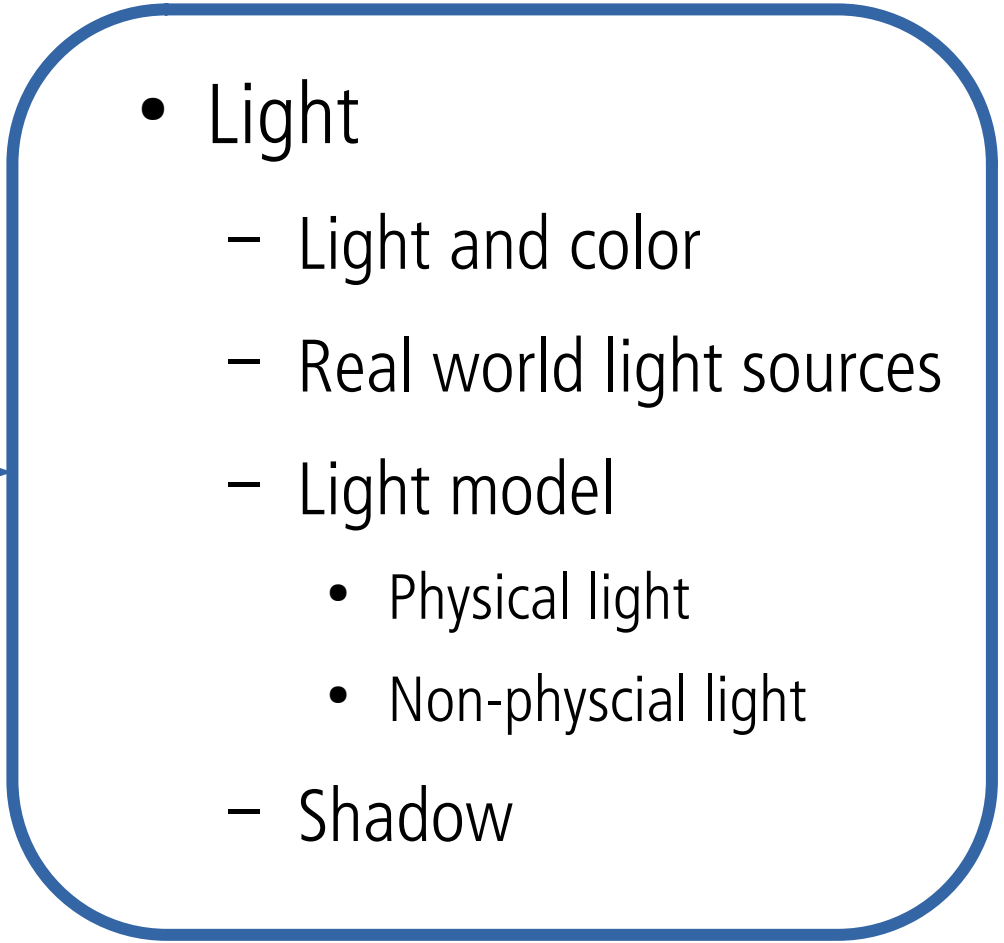
Light

Light makes it right

Syllabus

- 3D scene
  - Object
  - Camera
  - Light
- Rendering
- Image




FLY
https://discover.therookies.co/2018/06/24/learn-how-to-light-and-render-like-a-pixar-artist/

https://discover.therookies.co/2018/06/24/learn-how-to-light-and-render-like-a-pixar-artist/

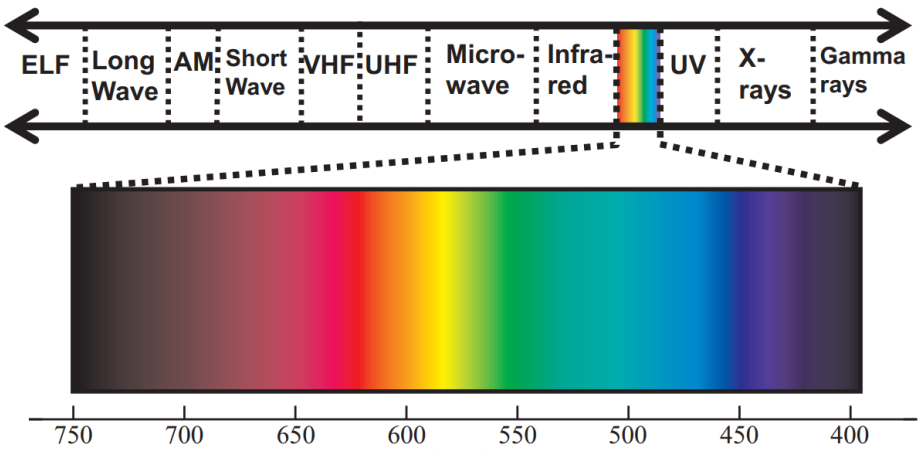
Light is important because without light...

Light and color

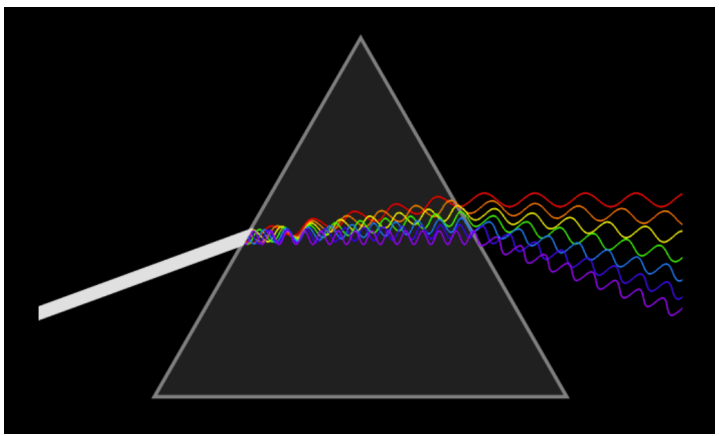
- Color can not be fully described scientifically: is also result of vision system thus subjective
- **Color science**:
  - How brain processes visual stimuli into what is perceived as color
  - Use of color from artist point of view
  - Study of electromagnetic waves: nature of light
- **Color management**
  - Study of color for digital displays
- Before color we need to investigate **light**

Light frequency and color

- Light is electromagnetic wave (or particle) visible by eye
  - Visible spectrum: wavelength 400 – 700 nm
  - Different wavelengths (frequencies) are perceived as **color** - color is **perceptual (psychophysical)** phenomena rather than **physical** one.
  - White light is made of all visible colors – adding all colors from light spectrum gives white light (color additivity, e.g. display)



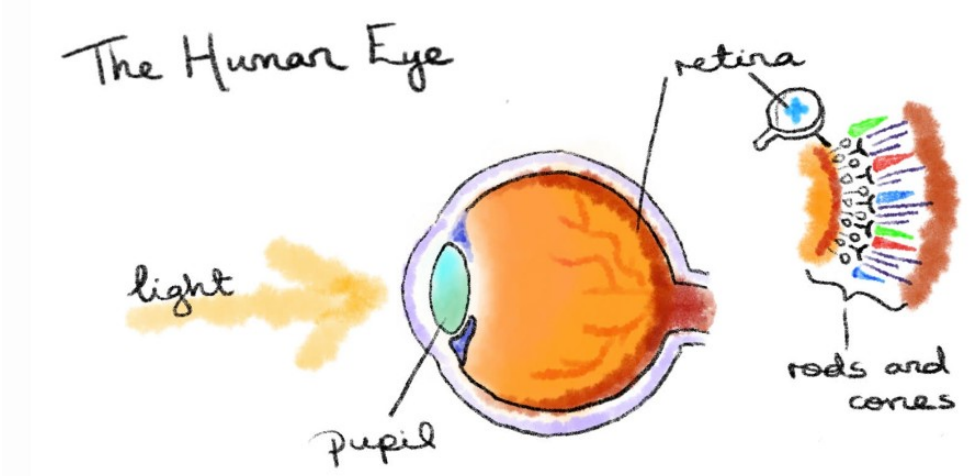
https://blog.selfshadow.com/publications/s2013-shading-course/#course_content



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

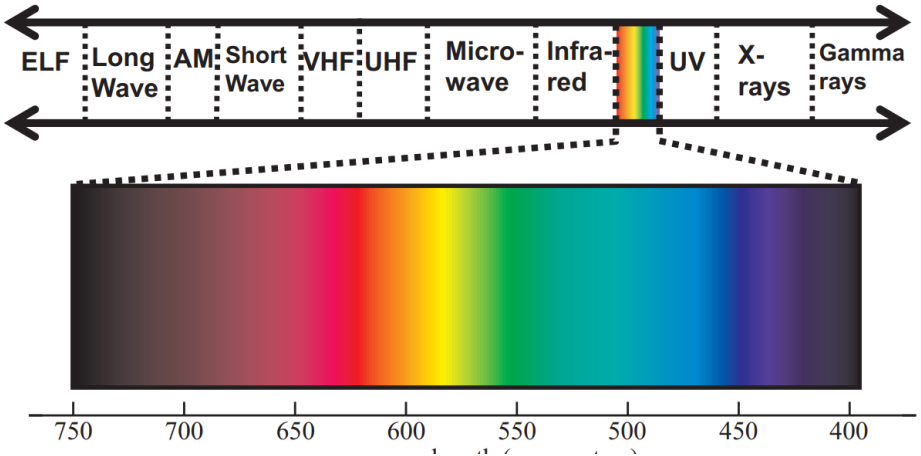
Light and eye

- Human visual system; back of eye (the retina) is covered with light sensitive receptors – photo-receptive cells:
  - **Cone cells** – responsible for **trichromatic** color vision
    - Three types sensitive to: **red, green and blue light**
  - Rod cells – sensitive to smaller amount of light but not reproducing colors



http://daisymolving.github.io/2018/07/30/design-fundamentals-colour.html

Additive and subtractive



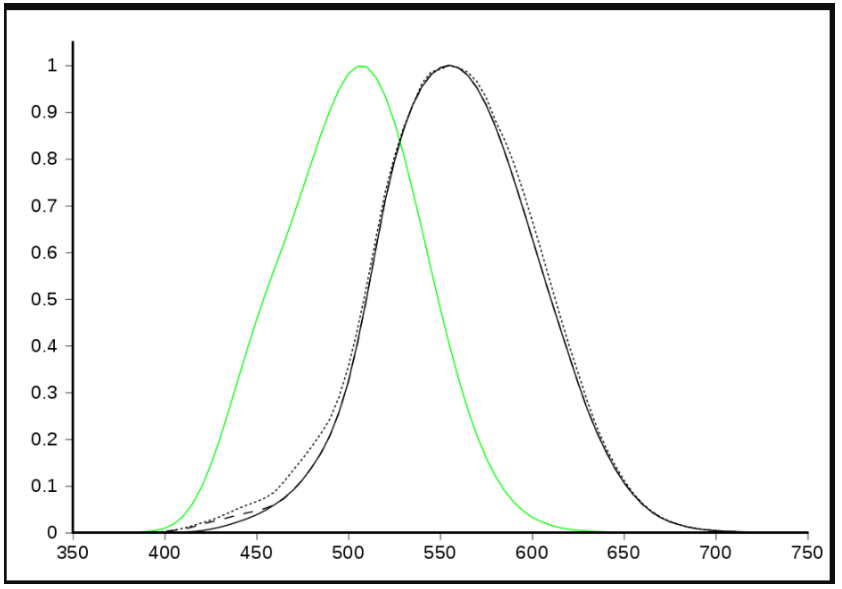
- **Additive**:
  - Main colors: **red, green, blue**
  - New colors and white light is made by adding
  - Usage: computer science, lighting technology – colors are created with light emission
- **Subtractive**:
  - Main colors: **yellow, magenta and cyan** - white light is made by subtracting
  - Usage: art, painting, printing – color from canvas is not a result of light emitted from canvas, but light reflected from canvas
    - When white light hits canvas, what is not absorbed is reflected

https://carsonparkdesign.com/what-makes-white-on-the-screen/

https://www.greenleafblueberry.com/blogs/news/modern-primary-colors

Color brightness

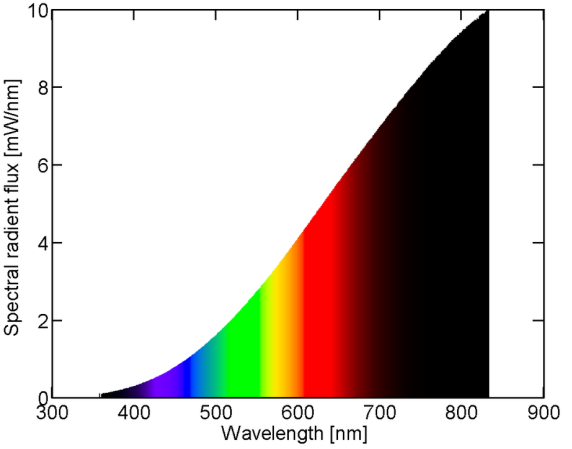
- 555 to 560 nm (green towards yellow) are perceived by the human eye as being the brightest
  - Blue color: the dimmest
  - Green color: the brightest
- How bright color appear to hum eye: **luminosity function**
  - Average sensitivity of human eye to different wavelengths for well lit conditions - photopic (cone rods).
- Brightness or lightness is present in **HSV** color model
- **Photometry**: science of measuring light taking in account human visual system
  - **CIE photopic spectral luminous curve**



Luminosity function for photopic – green - (well lit) and scotopic (low lit) – black.
https://en.wikipedia.org/wiki/Luminous_efficiency_function

Spectral power distribution

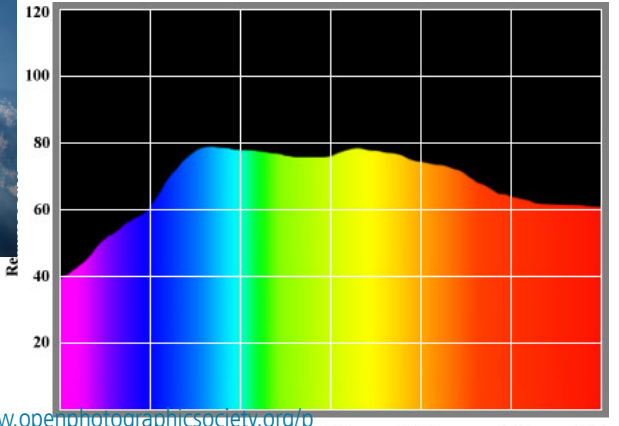
- Light is generally characterized by **spectral power distribution (SPD)**
  - range and intensity of colors it produces at each wavelength in the visible spectrum
- Sun is reference for natural light
  - Standard: **daylight illuminant - D65** by International Commission on Illumination (midday sun Western/Northern Europe)
- **Color rendering index**
  - Ability of light source to reproduce color of object seen under D65, standard by CIE (Commission Internationale de l'Eclairage)
- White color is composed of all colors in equal amount: constant SPD
  - Doesn't exist in real world: CIE; E illuminant



