3D Models: Material

Recap: shape and material – 3D object

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

<IMAGE: shape vs material intuition – use polyhaven mesh with different materials: BRDFs and textures>

- – "Let the form of an object be what it may, - light, shade and perspective will always make it beatuiful" – John Constable
    - Mental picture to takeaway: how shape of na object and material can be considered separated.

Appearance of 3D object

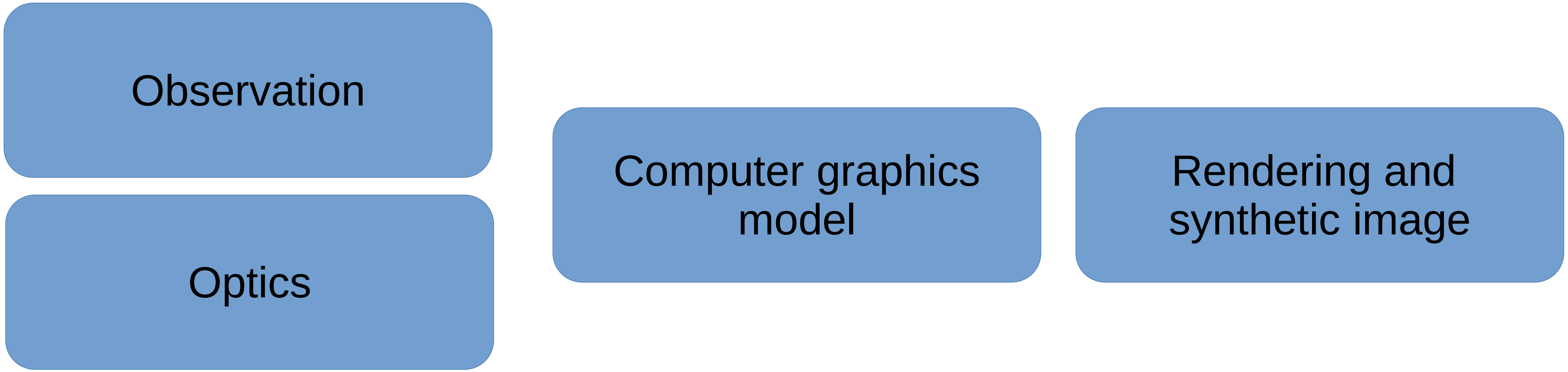
Material representation

Real-world phenomena

- Examples of various real-world objects that we would like to represent

Prior appearance modeling

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



Observation

Optics

Computer graphics model

Rendering and synthetic image

Understanding appearance

Observation

Observation

- 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**

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

- PDF COURSE: Digital modeling of the appearance of materials

<EXAMPLES: CHARACTERISTICS RESPONSIBLE FOR APPEARANCE>

Classifying materials

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

Examples of different materials

- TODO
- PDF COURSE: Digital modeling of the appearance of materials

Understanding appearance

Optics

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).

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.

Reflection on 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

Example: importance of texture

- Show objects with and without texture: texture is variation of scattering model parameters

Modeling appearance

Diversity of appearances

- Appearance of models, depending on application, can range from photorealism to various types of stylized appearance.
  - <examples>
- Focus: realistic image synthesis, then stylized.

Materials and shading

- Appearance of object highly depends on material description but also on shading method, a rendering step in which material information is used to calculate color of the object.
  - <comparison>

Elements of material model

- Scattering function
- Texture
- Material model is implemented in shading stage of rendering
- Final color of surface is calculated by:
  - summing all incoming light that falls onto surface – light transpot
  - Calculating color and intensity of light reflected into camera using material description - shading

Scattering models

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.
  - Defining this function is fundamental and core part of shading process in rendering.
- Scattering function can be separated in reflection and refraction (transmission).
  - Model describing reflection is called "bidirectional reflectance distribution function" – **BRDF**.
  - Model describing transmission is called "bidirectional transmission distribution function" – **BTDF**.

<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! Advanced global illumination book?>

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: practical tip

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

Basis and scattering function

- Scattering is defined for surface point and requires normal around which scattering is computed
- Normal defines so called **basis**
  - <IMAGE>
- 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!

