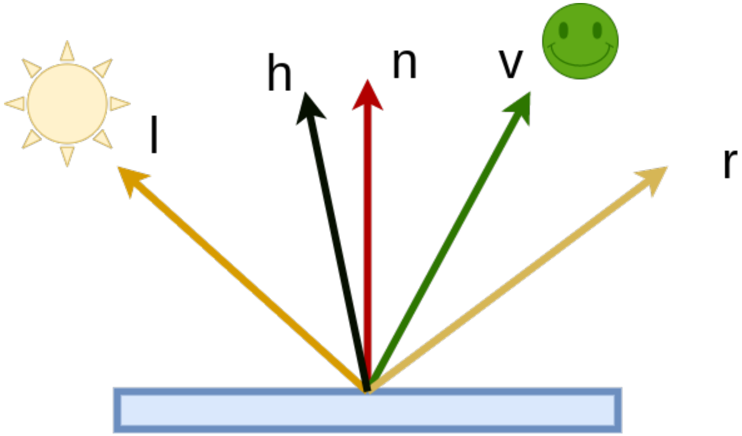


$$L_o = k_a i_a + \sum_j^n (k_d (l_j \cdot n) i_{j,d} + k_s (r_j \cdot v)^\alpha i_{j,s})$$



Blinn-Phong

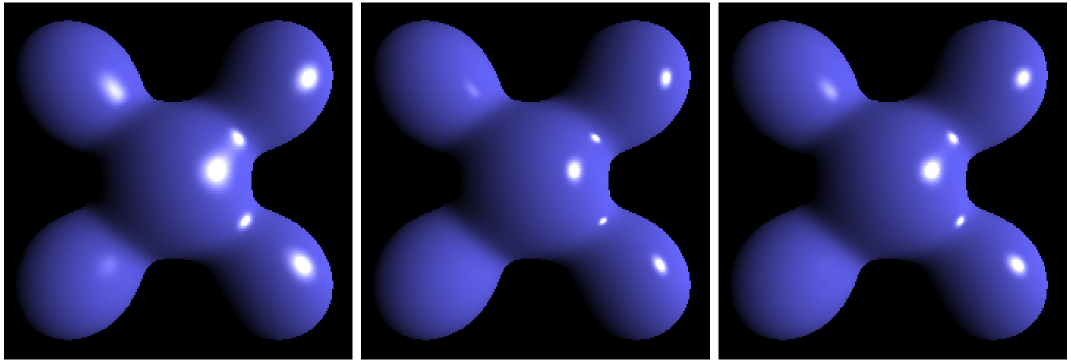
- Modification to Phong model, actual BRDF
- Introducing **half vector** between light and view vectors
- Parameters: Lambertian (k_L) and glossy (k_G), range: [0,1]
- Energy conserving if $k_L + k_G <= 1$



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

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

$$h = \frac{v+l}{2}$$

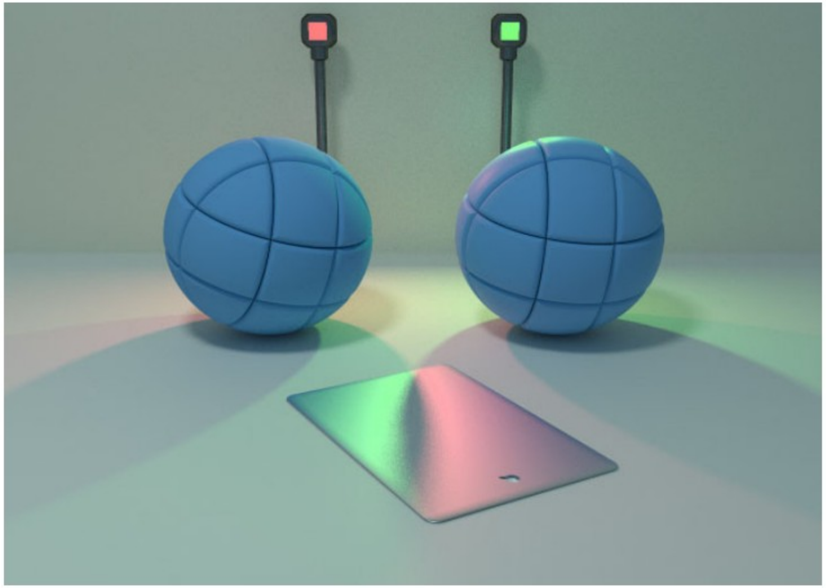


Blinn–Phong | Phong | Blinn–Phong (higher exponent)

