

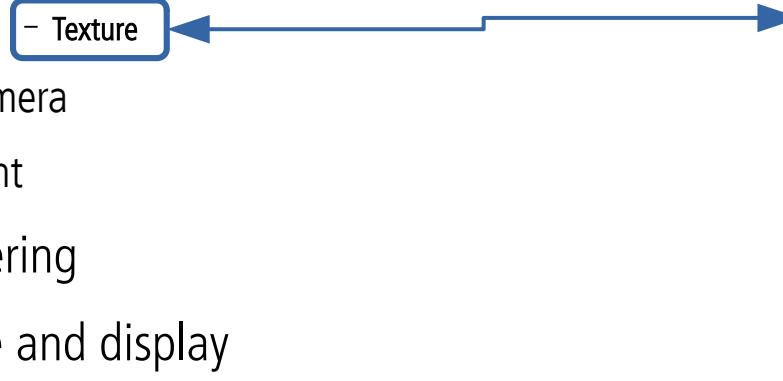
Lecture 8: Texture and mapping

DHBW, Computer Graphics

Lovro Bosnar

15.2.2023.

Syllabus

- 3D scene
 - Object
 - Shape
 - Material
 - Scattering
 - **Texture**
 - Camera
 - Light
 - Rendering
 - Image and display
- Texture and mapping
 - Texturing pipeline
 - Image textures
 - Procedural textures
 - Textures and material modeling
- 



Introduction

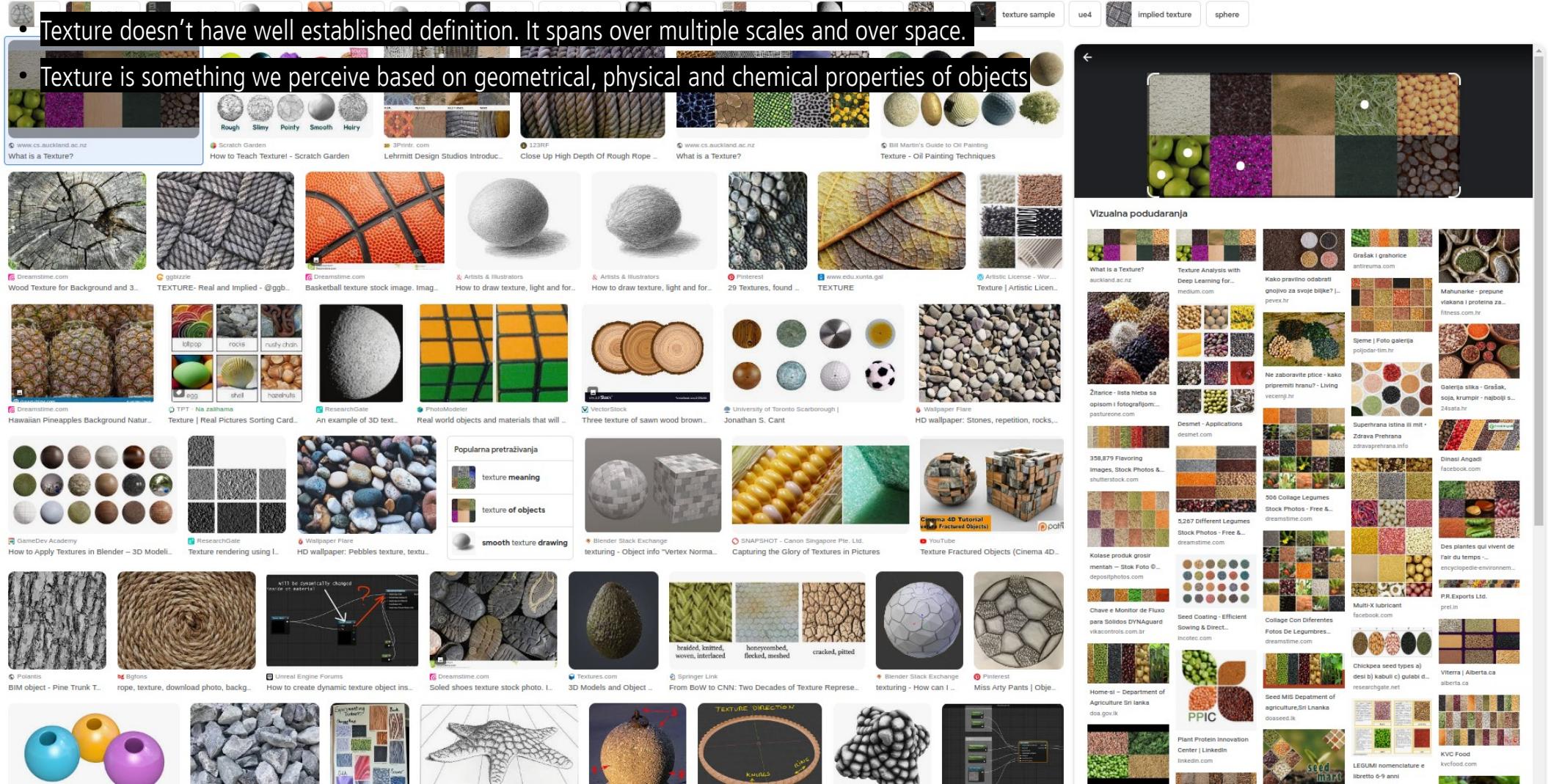


SUBSTANCE
DESIGNER

- Metal
- Plastic
- Glass
- Wood
- Fabric
- Stone
- Clouds
- Water
- Tree bark
- Leaf
- Plaster
- Paper
- Leather
- Sky
- Etc.



- Term **texture** is used differently in various disciplines and everyday life: texture of fabric, texture of food, texture in music, texture in image processing, texture in...



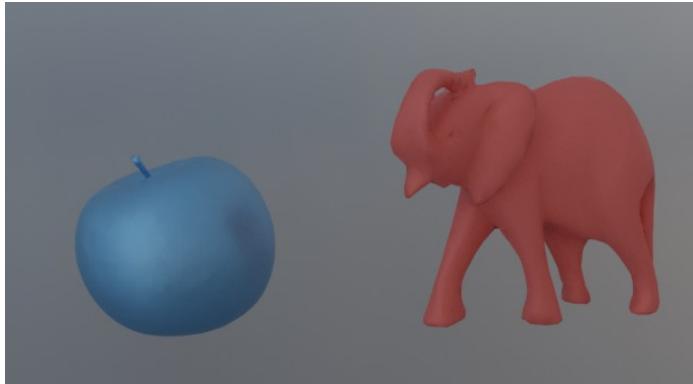
Big picture



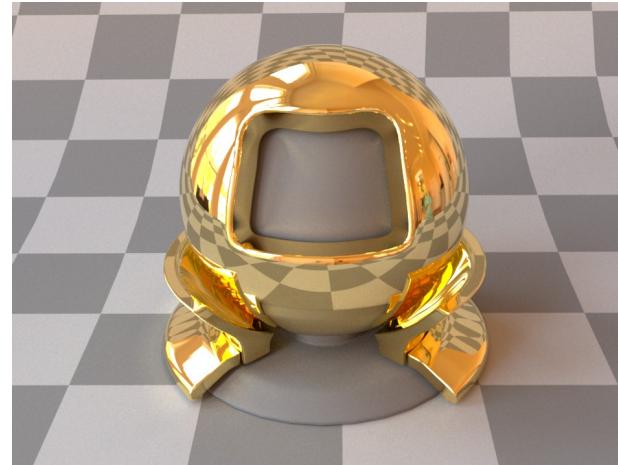
Material characteristics

- Characteristics that needed to be modeled in order to obtain required appearance:

Color



Directional (e.g., reflectivity)

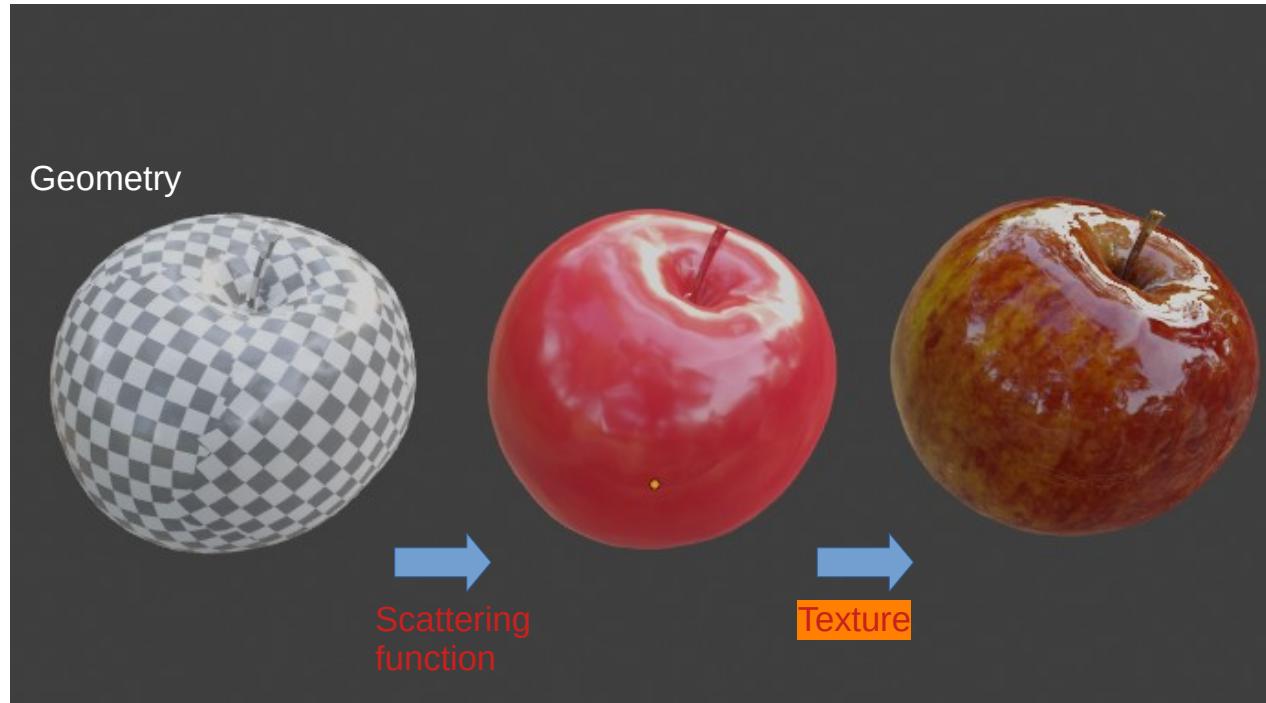


Texture and patterns



Texture in computer graphics

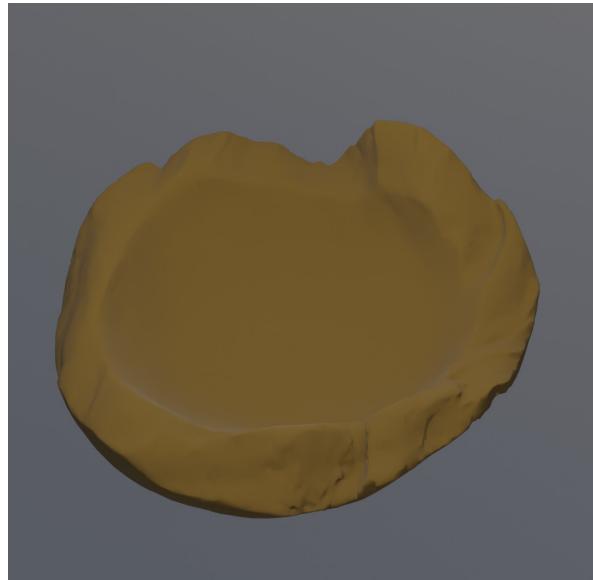
- For 3D modeling, we can try to define texture as function which **varies scattering function properties over surface**.



Variation of material over surface

- Real objects rarely have only one material or same material properties over the surface → **homogeneous material**
 - Example: wood has structure at a scale of about 1mm and lower. The material of wood fiber also varies. Therefore, the rich appearance of wood comes from structure and material variation of fibers. This richness is called **texture**.

Homogeneous materials are missing details and variations, thus look too smooth and too perfect.



Diffuse scattering model with constant albedo parameter → homogeneous material.



Diffuse scattering model with variation of albedo parameter using texture.

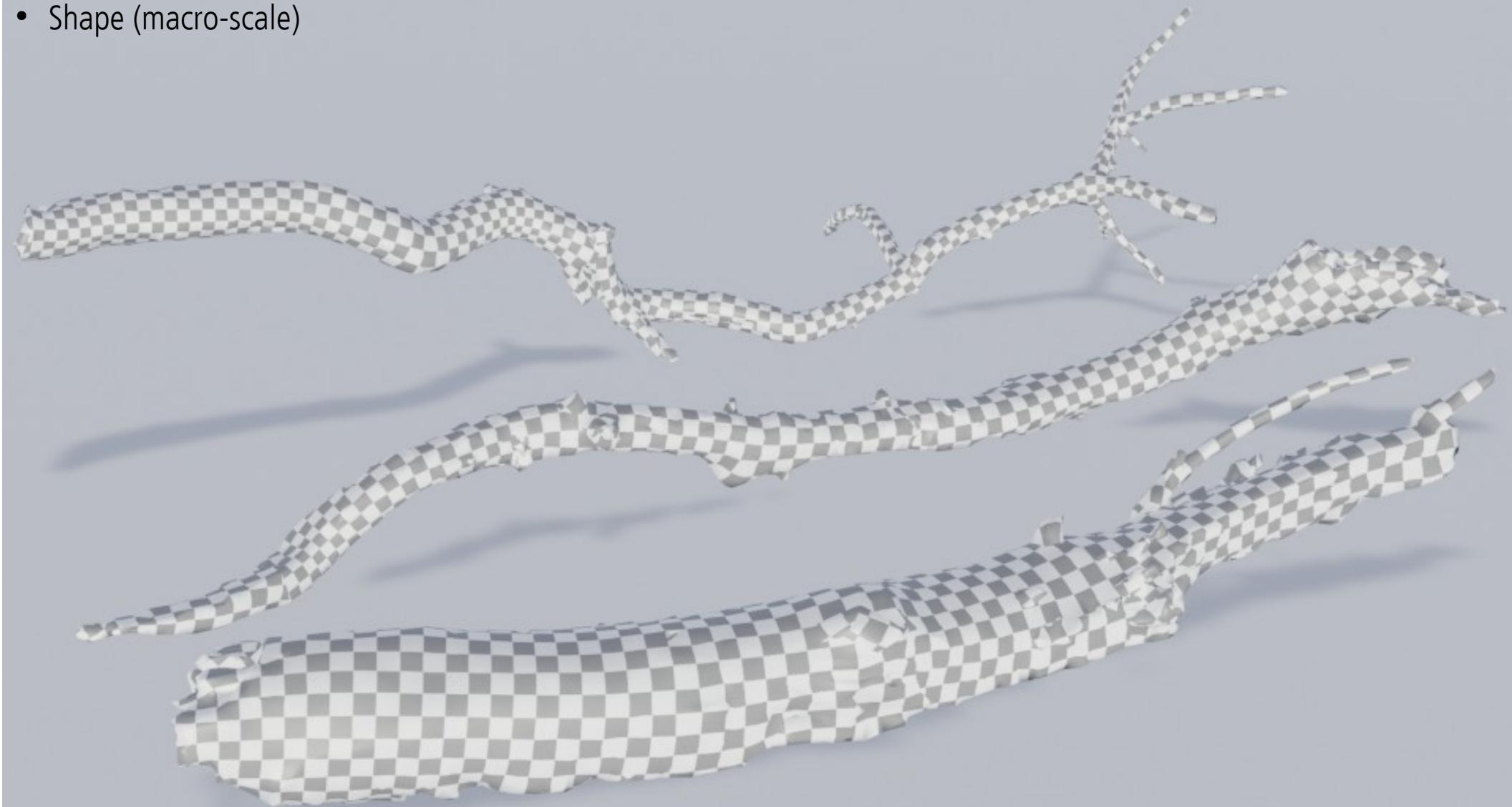
Texture

- Visual variation on the object surface – **spatial variation → details and richness of surface**
 - Directional or color characteristics → scattering function parameters
 - Small-scale geometrical characteristics: bumps, pores, imperfections, etc. → **surface normals**
- In computer graphics, **texturing** is process that takes surface and modifies its appearance at each location using image, function or other data source.
 - Its function is to add details to object surface while keeping computational cost low

