Light

Light makes it right

Light frequency and color

- Light is electromagnetic radiation visible by eye
  - Wavelenght: 400 – 700 nm.
  - Different wavelengths (frequencies) are perceived as **color** - color is **perceptual (psychophysical)** phenomena rather than **physical** one.
- Light can be described both on:
  - Microscopic scale: wave optics
  - Macroscopic scale: **geometric optics**
- Light is measured both using:
  - **Radiometry** – measurement of radiation, physical transmission of light
  - **Photometry** – measurement related to human visual system
    - Summary measures: computed from radiometic quantities.
  - **Colorimetry** – Color perception

Light: microscopic level

- Light is quantized – it comes in individual and indivisible packets called **photons**
- At same time light is **wavelike** – radiometric radiation with frequency
  - Light on microscopic level explains color and perception of light <spectrum image>
- Microscopic level is important to mentions since some effects of light-matter interaction can be only explained (and thus modeled*) using **wave optics**:
  - Interference
  - polarization
  - Diffraction
  - Iridescence
  - Pleochroism and birefringent
  - examples
- Also, knowing microscopic background often helps in getting intuition for some shading and light transport methods**

* 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.
  - If features with which light interacts are relative to light wavelength (or larger) then light can be represented using **geometric optics**.
- **Energy** that flows uninterrupted through empty space in **straight line**.
- It **absorbs** and **reflects** from surfaces it meets.

Light interaction with medium

- Light passing from one to another medium changes speed. In geometric optics this phenomena is well represented using **Index of refraction**.
- **Index of refraction*** is characteristics of medium which states the ratio of speed of light in vacuum to the speed of light in that medium
  - This parameter is approximating microscopic level of light behavior – its interaction with medium
- Difference in refractive index in different media causes light rays to be **bend**
  - **Snell's law** – angle of reflection and refraction example
  - Important for physically based rendering of transparent objects. Important information for light transport since it determines angle of refraction/reflection on optically flat interface. <example>
- Amount of reflected and refracted light is calculated using **Fresnel equations**.
  - TODO

* IOR is dependent on light wavelength. Therefore, light of different wavelengths gets bent by different amounts. This can be seen by white light passing through prism creating rainbow. Also, this causes chromatic aberration – effect of camera lenses.

Radiometry

- Measurement of electromagnetic radiation
- Radiometric quantities:
  - Energy
  - Power – energy over time
  - Power density over area or direction

Radiometric quantities

- **Radiant flux** – flow of radiant **energy over time** (W)
- **Irradiance** – density of radiant **flux over area (Wm^{-2})**
- **Digression: Solid angle**
  - 3D extension of the concept of an angle: continous set of directions in 3D space measured in steradians (sr)
  - Example: 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
- **Radiance** – electromagnetic radiation in single ray. 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

- **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
  - TODO

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

Radiance and wavelengths

- 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. <example>
- 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 in account.
- Radiometric quantities are converted to photometric by using CIE photometric curve.
  - TODO

Colorimetry

- Relationship between SPD and perception of color
- RGB
- TODO

Recap: Light color and intensity

- We have seen that light has physical but also perceptual properties
- Photometry deals with human perception of light - perceived **color** is due to frequency/wavelenth.
- Discussion on radiometry was needed to understand light **intensity** – proxy for radiance
- Color and intensity are two main parameters of light that we need for modeling.

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

Foundations of light modeling

- Reminder: when we discussed the material of 3D models, we mentioned **shading process** which uses material information and light information to calculate appearance of the object surface.
- **Light is emitted from a light source**, bounces around the scene, interacting with object and some (very small!) portion enters eye or camera enabling us to see objects in the scene
  - Interaction with objects is described with material model, that is **scattering model**.
  - Without light in a 3D scene (or real world) we wouldn’t see anything. Resulting image would be completely black.
- If multiple light sources are present, they add up linearly
- Light sources define position and distribution of light
  - Light sources have **size**, **shape**, **color** and **intensity**.

Light models

- Discussion before showed that lights have shape, size and certain light distribution.
- Representation and modeling of light physically: with shape and size is very computationally expensive. Such lights are called **geometric area light or physical lights***
  - 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
- Simplification are lights with no physical size, thus called **delta or non-physical lights**
  - enable us to control light fall-off with distance, which objects are illuminated, which objects cast shadows and so on.

* 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 and shading

Light and shading

- Light information is used in shading: rendering step in which color of the object is calculated:
  - Shaded_color = color_unlit(n,v) + sum(color_light * color_lit(l,n,v))
- For simple shading models, only direction of light is enough to compute the color
  - <example>
- Direct illumination considers only light coming from light sources
  - Parameters: distance from light source, shadows, facing of surface towards light source
- Advanced rendering takes in account direct and indirect light
  - Surfaces which reflect light
  - TODO

Light and shading

- Effect of light on surface can be visualized as rays with the density of rays hitting the surface corresponding 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
  - Shaded_color = color_unlit(n,v) + sum((dot(l,m))color_light * color_lit(l,n,v))*
  - <image>

* color_lit() is actually BRDF. If it is a constant color, then this corresponds to Lambertian shading – surface is perfectly matte.