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

Other empirical models

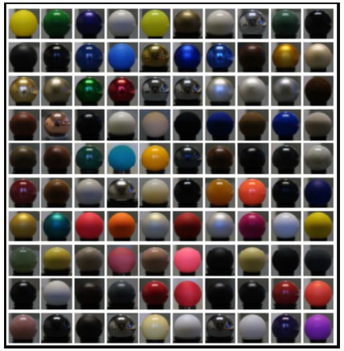
- Lafortune model
  - Generalization of Phong's model
  - Richer appearance with multiple lobes



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

Data-based models

- 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

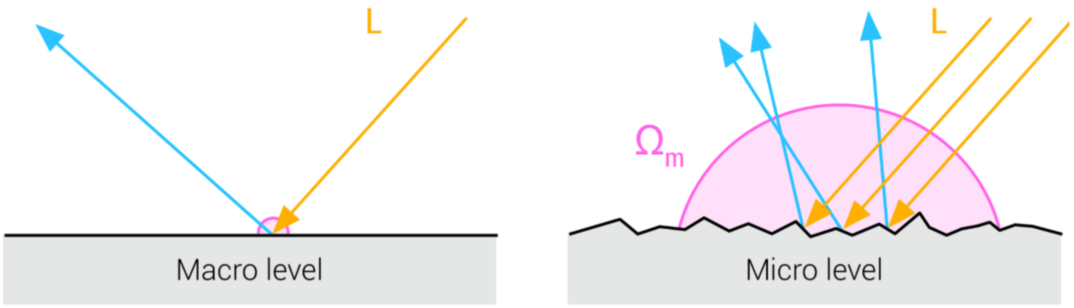


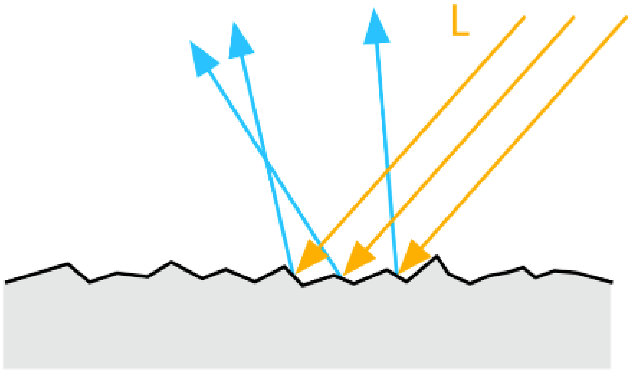
Isotropic materials:
https://www.merl.com/brdf/