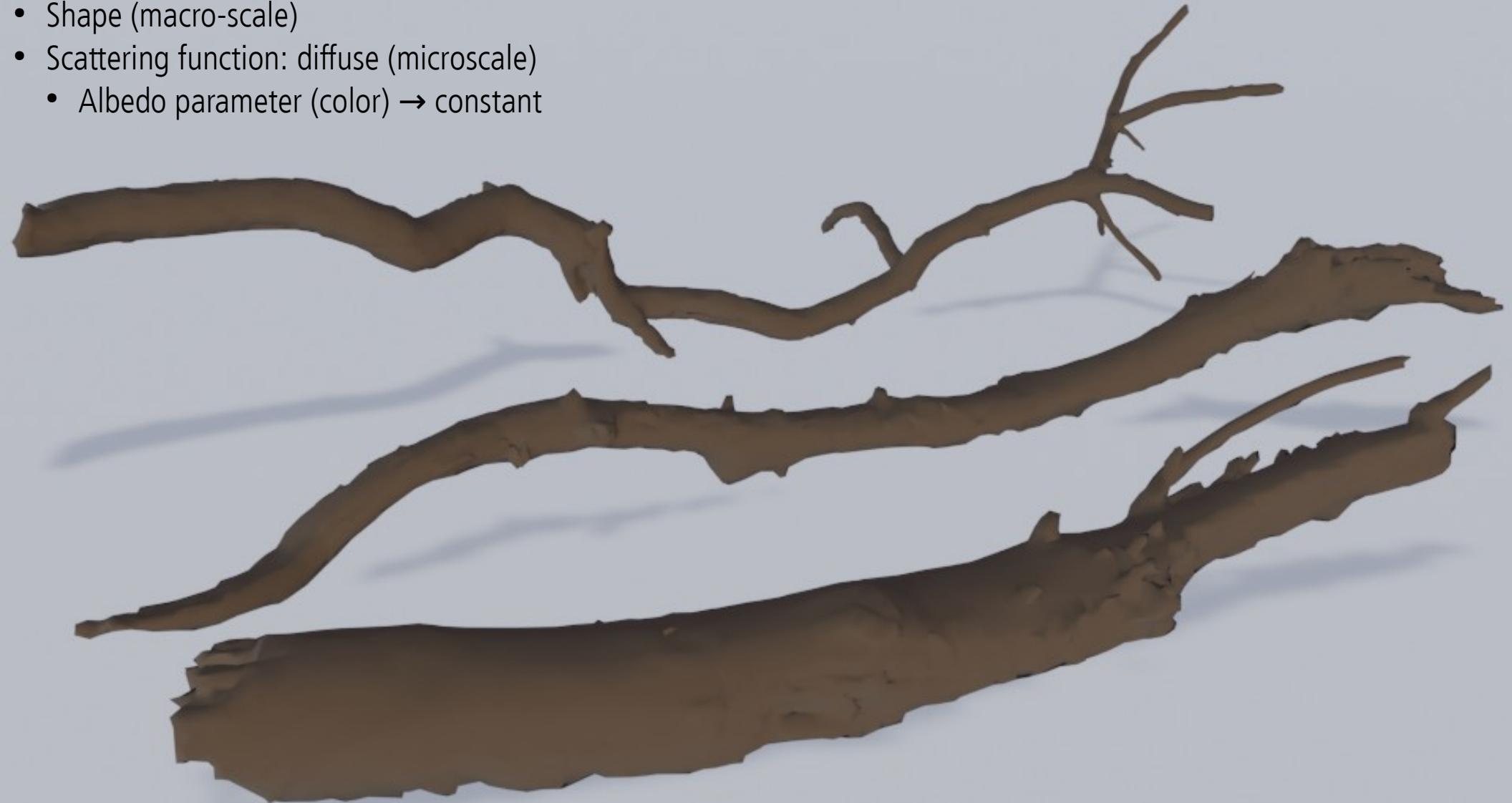


* Remember that computer graphics is all about simulation and approximation in order to achieve required appearance. It is a trade-off between quality and speed. Depending on viewing distance and size of objects in 3D scene, some details can be represented with lower quality. For example, modeling all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

- Shape (macro-scale)



- Shape (macro-scale)
- Scattering function: diffuse (microscale)
 - Albedo parameter (color) → constant



- Shape (macro-scale)
- Scattering function: diffuse (microscale)
 - Albedo parameter (color) → texture variation



- Shape (macro-scale)
- Scattering function: diffuse (microscale)
 - Albedo parameter (color) → texture variation
- Small-scale geometry: surface normals (mesoscale)
 - Normal perturbation → texture variation

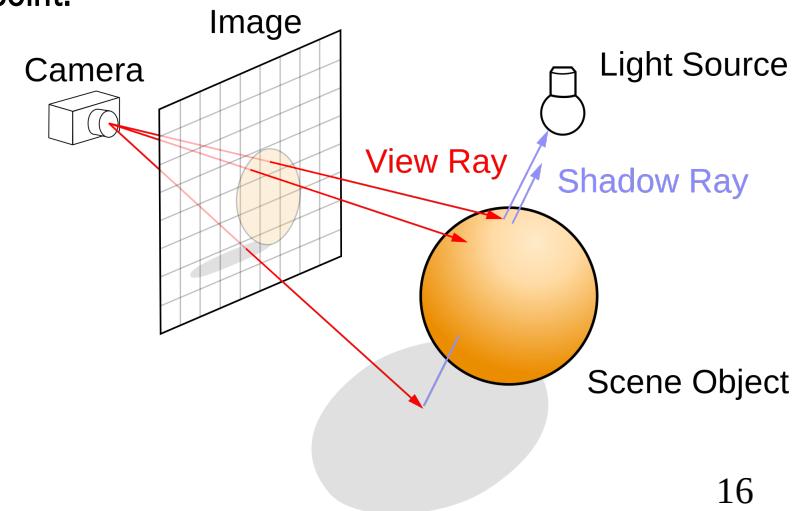


Texturing: variation

- Texturing: adding surface details which are too expensive to model explicitly with geometry
- Textures introduce
 - Scattering function parameters (e.g., color) variation
 - Small-scale geometry variation → Shading normal variation
- Texturing scale
 - **Micromscale** variation → scattering function parameters
 - **Mesoscale** variation → shading normal perturbation
 - **Macroscale** is given by the object shape

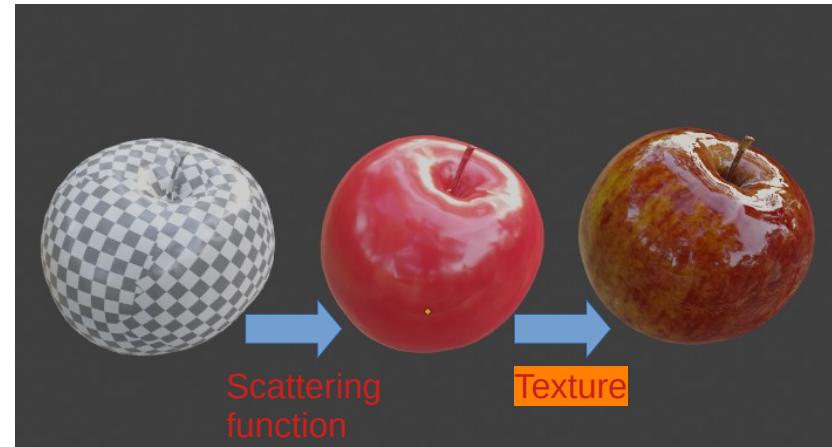
Texture and rendering

- Rendering: computing color of pixels in the virtual image plane
- Color of pixels → color of objects visible from camera
 - For each pixel, viewing ray is generated, traced into scene for closest intersection → **visibility solving**
 - Color is calculated at closest intersection → **shading**
 - The result of shading is color of pixel from which ray was generated
- **Shading:** calculating color at viewing ray intersection with object → **shading point.**



Texture and shading

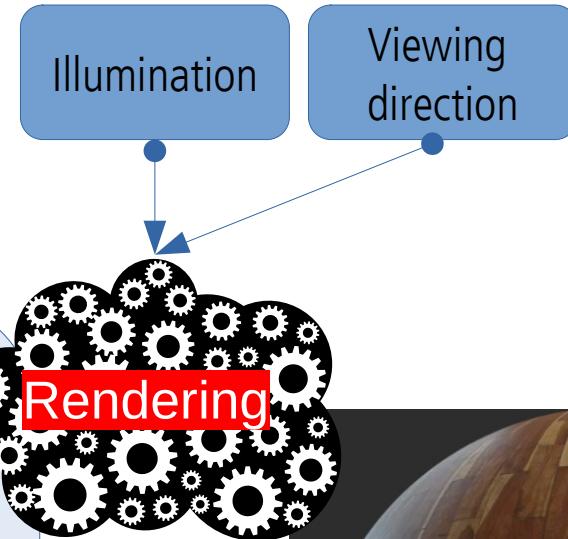
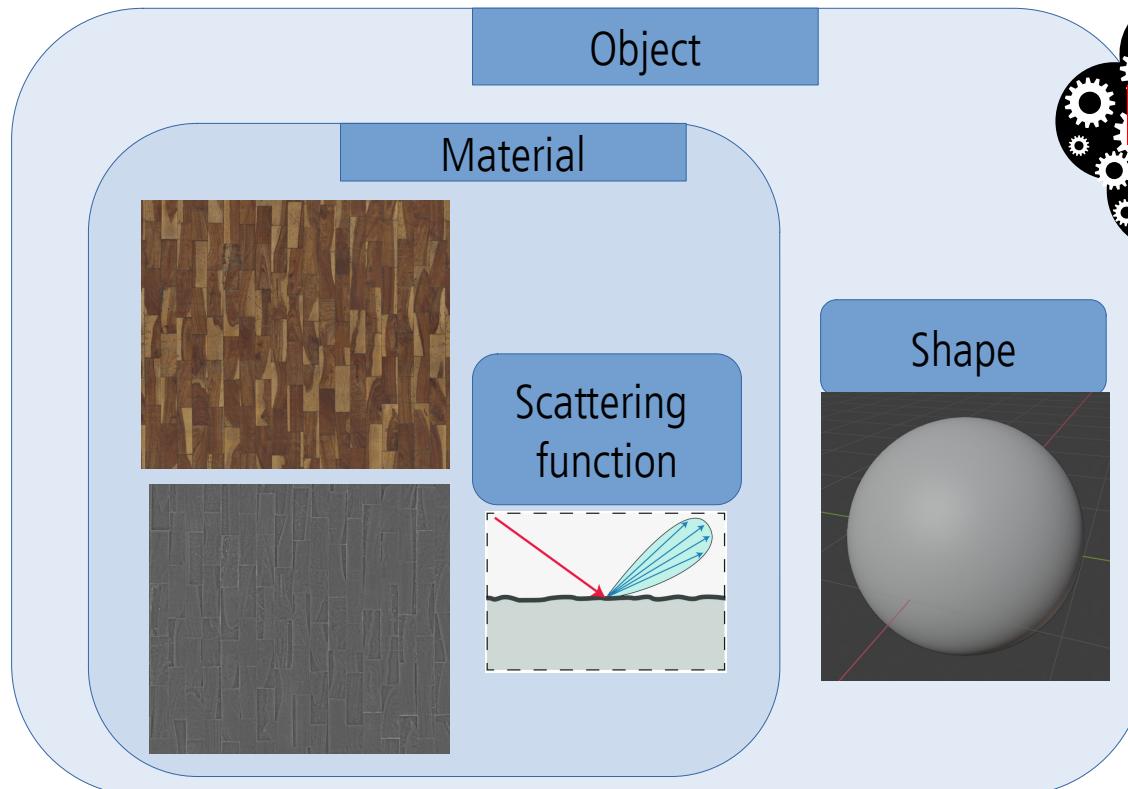
- Shading uses **material**, **shape**, **viewing** and **light** to calculate the color in shading point
- **Material** describes interaction of light with surface:
 - Scattering model
 - Texture model
- For each shading point, **scattering model is evaluated using texture information** at that point
- Final rendered image, due to variation of colors and intensities over object, the surface will contain pattern
 - Surface with pattern is called textured surface



Note on “texture”

Texture in modeling vs texture on rendered surface

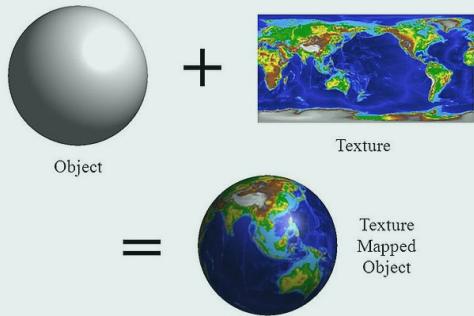
- Texture defines shading parameters over object surface → something that we model
- Resulting pattern of colors on rendered surface → generated texture



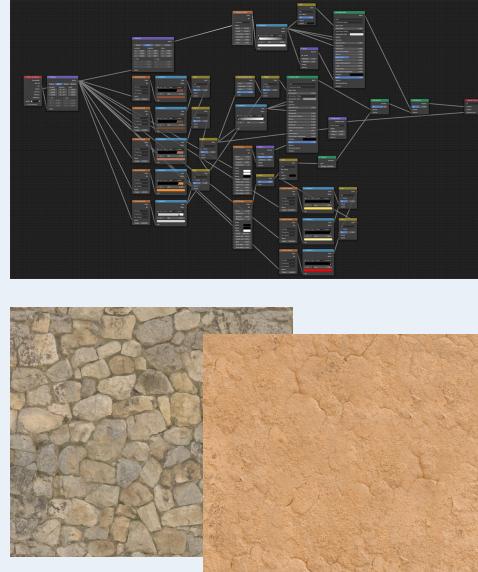
Note on “texture”

- Texture is generally and in computer graphics overloaded term. Meaning depends on the context:
 - Texture can be used for modeling object appearance (material)
 - On GPU rendering, texture can be used as memory buffer to send arbitrary data (e.g., geometry) from CPU to GPU

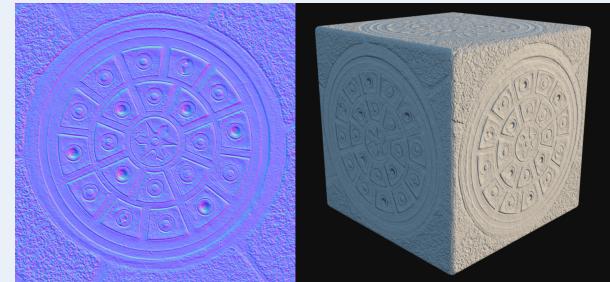
Learning objectives



How to apply textures on objects → **texturing pipeline**



Texturing approaches → **image and procedural**

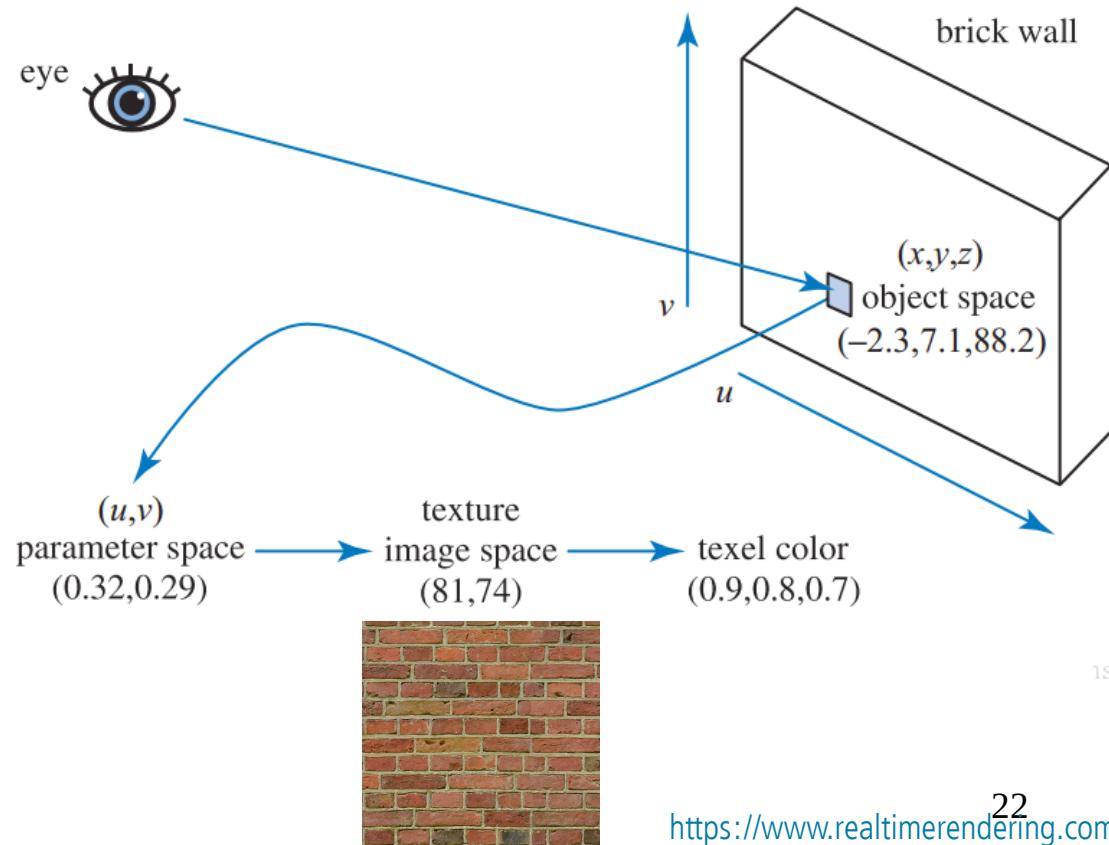


How to use texture for **material modeling** → variation of scattering function parameters and small scale geometry