Scattering models

- Main types are:
  - Empirical
  - Data-based
  - Physical-based

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

- Scattering models are parameterized.
- Parameters can be mainly decomposed in geometrical and substance
  - Geometrical: roughness, basis normal
  - Substance: color
- Uniform parameters result in overly smooth and perfect surface – not realistic.
- Variation of parameters is done using **texturing**

<IMAGE: variation of scattering parameters>

Scattering and shading: a note

- Scattering model is implemented in shading step in rendering for calculating color of the object
- Shading model takes name of scattering model
  - If Lambertian scattering model is implemented than shading is called Lamberitan shading.

Exploring BSDFs

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

More into topic

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

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

Texture

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>

<EXAMPLES:> https://www.realtimerendering.com/#texture

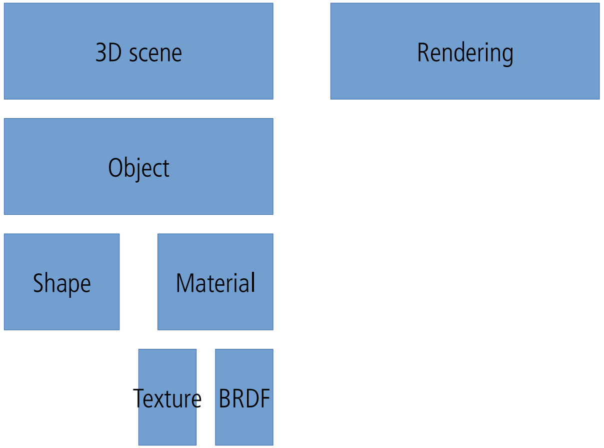
Texture and texture function

- 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>

Texturing: practical example

- Surface texture is its look and feel
  - Bark of a tree, surface of stones, oil painting, etc.
  - <IMAGE>
- In computer graphics, texturing is process that takes surface* and modifies its appearance at each location using image, function or other data source.
  - <IMAGE FOR INTUITION>
    - Texture is property of object
    - During rendering texture is obtained for each point of object



* Or volume. For example, variation of gas density can be defined using texture.

Texturing: practical example

- Texture is often used to add more details* to the surface.
  - <example>
    - Tree trunk: (1) model shape using cylinder, (2) add color image to add variation (3) add roughness to vary reflection (4) add normal map to break flatness (5) add displacement map to break illusion of normal map

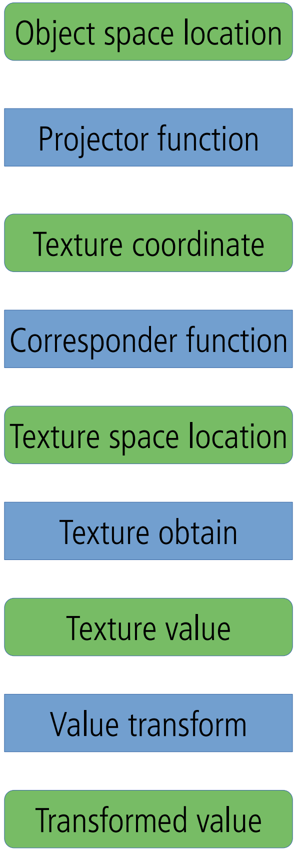
* Remember that computer graphics is all about simulation and approximation in order to achieve required appearance. It is a trade-off between quality and speed. Depending on viewing distance and size of objects in 3D scene, some details can be represented with lower quality. For example, modeling all details on geometrical (shape) level can be very expensive. Thus, texturing come in which represent cheaper way to model details

Texturing: variation

- In previous examples we have seen problems that are solved with textures:
  - Color variation
  - Roughness variation
  - Shading normal variation
  - Geometry variation
- Note that those are exactly parameters of scattering models!
  - Some of those describe variation on small scale: **microscale**
  - Some of those describe variation on bigger scale: **mesoscale**
  - **Macroscale** is given by the object shape.
- Different algorithms solving those problems with varying complexity (and thus quality) exists.