Recap: Light parameters

- **Color**
- **Intensity**
- **Direction**
- **Position**
- Shape
- Size

Light intensity and color

- For each light source (physical or non-physical) next to shape, size, position and direction we need to define:
  - Intensity – float value in [0, inf]
  - Color – RGB value in [0,1]

Physical lights

Physical lights

- Geometry with emissive material: shape and size
- TODO:
  - Examples
  - Hint that it will be discussed later

Non-physical lights

Non-Physical lights

- Directional (distant) lights
- Point (spherical, omnidirectional) lights
- 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 lights are also called distance because they are considered so far from the objects in a 3D scene that they can be represented by parallel rays. As such, we only care of the direction of those parallel rays.
  - Best 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.
  - 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.

<IMAGE: EXAMPLE OF DISTANT LIGHT>

Directional lights

- Direction light is simplest model of light source
  - No location, only direction
  - Direction (l), color (c) and intensity (I) are constant over 3D scene
    - light_color = light_color0
  - Intensity may be attenuated by shadowing

<IMAGE: EXAMPLE OF DIRECTIONAL LIGHT VECTORS IN THE SCENE>

Point lights

- Most common light sources in nature and around us are spherical (e.g., light bulbs or candle flame) or can be approximated as a collection of spherical light sources.
- As opposed to directional lights:
  - Point light **position** is important parameter, it is considered **infinitesimally small in size thus no shape**
  - **Light is emitted in all directions** (omnidirectional, isotropic) therefore, no “direction” parameter
- Point light position determines:
  - **Direction of incoming light** ray for each surface position for each object in the scene
  - **Distance** to the each surface position for each object in the scene – **light falloff**
    - example

Point lights: light direction and falloff

- Point lights emit radially
- **Direction and distance of point light** to point on the surface is obtained by tracing ray between these two points.
- Distance of point light to each point of surface of each object in the scene defined how much is that point illuminated – **intensity of light varies as a function of distance**.
- Energy emitted from point light is distributed across the space as 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. <INVERSE SQUARE LAW FORMULA>

<IMAGE OF POINT LIGHT, ILLUMINATED OBJECTS, SOLID ANGLE>

Inverse square light attenuation

- color_light(r) = color_light0 * (r0 / r)^2
  - Note the light falloff function can be any other function of distance; for stylized appearance different functions may be more interesting.
- Problems:
  - Small distances: as r goes to 0, light intensity increases to infinity
    - color_light(r) = color_light0 * (r0 / r + 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

Point lights: directional light falloff

- Illumination intensity from real-world also **varies by direction**
  - Generally, different directional light falloffs: color_light = color_light0 * f_dist(r) * f_dir(r)
- Different choices of directional light falloff functions produce various light sources:
  - **Spotlights** - emit light in a cone of directions from their position

Spotlights

- Projects light in circular cone.
  - <image>
- Parameters:
  - Angle of cone
  - Angle of umbra
  - Angle of penumbra
  - <image>
- Directional falloff function
  - example

Other directional light falloff functions

- Different types of directional variation of light intensity exist
  - **IES profiles:** tabulated patterns measured from the real world
    - example
  - **Textured lights**
    - example
  - **Goniophotometric diagram** describes the angular distribution of luminance from a point light source; it is widely used in illumination engineering to characterize lights
    - example

Shadows

Light and shadow

- Light falling on object causes object to cast shadow – blocking light to fall on another surface

<IMAGE WITH AND WITHOUT SHADOW>

- Shadows are important for:
  - Understanding relation of objects to one another
  - Realistic image synthesis
- Simulating shadow depends on rendering algorithm (more specifically, algorithm for solving the visibility problem)
  - As we will see, in rasterization-based rendering shadows will not be inherently present. Advanced, multi-pass rendering is required to obtain visibility of objects looking from the position of light. This way, shadow map is generated and used for rendering.
  - In ray-tracing based rendering, shadows are inherently present due to way incoming light on surface is calculated

Intuition: calculating light and shadow

- How to know if point of surface will be under shadow or not?
- Generate ray from that point in light direction and if no intersections are found, shadow won’t be present.
  - For point lights, we need to take in the account their maximum influence!
  - Shadow-acne problem → Later!

Sharp vs smooth shadows

- Size of light determines smoothness of shadows

Light and Shadow: Tips and Tricks

- Non-physical light sources as well as shadows they cause can be simulated efficiently
- For real-time rendering, full physically based simulation of light transport might not 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/

Literature

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