Texturing pipeline

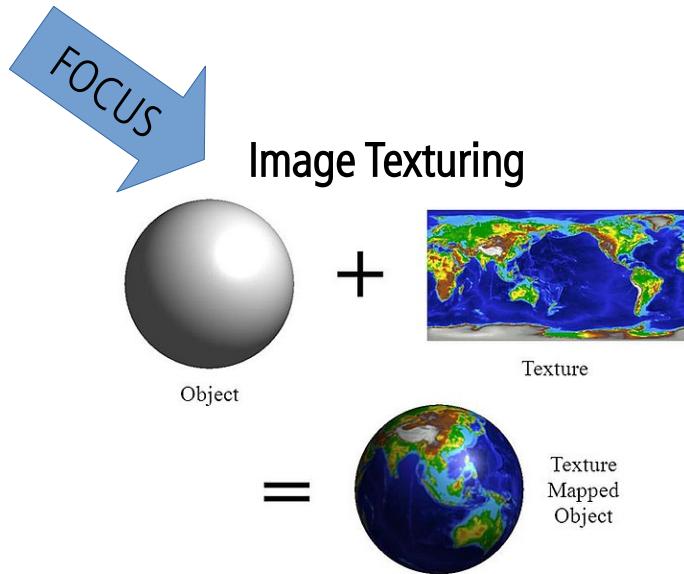
Texturing pipeline: example

- Brick wall
 - Camera ray \rightarrow 3D object position (x, y, z)
 - Projector function: mapping from 3D (x, y, z) to 2D $(u, v) \rightarrow$ texture coordinates
 - Correspondence function: continuous texture coordinates $(u, v) \rightarrow$ discrete texel location (s, t) in the texture image.
 - Texture reading: texel values (e.g., RGB color) are obtained using (s, t)
 - Optional transformation on values
 - Obtained value is used as input to scattering function which is evaluated for shading

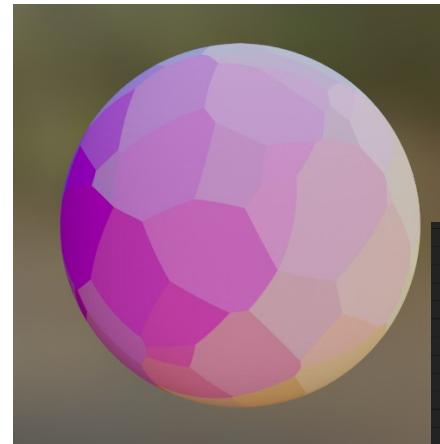


Texturing pipeline

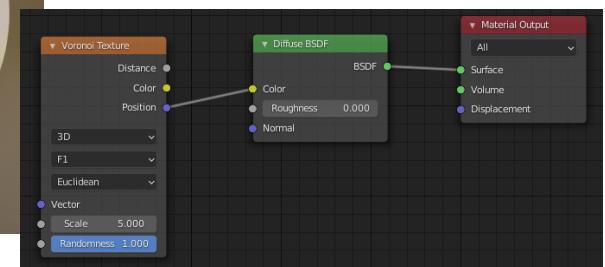
- Texturing pipeline is performed by rendering engine and can be applied on **two main types of texturing**:



2D image (discrete 2D array of texels) is “pasted” on 3D object.



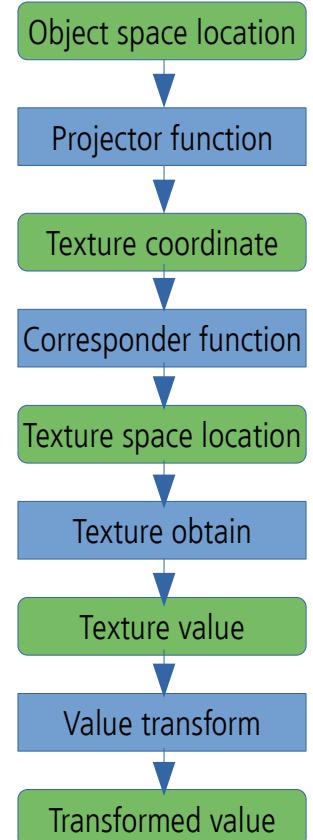
Procedural texturing



An algorithm generates pattern on 3D object

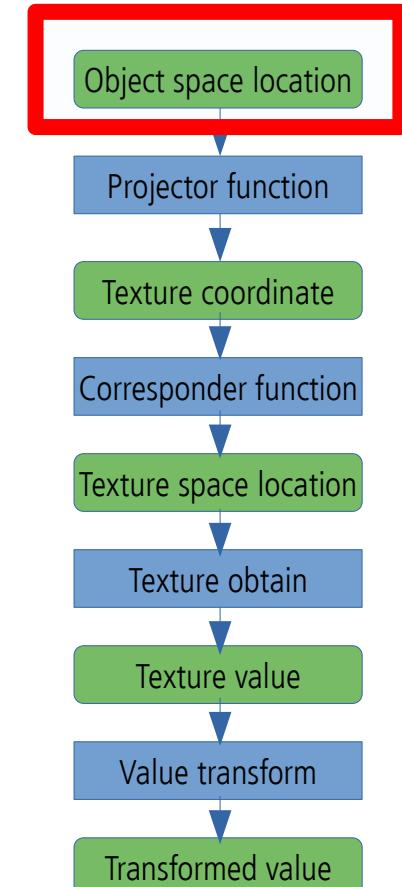
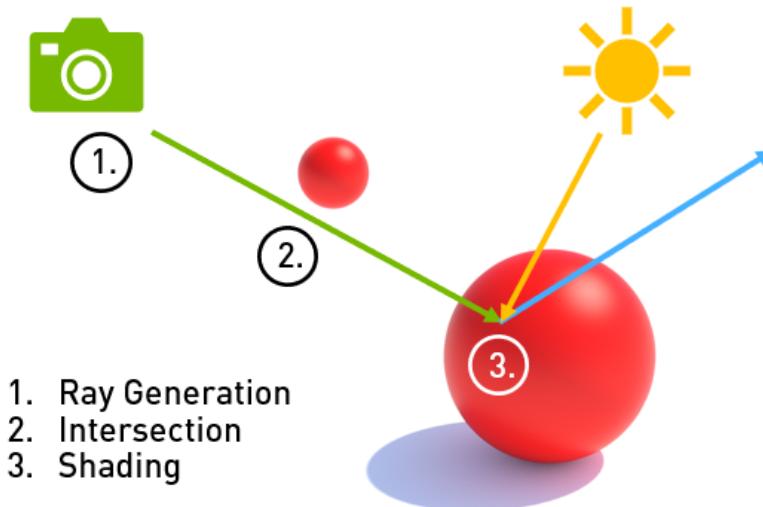
Texturing pipeline

- **Texturing:** variation of shading parameters over surface – **position dependency**
- **Object space location**
 - Shading point → 3D object-space coordinates (x, y, z), e.g., (1.2, 3.3, -3.4)
- **Projection function**
 - Mapping process: 3D object space coordinates → 2D texture space coordinates (u, v) in $[0, 1]$, e.g., (0.2, 0.5)
- **Corresponder function**
 - Transform: continuous texture space coordinates (u, v) → discrete texel locations in image texture (s, t)
e.g., [image_width, image_height], e.g., [128, 44]
- **Obtaining texture values (sampling)**
 - Texture space location is used for obtaining texture value
- **Value transform**
 - Optional additional transformations are done on texture value
- **Usage**
 - Final value is used to modify property of surface at that point: scattering function parameter or normal.



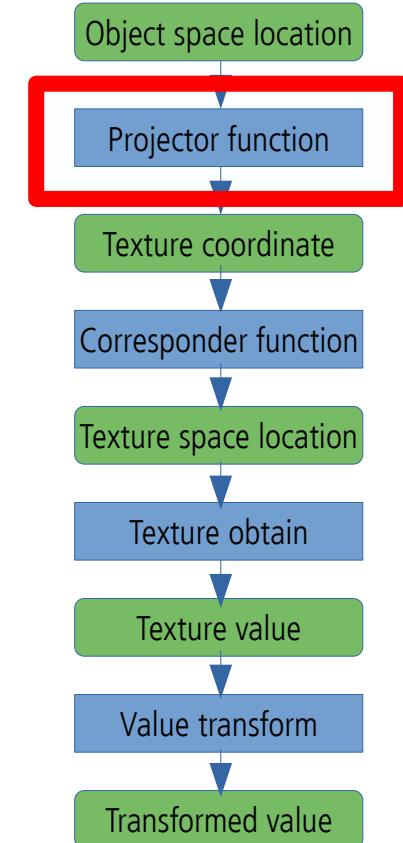
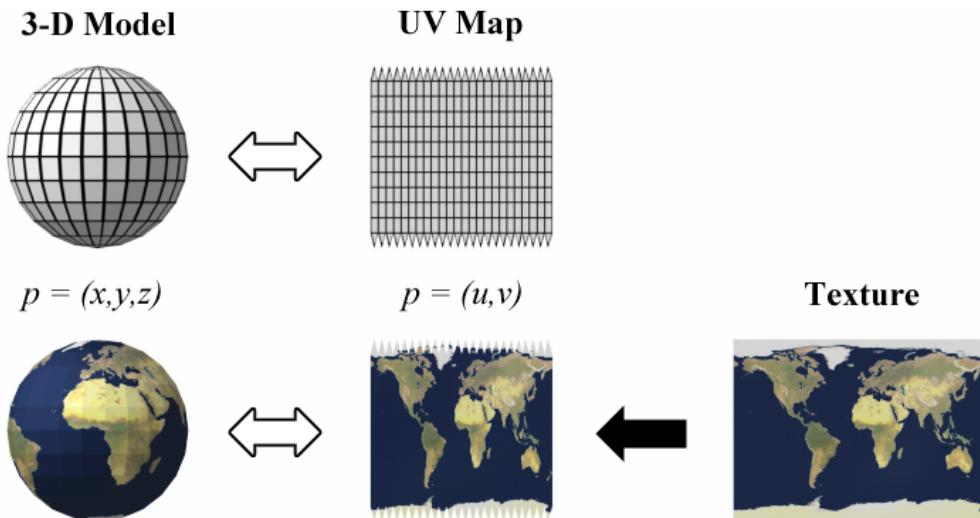
Object space location

- Intersection (shading) point
 - Object space location (x, y, z)
 - World space object location can also be used
 - In this case, as object moves, the coordinates change!



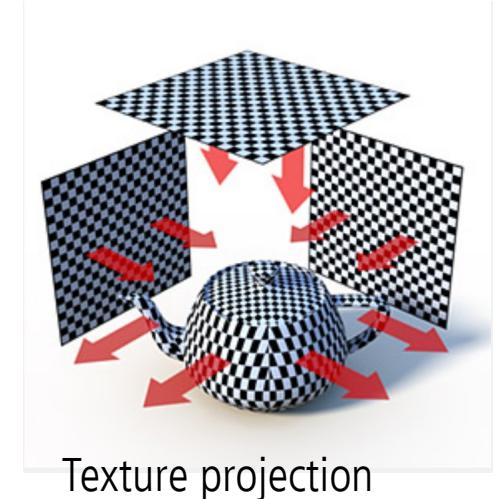
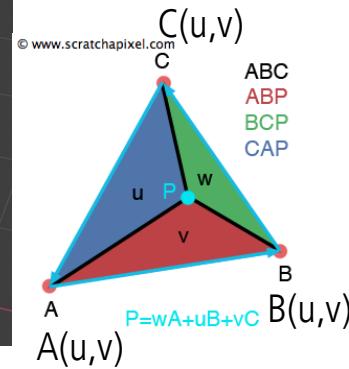
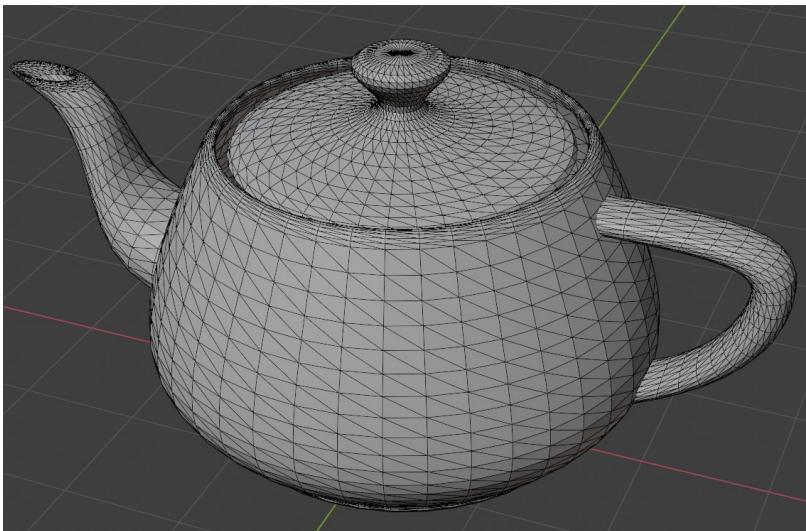
Projector function

- Projector function maps **object space location** into **texture coordinate space**
 - Thus “texture mapping” term
- For image texture: 3D object point (x, y, z) to 2D space (u, v) in $[0, 1]$



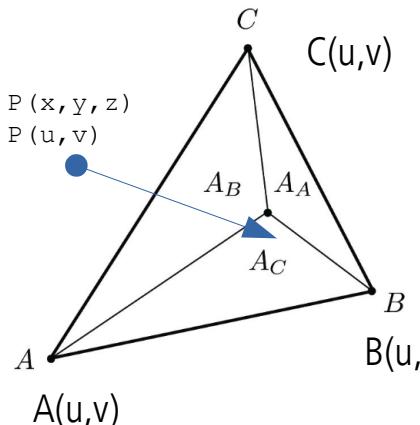
Projector function

- Object space location is used to:
 - Interpolate precomputed texture coordinates stored per vertex
 - Calculate texture coordinates using texture projection on the fly



Vertex texture coordinates

- For intersected/shading point $P(x, y, z)$ on triangle of mesh, **barycentric interpolation** is used to calculate texture coordinate $P(u, v)$ from ones stored per vertex.



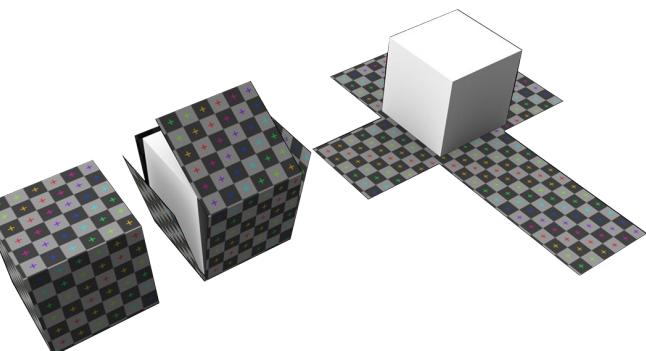
$$\alpha = \frac{A_A}{A_A + A_B + A_C}$$