Texturing pipeline*

- Texturing: variation of scattering/shading** parameters over surface – **position dependent**
- **Location in space of object surface/volume**
  - Often, **object-space locations** are used so that is object moves, texture stays the same
- **Projection function.**
  - This function maps location in object space into location in texture space → **texture coordinates**
  - This process is called mapping and thus texture mapping (and sometimes texture image is called texture map which is not strictly correct)
- **Corresponder function**
  - Transform texture coordinates in **texture space location**s
  - For image texture, this might be indices to retrieve pixel values
  - For procedural texture, this might be domain of procedural function
- **Obtaining texture values (sampling)**
  - Texture space location is used for reading image texture or evaluating procedural texture
- **Value transform**
  - If needed additional transformations are done on value that is obtained from texture
- **Usage**
  - Final value is used to modify property of surface at that point: scattering function parameter or normal.



Object space location

Projector function

Texture coordinate

Corresponder function

Texture space location

Texture obtain

Texture value

Value transform

Transformed value

* Note that all steps do not have to be used in different applications!

** Value of texture is used for shading to obtain the final color

Texturing pipeline: example

- Wooden floor
  - During rendering, **object position** (x,y,z) on wooden floor is found
  - **Projector function** finds mapping from (x,y,z) to (u,v). In this case simple projection can be used: u~=x, v~=y so that u,v are in [0,1] – texture coordinates
  - **Corresponder function** uses texture coordinates for finding corresponding pixel in the image of wooden floor. If image has resolution 1024x1024 then pixel positions are integer of 1024*u, 1024*v
  - **Texture reading** is performed using texture space locations
  - Finally, color encoded in texture can not be directly used for rendering, **transformation on values** is done (e.g., sRBG → linear). Resulting values are used.
  - <ILLUSTRATE>

Projector function

- First step in texturing process:
  - Obtaining surface location (given by renderer)
  - Projecting surface location into texture coordinate space (often, but not always, 2D space (u,v)).
- Texture coordinates can be calculated:
  - On the fly during rendering or
  - During object modeling and stored per-vertex – Modeling packages allow artists to edit (u,v) coordinates.
- Many possible ways of obtaining texture coordinates exists:
  - Texture projections
  - Mesh unwrapping

Projector function: mesh unwrapping

- Objects are, often, surfaces in 3D space. Image texture lives in 2D space.
- Mesh unwrapping tries to “unwrap” 3D surface onto 2D space.
  - Analogy: world globe and world atlas
- Different methods exists. Unwrapping belongs to larger field called **mesh parametrization**
  - TODO
- <Example of mesh unwrapping>
- Modeling packages offer different methods for unwrapping and a way to manually enhance the results
  - Goal is that each polygon gets fair share of texture area (e.g., evade stretching) but mantaining connectivity – which determines where separate parts of texture meet and visible seams.
  - EXAMPLE

Projector function: texture projection

- The goal is to transform 3D point in space into texture coordinate*
- Commonly used methods in modeling programs are:
  - Spherical
  - Cylindrical
  - Planar
  - <EXAMPLES>
- For highly complex shapes, separating into simpler shapes can be done and then texture projection can be done separately.

<EXAMPLES>

- Spherical projection can be used in environment mapping
- Planar projection uses orthographic projection (usefor for, e.g., decals)

* Note that the goal is really to find texture coordinates and not to find a way of pasting a 2D image on 3D object. This is more general. Once texture coordinates are found, different types of textures can be used: image or procedural, etc.

Projector function: texture projection

- Often **surface normals** are used:
  - This enables **triplanar mapping** – which of six planar projection directions are used for projecting
  - For curved and tilted surfaces efficient **blending** of multiple projection planes must be used.
  - EXAMPLE

Projector function: different approaches

- Encapsulating object in volume of simpler shapes can make finding texture coordinates more tractable
  - Polycube maps
  - TODO
-
  -

Projector function: different approaches

- View direction can be used for defining projection
  - example
- If object is supplied with any kind of additional information (e.g., curvature or temperature) this can be used for texture coordinate generation
  - Main point is that texture coordinates must be generated in this step. Using position and normal for deriving those is only one way of doing it.

Projector function: inherent texture coordinates

- Parametric surfaces have natural set of (u,v) which defines any (x,y,z) point on surface
  - <EXAMPLE>

- In this case, we can say that surface representation already has inherent texture coordinates and projector function is not needed.