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

Physically-based models

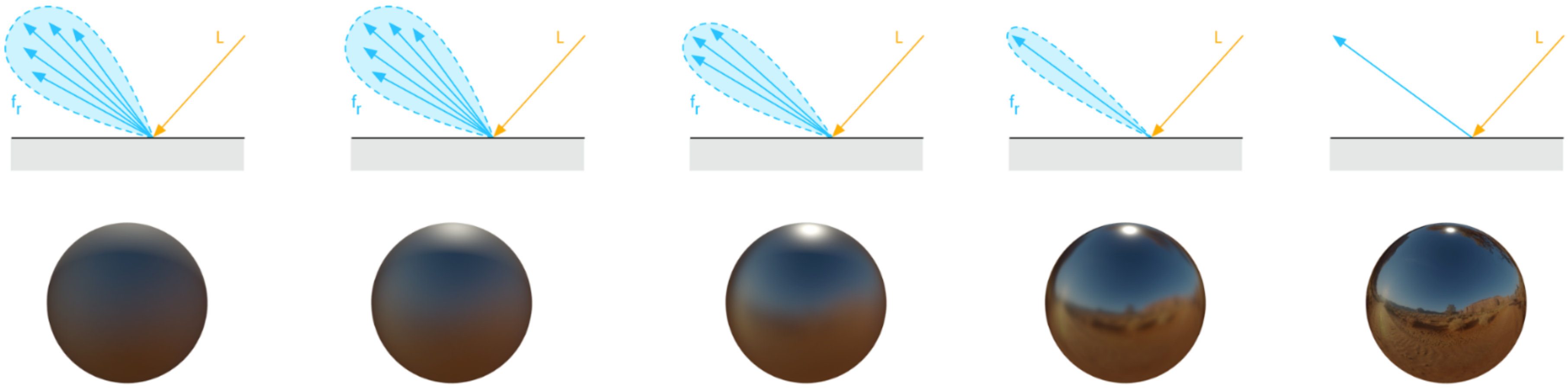
- Real-world surfaces have geometrical detail on multiple and thus very small scales
  - Although we can not see those small-scale details individually, we can see their aggregate response and they define how surface actually appears
- **Small-scale surface irregularities** (smaller than a pixel) can not be modeled explicitly, therefore this is modeled using BRDF
  - **Geometric optics** assumption: these irregularities are much smaller than light wavelength (they have not effect of appearance) or much larger than light wavelength (they cause light redirection). Wave optics describes phenomena in between.





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

Physically-based models

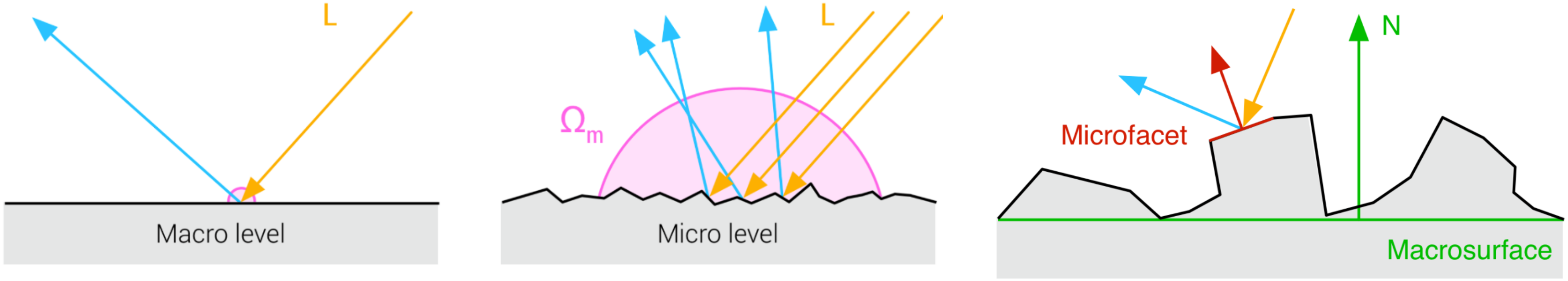


Varying roughness

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

Physically-based models

- Physically based models represent small scale irregularities as **facets** with **microsurface normals***.
  - **Micro-facet theory**: statistical distribution of microfacets which have strong peak at macrosurface normal. Spread of this distribution is called **roughness**
  - Higher roughness means more blurred surface since micronormals will be more spread (**glossy-diffuse**). Small roughness gives mirror-like surface (**specular**).
- With assumption of microfacets which are **optically-flat**, geometric optics can approximate what happens with light in interaction with such interface using **IOR, Fresnel equations and Snell's law**



* Note how important normal information in computer graphics is. Different scales of geometry are always described with normal information.

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

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 reflectances in 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).