$$\beta = \frac{A_B}{A_A + A_B + A_C}$$

$$\gamma = \frac{A_C}{A_A + A_B + A_C}$$

$$P(u, v) = \alpha A(u, v) + \beta B(u, v) + \gamma C(u, v)$$

$$\alpha + \beta + \gamma = 1$$



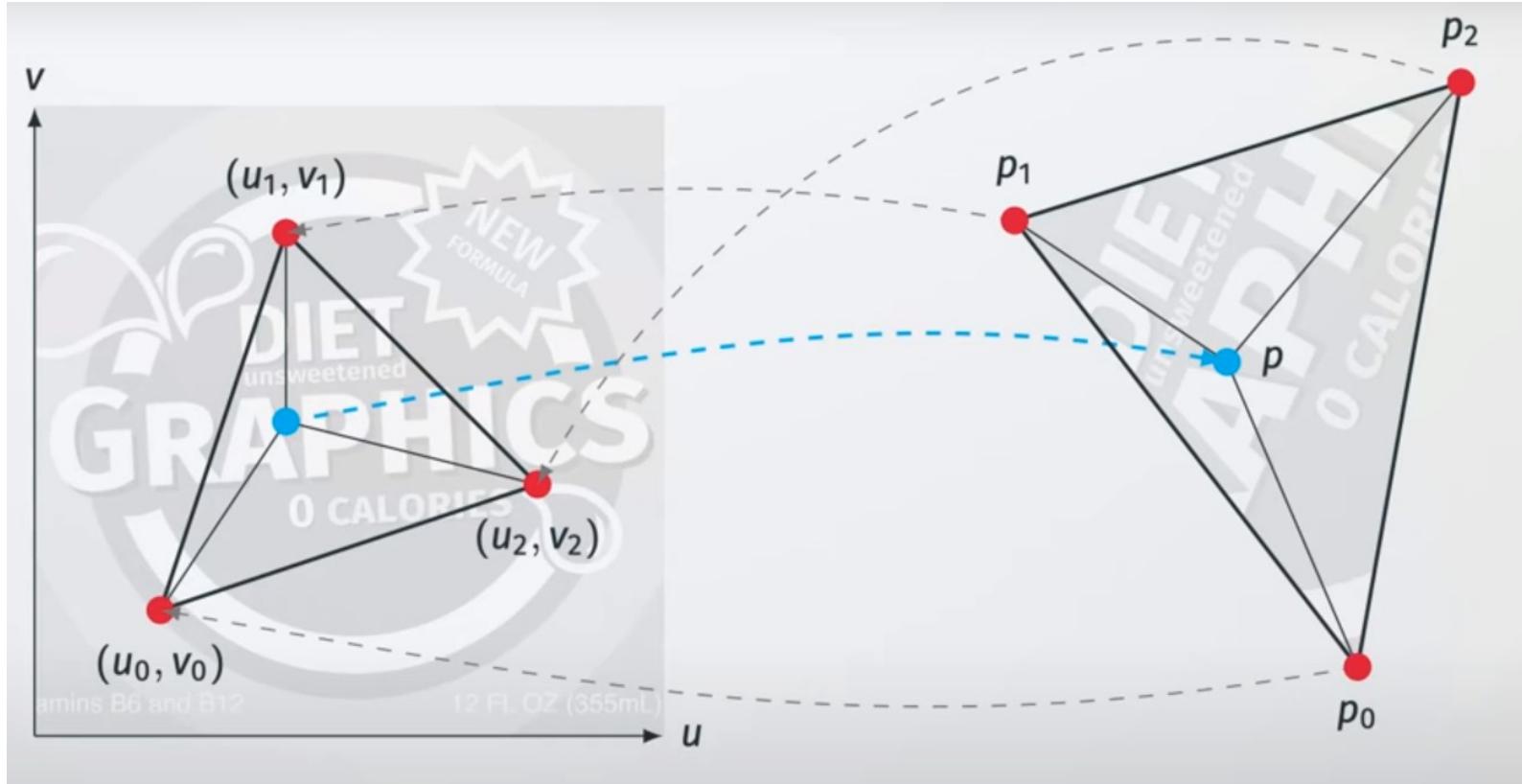
<https://help.disguise.one/en/Content/3D-Workflow/UV-Mapping/What-is-UV-mapping.html>

```

1 # Blender v2.92.0 OBJ File: ''
2 # www.blender.org
3 o Cube_Cube.002
4 v -1.000000 -1.000000 1.000000
5 v -1.000000 1.000000 1.000000
6 v -1.000000 -1.000000 -1.000000
7 v -1.000000 1.000000 -1.000000
8 v 1.000000 -1.000000 1.000000
9 v 1.000000 1.000000 1.000000
10 v 1.000000 -1.000000 -1.000000
11 v 1.000000 1.000000 -1.000000
12 vt 0.625000 0.000000
13 vt 0.375000 0.250000
14 vt 0.375000 0.000000
15 vt 0.625000 0.250000
16 vt 0.375000 0.500000
17 vt 0.625000 0.500000
18 vt 0.375000 0.750000
19 vt 0.625000 0.750000
20 vt 0.375000 1.000000
21 vt 0.125000 0.750000
22 vt 0.125000 0.500000
23 vt 0.875000 0.500000
24 vt 0.625000 1.000000
25 vt 0.875000 0.750000
26 vn -1.0000 0.0000 0.0000
27 vn 0.0000 0.0000 -1.0000
28 vn 1.0000 0.0000 0.0000
29 vn 0.0000 0.0000 1.0000
30 vn 0.0000 -1.0000 0.0000
31 vn 0.0000 1.0000 0.0000
32 s off
33 f 2/1/1 3/2/1 1/3/1
34 f 4/4/2 7/5/2 3/2/2
35 f 8/6/3 5/7/3 7/5/3
36 f 6/8/4 1/9/4 5/7/4
37 f 7/5/5 1/10/5 3/11/5
38 f 4/12/6 6/8/6 8/6/6
39 f 2/1/1 4/4/1 3/2/1
40 f 4/4/2 8/6/2 7/5/2
41 f 8/6/3 6/8/3 5/7/3
42 f 6/8/4 2/13/4 1/9/4
43 f 7/5/5 5/7/5 1/10/5
44 f 4/12/6 2/14/6 6/8/6

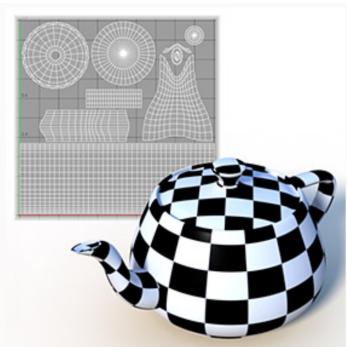
```

Vertex texture coordinates



Generating vertex texture coordinates

- Mesh unwrapping or **texture projection** → generates texture coordinates per triangulated mesh **vertex** (performed prior rendering)
- Modeling packages implement different methods for generating texture coordinates per vertex and enable artist to edit texture coordinates



Unwrapping



Texture projection

The screenshot shows the Blender 3.4 Manual UV Tools page. The header reads "Blender 3.4 Manual" and "blender". The navigation bar includes links for "GETTING STARTED", "About Blender", "Installing Blender", "Configuring Blender", "Help System", "SECTIONS", "User Interface", and "Editors". The main content area is titled "UV Tools" and contains information about mapping UVs, mentioning projection methods and advanced uses.

<https://docs.blender.org/manual/en/latest/modeling/meshes/editing/uv.html>

Home / Modeling / Meshes / Editing / UV Tools

UV Tools

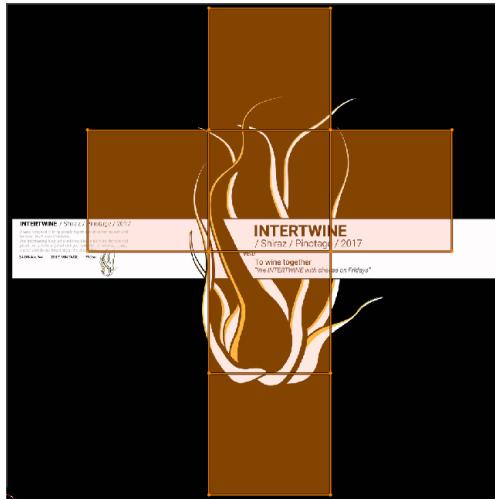
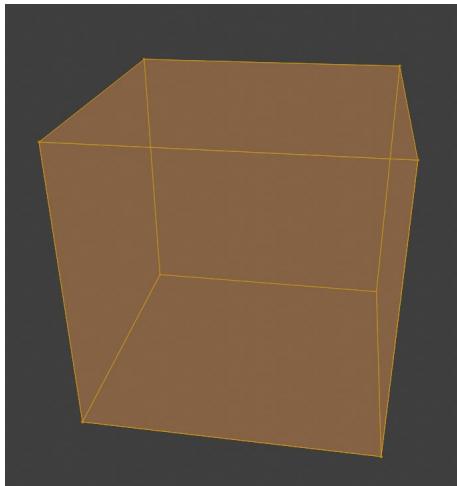
Reference

Editor:	3D Viewport
Mode:	Edit Mode
Menu:	Header ▾ UV
Shortcut:	U

Blender offers several ways of mapping UVs. The simpler projection methods use formulas that map 3D space onto 2D space, by interpolating the position of points toward a point/axis/plane through a surface. The more advanced methods can be used with more complex models, and have more specific uses.

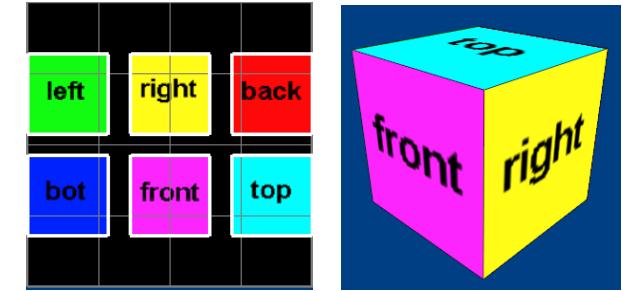
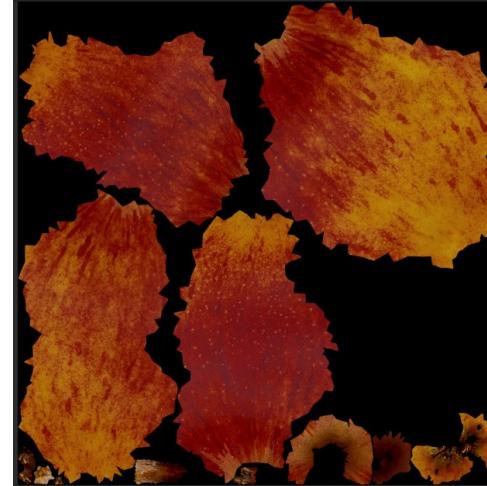
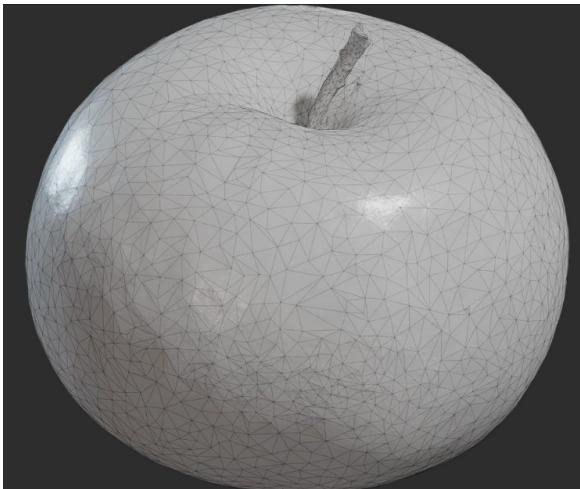
Mesh unwrapping

- Mesh (UV) unwrapping: each vertex is assigned with 2D texture coordinate (u, v) in $[0, 1]$
 - Unwrapping methods belongs to larger field called **mesh parametrization**
- Goal is that each polygon gets fair share of texture area (e.g., evade stretching) but maintaining connectivity – which determines where separate parts of texture meet and visible seams.



Mesh unwrapping and texture atlas

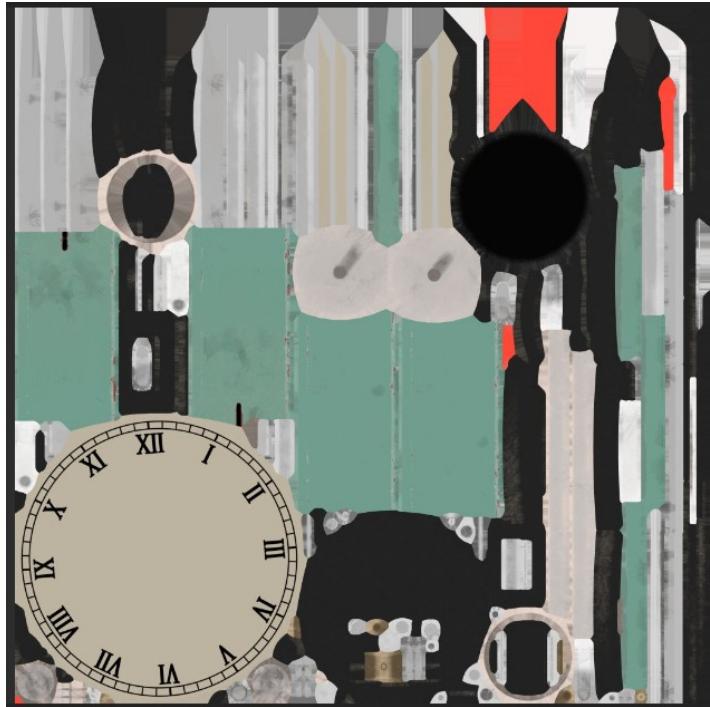
- For complex meshes, **unwrapping separates mesh into multiple parts** which are more convenient to represent on flat plane.
- **Each mesh part is assigned with image texture** → piecewise parametrization
- All image textures for each part can be stored into single texture → **texture atlas**
 - Highly memory efficient



https://www.unwrap3d.com/u3d/tutorial_uv_mapping_texture_atlas.aspx

Blender example: https://www.youtube.com/watch?v=gZRDwbHEB34&ab_channel=GrantAbbitt

Texture atlas

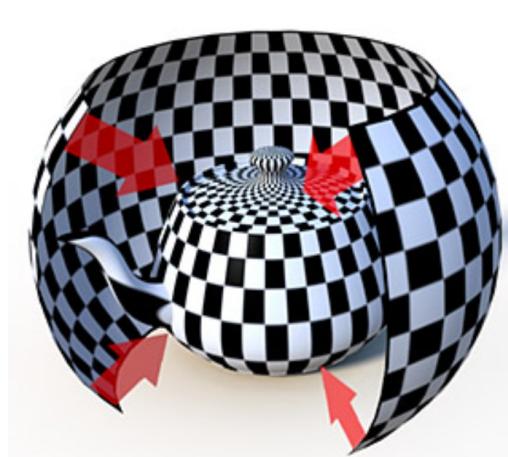


Texture projection

- Transform 3D object point (x, y, z) in space into texture coordinates (u, v) using projections:
 - Spherical
 - Cylindrical
 - Planar
 - Cubic
 - Box
 - Front

Spherical texture projection

- Texture is wrapped into a spherical shape and projected onto a shape.
- Good for texturing round objects.
- Surfaces perpendicular to projection cause stretching.
- Blinn and Newell developed environment mapping based on sphere projection that is called latitude-longitude mapping



[https://learn.foundry.com/modo/901/content/help
/pages/shading_lighting/shader_items/projection
_type_samples.html](https://learn.foundry.com/modo/901/content/help/pages/shading_lighting/shader_items/projection_type_samples.html)

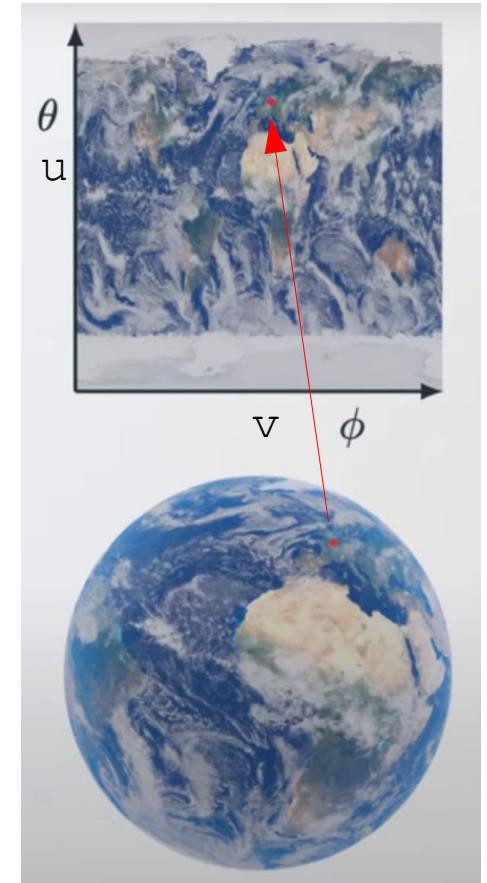
Spherical texture projection

- Example: mapping 2D image texture on 3D sphere
- Any point (x, y, z) on 3D sphere with radius r can be transformed to polar coordinates:
 - Azimuth Φ in $[0, 2\pi]$
 - Elevation θ in $[0, \pi]$
- Azimuth and elevation coordinates are normalized to obtain texture coordinates u and v

$$\theta = \cos^{-1} \left(\frac{z}{r} \right)$$

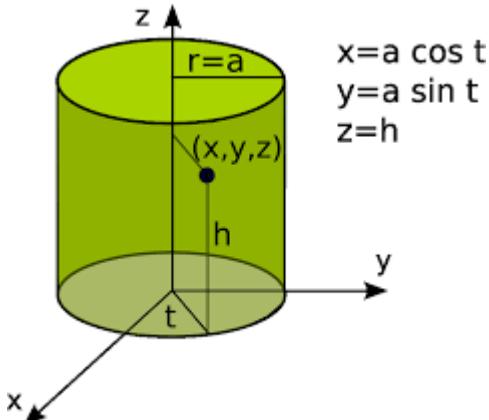
$$\phi = \text{atan2}(x, y) = \begin{cases} \cos^{-1} \left(\frac{x}{r} \right) & y \geq 0 \\ -\cos^{-1} \left(\frac{x}{r} \right) & y < 0 \end{cases}$$

$$u = \theta/\pi, v = \phi/(2\pi)$$



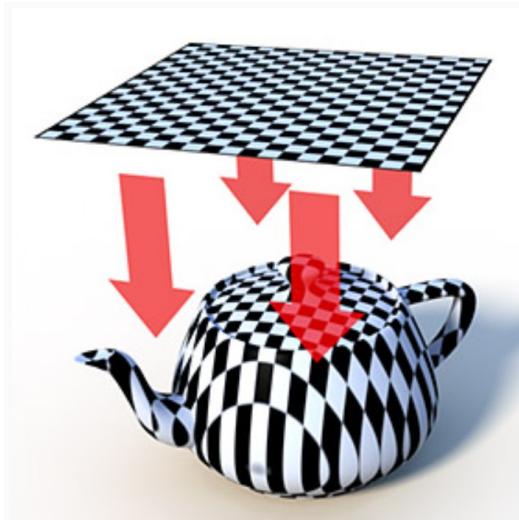
Cylindrical texture projection

- Texture is wrapped in cylindrical shape and projected onto surface.
 - Cylinder coordinates (t, h) → texture coordinates
- Good for cylindrical surfaces (cans, bottles).
- Surfaces perpendicular to projection might cause stretching.

