3D Models

3D models: shape and material

Looking at real world phenomena, we can say that in order to create objects in a 3D scene, we need a way of representing:

- Shape, size, relative position in the space and to other shapes
- Appearance

<IMAGE: shape vs material intuition>

Therefore, we can conclude that representing 3D models requires:

- Representation of **shape** - geometry
- Representation of **material** – appearance

Appearance of 3D object

Material representation

Foundations of materials: observation of world around us

- Modeling materials begins with observation to understand what makes each material look different than other materials
- We don’t want to observe just appearance (like artists do). We want to observe characteristics which are responsible for object appearance:
  - Shape
  - Illumination
  - Sensor/Perception
  - **Material**
- **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
  - Directional
  - Spatial

<BOOK: DIGITAL MODELING OF MATERIAL APPERANCE (J. DORSEY)>

Foundations of materials: physics

- Material defines **interaction of light with objects**
  - Light is electromagnetic wave (visible part of spectrum). In computer graphics we work with **geometrical optics** which is approximation and light is represented using **rays**.
- Light falling on objects, based on **index of refraction** will*:
  - **Absorb**
  - **Scatter**
- **Homogeneous material:** light travels on a straight line, it can only be absorbed, meaning that direction is same, but intensity might be lower.
  - In **transparent material** (e.g. glass or water) light propagates in straight line – no scattering (scattering happens on interface – boundary between materials). Also, low absorption of light.
  - Homogeneous material with higher absorption will attenuate light traveling through it or completely absorb it if distance is large – but the direction will not change! An example is water over larger distances.
  - Note that also light can be selectively absorbed, meaning that it changes color (alongside intensity).
- **Heterogeneous material**: light is scattered → direction of light is changed but not necessary the intensity
  - Light can scatter in all directions, mostly non-uniformly: forward or back scattering
  - **Translucent** or **opaque materials** are examples of heterogeneous materials → light is scattered so much that we can not see (clearly) through the object
  - Longer distances cause more scattering, but not necessary more absorption (e.g., clean air)

<IMAGES OF REAL WORLD OBJECT SHOWING THOSE CHARACTERISTICS>

* Light interaction with matter (on geometrical optics) is determined by index of refraction – complex number. Real part determines speed of light, imaginary part determines absorption.Constant index of refraction is present in homogeneous materials where index of refraction is constant. For such materials, only absorption happens. Varying index of refraction is present in heterogeneous materials causing scattering (next to absorption).

Foundations of materials: reflection on optically flat surfaces

- Light interaction with matter can be described with Maxwell’s equations. Those are too heavy for computer graphics thus we work with (1) geometrical optics approximations and (2) special case which is can be simplified and used in graphics for material modeling.
- Perfectly planar (optically flat, perfectly smooth) surface* between two homogeneous materials with different index of refraction is starting point for describing the behavior of light interaction with surface. This special case is described with Fresnel's equations:
  - Light falling on such surface can: reflect and refract
  - Amount and directions of light depend on index of refraction

<IMAGE: REFLECTION AND REFRACTION>

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

Foundations of materials: reflection general surfaces

- 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)

<IMAGE: variation of facets and roughness>

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

<IMAGES: REFLECTION ON METAL AND DIELECTRIC SURFACES>

<IMAGES: real world objects with such properties>

<IMAGE: reflection from metal and dielectric surface: not the color of reflection!>s

* 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.

Notes on material

- In graphics material is used to describe light-matter interaction. It is a model of a real-world. Note that “material” in graphics encapsulates bit more then just chemical property (which might be the common conception we have about term material) – in graphics it also defines small scale geometrical information that is simply too expensive to represent using actual geometry and shape.
- Based on previous discussion we can see that material can be decomposed and describes both:
  - Scale of geometrical information that is too small to represent explicitly by geometry/shape. Note that most important geometrical information in graphics is normal. For smaller scales, we will describe smaller surfaces thus smaller normals.
  - Substance information encapsulating information on absorption that is color and intensity which will be reflected