Perceive light as yellow since eye is less sensitive to red

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

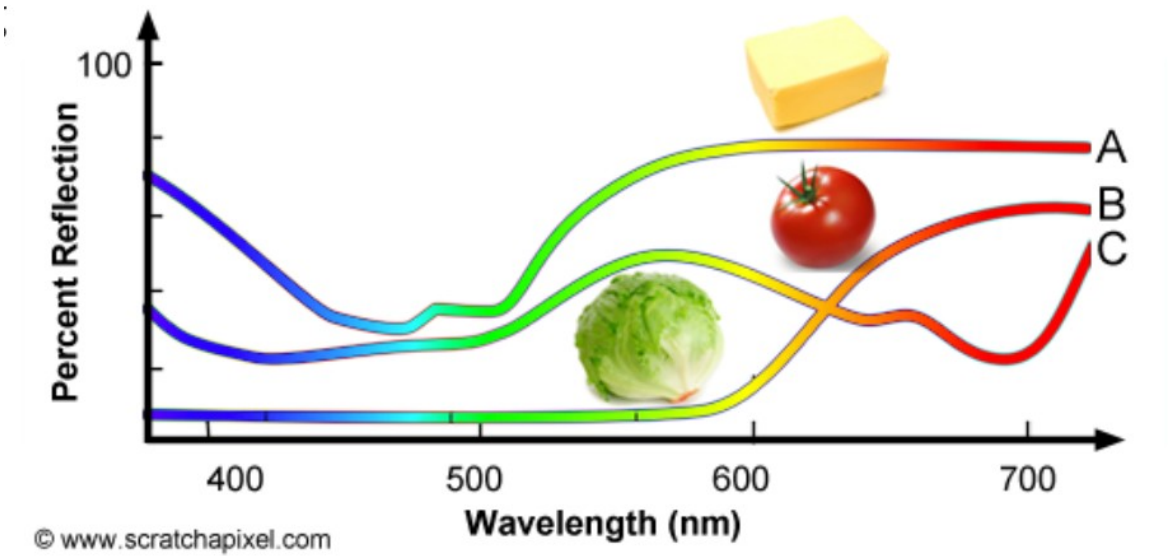
https://commons.wikimedia.org/wiki/File:Sun-in-the-sky.jpg



http://www.openphotographicsociety.org/photography/colour-light-and-optics/colour/203-spectral-power-distribution

Spectral reflectance curve

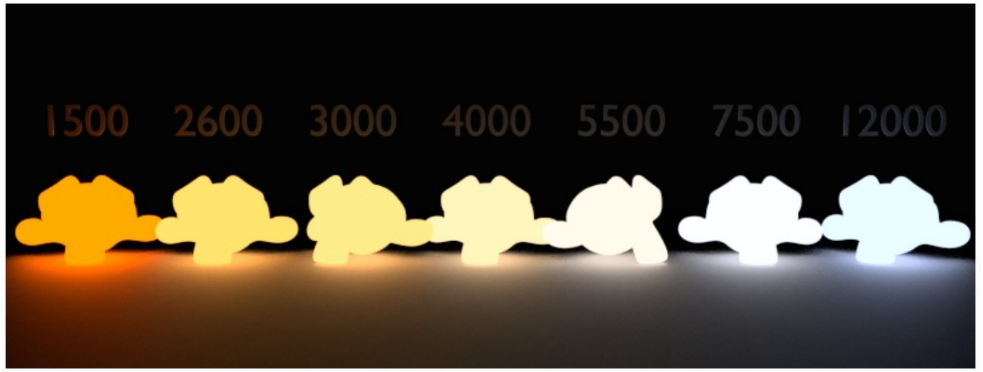
- SPD is also used for light reflected from objects: **spectral reflectance curve**
- **Important:** PSD for of light from light sources vs reflected light from objects
  - SPD of light source defines color and intensity
  - SPD of reflected light represents fraction of the light reflected by the surface of the object over the amount of white light illuminating the object.



https://www.scratchapixel.com/lessons/digital-imaging/colors

Color temperature

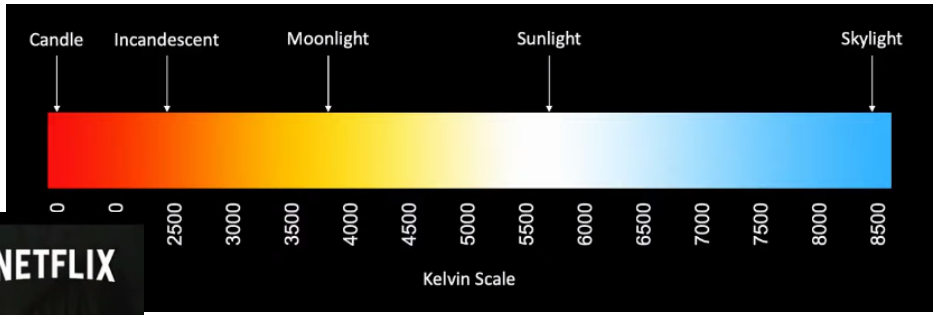
- Object which is heated to certain temperature emits light
- Color of emitted light depends on temperature
- Black body radiation



https://docs.blender.org/manual/en/latest/render/shader_nodes/converter/blackbody.html

https://www.inlineelectric.com/color_temperature

Color temperature



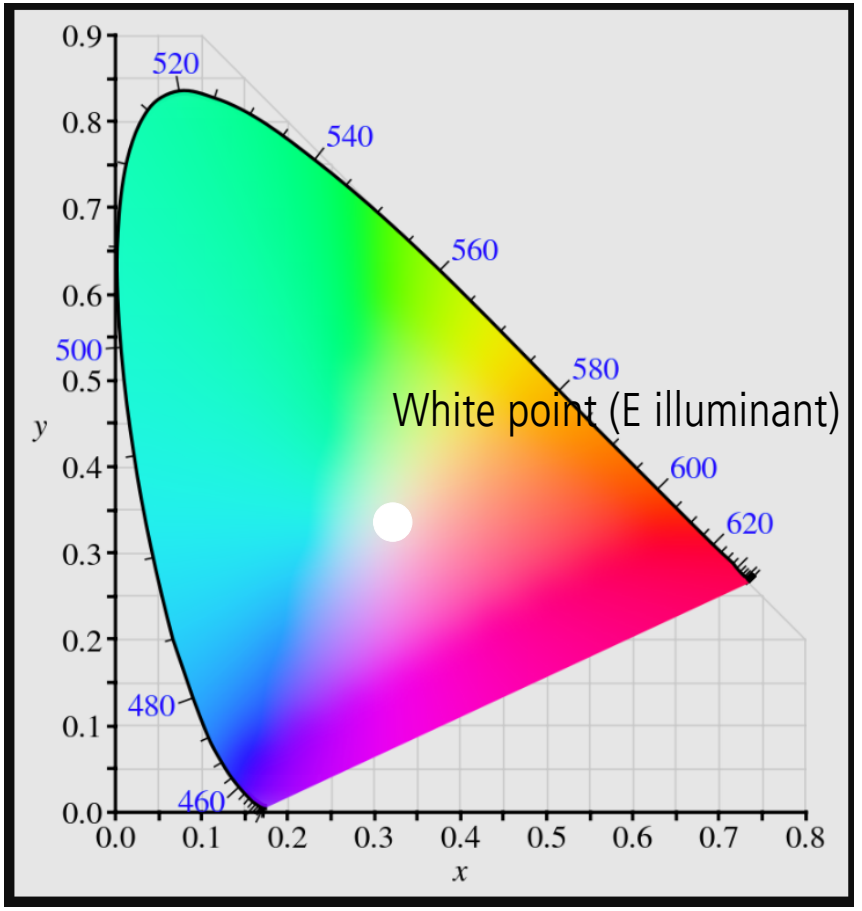
Secrets of photorealism:
https://www.youtube.com/watch?v=Z8AAX-ENWvQ&t=2s&ab_channel=Blender

Color space and PSD

- Light from light source or reflected from the object is defined with PSD
- Human visual system can not directly perceive PSDs
- PSDs must be transformed in color models or color spaces suited for trichormatic vision
  - Note PSDs is transformed in color **hue** and color **brightness** values which we can perceive
- **CIE XYZ** is foundation for all color models
  - **RGB** model is most important for computer graphics

Colorspace and gamut

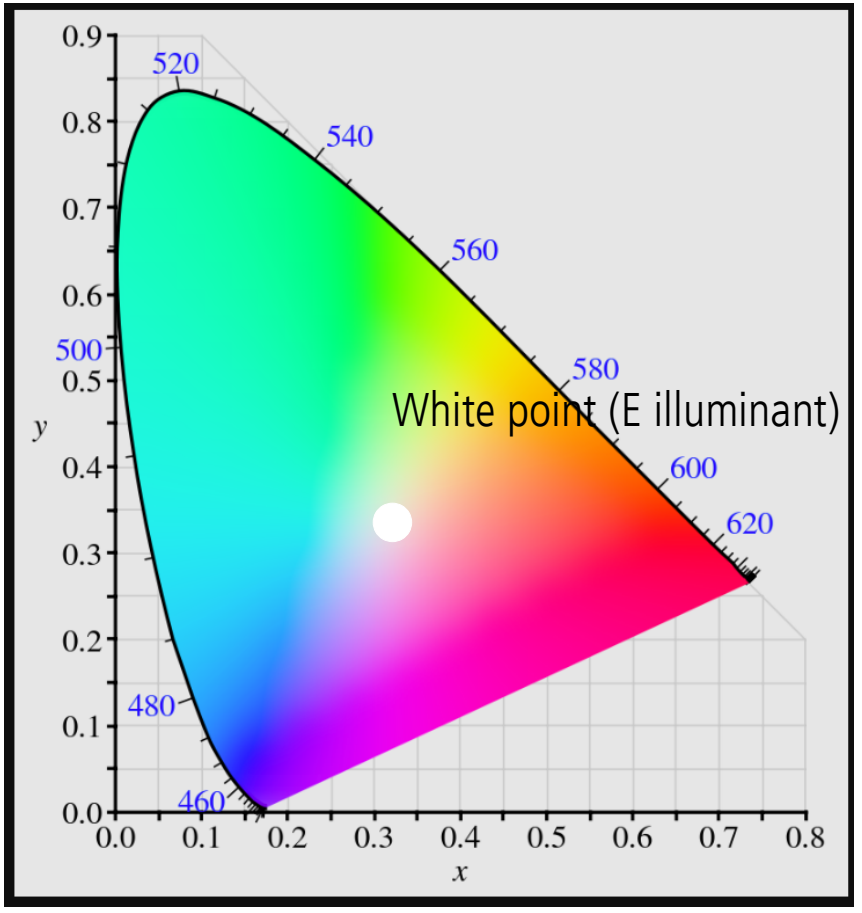
- **Colorspace**
  - Model to represent colors perceived by human visual system
- **Gamut**
  - Range of possible colors that can be represented by particular colorspace



Gamut of XYZ color space:
https://en.wikipedia.org/wiki/CIE_1931_color_space

XYZ colorspace

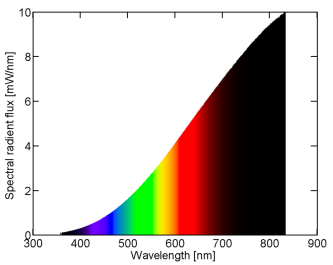
- Assumption: any color (in an additive color model) can be represented by a combination of red, green and blue light
  - Based on cone cells – trichromatic system
- Three curves: **CIE standard observer color matching functions**
  - Y curve is close to luminosity function → expressing the brightness
- Using color matching curve, PSD can be converted to X, Y and Z values
- **Gamut of XYZ color space** - gamut of human vision
  - Full range of possible colors visible by human visual system
- XYZ colorspace:
  - System capable representing all colors human visual system can percieve
  - Gold standard for color storage
  - **XYZ have to be transformed to RGB space to be visualized**



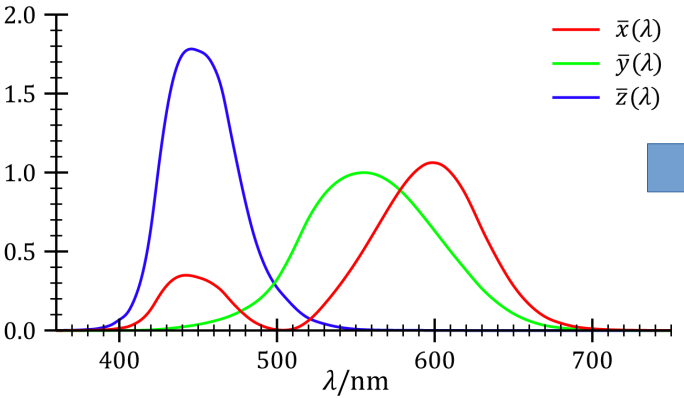
Gamut of XYZ color space:
https://en.wikipedia.org/wiki/CIE_1931_color_space

From PSD of lightsource to XYZ

- XYZ colorspace is obtained from PSD of light source using color matching curves
  - spectrum and the color-matching functions are discrete in a computer

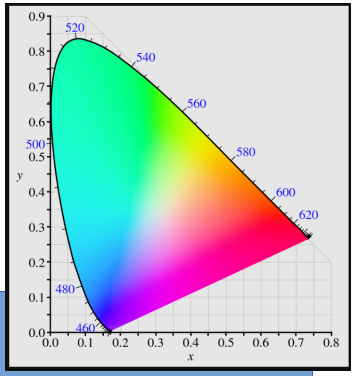


PSD of light source



https://en.wikipedia.org/wiki/CIE_1931_color_space

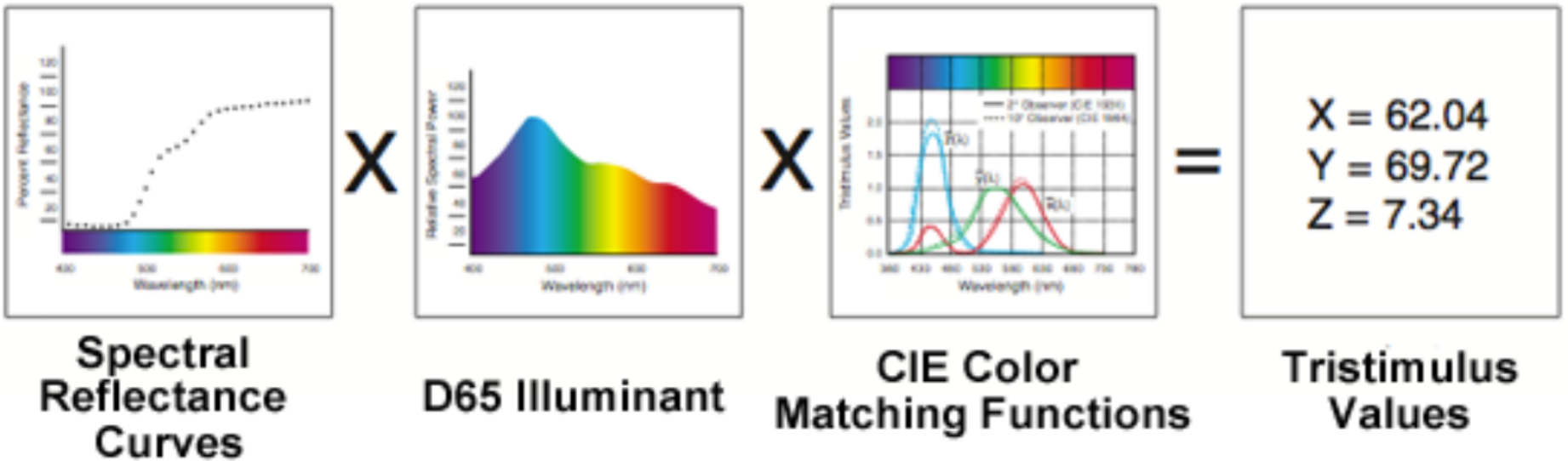
Color matching curves



X = v1
Y = v2
Z = v3

From PSD of reflected light to XYZ

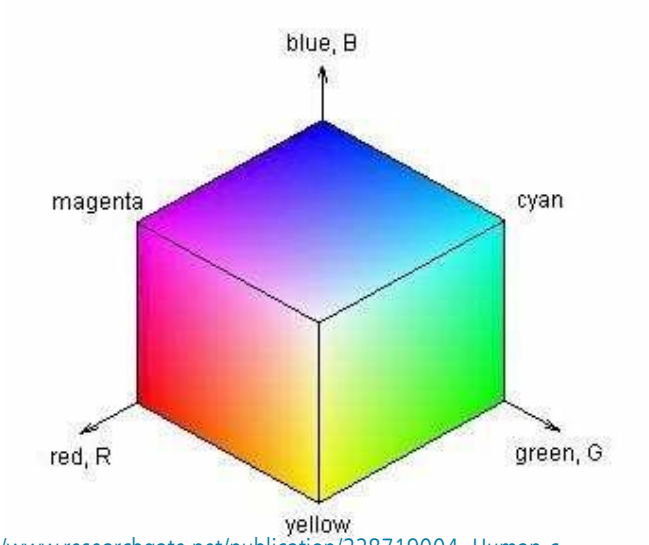
- Light reflected from object is represented as spectral reflectance curve
  - Therefore it must be multiplied by white light which caused the reflection and the standard is D65.