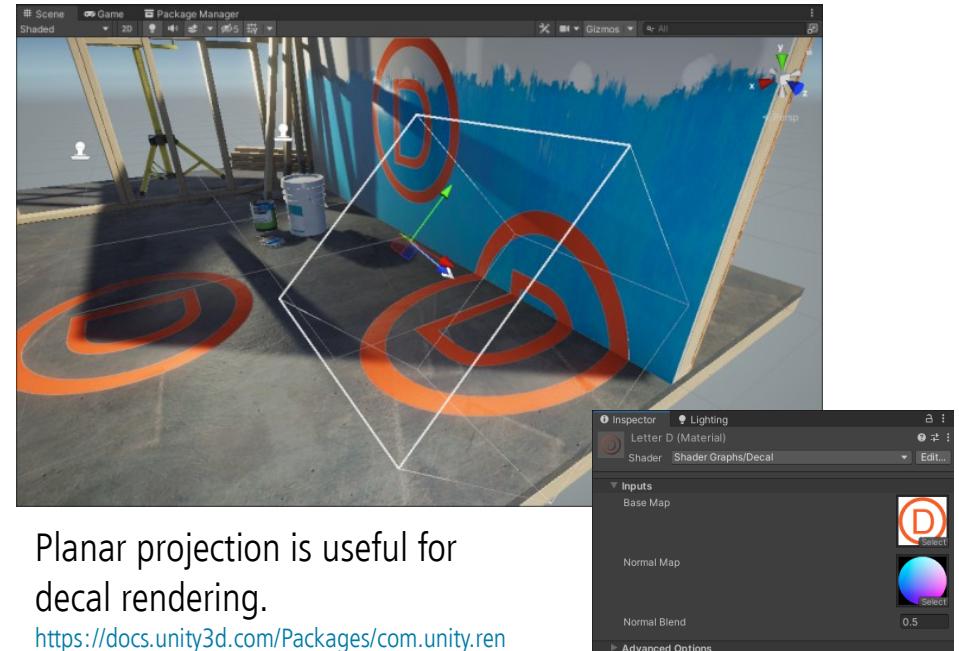


Planar texture projection

- Similar to concept of movie projector but image is projected orthographically.
 - Any vector defining projection plane can be used.
- Great for flat or nearly flat surfaces.
- Other surfaces might cause stretching of texture.



https://learn.foundry.com/modo/901/content/help/pages/shading_lighting/shader_items/projection_type_samples.html

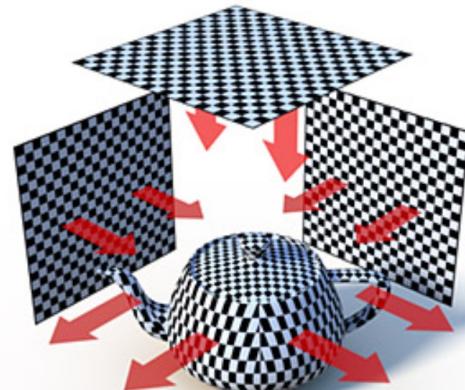


Planar projection is useful for decal rendering.

<https://docs.unity3d.com/Packages/com.unity.render-pipelines.universal@12.0/manual/renderer-feature-decal.html>

Cubic texture projection

- Texture is planar-projected on a surface from all three axis directions: X, Y, and Z
- Polygon receives a certain projection, based on its normal direction.
- Best for cube-shaped objects, and occasionally on detailed surfaces where texture seams are not of great concern

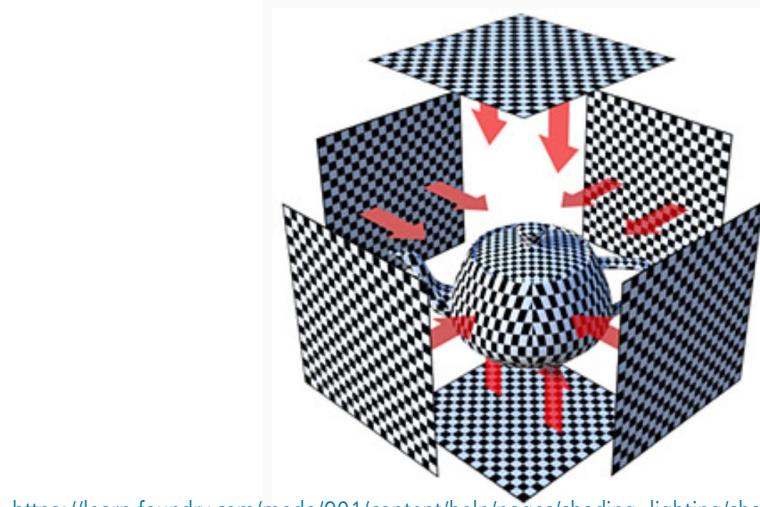


Box texture projection

- Projects a texture in a planar fashion from all six directions, eliminating reverse projections on rear facing polygons inherent to the Cubic method (aka **triplanar mapping**)
- Best on cube-shaped objects, and occasionally on detailed surfaces where texture seams are not of great concern
 - For curved and tilted surfaces efficient **blending** of multiple projection planes must be used.



<https://ryandowlingsoka.com/unreal/triplanar-dither-biplanar/>



https://learn.foundry.com/modo/901/content/help/pages/shading_lighting/shader_items/projection_type_sam_ples.html

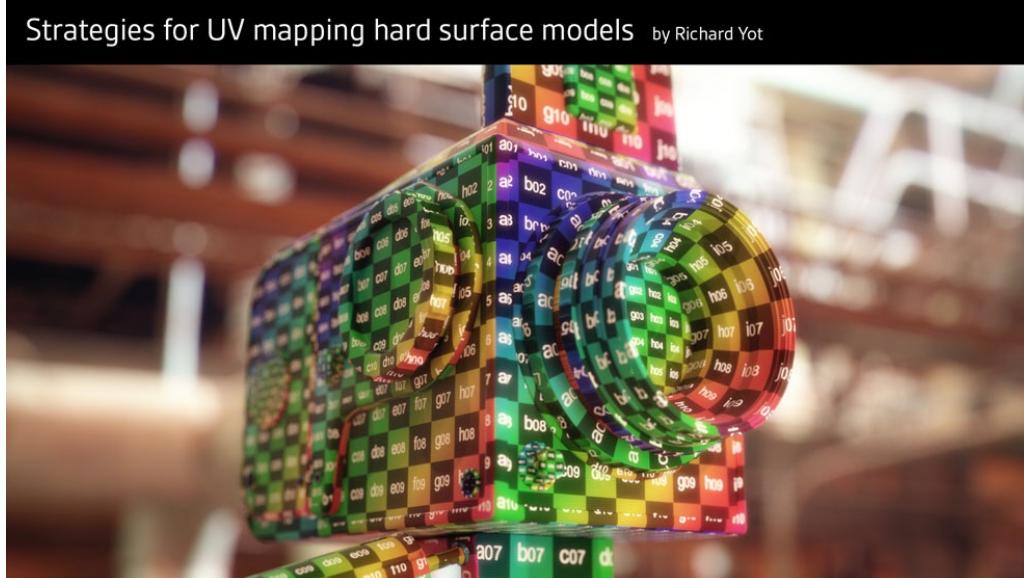
Front texture projection

- Texture is projected out from a camera or light's position



Projector function: complex shapes

- For highly complex shapes, separating into simpler shapes can be done and then texture projection can be done separately.



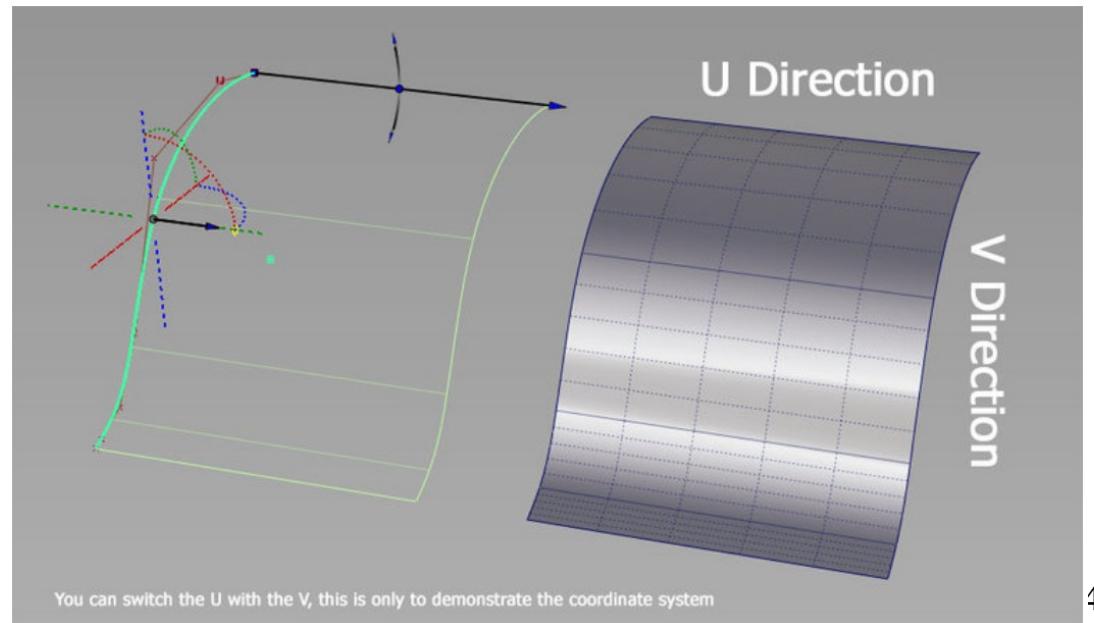
[983] Pagán, Tito, "Efficient UV Mapping of Complex Models," Game Developer, vol. 8, no. 8, pp. 28-34, August 2001

Projector function: different approaches

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

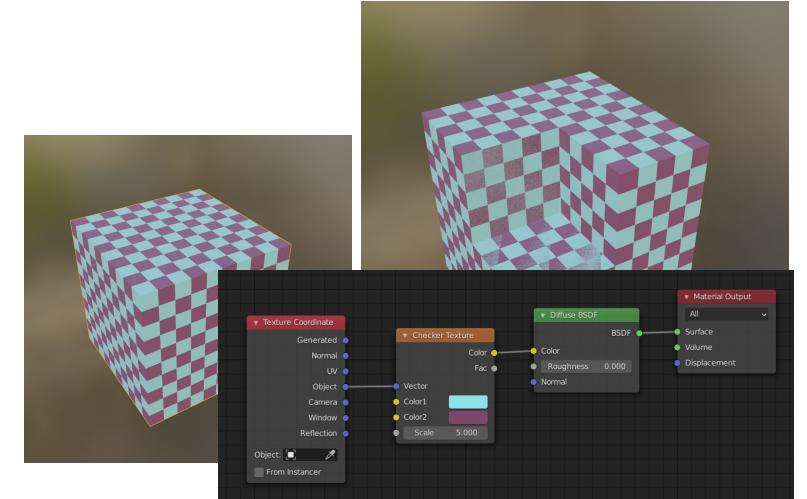
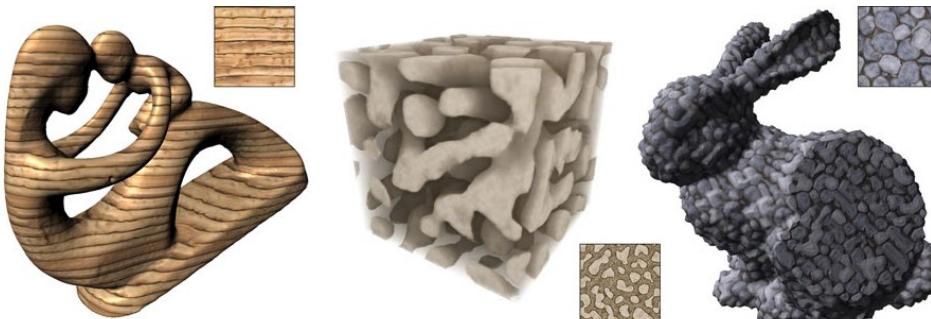
Projector function: inherent texture coordinates

- Parametric surfaces (e.g., NURBS) have natural set of (u,v) texture coordinates which defines any (x,y,z) point on surface
- 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

- Some steps of texturing pipeline can be omitted depending on texturing method
- Texture coordinate space doesn't have to be always 2D → for volumetric objects, texture coordinates are (u,v,w)
- Procedural texturing can directly use object space locations (x,y,z) – **solid texturing**
- For animation, texture coordinates can be (u,v,w,t) where t is time and determines change in texture



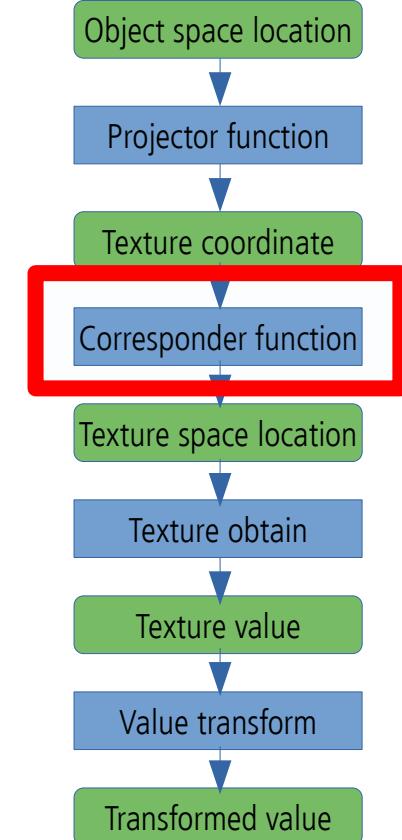
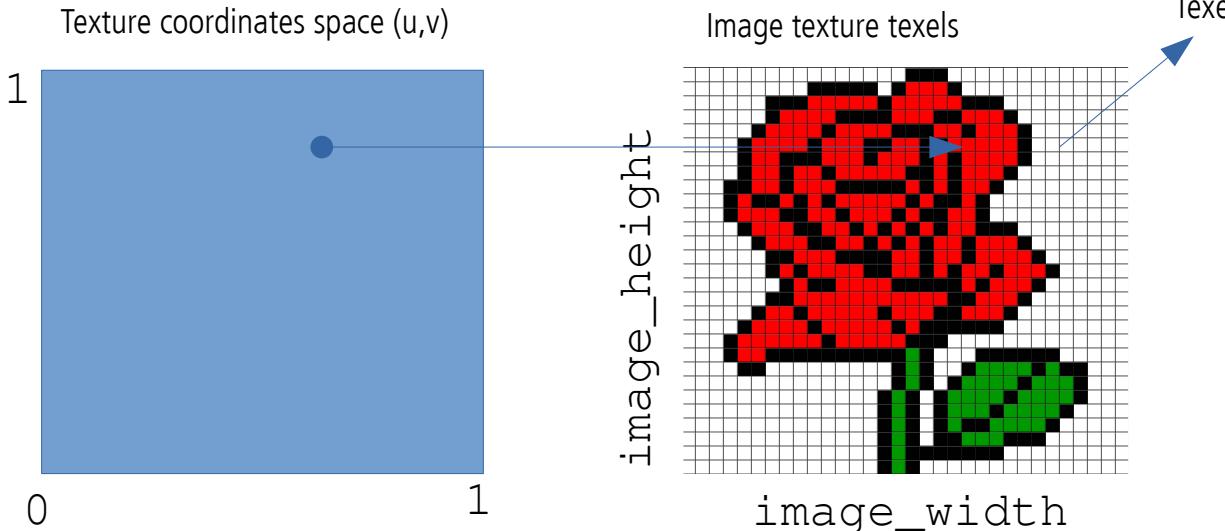
Examples of solid texturing: <https://johanneskopf.de/publications/solid/>

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

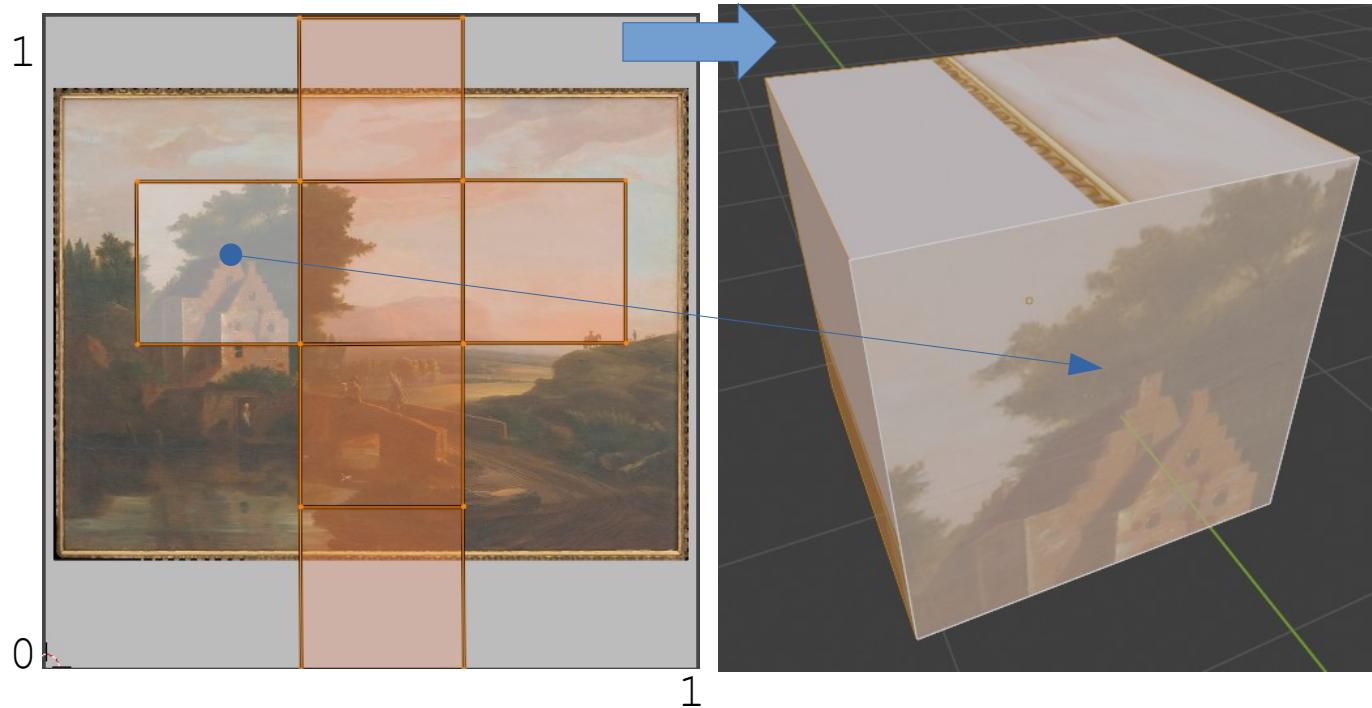
Corresponder function

- Transform: **texture coordinates (u, v)** in $[0, 1]$ \rightarrow image texture **texel locations (s, t)** in $[\text{image_width}, \text{image_height}]$
 - This transformation is independent of texture resolution! That is, image of any resolution can be used for sampling given texture coordinates.