Projector function: different texture coordinates

- Texture coordinate space doesn’t have to be always 2D
- If texture is used for volumetric objects, then texture coordinates are (u,v,w)
- For animation, texture coordinates can be (u,v,w,t) where t is time and determines change in texture
- Furthermore, procedural texturing can directly rely on object locations – solid texturing.

Projector function: different texture coordinates

- Texture coordinate, next to positional, can also be directional
  - Each point in space is accessed by input direction
- Common type of using directional parametrization is **cube map**
- EXAMPLE

Projector function: multiple texture coordinates

- Multiple textures can be applied on objects and thus multiple sets of texture coordinates can be applied
- Idea is the same: those texture coordinates are interpolated across surface and used for obtaining texture value
- <example of multiple textures>

Corresponder function

- Convert texture coordinates to texture space locations
  - e.g., u,v to pixel index in image
- Corresponder functions:
  - Which part of sub-texture will be used
  - Transformations: rotate, scale, translate, shear or project
  - How image is applied if (u,v) is larger than 1 or smaller than 0: wrap, mirror, clamp, border, repeat, wang tiles, etc.
- TODO

Obtaining texture values

- Corresponder function gave texture space coordinates
- Those coordinates are used for:
  - Obtaining image texture values
  - Evaluating procedural textures values
- TODO

Transforming texture values

- Image textures contain RGB(A) values.
- Many data types can be stored/encoded using those values. Thus, although image textures always contain color values, those values can be interpreted differently then color.
- Therefore, values obtained from texture are optionally transformed to required datatype.
- <example: encoding vector in image texture>

Image textures

- Image texturing process can be seen as “gluing” image on 3D surface
- For particular position on surface we explained how to obtain texture coordinates. These coordinates are (u,v)
- Image textures are usually 2^m x 2^n texels. Thus called power-of-two textures (POT)*
- Texture image can be created:
  - By drawing
  - Taking photographs
  - Measurements
  - Baking

* Older GPUs couldn’t support mipmapping for non-POT textures. Modern GPUs handle all textures correctly.

Magnification and minification

- Example: smaller texture image (256x256) is used and projected on square. Number of texels may be different as number of pixels.
- If projected square on screen contains more pixels than original image then it comes to magnification. Texture system must magnify the texture. Magnification types:
  - Nearest neighbour: pixelization
  - Bilinear interpolation: blur
  - Cubic filtering
  - <examples>
- If several texels cover pixel cell, then cumulative effect of texels influencing the pixel must be taken in account.
  - Nearest neighbour: heavy aliasing and temporal aliasing (when camera is moving)
  - Bilinear interpolation: if pixel is covered by more than four texels then aliasing again becomes the problem
  - Problem of aliasing is solved using sampling and filtering techniques
  - <examples>

Anti-Aliasing: sampling and filtering

- Frequency of a texture depends how closely are spaced texels on the screen.
- Nyquist limit – texture frequency must be not larger than half the sample frequency. To properly display a texture on a screen, we need at least one texel per pixel:
  - Pixel sampling frequency must increase
  - Texture frequency must decrease

Anti-aliasing: mipmapping

- Most popular anti-aliasing method
- MIP – multum in parvo (latin) – many things in small place – minimization filter:
  - Process in which original image is filtered down repeatedly into smaller images.
- Before rendering, original image is augmented with sets of smaller versions of this image
  - Image pyramid: <image>
- Mipmap chain:
  - Original texture is downsampled by quarter of original area. New texel is calculated as average of four neighbour texels in original image. Newly create texture is called sub-texture
  - This process is repeated until one or both of image texture dimensions equal to one.
  - <image>
- High quality mip mapping requires:
  - Good filtering: when averaging new texel value from 2x2 of texels it is recommended to use Gaussian, Lanczos or Kaiser filter (Box filter gives bad results)
  - Gamma correction. Images are often stored in sRGB colorspace. This colorspace is useful for displaying images but not computing. Therefore, always before filtering, image must be in linear colorspace.