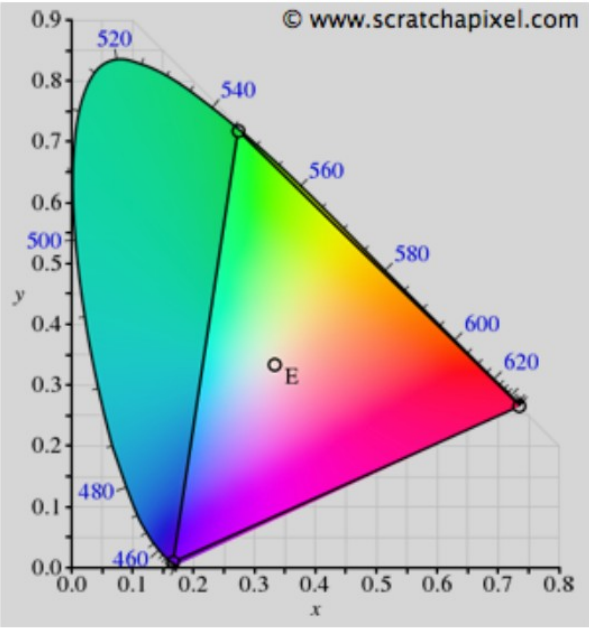
https://www.scratchapixel.com/lessons/digital-imaging/colors/color-space

RGB colorspace

- Similar as human visual system: represent colors as simple sum of primary colors (R, G, B).
- Visualized as cube where R, G and B are placed on axis.
- Limited gamut compared to XYZ colorspace



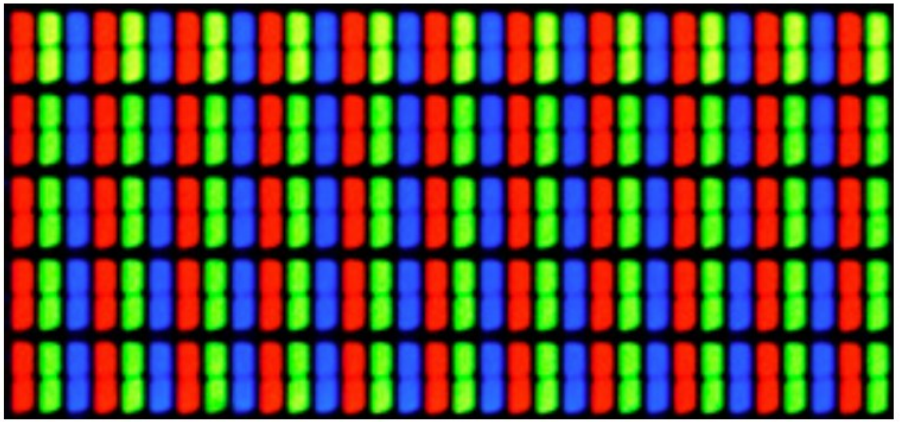
https://www.researchgate.net/publication/228719004_Human-centered_content-based_image_retrieval



https://www.scratchapixel.com/lessons/digital-imaging/colors/color-space

RGB colorspace

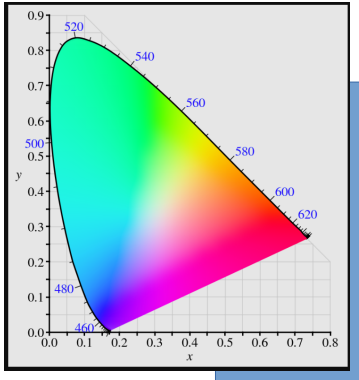
- Most **computer screens technology** is based on system similar to RGB color model.
  - Summing all RGB values gives white color
- RGB and XYZ are **linear** colorspace
- For rendering, RGB color space is often used
  - PSD is used in **spectral rendering** - more correct rendering, but expensive: computing XYZ from PSD for calculation takes time



Close-up of LCD screen:
https://jakubmarian.com/the-illusion-of-rgb-screens/

XYZ to RGB

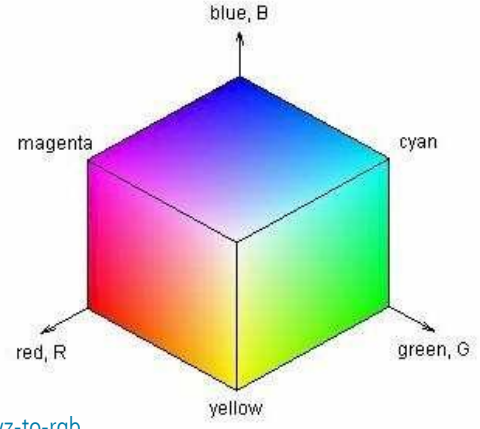
- XYZ and RBG colorspaces are defined by three coordinates
  - They define a 3D space, which can be plotted (cube for RGB)
- Conversion of color from XYZ to RGB can be seen as moving a point from one 3D space to another.
  - **Linear transformation** performed using **3x3 matrix**
  - Color is not changed, only expressed in different colorspace



XYZ

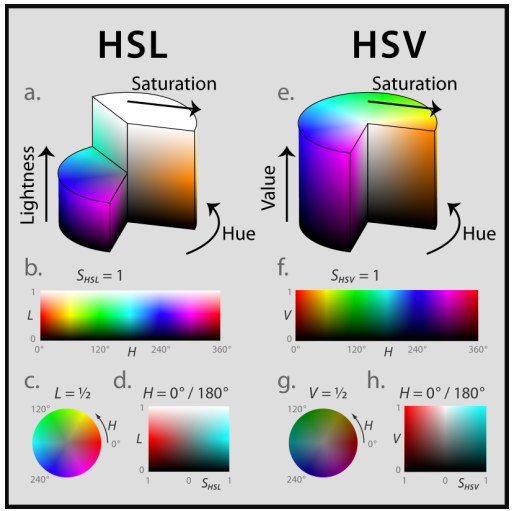
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4124564 & 0.3575761 & 0.1804375 \\ 0.2126729 & 0.7151522 & 0.0721750 \\ 0.0193339 & 0.1191920 & 0.9503041 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

http://www.brucelindbloom.com/index.html?Eqn_RGB_XYZ_Matrix.html
http://www.russellcottrell.com/photo/matrixCalculator.htm
https://www.oceanopticsbook.info/view/photometry-and-visibility/from-xyz-to-rgb
https://terathon.com/blog/rgb-xyz-conversion-matrix-accuracy/



Colorspaces and transformations

- RGB and XYZ are linear colorspaces and can be transformed using 3x3 matrix
- There are other colorspaces such as **sRGB**, HSV, HSL are non-linear
- 3x3 matrices can not be used to convert between non-linear and linear colorspace (and vice versa)
  - Any non-linear colorspace must be converted to linear colorspace before 3x3 matrix transformation.

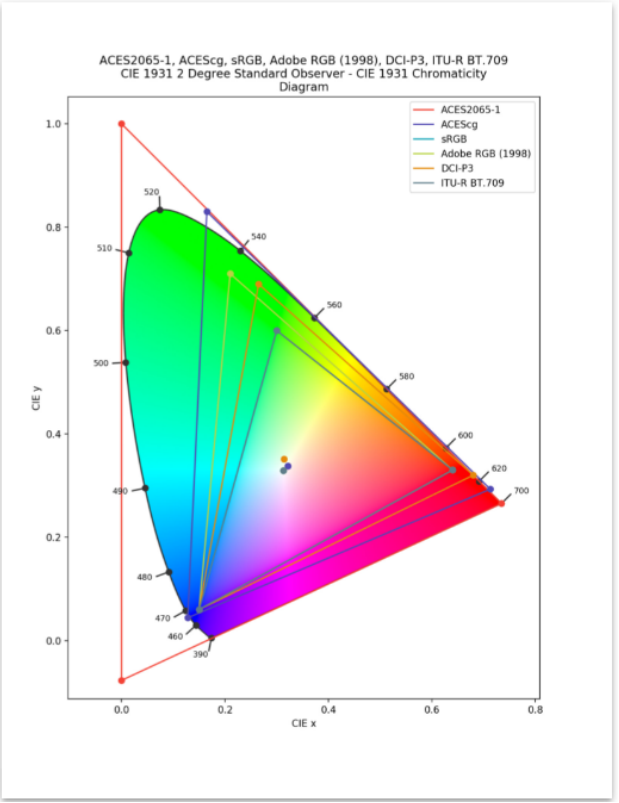


https://en.wikipedia.org/wiki/SRGB

SRGB gamut

Note: ACES colorspace

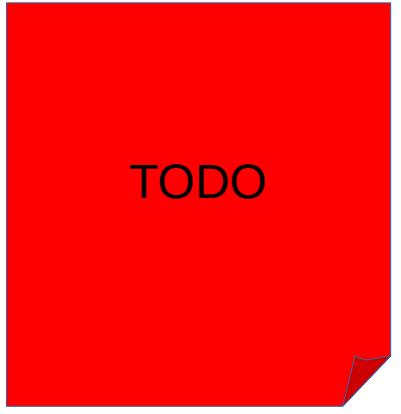
- Academy Color Encoding Specification (ACES) is developed by Academy of Motion Picture Arts & Science technology committee
- Designed to cover the full gamut
- Goal: images should always look the same regardless of used camera and display device.
- Images in ACES color space can't be directly displayed to the screen. Conversion steps:
  - Reference rendering transform
  - Output device transform: depends on display device (computer monitor, digital projector, etc.)
- Becoming defacto standard for professional production



https://acescolorspace.com/

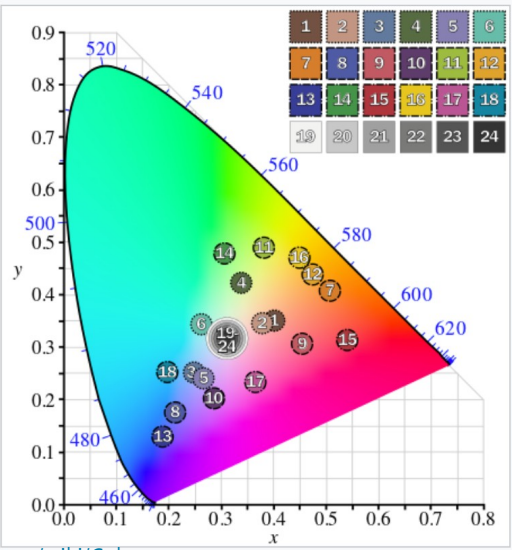
Color in production

- Digital drawing and image manipulation:
  - Krita: https://krita.org/en/item/krita-features/
  - Gimp
- 3D modeling:
  - Blender
- Game engines:
  - Godot



Note: Macbeth ColorChecker

- Colors have spectral reflectances mimicking materials which are often photographed.
  - Human skin, sky, flowers, etc.
- Goal: consistent color appearance under varying lighting conditions
  - Reference for tweaking exposition and color settings of camera



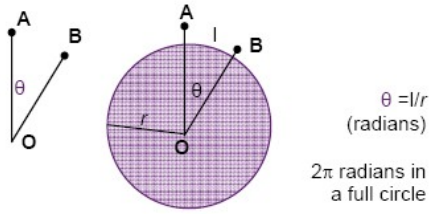
https://en.wikipedia.org/wiki/ColorChecker

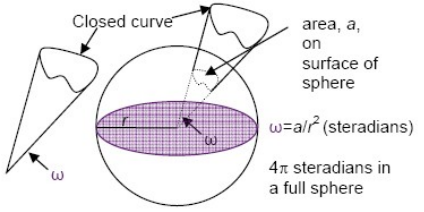
Light characterization

- Quantifying light:
  - **Radiometry** – measurement of radiation, physical transmission of light
  - **Photometry** – measurement related to human visual system
    - Summary measures: computed from radiometic quantities.
  - **Colorimetry** – Color perception

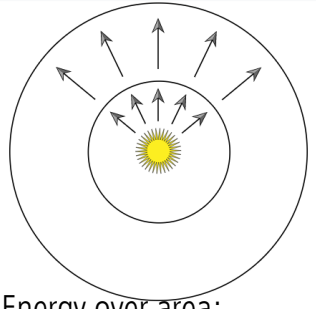
Radiometric quantities

- Measuring light energy, power and power over area and/or direction.
- **Radiant flux** – flow of radiant **energy over time** (W)
- **Irradiance** – density of radiant **flux over area (W/m²)**
- **Solid angle**
  - 3D extension of the concept of plane angle: continuous set of directions in 3D space measured in steradians (sr)
  - area of the intersection patch on an enclosing sphere with radius 1
  - 4*PI steradians close the whole area of unit sphere
- **Radiant intensity** – flux density with respect to **solid angle** (W / sr)





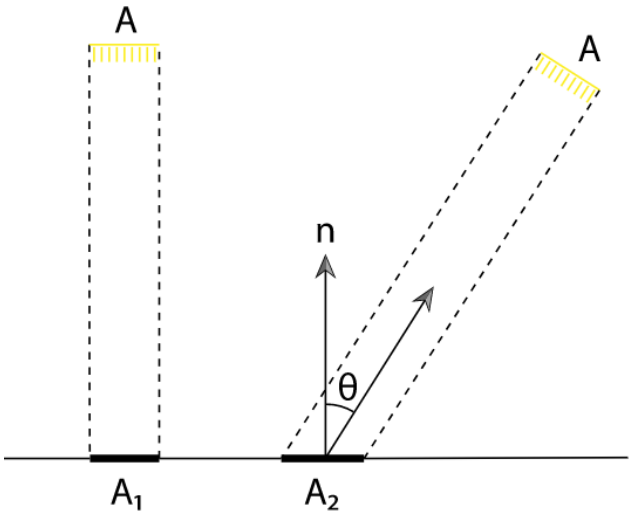
https://spie.org/publications/fg11_p02_solid_angle?SSO=1



Energy over area:
https://www.pbr-book.org/3ed-2018/Color_and_Radiometry/Radiometry

Radiance

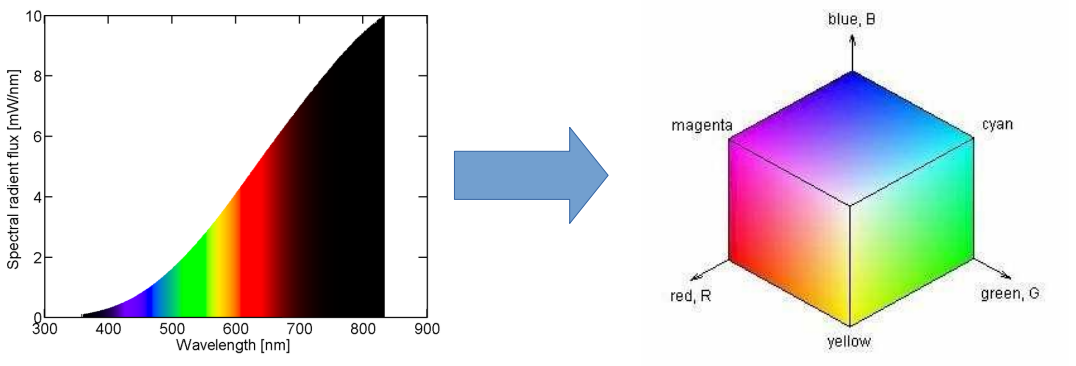
- **Radiance** – electromagnetic radiation in single ray (W / (m^2 sr))
  - Density of radiant flux over area and solid angle.
  - This area is measured in a plane perpendicular to ray, if surface has orientation then cosine correction factor must be used
- **Radiance is what cameras measure** – prime importance for rendering
- The **purpose of shading is to calculate radiance** along a given ray from a shaded point on object to camera
  - Radiance is physically based value which is simplified with **color and intensity**
- **Radiance distribution** describes light traveling anywhere in space
  - Rendering can be seen as evaluating radiance distribution for each eye-camera direction*
- Radiance is not affected by distance
  - Surface is more distant and covers less area.