<IMAGE: SUBSTANCE OF GLASS AND SMALL SCALE GEOMETRICAL INFORMATION OF GLASS>

Surface material representations in 3D scene

- To simplify and understand modeling of 3D object, we separated 3D object in shape and material.
  - By material we mean characteristics of object independent of shape and position. For example, aluminum sphere and aluminum statue – in both cases aluminum properties are the same. Also, changing position of aluminum sphere in space doesn't change aluminum properties.
  - 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 and reuse this knowledge at other points.
  - Having same description of material for each point of the 3D object, we would end up with homogeneous material. 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.
- By Material modeling we describe how light should behave when it interacts with objects. For now we will limit our discussion to light interaction with surfaces, and leave light interaction with volume for later.
- Description of light interaction with surface, when considered locally, is called scattering. Once we have a scattering model, we can parameterize it and vary its properties over the surface.
- Shading step in rendering takes material information (alongside with viewing position, object shape and light information on the object) to calculate the object appearance → object color
- Based on discussion above, we can separate material in:
  - **Scattering** → description of light-matter interaction in a point
  - **Texture** → variation of scattering function properties across 3D object

Material: scattering function

- We already know that surface orientation (normal) is important shading information since it gives us fundamental information of object appearance – how much is lit.
- How light scatters when it falls on surface point is defined by **scattering function** which takes in account the normal in this point.
- Scattering function can be separated in reflection and refraction. For now we will focus on reflection. Such scattering function is generally called "bidirectional reflectance distribution function" – **BRDF**. Defining this function is fundamental and core part of shading process in rendering.

<IMAGE OF BRDF AND ITS ELEMENTS>

Note: two faces of BRDF

- BRDF has the name "bidirectional". This means that given given incoming and outgoing direction, we can compute **amount of reflected light** in outgoing direction.
- Incoming and outgoing directions can be viewed in two ways:
  - If light is falling on the surface, what is the distribution of **reflected light directions** (lobe of directions) – this information is particularly useful for ray-tracing (light transport element) as we will see later.
  - If we are looking at the surface from particular direction, how much light will be reflected in this direciton.

<IMAGES: 2 WAYS HOW BRDF CAN BE VIEWED>

<FIND THE BOOK DISCUSSING THIS!>

Types of scattering

- **Reflective** – all light is scattered above surface
- **Transmissive** – all light is scattered below surface
  - Refractive – special case of transmissive
- **Mirror-like** (specular) – 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
- **Glossy** – scattered light is concentrated around particular direction (lobe). Appears blurred. Dependent of viewing direction.
- **Diffuse** – light is scattered in all possible directions. Independent of viewing direction. Equally bright from all directions.
- **Retro-reflective** – scattered light is particularly large when viewing and light directions are close

TODO: IMAGES OF NORMAL AND LIGHT REFLECTION TYPES WITH REAL WORLD IMAGES

TODO: BLENDER EXAMPLE OF BASIC SCATTERING FUNCTIONS

Scattering models

- 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.

Basis and scattering function

- On the different scattering types we have seen that they always require normal around which scattering is computed
- Normal defines so called **basis**
- Note that perturbing the bases can be constructed using geometrical (object shape) normal. So what would happen if we would somehow vary this normal across smooth shape which has constant geometrical normal? More on this will come when we introduce textures!

Empirical models

- Discuss the way of modeling: by observation, phenomenological approach
- Discuss importance of normal, light position and viewing position.
- Mirror: TODO
- Lambertian: TODO
- Phong and Blinn-Phong: TODO
- Discuss parameters

Data-based models

- Discuss measurements need for those models

Physically-based models

- Highlight importance of normal on different scales
- Reflectance model is half substance information half meso and micro geometry information!
- Microfacets*

* just announce, details in “More on 3D scene modeling”

Scattering model parameters

- Discussed models are parameterized
- Parameters can be mainly decomposed in geometrical and substance
- Geometrical: roughness, basis normal
- Substance: color

<IMAGE: variation of scattering parameters>

Variation of material over surface

- Real objects rarely have only one material or material with same properties in each point.
  - Let's consider wood. Wood has structural texture (e.g., grain) at a scale of about 1mm. Also it has cellular texture at lower scale. The material of wood fiber is different. Therefore, the rich appearance of wood comes from material variation of fibers. This richness is called texture.
- By now, we have seen homogeneous description of material using scattering functions. And objects looks too perfect (too smooth and artificial).
- In order to obtain variation of material across surface (spatial variation) we can vary scattering functions or its properties over it. One material parameter is color. In graphics, we use **texture function** to vary material properties over surface.