Anti-aliasing: mipmapping

- Using mipmaps to achieve 1:1 pixel to texel ratio. TODO
- Texture level of detail
  - TODO
- RTR: 6.2.2

Examples of image textures

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

Volume textures

- Extension of 2D image is 3D image accessed with (u,v,w) coordinates
- Example: medical imaging data
  - Three dimensional grid is visualized as slices by moving polygon through it
  - <image>

Volume textures

- Complex problem of finding good 2D parameterize for 3D mesh is not needed since object locations can be used as texture coordinates.
  - example
- Volume texture can represent volumetric structure of material such as wood or marble.
  - Image
- Problem: volumetric image textures are very space demaning

Procedural textures

- Instead of image lookup for texture values, those can be evaluated from a function
- Procedural texturing is much more popular in offline applications while in real-time rendering image textures are far more common*
- Procedural texturing is based on algorithm which defined values for each point of 3D space or object surface.
  - Parametrization of surface is therefore not needed**

<IMAGES: PROCEDURAL TEXTURING>

<IMAGES: NODE SYSTEM FOR PROCEDURAL TEXTURING>

* GPUs are extremly efficient with image textures and antialiasing is easier.

** Procedural texturing of complex shapes on complex surfaces is technically challenging and active area of research. For example, textures can be decomposed in stationary and globally varying. Stationary textures are easly to be procedurally generated on any shape. Globally varying textures have certain elements which have direction and shape, thus procedurally modeling of those on complex surfaces is hard

Procedural textures: volumetric textures

- Storing volume textures into image is very costly
- Therefore, volume textures are attractive application for procedural texturing since they can be synthesized with various methods
- Often, **noise function** is used:
  - Sampled at power-of-two frequencies called **octaves**. Each octave has weight which falls as frequency increases
  - Sum of weighted samples is called **turbulence** function
  - <example>
- Lattice points in 3D array are often precomputed and used to interpolate texture values

Procedural textures: Perlin noise

- Most popular noise function upon which wide range of methods is built
- TODO

Procedural textures: Cellular texture

- Widely used texture for representing Voroni-like textures and many natural textures: cells, flagstones, lizard skin
  - Another fundamental procedural texture upon which diferent methods are built
  - examples
- It is based on measuring distances from each location to a set of feature points
  - Intuition

Procedural texture: physical simulation

- Perlin and Cellular textures are mathematical models and phenomenological models for representing natural phenomena
- Phyiscally based simulation can also be used to create textures
  - Diffusion-rection: TODO
  - Practical: houdini simulation to texture

Procedural textures: Antialiasing

- Procedural textures can be hard to antialias
- Helping factor is that “inside information” about the texture is available:
  - For example, if procedural texture is built on summing noise functions, then frequencies which would cause aliasing can be omitted

Material mapping: variation of parameters

- Until now we have discussed how to obtain texture value given location on object surface.
- Now, we will discuss how texture values are used to modify material across object, that is scattering function and shading parameters over surface
  - Example: 3D scene → rendering → shading: shading reads texture information and uses it for calculating surface color

Usage of texture values

- Modify scattering/shading parameters
  - Surface color using albedo/diffuse texture values (Example of linear parameter*)
  - Roughness values using roughness texture values
- Distributing different materials over surface
  - Texture can be used as a “mask” which determines which scattering function and shading calculations will be performed where: rusty and shiny material example
- Modify scattering basis
  - Bump, normal (Example of non-linear parameter*)
  - Parallax
  - Displacement

* Antialiasing must be also performed on shading results since pixel may cover large patch of the scene containing different materials. Linear parameters are easier to antialias then non-linear ones.

Alpha texture values

- Alpha values are used for blending or alpha testing for transparency
- This enables **decals/cutouts**: rendering only parts of the image on object surface.
  - Example
- **Bilbording** method, which is used for standalone flat polygons with image texture, is also using alpha texture values
  - Example: large forest - https://80.lv/articles/how-to-fake-a-large-scale-forest-in-blender/
- Alpha value is very much used when adding VFX to rendered or real images - **compositing**.
  - Example

Bump mapping

- Large family of small-scale detail representations
- Typically, texture value is processed in shading step during rendering to achieve more 3D appearance of surface details than compared to color texture
  - No additional geometry is generated thus this is often used approximation to achieve required surface details
  - <examples>