* Image-based rendering uses this concept, namely light field technique.

Radiometric quantities and PSD

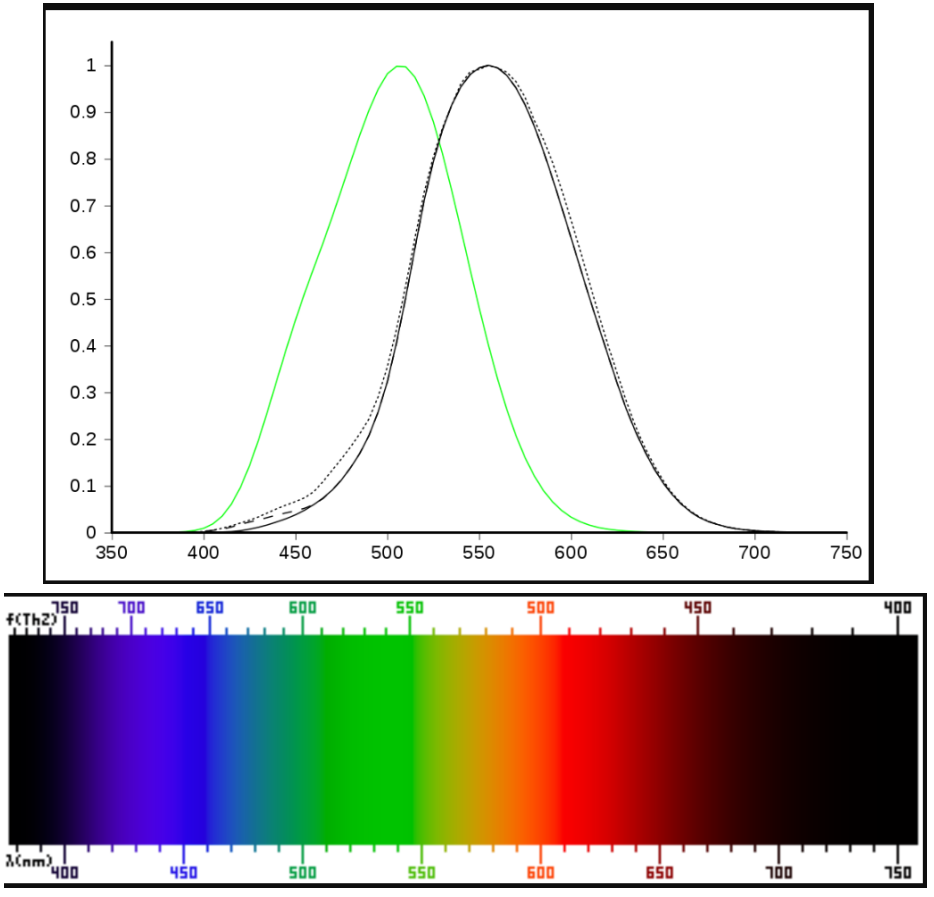
- Most light waves contain mixture of many different wavelengths – **polychromatic** (light with one wavelength is called **monochormatic**).
  - Visualized using spectral power distribution (SPD) – plot showing how light's energy is distributed across wavelengths.
- All radiometric quantities have spectral distributions
  - Using full SPDs for rendering is complex*, often radiometric quantities are represented as RGB triplets.



* Area of research dealing with spectral rendering exists and it is highly active. https://www.fxguide.com/fxfeatured/manuka-weta-digitals-new-renderer/

Photometry

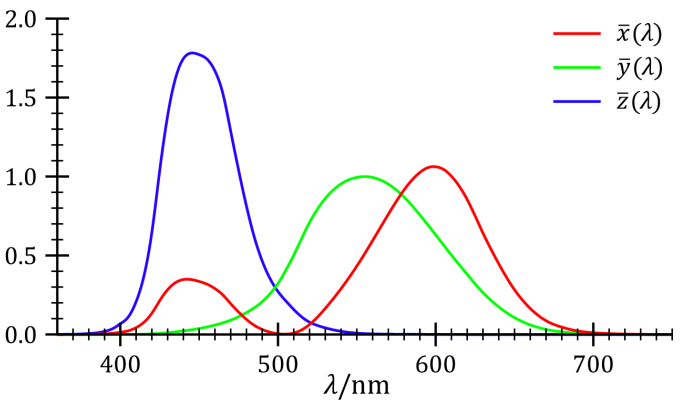
- Photometry is field like radiometry but it takes visual system and perception in account.
- Each radiometric quantity has equvivalent photometric quantity
  - Radiant fluix → Luminous flux (lumen - lm)
  - Irradiance → Illuminance (lux - lx)
  - Radiant intensity → Luminous intensity (candela - cd)
  - Radiance → Luminance (cd / m^2)
- Radiometric quantities are converted to photometric by using **CIE photopic spectral luminous curve**.

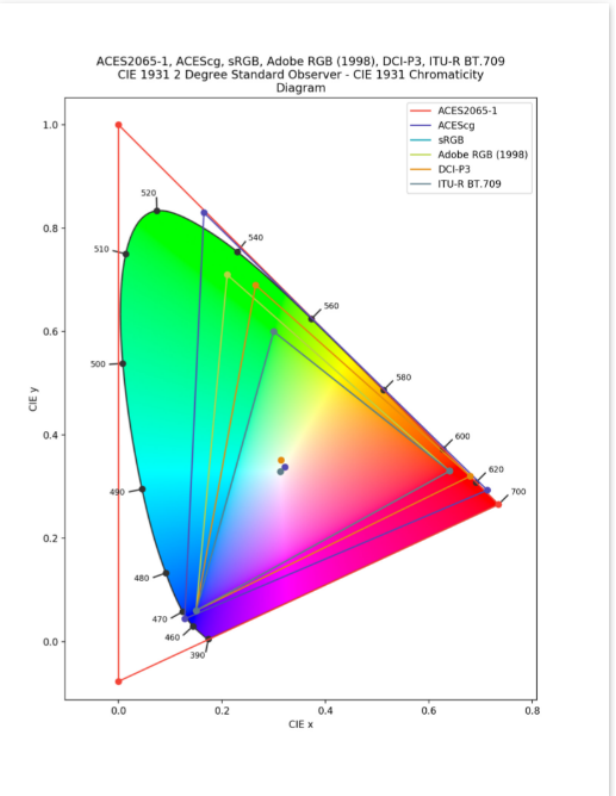


Luminosity function for photopic – green - (well lit) and scotopic (low lit) – black.
https://en.wikipedia.org/wiki/Luminous_efficiency_function

Colorimetry

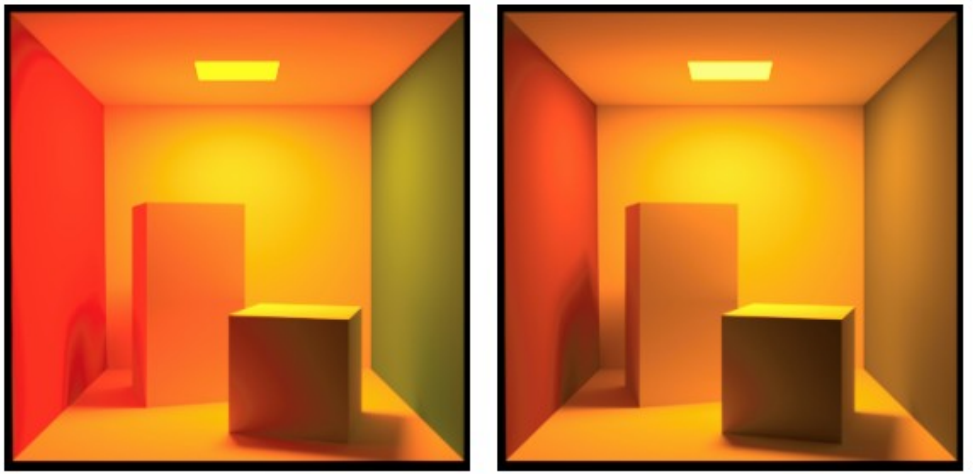
- Colorimetry: relationship between PSD and perception of color
- **CIE standard observer color matching functions**
  - PSD → XYZ colorspace
- Define colorspaces and their gamut for visaulization
- RGB color spaces are most interesting for rendering:
  - **SRGB (**linear colorspace with sRGB primaries and white point)





Rendering with RGB

- RGB is perceptual rather than physical quantity
- RGB in Physically based rendering is a category error
  - Correct would be to use spectral quantities for rendering and RGB conversion in the end for visualization
- For interactive and appearance-based applications (e.g., film) RGB rendering is acceptable.
  - Object surface reflection is defined using RGB rather than spectral reflectance curve
  - Light sources are described with RGB rather than PSD
- For predictive simulations rendering spectral quantities must be used.



Tristimulus vs spectral rendering:
https://hal.inria.fr/hal-03331619/document

Recap

- Light has physical but also perceptual properties.
- Discussion on radiometry, photometry and colorimetry was needed to understand light and its perception:
  - Color (hue)
  - Intensity
- Light in computer graphics is represented using:
  - RGB values in [0,1]
  - Intensity, multiplier of RGB values

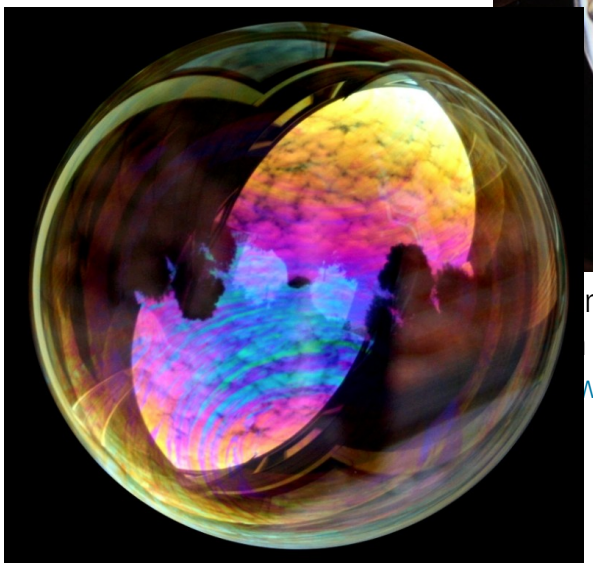
Real world light and sources of light

Light description

- Light can be described both on:
  - Microscopic scale: wave optics
  - Macroscopic scale: **geometric optics**

Light: microscopic level

- Light is quantized – it comes in individual and indivisible packets called **photons**
- At same time light is **wave-like**
- Some effects of light-matter interaction can be only explained (and thus modeled*) using **wave optics**:
  - Interference
  - polarization
  - Diffraction
  - Iridescence
  - Pleochroism and birefringent
  - Etc.
- Also, knowing microscopic background often helps in getting intuition for some shading and light transport methods**



White light interference in a soap bubble – iridescence phenomena (thin-film interference) - https://en.wikipedia.org/wiki/Wave_interference

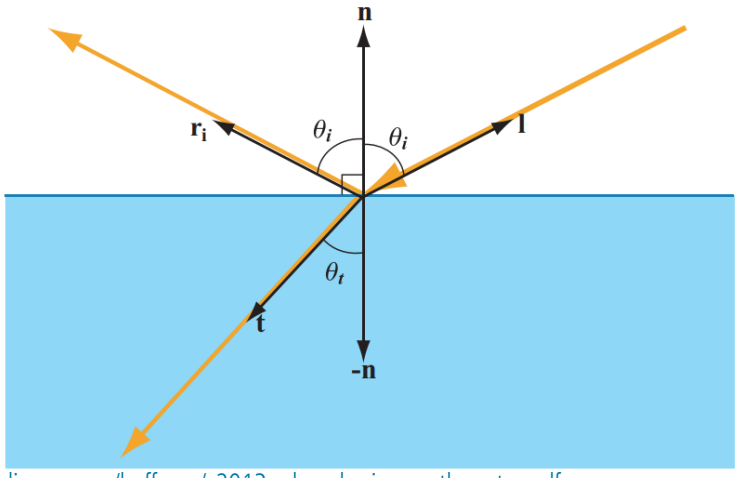
rn of Birefringence effect when a plastic box between two polarizers: wikipedia.org/wiki/Polarization_(waves)

* It is important to note that complexity of model level depends on application. Often, in computer graphics wave effects can be "faked" to achieve desired apperance: https://developer.nvidia.com/gpugems/gpugems/part-i-natural-effects/chapter-8-simulating-diffraction. On the other hand, physically based methods for achieving wave-effects is actively researched area: https://sites.cs.ucsb.edu/~lingqi/publications/202203_practical_plt_paper_lowres.pdf

** For example photon mapping: http://web.cs.wpi.edu/~emmanuel/courses/cs563/write_ups/zackw/photon_mapping/PhotonMapping.html

Light: macroscopic level

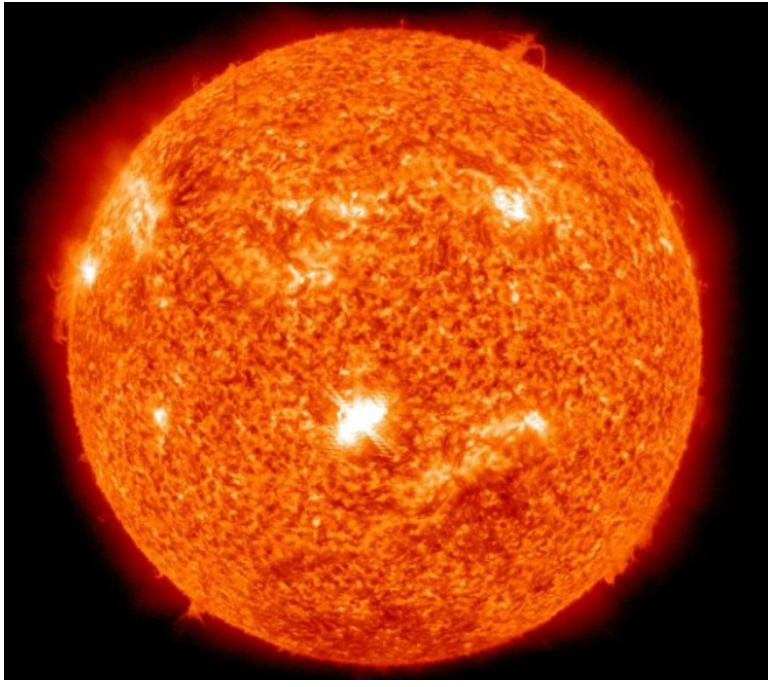
- Light in computer graphics is often modeled at macroscopic level – **geometric optics**.
  - Assumption: features with which light interacts are relative to light wavelength (or larger)
  - Light is described with rays.
  - Microscopic light behavior is described with **index of refraction** (IOR)
- In medium of constant IOR, light energy travels in a straight line
  - It only can get **absorbed**
- Light passing from one to another medium with different IOR changes speed
  - This is described with light **scattering**
  - Interface between media is represented by **surface**
- Scattering of light on surface is described with reflection and refraction described with Snell law (light direction) and Fresnel equations (light energy).