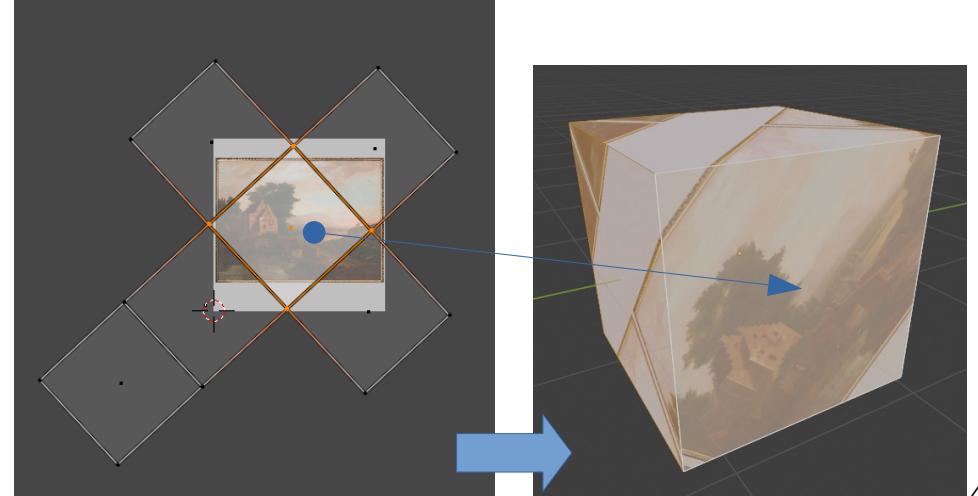
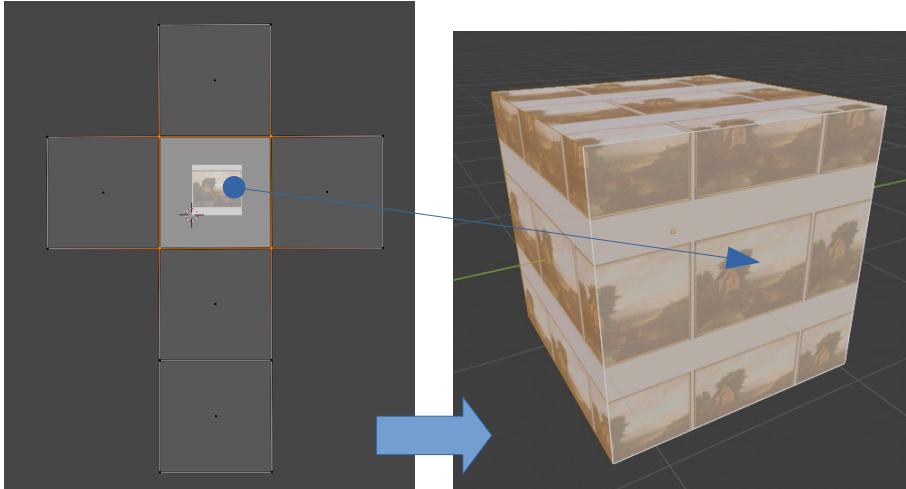
Corresponder function

- Corresponder function determines which part of image texture will be used



Corresponder function

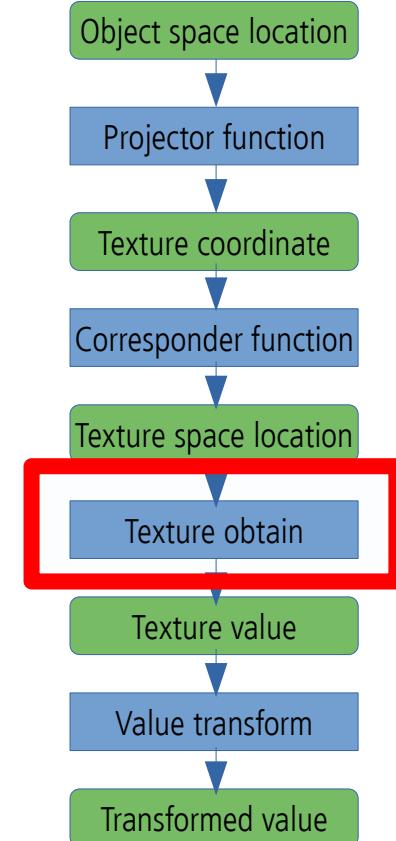
- Transformations on texture coordinates: rotate, scale, translate, shear or project
- Originally (u,v) is in $[0,1]$. Scaling can move (u,v) to be larger than one
 - Image wrapping: **repeat** (other: wrap, mirror, clamp, border, wang tiles, etc.)



Demo: <https://math.hws.edu/graphicsbook/demos/c4/texture-transform.html>

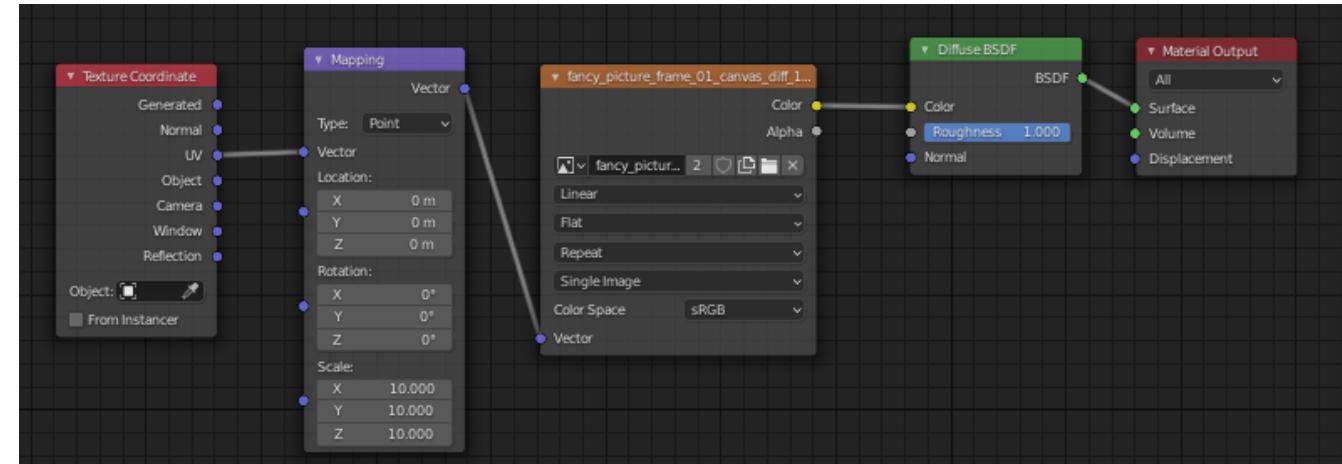
Obtaining texture values

- Texture space location is used for obtaining texture value:
 - Reading image texture
 - Evaluating procedural texture



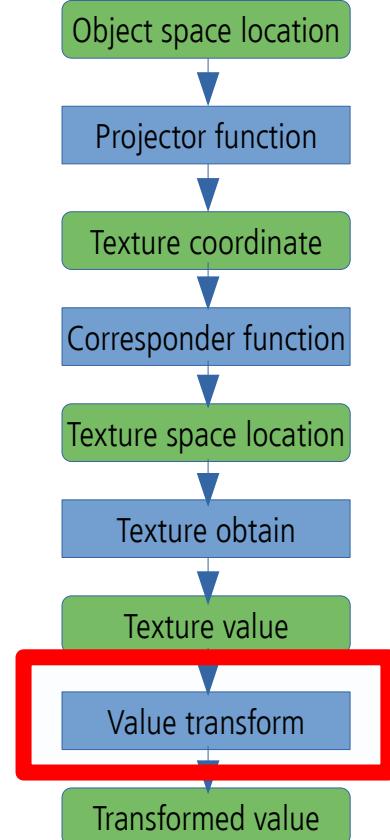
Obtaining texture values

- Correspondence function gave image texture texel coordinates
 - Those coordinates are used for reading texel values
- Note: procedural textures values can be obtained without correspondence function, e.g., directly from object or texture space coordinates



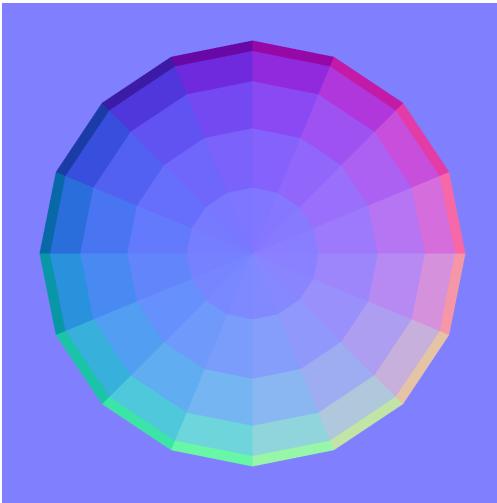
Transforming texture values

- Optional additional transformations on texture value
 - e.g., normalization of image texture values
- Image textures contain RGB(A) values
 - Many data types can be stored/encoded using those values.
 - Although image textures always contain color values, those values can be interpreted differently than just color

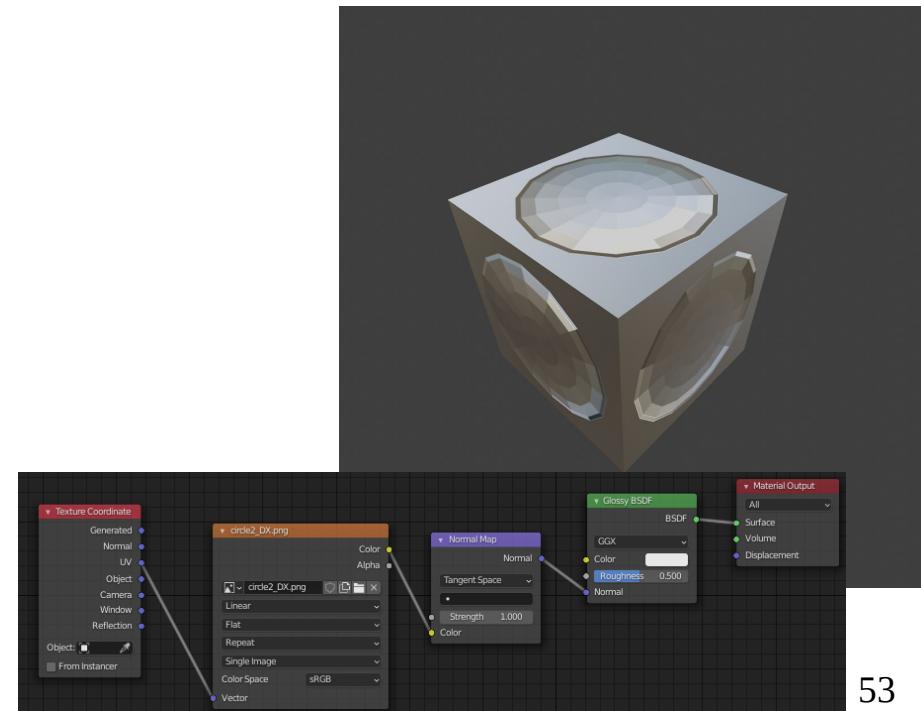
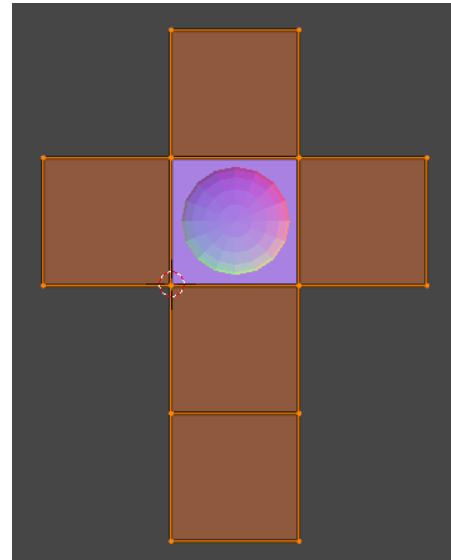


Transforming texture values

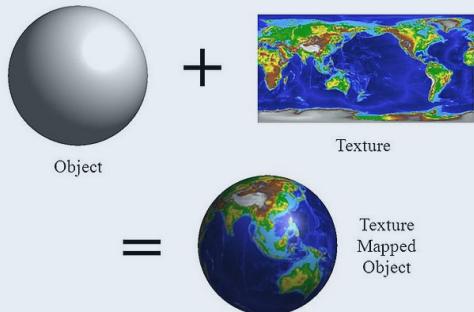
- Example: RGB values can be interpreted as vectors.
 - Normal map image texture contains vectors encoded in RGB



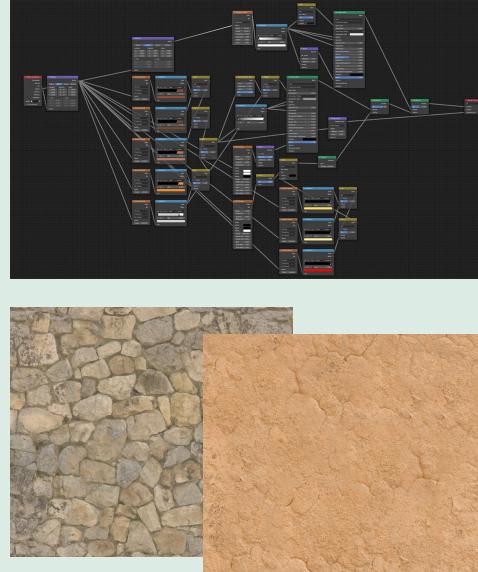
Example: encoding normal vectors
into image: **normal maps**



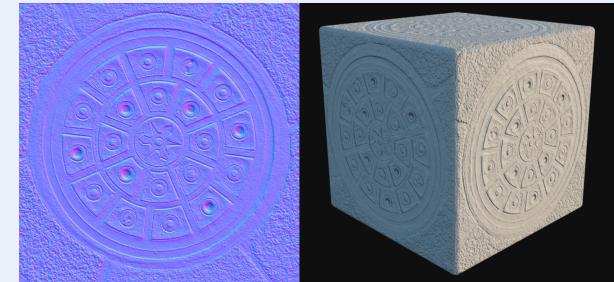
Learning objectives



How to apply textures on objects → **texturing pipeline**



Texturing approaches → **image and procedural**

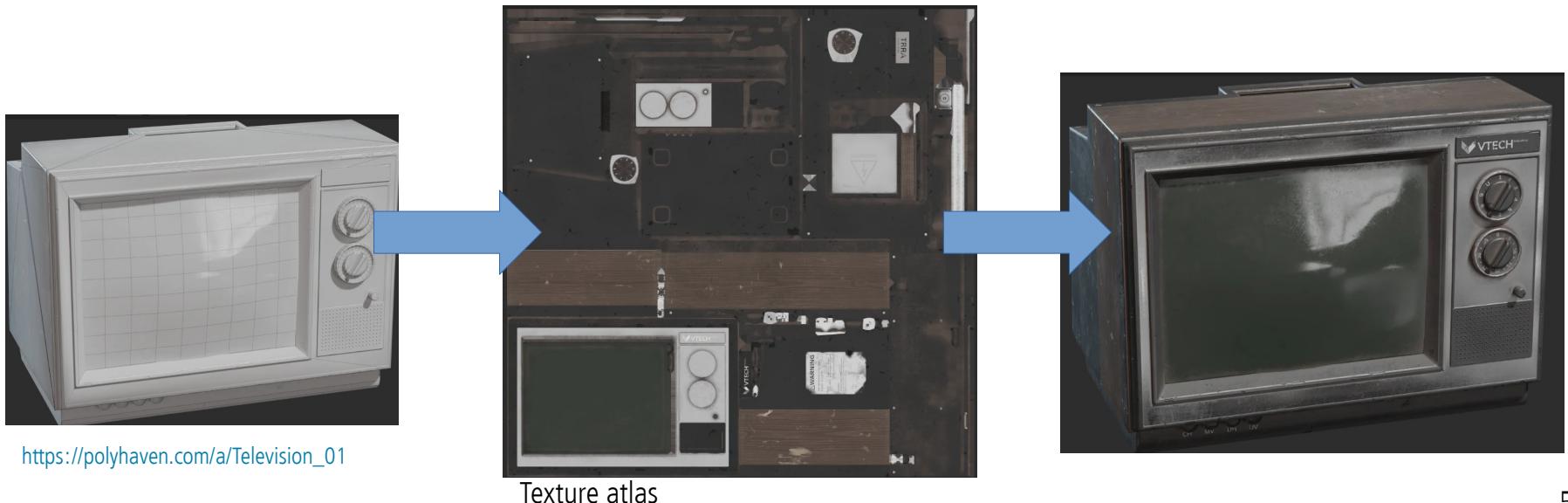


How to use texture for **material modeling** → variation of scattering function parameters and small scale geometry