Physically-based models

- Microfacet-based BRDFs are state of the art reflectance models using in professional modeling and rendering software.
- Fundamental models are:
  - Torrance–Sparrow microfacet model for glossy surfaces
  - Oren-Nayar model for diffuse surfaces

https://www.pbr-book.org/3ed-2018/Reflection_Models/Microfacet_Models

Scattering models: practical tip

- In graphics, **various scattering models have been developed** (and still are!) to represent surface even more correctly or efficiently. R&D approaches can be classified in: empirical, data-based and physically-based
- Choice of the model depends on application and what is trying to be achieved.
- 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 photo-realistic, 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 diferent 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/

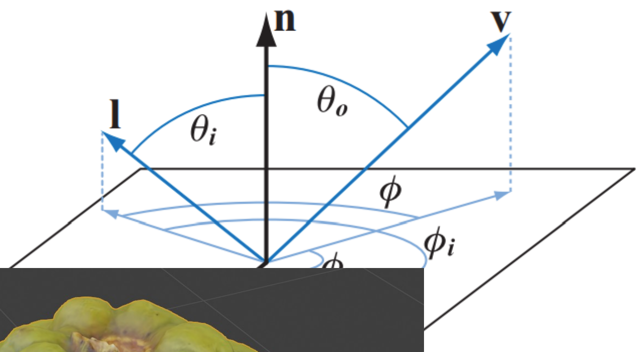
More into topic

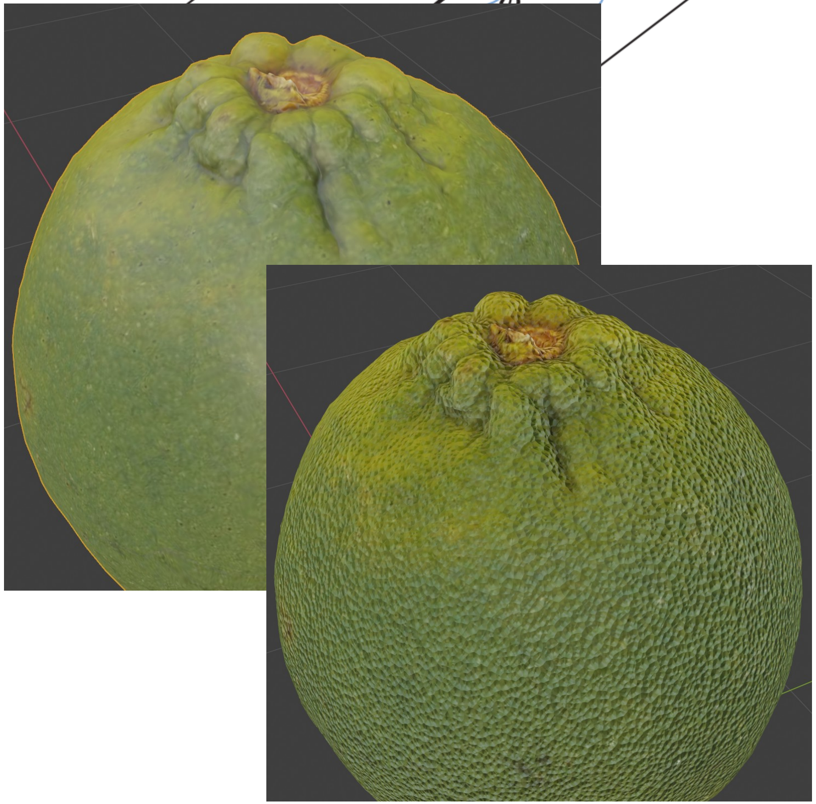
- Note that BSDFs describe interaction of light with surface (opaque or transparent)
- Other objects have specific appearance due to sub-surface scattering. Example for such material is wax. Such material is not transparent, but it is important what happens under surface since some light scatters outside 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 were 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, phyiscally 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 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.
  - Volumentric 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.
- We discussed light scattering on geometric optics. **Wave optics** is active research area.
- https://www.realtimerendering.com/#visapp

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

Normal and BRDF

- 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**

To remember

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

Literature

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