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

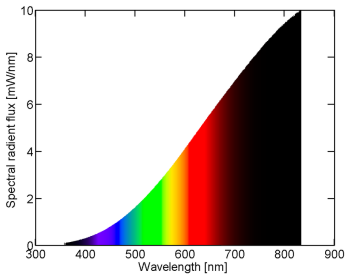
Sources of light

- In a real world, **every light source has a physical shape and size**, e.g., Sun or very hot objects.
- Motion of atomic particles that hold electrical charge causes objects to emit electromagnetic radiation over a range of wavelengths (Maxwell's equations)
- Different way how energy is converted into electromagnetic radiation:
  - **Incandescent (tungsten) lamps**
  - **Halogen lamps**
  - **Gas-discharge lamps**
  - **LED lights**

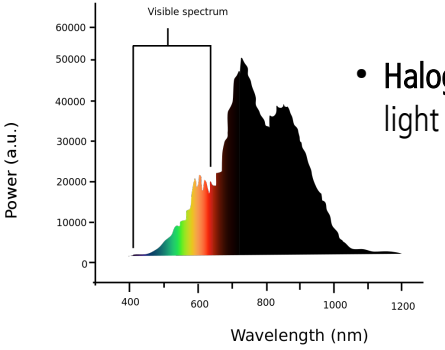


https://education.nationalgeographic.org/resource/sun

Sources of light



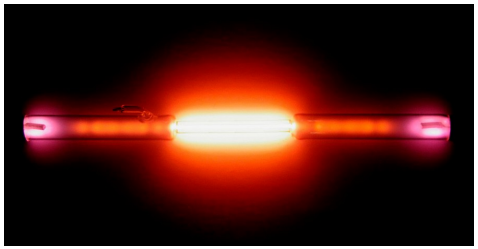
- **Incandescent (tungsten) lamps**:
  - flow of electricity through tungsten filament heats is up and causes to emit electromagnetic radiation with distribution of wavelengths depending on filament temperature.
  - A frosted glass enclosure is often present to absorb some of the wavelengths.



- **Halogen lamps**: tungsten filament is enclosed in halogen gas. Part of the filament in an incandescent light evaporates when it's heated. Halogen causes evaporated tungsten to return to filament

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

Sources of light



Helium: https://en.wikipedia.org/wiki/Gas-discharge_lamp

- **Gas-discharge lamps:** passing electrical current through hydrogen, neon, argon, or vaporized metal gas, causes light to be emitted at specific wavelengths that depend on the particular atom in the gas.
- Fluorescent coating on the bulb's interior is often used to transform the emitted frequencies to a wider range.

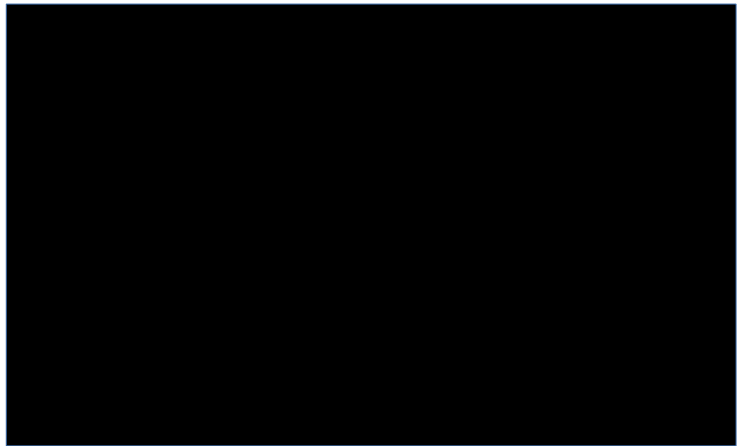
LED lights:
https://en.wikipedia.org/wiki/Light-emitting_diode

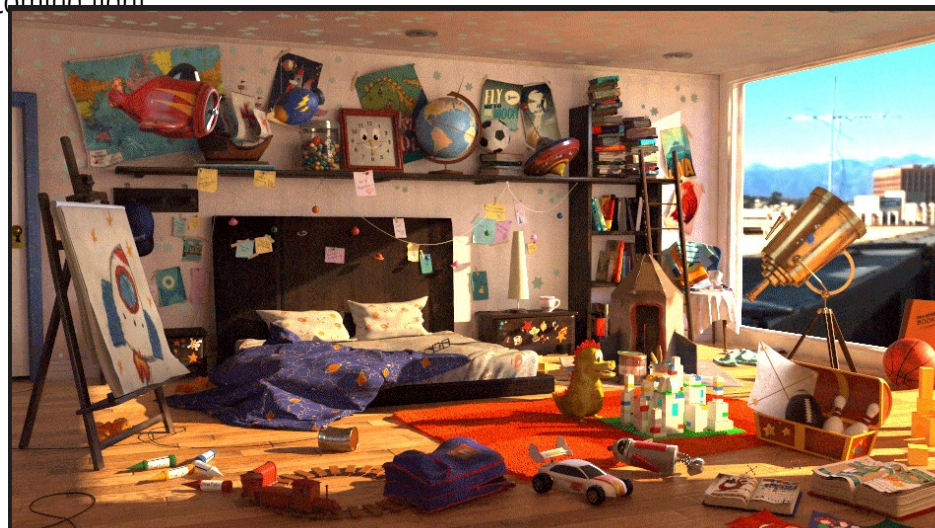
- **LED lights** are based on electroluminescence: they use materials that emit photons due to electrical current passing through them.

Light model

Rendering and light

- **Light is emitted from a light source**, bounces around the scene, interacting with object and some (very small!) portion enters camera enabling us to see objects in the scene
- Rendering:
  - Generating image from 3D scene
  - Each pixel of rendered image is associated with 3D surface point visible to camera.
- Color of the object surface is calculated in shading step.
  - Shading takes in account 3D object shape (i.e., normal), object material and incoming light
  - Without light resulting image would be completely black.





Light and shading

- **Shading**: calculating color of the objects in 3D scene
- Simple shading: light color and scattering model `f(l,n,v)`

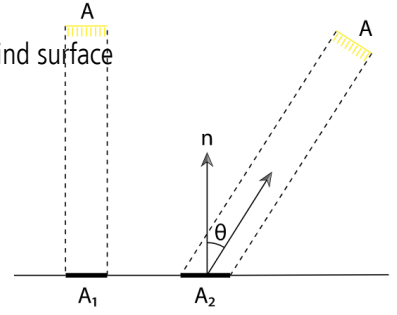
$$c_{shaded} = f(l, n, v) c_{light}$$

- If multiple light sources are present, they add up linearly

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

- Effect of light on surface can be visualized as rays
  - Density of rays hitting the surface correspond to the light intensity.
  - Density of light rays (their spacing) is proportional to cosine of angle between l and n.
  - Ray density is proportional to dot product when positive, otherwise light comes from behind surface

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



Light and shading

- Final, simplified shading:

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

- If `f(l,n,v)` is constant color, → Lamberitan shading
- Conclusion, light source interacts with shading model with:
  - Vector l pointing toward light
  - Light color
- Different types of light sources differ in how these two parameters are varied over the scene

Local and global illumination

- More generally, light reflected from surface is represented with **reflectance equation**:

$$L_o(p,v) = \int_{l \in \omega} f(l,n,v) L_i(p,l)(n \cdot l) dl$$

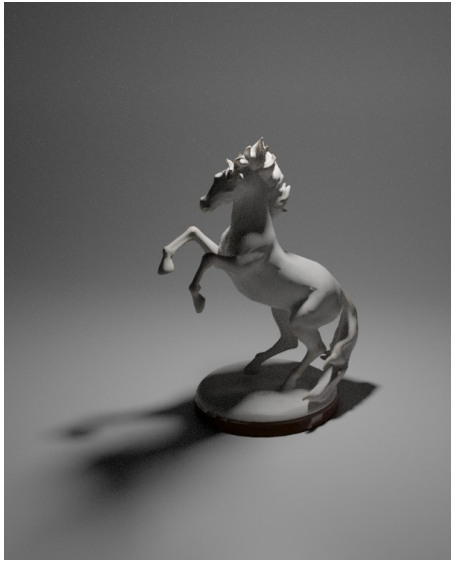
- If shading is considering only light coming from light sources: **local illumination**
  - L_i is given as color and intensity. Position of light source is calculated from its position
  - Therefore, introduced simplified version can be used

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

- Any surface can reflect light on another surface: indirect illumination → **global illumination**
  - Integrating over hemisphere to gather all incoming light L_i is needed
  - Global illumination algorithms simulate light transport through the scene.
  - They solve **rendering equation** where reflectance equation is special case.

Local illumination is used in rasterization-based rendering (Blender, EEVEE)

Global illumination is used in ray-tracing-based rendering (Blender, Cycles)

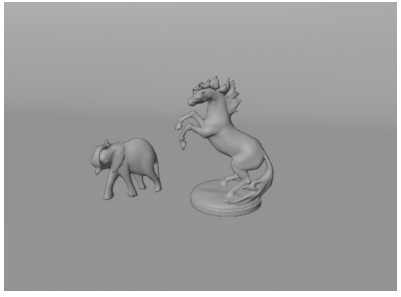


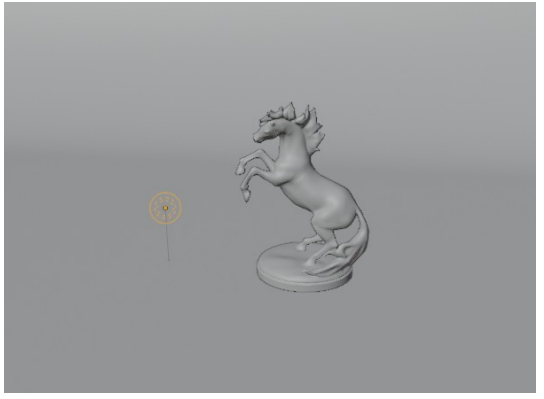
Light and shading

- **Light sources** must define
  - **Position** and thus **direction** of light
  - **Color** and **intensity** of light
- Additionally, light sources can have:
  - **Size**
  - **Shape**

Light models

- Representation and modeling of light **physically,** with shape and size is very computationally expensive. Such lights are called **geometric area light or physical lights***
- Simplification are lights with no physical size, thus called **delta or non-physical lights**





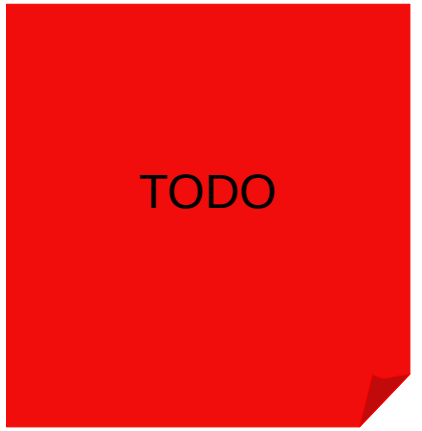

* When we discussed surface material we mentioned scattering and absorption. Also, materials are able of emission. Therefore, physical lights have 3D shape and material which is emissive. Emissive material is modeled as black body meaning that is absorbs all light falling on it.

Light models parameters

- **Non-physical:**
  - **Color:** RGB triplet in [0,1]
  - **Intensity:** floating point [0,1] as multiplier to color
  - **Position ➞ Direction**
- **Physical**
  - Color
  - Intensity
  - Position
  - Shape
  - Size

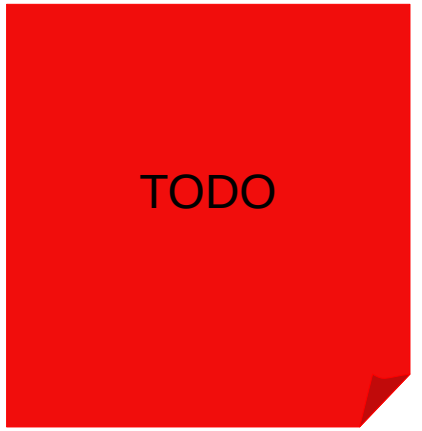
Physical lights

Physical lights



- Geometry with emissive material
  - Color and intensity
  - Position
  - shape and size
- Physical lights have area which has to be sampled
  - Interaction of physical lights with the scene can not be computed in closed form. Advanced, approximation-based methods such as Monte Carlo integration must be used
- Often used in offline rendering, ray-tracing based rendering

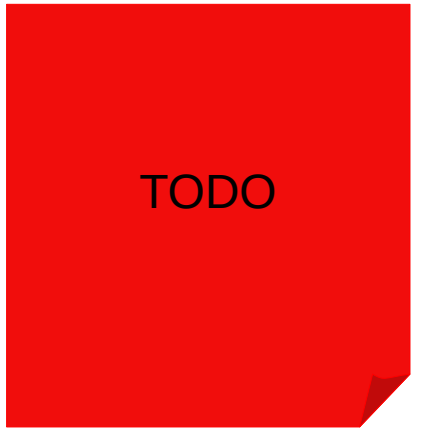
Physical lights: offline rendering



Physical lights: real-time rendering

- For real-time applications non-physical ligh
  used by artists to simulate effects of physic
- Another alternative is to precompute light a
  texture which is then used during shading in render-time
  - General note: this is another example showing that it is always important to assess the application of Computer graphics and see what is really important to model.

Non-physical lights



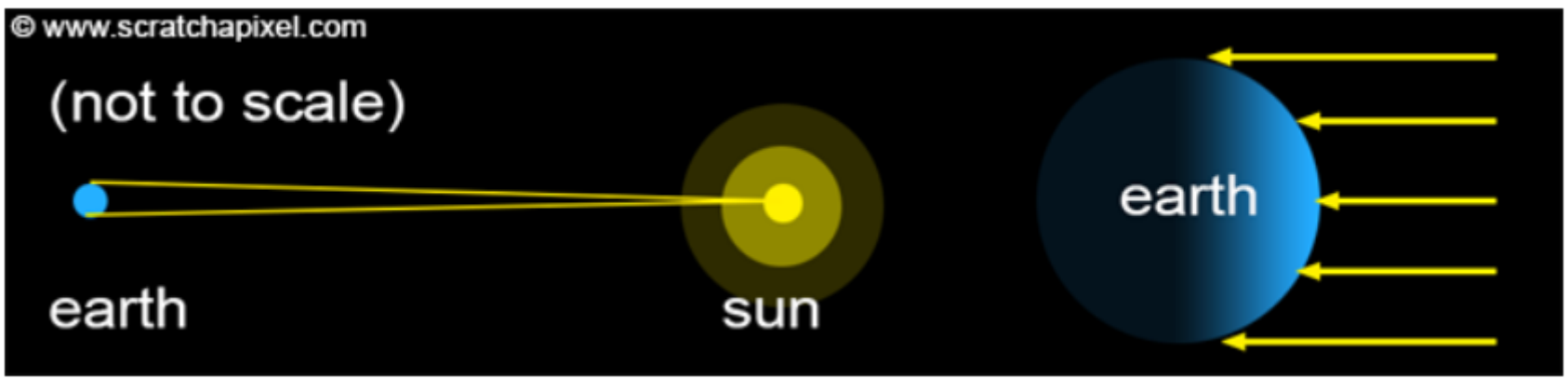
Non-Physical lights

- Types:
  - Directional (distant) lights
  - Point (spherical, omnidirectional) lights

- Non-phyiscal lights enable us to control light fall-off w… which objects are illuminated, which objects cast sha… n.
- For physically-based rendering, non-physical light should be avoided
  - Example: size of reflection of object by glossy or mirror-like surface depends on its size and distance to reflective surface. If light source has no shape nor size how reflection should look like? Hack: size parameter which is only used during shading.