Bump mapping: scale of modeling

- Details on object can be classified:
  - **Macro-features**: cover many pixels. Represented by model shape (e.g., polygonal mesh). For character modeling, limbs are modeled at macroscale
    - example
  - **Meso-features**: cover few pixels across. Everything between two scales. It represents detail that is too complex to render using shape representation (e.g., polygonal mesh) but large enough to be observable. For character modeling: skin or cloth wrinkles are modeled on mesoscale. For this scale family of **bump mapping methods** is used.
    - example
  - **Micro-features.** Described with scattering function in shading step. It uses texture values for computing the color. It simulates the microscopic response of surface geometry and substance. Shiny and diffuse objects are modeled on micro-scale
    - example

Bump mapping: idea

- Difference between methods is how they represent details
  - Tradeoff: level of realism and complexity
- Main idea (Blinn):
  - Surface will appear to have small scale details is during shading process, surface normal is slightly perturbed. <example: 2d sketch and rendered images>
- Information for perturbing surface normal can be encoded in texture just like color.
- Problem:
  - Actual geometry is not changed.

Bump mapping: frame of reference

- Perturbing surface normal must be done with respect to some frame of reference
- To do so, **tangent frame** is used – tangent frame **basis**
  - TBN: TODO
- On this basis, scattering model is evaluated
  - Perturbing the basis by perturbing the normal we achieve different incoming light and viewing directions – just like the surface contain small bumps and dents.
  - Also, directions of light and viewing are often transformed in this space – so they are in the same space as surface normal which is needed for correct for evaluation.
  - Tangent frame is used to determine orientation of material on the surface which is important for **anisotropic** surfaces

Bump mapping: Blinn method

- Original bump mapping – **offset vector bump map** - method required two signed values to be stored per texel in texture
  - Those correspond to amount of normal to be varied in u an v image axis – which way surface faces at the point.
  - Those values are used to scale vectors perpendicular to normal (tangent and bitangent)
  - Resulting vectors are added to normal to change direction
  - <example>
- Another approach is to use **heightfield** to modify surface normal direction
  - Image texture contains one floating point number per texel representing height
  - Those values are used to derive u and v signed values similar to those in original method – this is done by taking differences between neighbouring columns are rows to obtain u and v (Sobel filter an be used)

Normal mapping

- Instead of calculating perturbed normal using height values, normal vectors can be directly stored into image texture or evaluated from procedural texture.
- Normal map image texture encodes (x,y,z) vector with values in [-1,1] to rgb image texture
  - For PNG images, 8bit unsigned int is used. Therefore 0 represents -1 and 255 represents 1
- Normal map are often defined in **tangent space***
  - Normal map can be then maximally reused for different objects, transformations and deformations.
  - Color of normal map is determined with x,y and z directions of encoded vectors <example>
- <examples>

* Originally, they were defined in world or object space but this was limited to specific geometry for particular orientation

Normal mapping: practical notes

- Relationship between normal and shaded color is not linear*. Therefore, filtering of normal maps for **anti-aliasing** requires additional work.
- Normal map can be easly **derived from height map**
  - Example
- Problem with normal mapping, as with bump mapping, is that additional geometry is not created. Thus effects of light being shadowed** by geometry and casting shadow on its own surface is not possible.
  - Solution is **horizon mapping** method which enables normals having bumps which cast shadow on their surfaces.

* Normal map applied to specular surface results in non-linear relationship between shaded color and normal map. Lambertian (diffuse) surface has almost linear relationship between shaded color and normal map since base of lamberitan shading is based on dot product with normal which is linear operation.

** Generally, when light falls on surface with bumps, multiple scattering, masking and shadowing effects happen which are not possible with normal mapping.

Creating bump/normal mapping

- Often for purposes in real-time graphics, high quality mesh is created. This mesh is then simplified and normal map is **baked** from high quality mesh.
  - Low quality mesh and baked normal are then used for real-time applications
  - Example
- Another possibility is to create bump map by scanning heights from real world
  - Example

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.

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

Practical note: textures

- Generally, outside of computer graphics field, term texture is overloaded
- In computer graphics this term is also overloaded
- On modeling level of abstraction, texture is a way to modify scattering function/shading parameters over surface.
- On development level of abstraction, especially while programming in graphics API, texture is nothing more than a memory buffer that is sent from CPU to GPU.
  - RGBA channels can encode any information. Examples: octree, mesh, etc.

Practical insights

- Show how is material generated in practice using different scattering functions and textures

Further into topic

- TODO

Literature

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