Image textures

Image textures

- Image texturing process can be seen as “gluing” image on 3D surface
- For particular position on surface (x, y, z) we explained how to obtain texture coordinates (u, v)
- Image textures are usually $2^m \times 2^n$ texels. Thus called power-of-two textures (POT)*

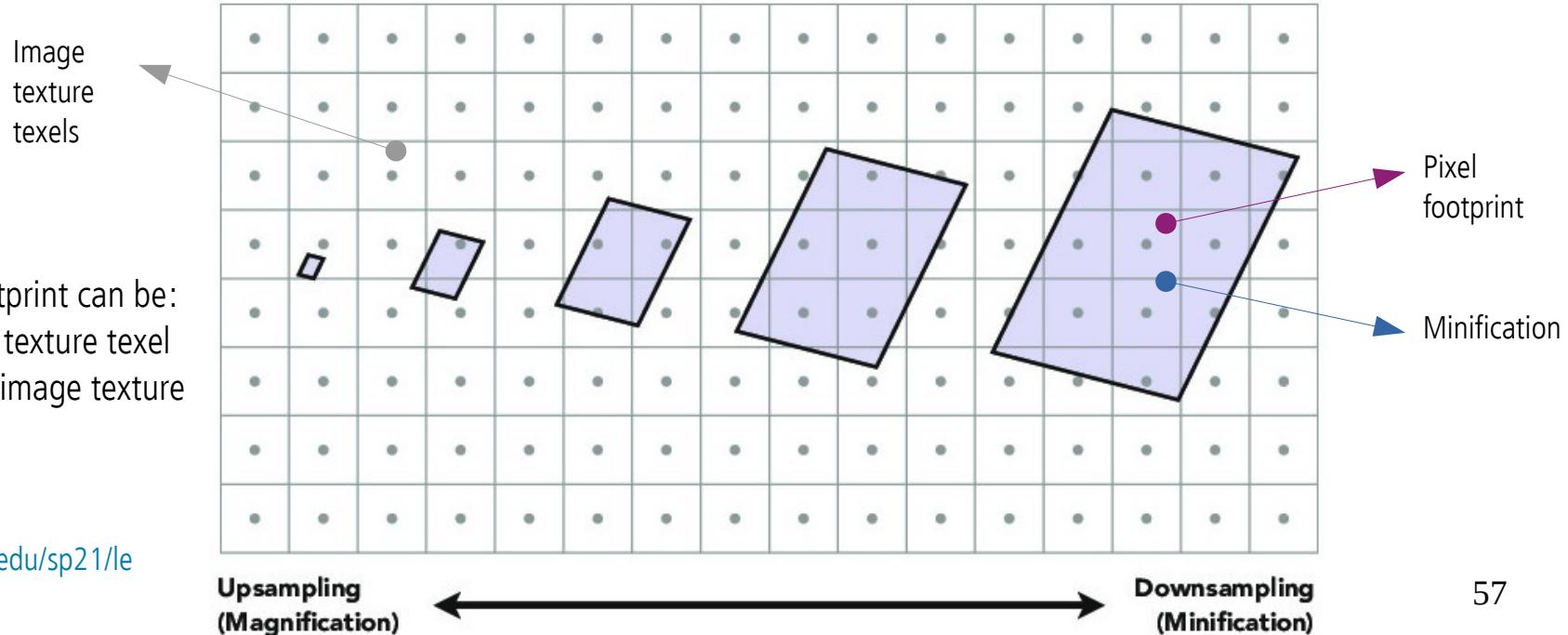


Magnification and minification

- If one or more pixels of virtual image plane falls under one image texture texel: **magnification**.
- If one pixel of virtual image plane covers more than one image texture texels: **minification**.

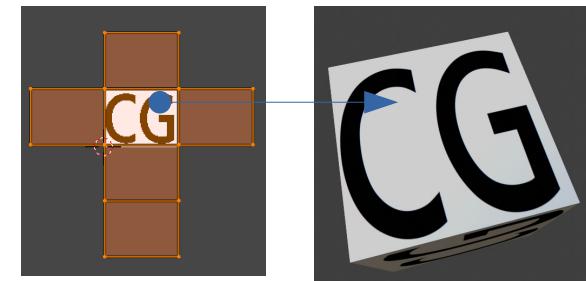
Virtual image pixel footprint can be:

- Smaller than image texture texel
- Larger than several image texture texels

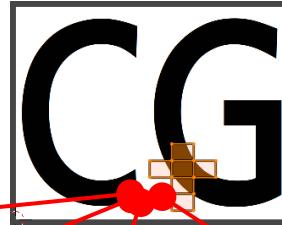


Texture magnification

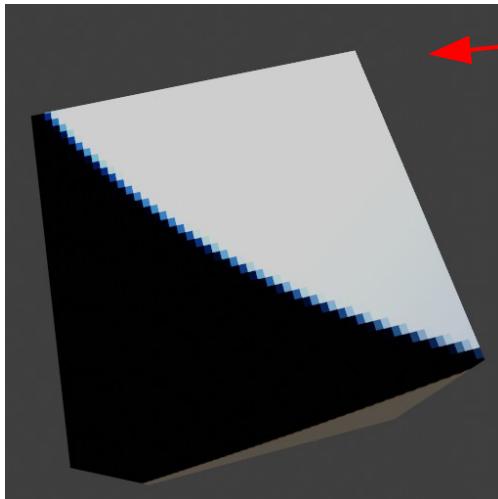
- System for reading image texture must magnify the image texture.
 - https://docs.blender.org/manual/en/latest/render/shader_nodes/textures/image.html
 - https://www.khronos.org/opengl/wiki/Sampler_Object
- Magnification types:



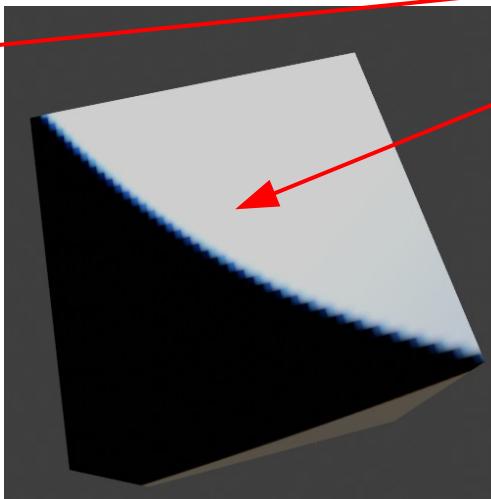
No texture magnification needed.



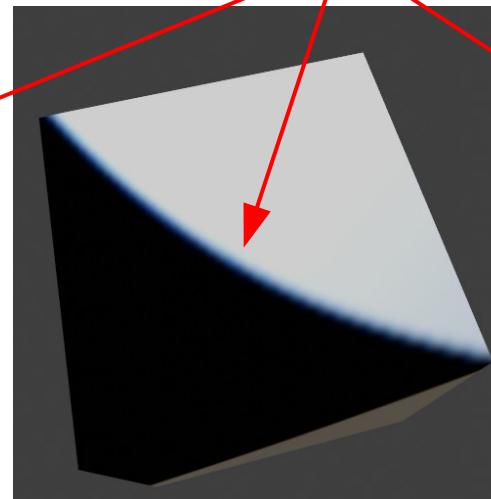
Texture magnification needed!



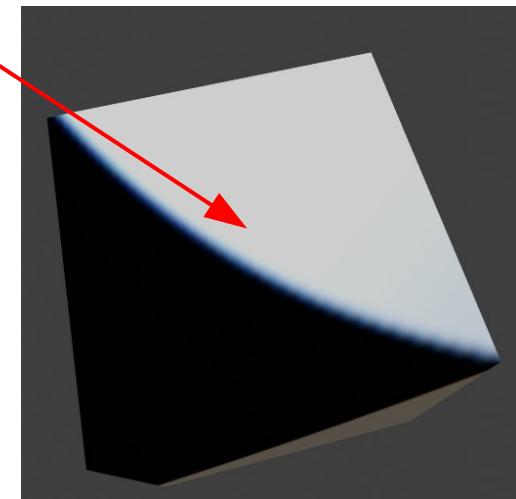
Nearest neighbor (closest)
Problem: pixelization



Linear



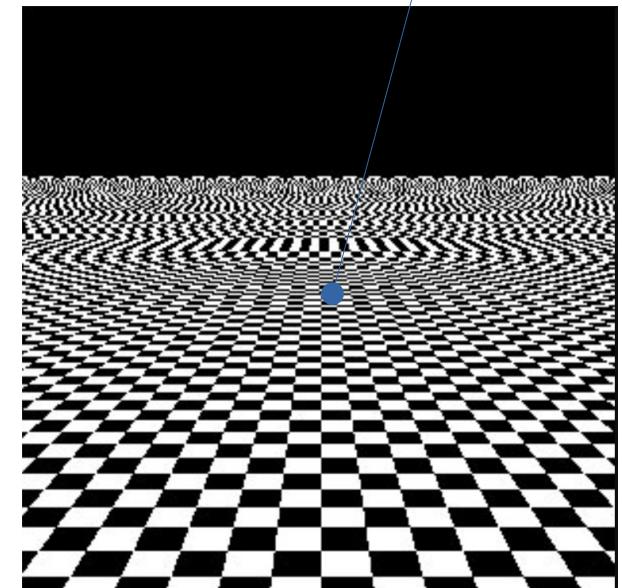
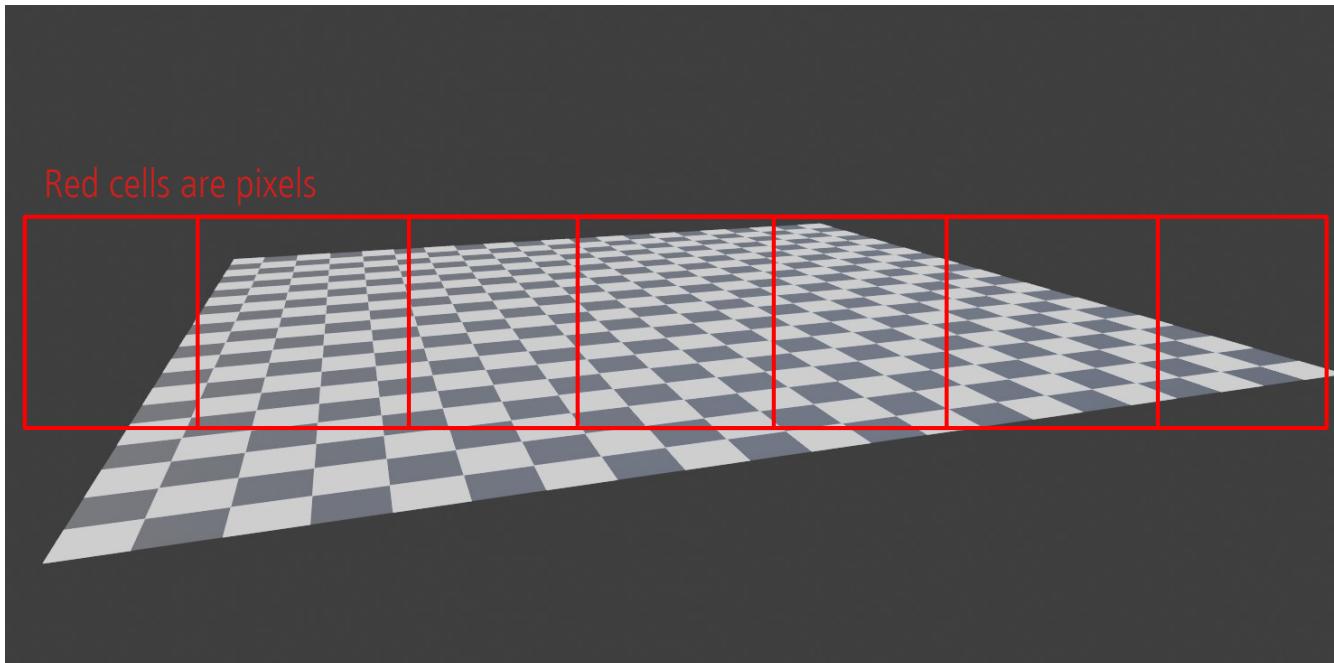
Cubic filtering



Bilinear interpolation
Problem: blur

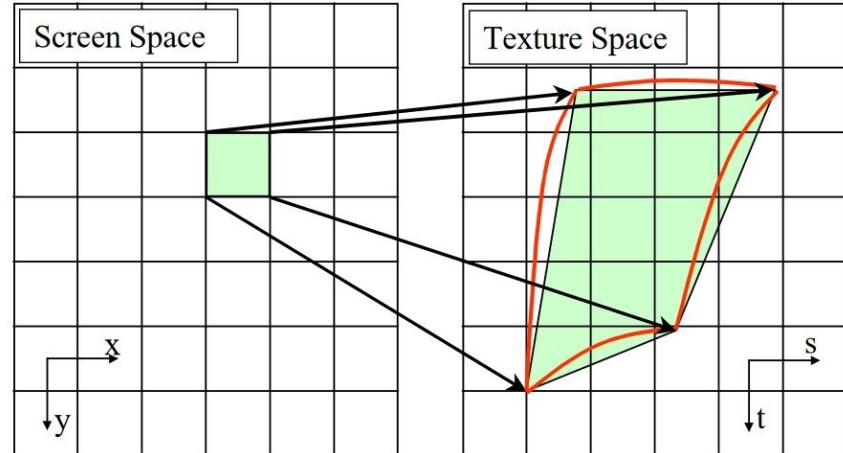
Texture minification

- If one pixel of virtual image plane covers more than one image texture texels → **minification**
 - 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



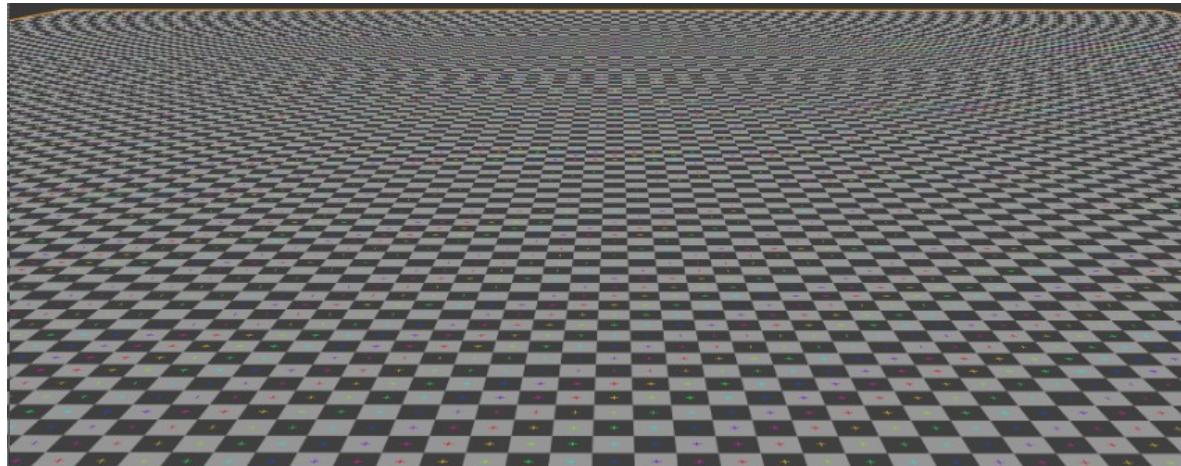
Aliasing

- 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
- Anti-aliasing techniques:
 - Texture frequency must decrease: **mip-mapping** - most popular anti-aliasing method
 - Pixel sampling frequency must increase: **multiple samples per pixel**



Minification

https://www.researchgate.net/publication/3410856_MIP-map_Level_Selection_for_Texture_Mapping