Directional lights

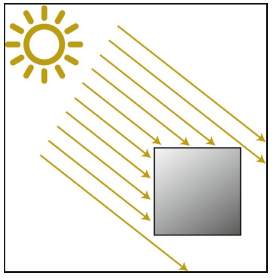
- Directional - **distant** lights - considered so far from the objects in a 3D scene that they can be represented by parallel rays.
  - We only care for the **direction** of those parallel rays
  - Example of directional light: is Sun light on Earth.
    - Sun has spherical shape, but it is so far and Earth is so small compared to it that light rays reaching Earth can be considered parallel (small cone of directions – solid angle).
  - For scenes that cover small area of Earth's surface, Sun light can be assumed parallel.



https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-to-shading/shading-lights

Directional lights

- Directional light is simplest model of light source. Parameters:
  - **Direction** – unit vector (not affected by position!)
  - **Color** – RGB vector in [0,1]
  - **Intensity** – float value in [0,inf]
  - Direction (l), color (c) and intensity (I) are constant over 3D scene
- Intensity may be attenuated by shadowing and surface orientation
- Works well when light source distance is large compared to size of the 3D scene

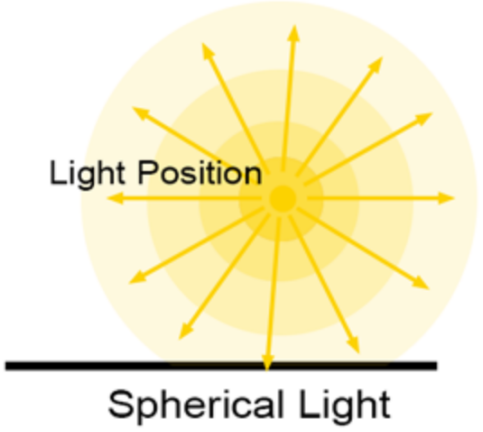


https://link.springer.com/chapter/10.1007/978-1-4842-4457-9_12

Point lights

- Most common light sources in nature and around us are spherical
  - e.g., light bulbs or candle flame
  - Can be approximated as a collection of spherical light sources.
- Point light
  - **Infinitesimally small in size ➞ no shape**
  - **Light is emitted in all directions** (omnidirectional, isotropic) therefore, no "direction" parameter
- Parameters
  - **Position** – vector determining position in world space (lights can be also transformed using 4x4 matrices)
  - **Color** – RGB vector in [0,1]
  - **Intensity** – float value in [0,inf]
  - Not affected by scale or rotation.

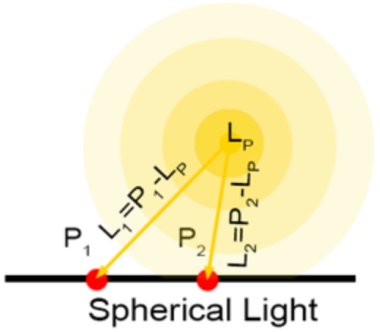
https://polyhaven.com/models

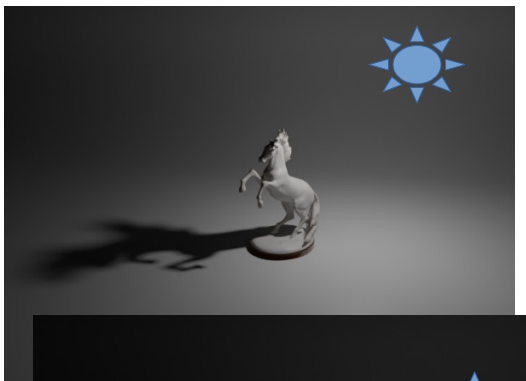


https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-to-shading/shading-lights

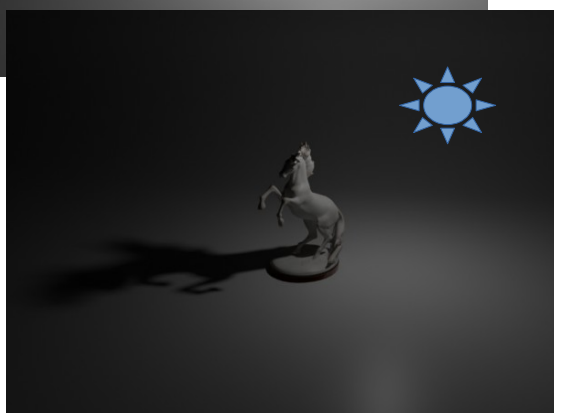
Point lights

- Point light position determines:
  - **Direction of incoming light** ray for each surface position for each object in the scene
    - `LightDirection = normalize(P – L`$_p$`)`
  - **Distance** to the each surface position for each object in the scene – **light falloff**





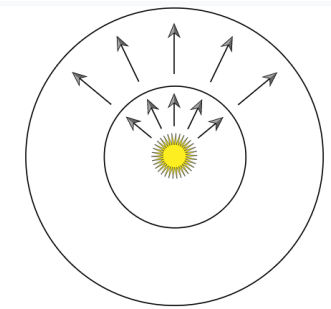
Intensity= 200

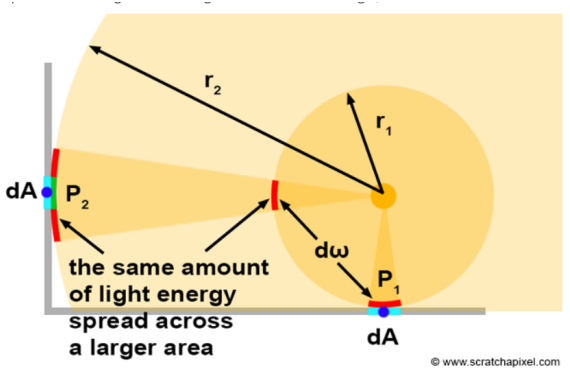


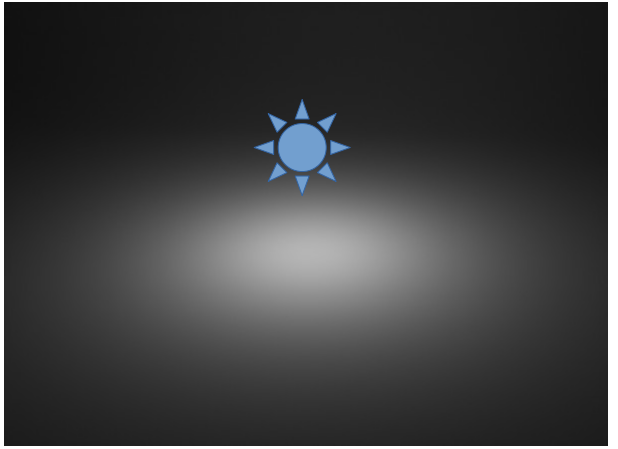
Intensity= 50 → falloff

Point lights: direction and light falloff

- Line between point light and surface point (shading point):
  - **Direction of light**
  - **Distance of point light**
- Point light sources emit light radially
  - Energy of light source is redistributed over sphere
  - As the sphere keeps expanding in the space, energy becomes spread across much larger area → more distant objects in the scene receive less light – **light falloff**.
  - Distance of point light to surface point determines how much is that point illuminated → **intensity of point light varies as a function of distance**.



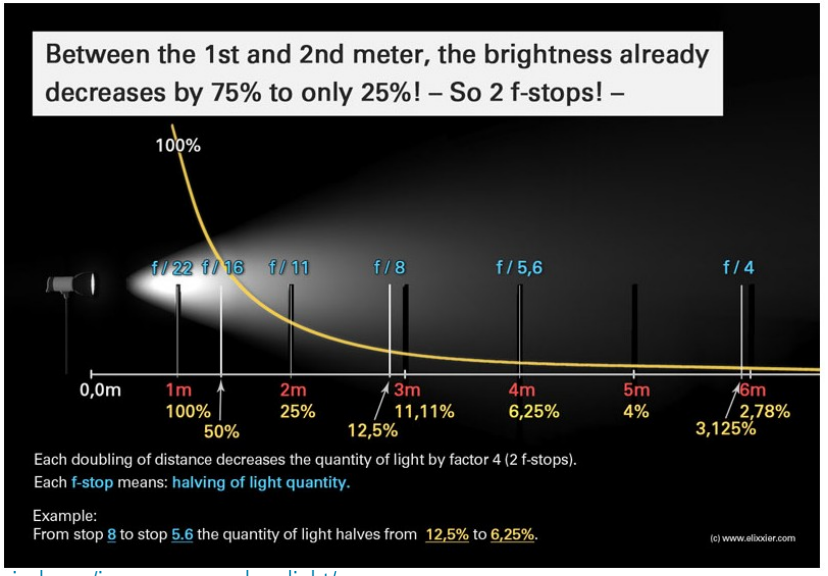




Point light - light falloff

- Point light distributes energy spherically. Larger distance → larger sphere → smaller energy → attenuated light - **inverse square law falloff**:

$$L_i = \frac{\text{light intensity} * \text{light color}}{4\pi r^2}$$



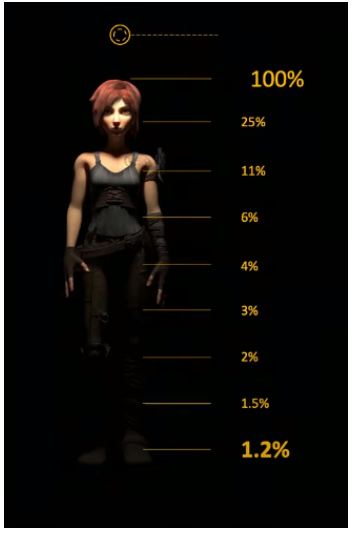
https://petapixel.com/inverse-square-law-light/

- Problems:
  - **Small distances**: as r → 0, light intensity → infinity. Fix:

$$L_i = \frac{\text{light intensity} * \text{light color}}{4\pi(r + \text{epsilon})^2}$$

  - **Large distance**: for efficient rendering, it is desired to light reach 0 at some point. Otherwise, light calculation should be done no matter how far the camera is from the light

https://www.youtube.com/watch?v=Z8AAX-ENWvQ&t=2s&ab_channel=Blender



- Light falloff function can be any other function of distance
  - For stylized appearance different functions may be more interesting

Point light - light falloff

https://www.youtube.com/watch?v=Z8AAX-ENWvQ&t=2s&ab_channel=Blender

Point lights: directional light falloff

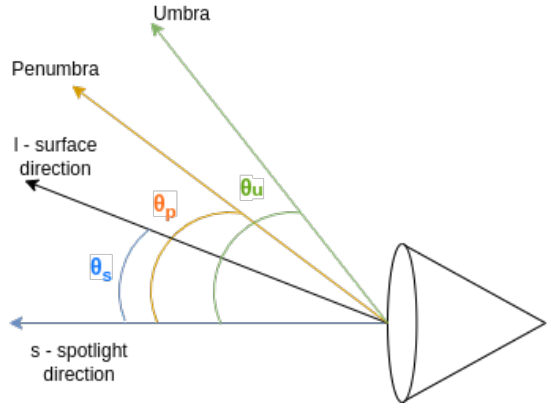
- Next to distance light falloff, real-world illumination intensity also **varies by direction,** generally:

$$L_i = (\text{light intensity} * \text{light color}) f_{distance}(r) f_{direction}(l)$$

- Different choices of distance and directional light falloff functions produce different light sources:
  - **Spotlights** - emit light in a cone of directions from their position

Spotlights

- Projects light in circular cone.
- Directional falloff function is rotational symmetric around a spotlight direction s
- Parameters:
  - Angle of umbra θ_u
    - Outer cone shell
  - Angle of penumbra θ_p
    - Inner cone where the light is at full inte
  - Color: RGB vector in [0,1]
  - Intensity: float in [0, inf]

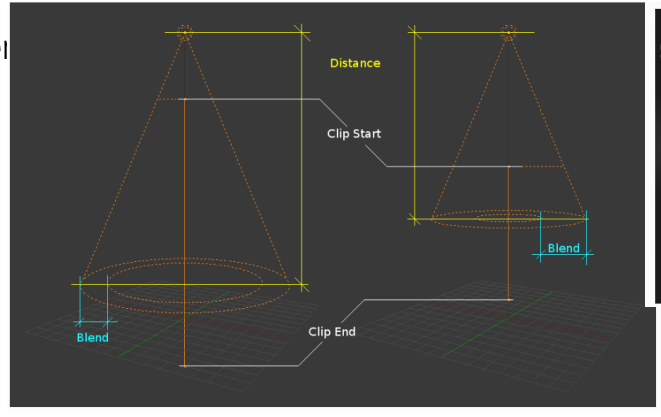


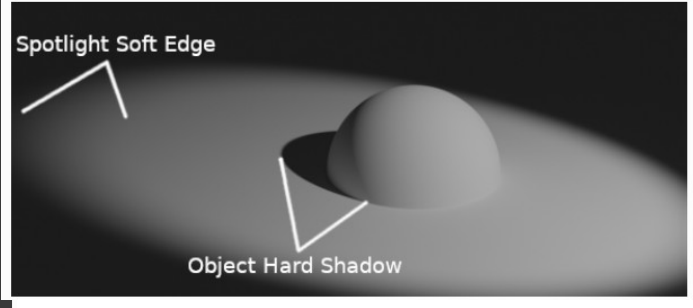
$$L_i = (\text{light intensity} * \text{light color}) f_{distance}(r) f_{direction}(l)$$

$$t = clamp(0, 1, \frac{cos(\theta_s) - cos(\theta_u)}{cos(\theta_p) - cos(\theta_u)})$$

https://seblagarde.files.wordpress.com/2015/07/course_notes_moving_frostbite_to_pbr_v32.pdf

$$f_{directional}(l) = t^2$$

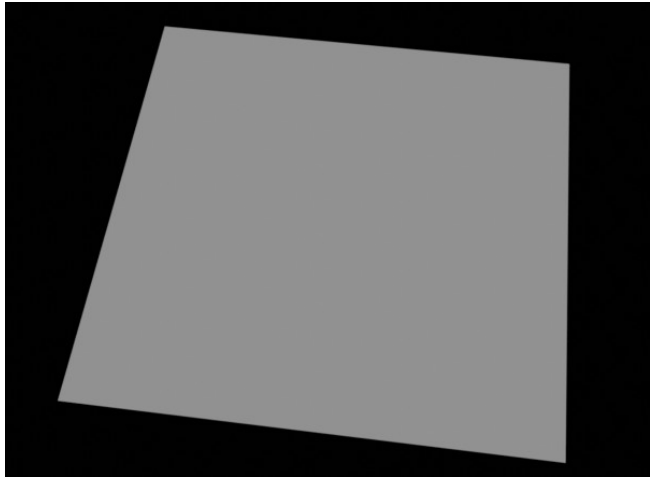
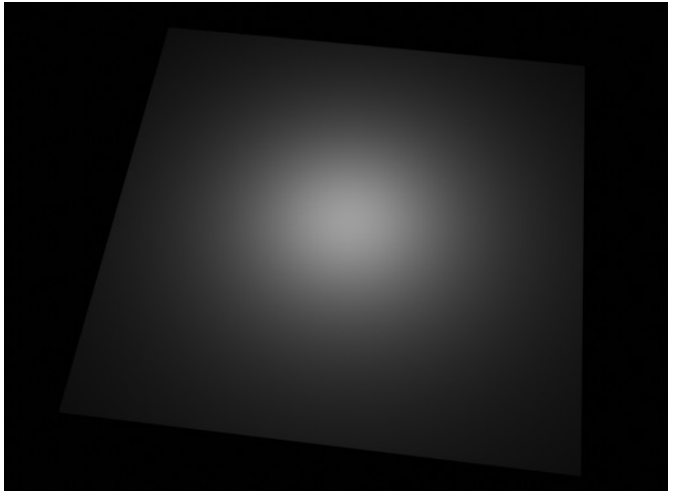
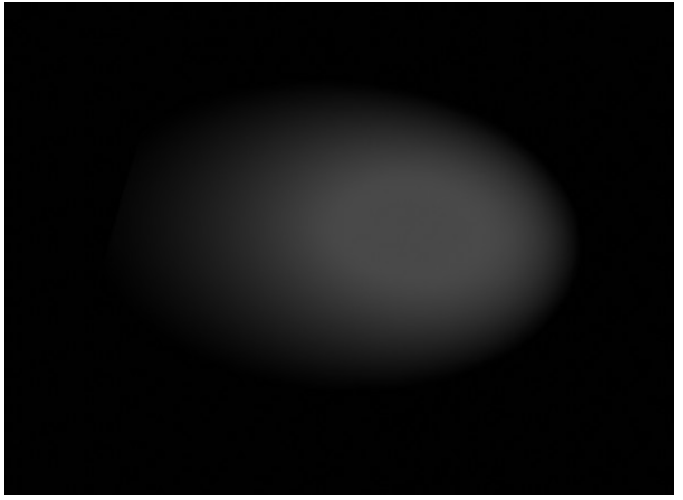