<IMAGES OF HOMOGENEOUS MATERIAL AND MATERIAL WITH VARIATION>

<EXAMPLE IN BLENDER WITH AND WITHOUT TEXTURES>

Texture and texture function

- Term texture is used in various disciplines and everyday life: texture of fabric, texture of food, texture in music, texture in image processing, texture in...
- Texture doesn't have well established definition. It means differently in different disciplines. It spans over multiple scales and over space. But, for our purposes of 3D modeling, we can try to define it as variation of material properties over surface. Therefore, a texture is something that we can completely define and model.
- Texture model is used alongside scattering model during shading rendering step to calculate color of surface in each point. Looking in the rendered image, we will perceive texture on the surface.
  - Note that color of texture in most cases (especially in physically based rendering) is not one on one in the rendered image. Texture merely defines properties of scattering function which is used in rendering process.
  - Note the difference in texture function and texture. Texture is generally overloaded term and it is furthermore overloaded in computer graphics as we will see.

<IMAGE: IMAGE TEXTURE AND RENDERED OBJECT WITH TEXTURE>

Values varied by texture

- Texture varies parameters of scattering models
- It is also important to note that texture is used to vary meso-scale geometrical information which is used for evaluating scattering models.

Texture modeling and texture application

- When we talk about textures in computer graphics, we can separate the work in creating/modeling a texture and applying it. Often, line between these two is blurred.
- Reminder: we said that material modeling (which includes texture) can be performed separately of modeling 3D shape.
  - Creation of texture is often separated of modeling 3D shape and it is done in so called “texture space”.
  - Texture application is process where we “apply” texture on a 3D shape. That is, map it from texture to object space.
- Texture modeling can be described as process of developing a function which maps some property to each point of the surface. Texture modeling can be separated into:
  - Creating image textures
  - Creating procedural textures
- Texture application can be described as a process of adding actual texture on the object.
  - Often, term texture mapping is used. This term is due to historical reasons where details were painted on 3D model and those details were stored in array of images called textures. The process of corresponding each vertex of model to a location in image was called mapping.
  - Main task in texture application is to find mapping between texture and object space.
- Texture, simply speaking, contains information about surface details. It can be color (albedo), normals, roughness, etc.

Image textures

- Texture information can be created in form of images:
  - Drawing images
  - Taking photographs
- Once image textures are created, we need to map them on the 3D object:
  - UV parametrization of 3D object
    - Assign texture coordinates to vertices of 3D object
    - Unfold/unwrap surface onto plane
    - Separate object into patches on which texture is applied
    - Paint texture directly on texture
  - Planar mapping
  - Cylindrical mapping
  - Spherical mapping

Examples of image textures

- Substance: https://substance3d.adobe.com/assets/allassets?assetType=substanceMaterial&assetType=substanceAtlas&assetType=substanceDecal
- PolyHaven: https://polyhaven.com/textures
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Procedural textures

- Procedural texturing is based on algorithm which defined values for each point of 3D space or object surface. Examples:
  - Fourier-like synthesis
  - Perlin noise
  - Reaction-diffusion

<IMAGES: PROCEDURAL TEXTURING>

<IMAGES: NODE SYSTEM FOR PROCEDURAL TEXTURING>

Storing and transferring materials

- Similarly to mesh information, standards for material storage and transfer are defined
- Material standards:
  - MaterialX
- Certain formats that we mentioned for mesh storage are used for storing the whole scene including the material:
  - GLTF, USD

Literature

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