https://docs.blender.org/manual/en/latest/render/lights/light_objec

Non-physical lights recap

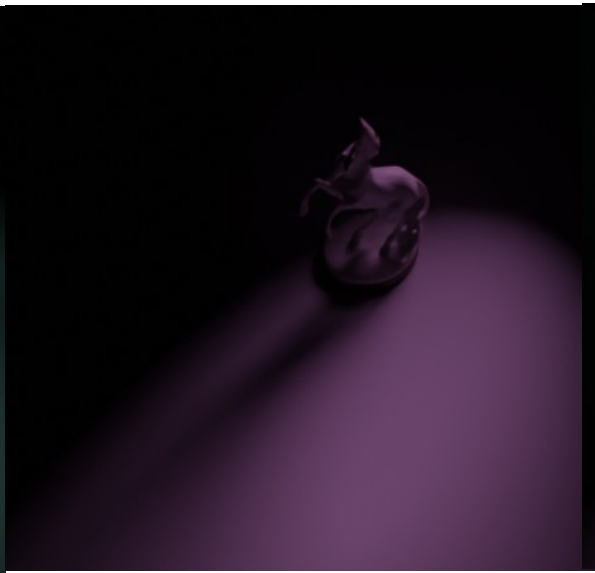
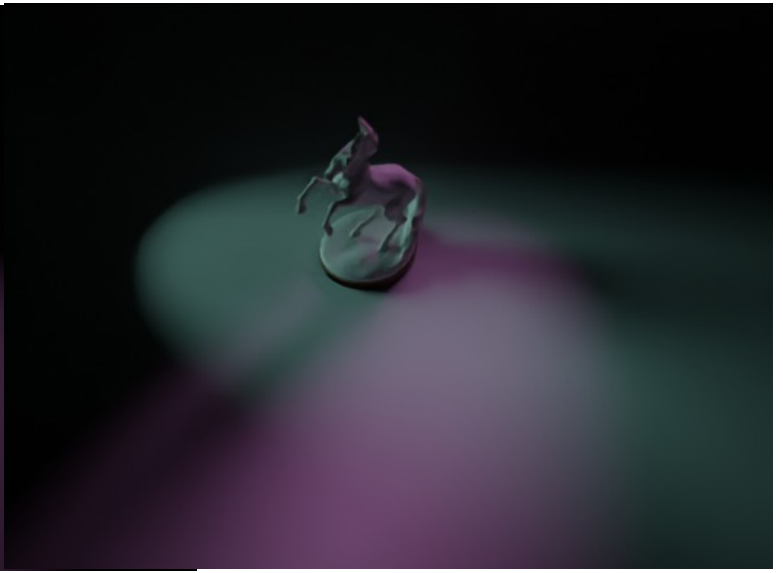
- Directional, point, spot light

Multiple lights

- Contribution of light adds up linearly
  - Required for photorealistic rendering where scene contains multiple lights
  - Required for Compositing rendered images: adding multiple rendered images where each has contribution from one light

$$L_o(p,v) = \int_{l \in \omega} f(l,n,v) L_i(p,l)(n \cdot l) dl \qquad L_o(p,v) = \sum_{i=1}^{n} f(l_i,n,v) c_{light_i}(n \cdot l_i)$$

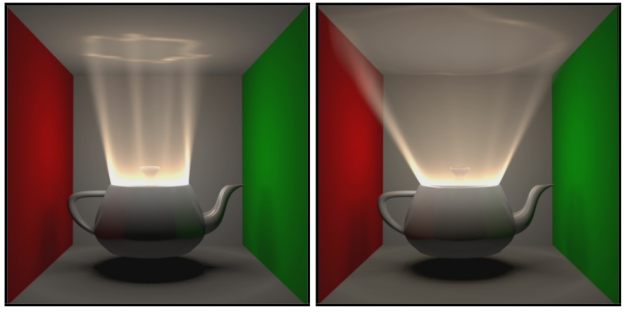




Other distance and directional light falloff functions

- **Textured lights**
  - **Use of texture** for visual richness of light sources: intensity, color and directional/distance variations
  - For **cone-type lights**: projective textures (slide projector effect, gobo/cookie lights)
  - For **omni-directional-type lights**: texture for distance falloff – attenuation maps (e.g., light beams)

$$L_i = (\text{light intensity} * \text{light color}) f_{distance}(r) f_{direction}(l)$$

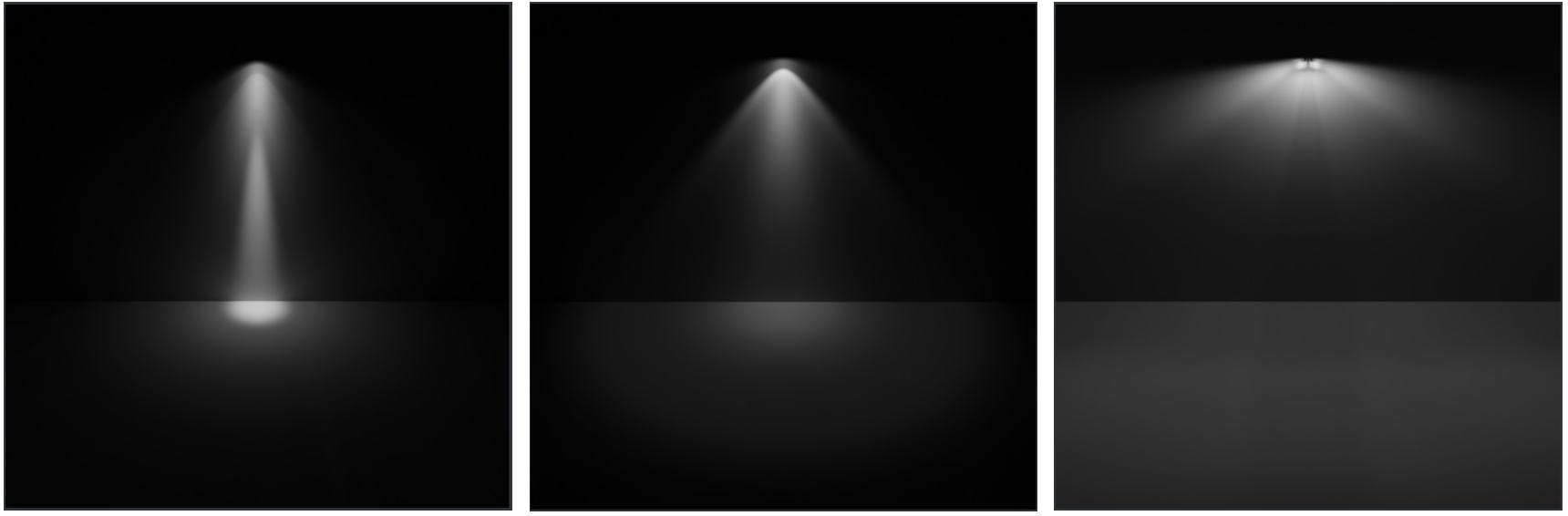
https://developer.valvesoftware.com/wiki/Env_projectedtexture



https://www.researchgate.net/publication/220183756_A_Programmable_System_for_Artistic_Volumetric_Lighting

Other distance and directional light falloff functions

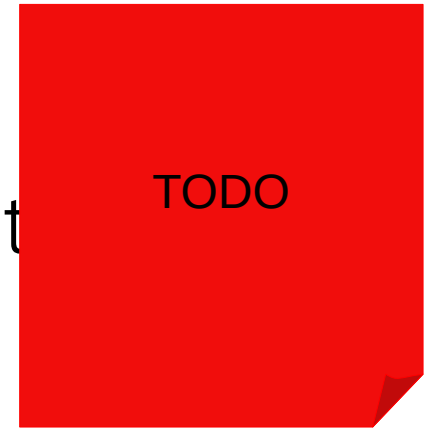
- **Tabulated patterns**
  - Standard: (illuminating engineering society) **IES profiles**
  - Measured from the real world using: Goniophotometer



IES profiles: https://ieslibrary.com/en/home

Practical tip: modeling with lights

- Non-physical lights can be placed to simulat illumination
  - TODO



Practical tip: modeling with lights

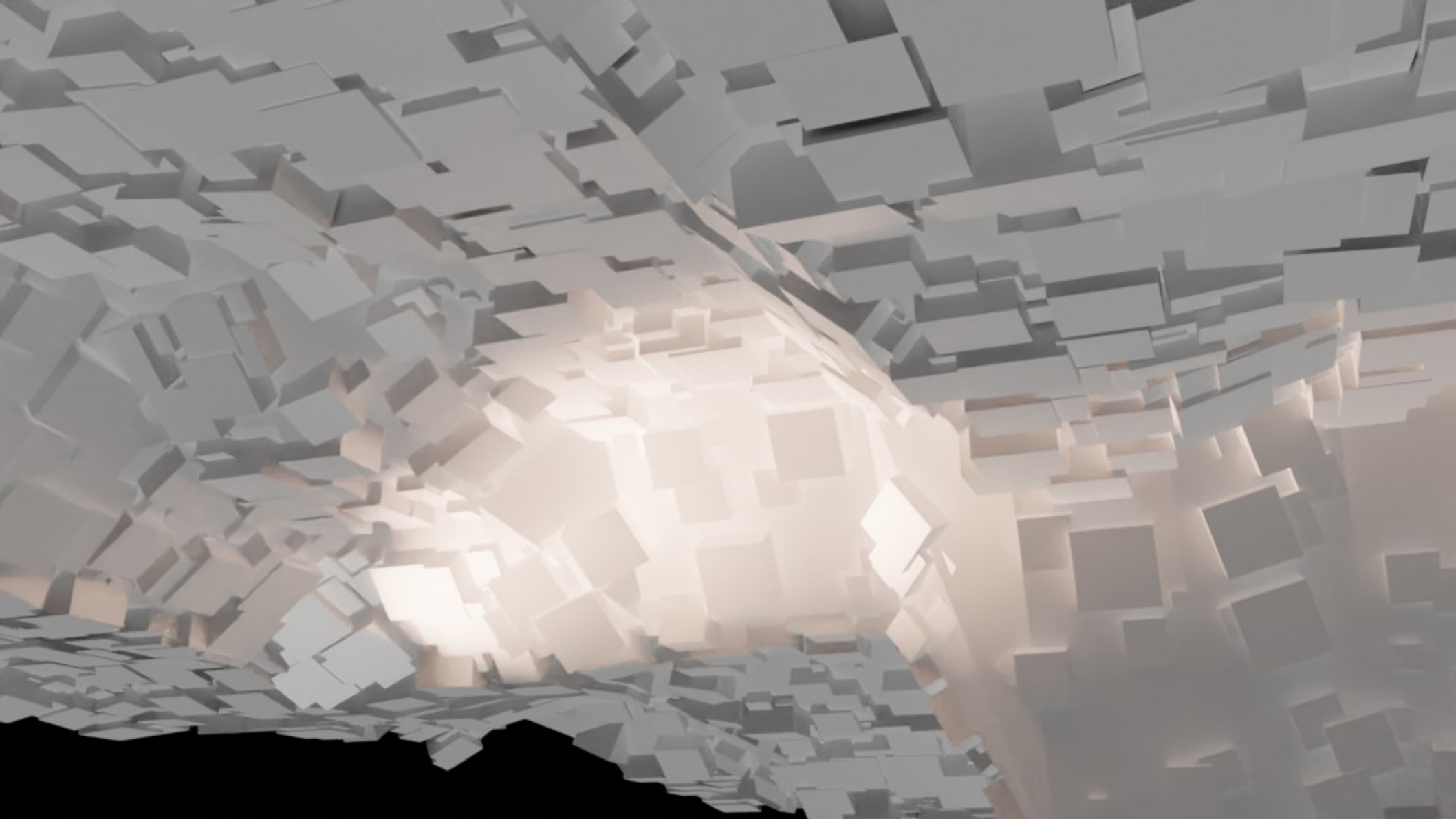
- Placement and orientation of light greatly determines object appearance

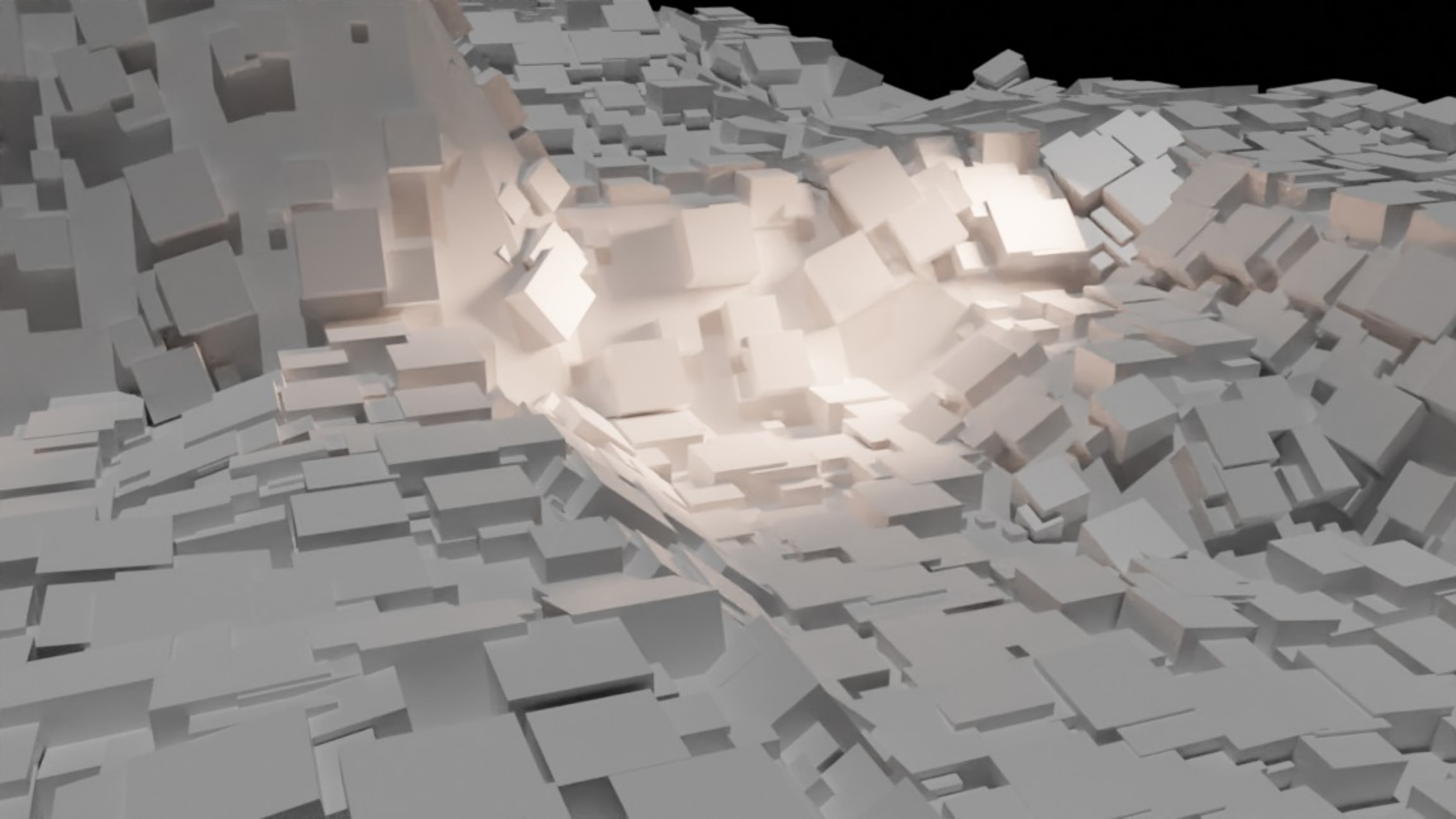
https://www.youtube.com/watch?v=Ys4793edotw&t=1s&ab_channel=BlenderGuru

More into light

- Lighting Artstation: https://www.artstation.com/channels/lighting
- Lighting artist: https://80.lv/articles/amazing-lighting-for-simple-scenes/
- Lighting for artists: https://www.youtube.com/watch?v=Ys4793edotw&ab_channel=BlenderGuru

Shadows





Light and shadow

- Light falling on object causes object to cast shadow – blocking light to fall on another surface
  - Occluders: objects casting shadow
  - Recievers: objects on which the shadow is cast
- Shadows are important for:
  - Understanding relation of objects to one another
  - Realistic image synthesis: needed for understanding details and surface characteristics

https://creativecoding.soe.ucsc.edu/courses/cs488/reportsA/shadows.pdf

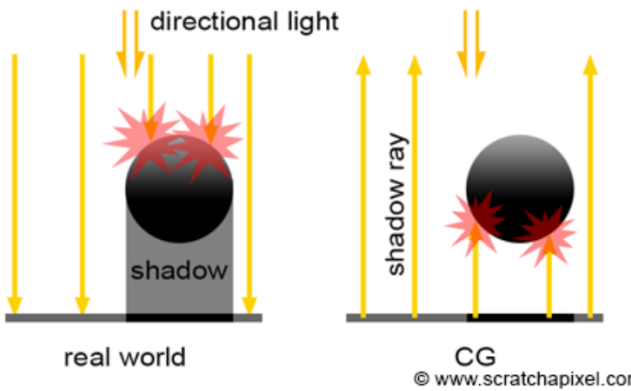
https://lumion.com/blog/feature-spotlight-sky-light-soft-shadows-and.html

Rendering and shadow

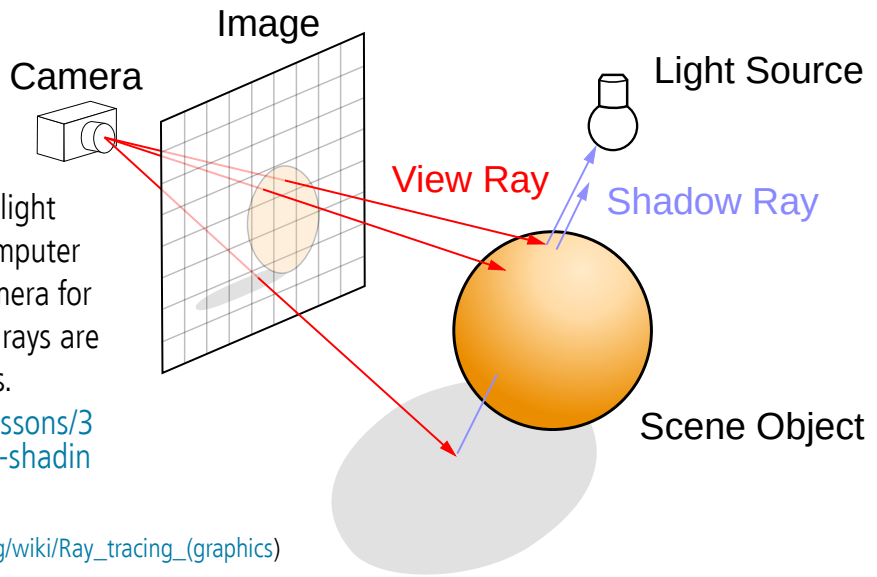
- Simulating shadow depends on rendering algorithm
  - Specifically: algorithm for solving the visibility problem
- In **ray-tracing based rendering**, shadows can be calculated during the main image is being rendered
- In **rasterization-based rendering** multi-pass rendering is required. Example:
  - One pass is needed to obtain visibility of objects looking from the position of light – **shadow map –** for each light in 3D scene
  - Shadow map is used in final pass which renders final image

Shadow in ray-tracing

- For surface point for which color is being calculated (shading), ray is casted towards light source – **shadow ray**
  - If shadow ray intersects object on its way, then shaded surface point is in shadow
  - If object is opaque, shadow is dark
  - If object is transparent, shadow is lighter



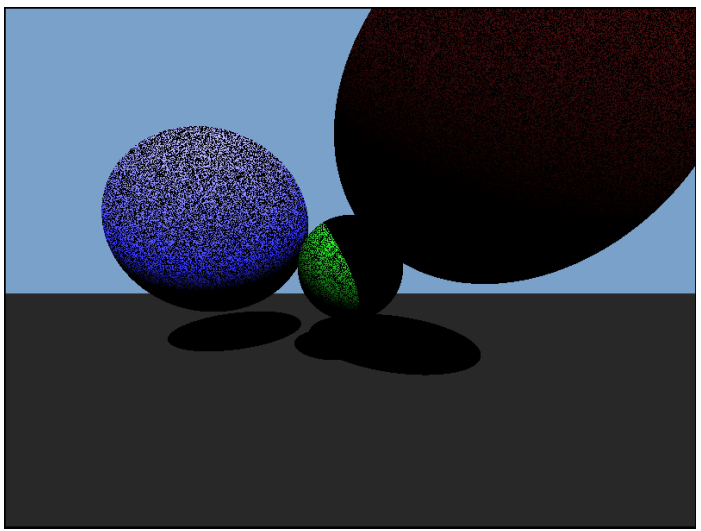
In real world, shadow is result of light being obstructed by object. In computer graphics, rays are traced from camera for intersections and then additional rays are sent to check if shadowing occurs.
https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-to-shading/ligth-and-shadows

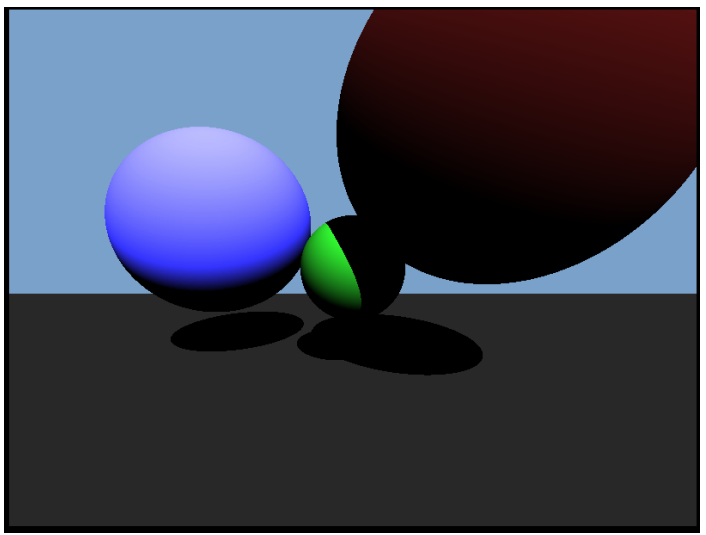


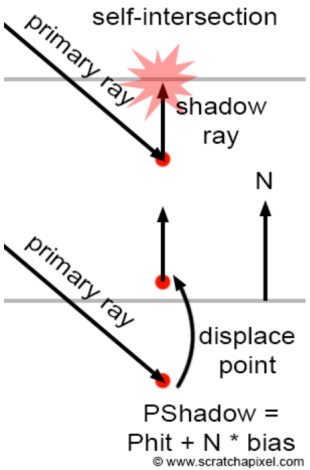
https://en.wikipedia.org/wiki/Ray_tracing_(graphics)

Shadow in ray-tracing: shadow acne

- Due to numerical limits in precision, intersection point might end up under the surface
  - Casting shadow ray from this point causes intersection and thus light obstruction
  - When surface is rendered, some points are light and some are dark → shadow acne
  - Solutions:
    - Use double float precision
    - Add small displacement to intersection point in direction of normal: **shadow bias** parameter





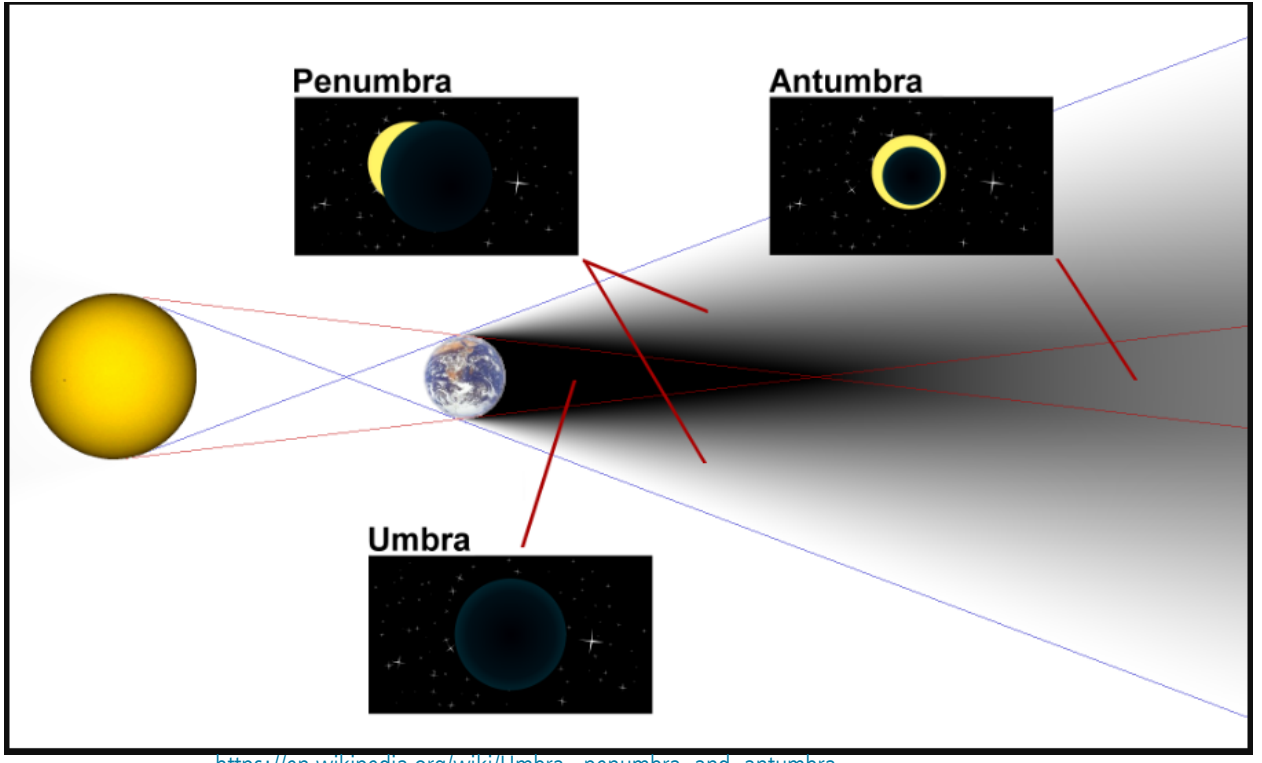


https://www.scratchapixel.com/lessons/3d-basic-rendering/introduction-to-shading/ligth-and-shadows

https://bheisler.github.io/post/writing-raytracer-in-rust-part-2/

Elements of a shadow

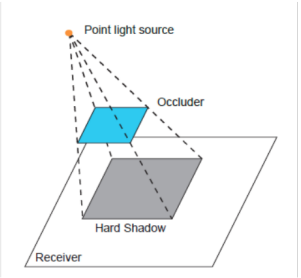
- Penumbra
  - Partially shadowed region
- Umbra
  - Fully shadowed region

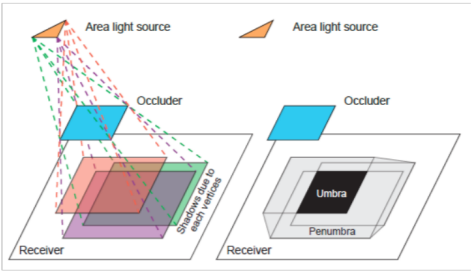


https://en.wikipedia.org/wiki/Umbra,_penumbra_and_antumbra

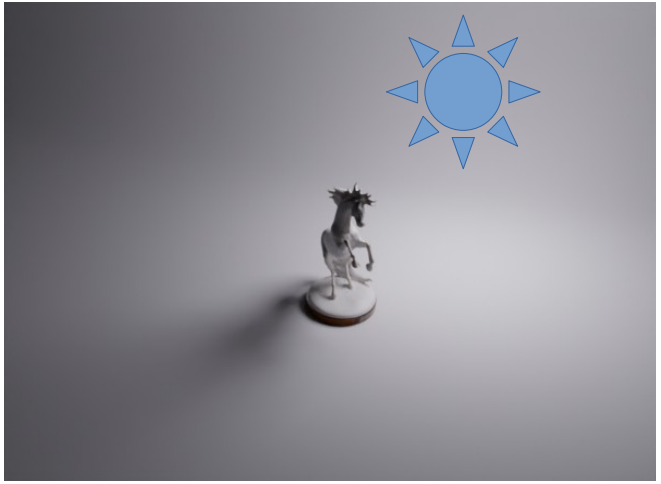
Sharp vs smooth shadows

- Size of light determines shadow smoothness
  - Softer shadow edges are more realistic, but more expensive to render
  - Small light sources (e.g., point lights) → hard shadows; only umbra componer
  - Large light sources (e.g, physical lights) → soft shadows; both umbra and penumbra component

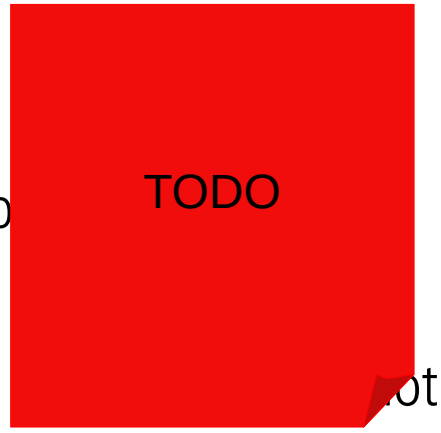




https://creativecoding.soe.ucsc.edu/courses/cs488/reportsA/shadows.pdf



Light and Shadow: Tips and Tricks



- Non-physical light sources as well as shadows they cause can b
  efficiently
- For real-time rendering, full physically based simulation of light ot
  be feasible
- When creating 3D scene, (environment) artists understand the how the scene should be illuminated given some main sources of light. Using this knowledge they place non-physical light to fake actual light flow through the scene
- https://80.lv/articles/dishonored-interiors-lighting-props/

To remember

- Light and color
  - PSD
  - Colorspaces (XYZ, RGB) and gamut
  - Rendering with RGB
- Light model
  - Geometric optics
  - Directional, points and spot lights
- Shadow
  - Rasterization vs raytracing
  - Shadow elements

Literature

- https://github.com/lorentzo/IntroductionToComputerGraphics/wiki/Foundations-of-3D-scene-modeling