Anti-aliasing: mip mapping

- MIP – minimization filter

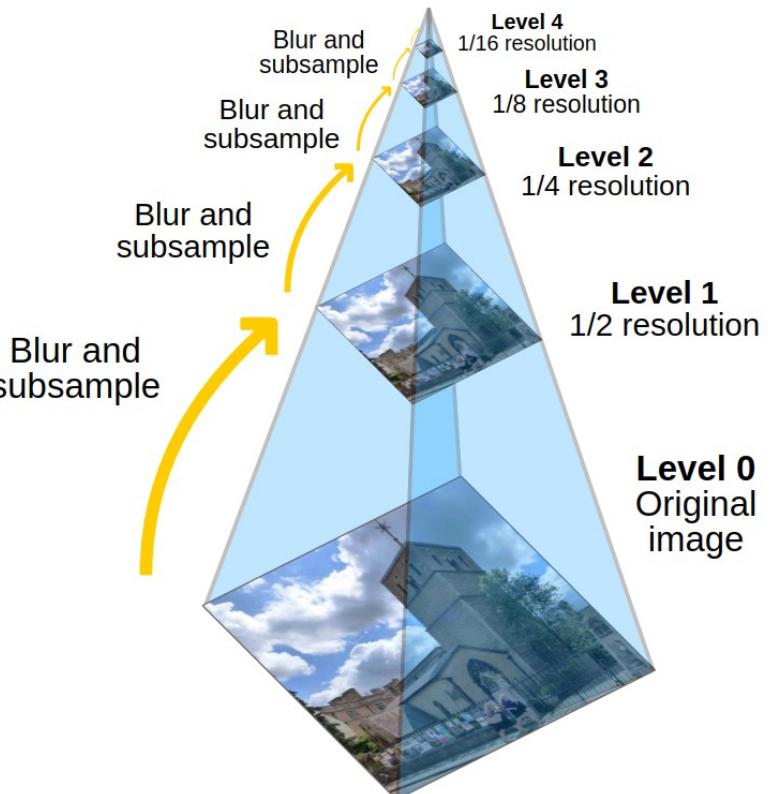
- Original image is filtered down repeatedly into smaller images.
 - Before rendering, original image is augmented with sets of smaller versions of this image

- Image pyramid, Mip map chain:

- Original texture is downsampled by quarter of original area
 - New texel is calculated as average of four neighbor texels in original image.
 - This process is repeated until one or both of image texture dimensions equal to one

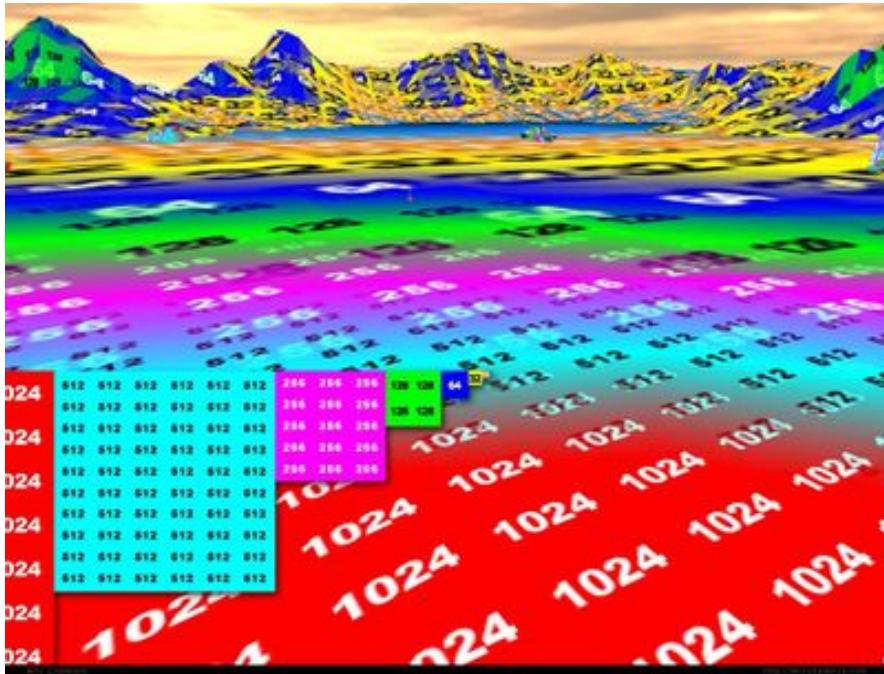
- High quality mip mapping requires:

- Good filtering: for averaging new texel value from 2x2 of texels it is recommended to use Gaussian, Lanczos or Kaiser filter
 - Images must be in linear colorspace

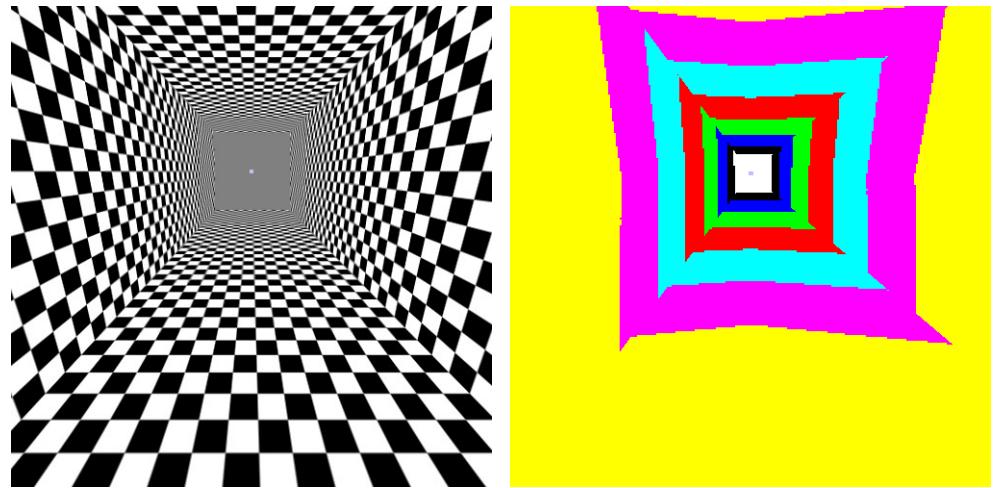


Anti-aliasing: mipmapping

- Depending on camera distance to texture, different mipmap levels are used to achieve 1:1 pixel to texel ratio to achieve Nyquist rate.
 - OpenGL: https://www.khronos.org/opengl/wiki/Sampler_Object



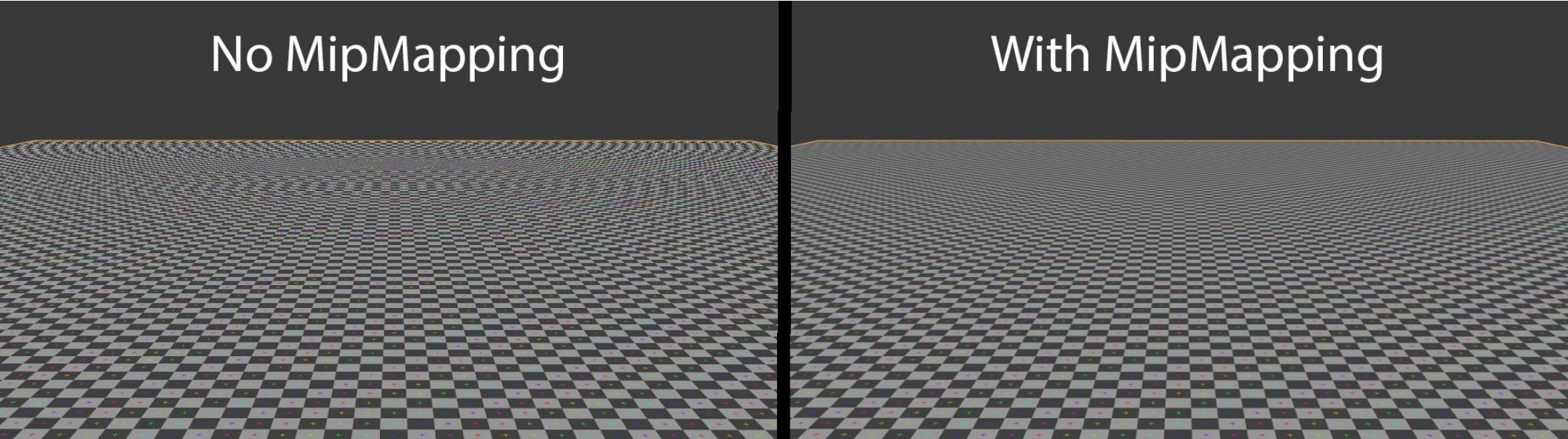
http://wiki.polycount.com/wiki/Mip_Mapping



<https://paroj.github.io/gltut/Texturing/Tut15%20Needs%20More%20Pictures.html>

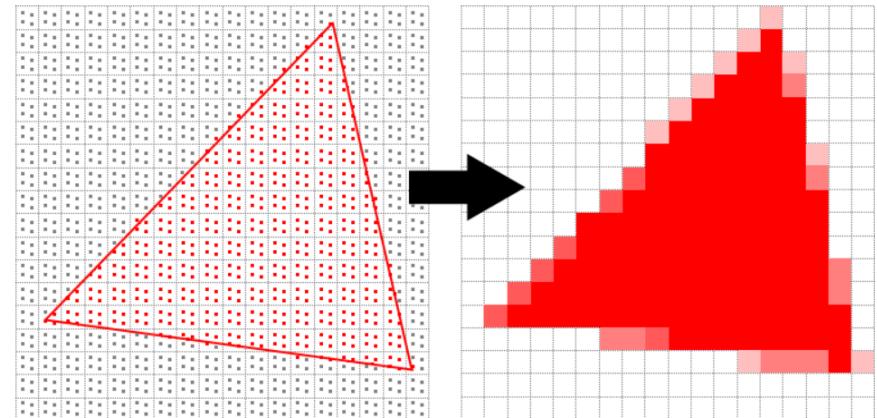
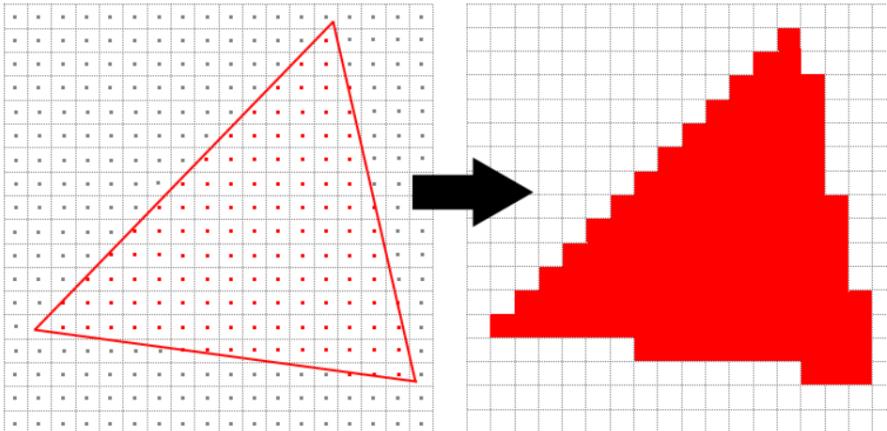
Anti-aliasing: mipmapping

- Achieving 1:1 pixel to texel ratio removes aliasing
 - Moire pattern is removed



Antialiasing: sampling

- If one pixel of virtual image plane covers more then one image texture texels → **minification**
- Aliasing appears always when there are a lot of details under a pixel footprint in the scene
- To solve this, multiple sample per pixels can be used to “catch” high frequency details.
 - This method is called Multisample anti-aliasing (MSAA)



MSAAx4

Alpha texture values

- Image textures have (R,G,B) and **alpha channels**.
- Alpha values are used for blending or alpha testing for transparency.



Decals/cutouts: rendering only parts of the image on object surface.

<https://xoio-air.de/2017/10-free-cutout-trees-from-tony-textures/>



Billboarding method is used for standalone flat polygons with image texture, always facing the camera.

<https://80.lv/articles/how-to-fake-a-large-scale-forest-in-blender/>



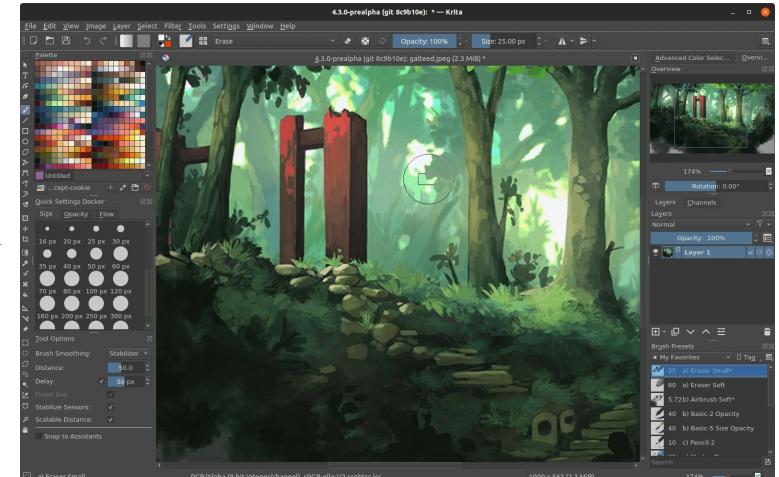
Alpha texture values

- Alpha value is extensively used when adding VFX to rendered or real images - **compositing**.

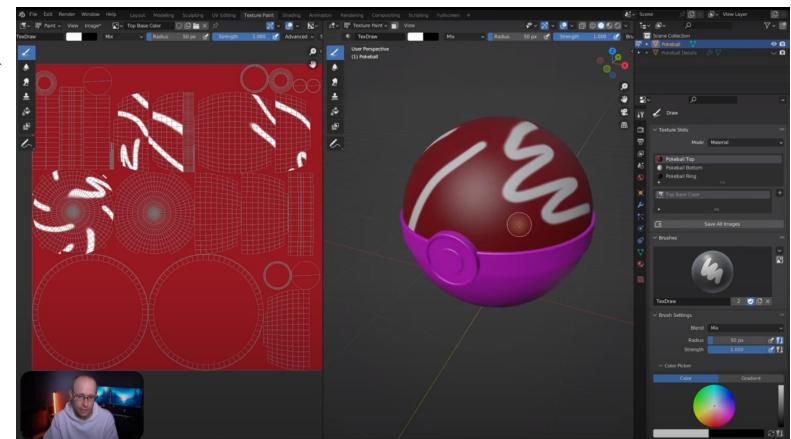


Sources of image textures

- Texture image can be created by:
 - Drawing on canvas: <https://krita.org/en/>
 - Drawing on 3D object directly:
https://docs.blender.org/manual/en/latest/sculpt_paint/texture_paint/index.html
 - Taking photographs
 - Performing measurements of real surfaces
 - Creating from existing geometry or surfaces (process called baking:
<https://docs.blender.org/manual/en/latest/render/cycles/baking.html>)
- Library of textures:
 - PolyHaven: <https://polyhaven.com/textures>
 - Substance library:
<https://substance3d.adobe.com/assets/allassets?assetType=substanceMaterial&assetType=substanceAtlas&assetType=substanceDecal>



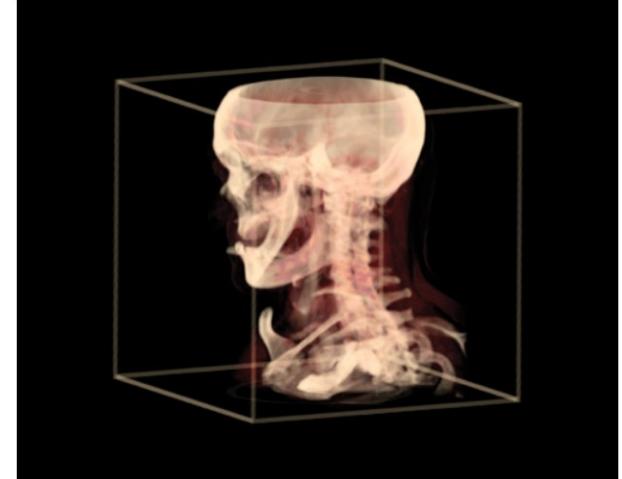
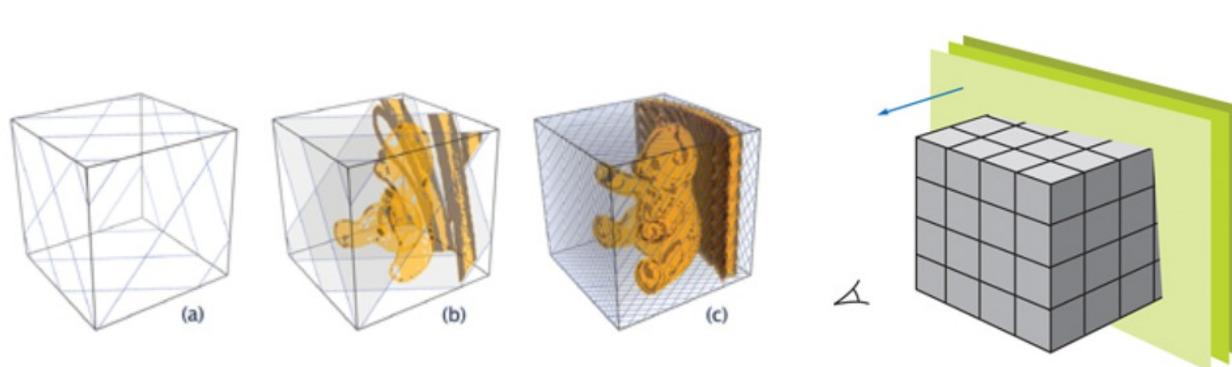
Painting on canvas



Texture painting on 3D object

Volume textures

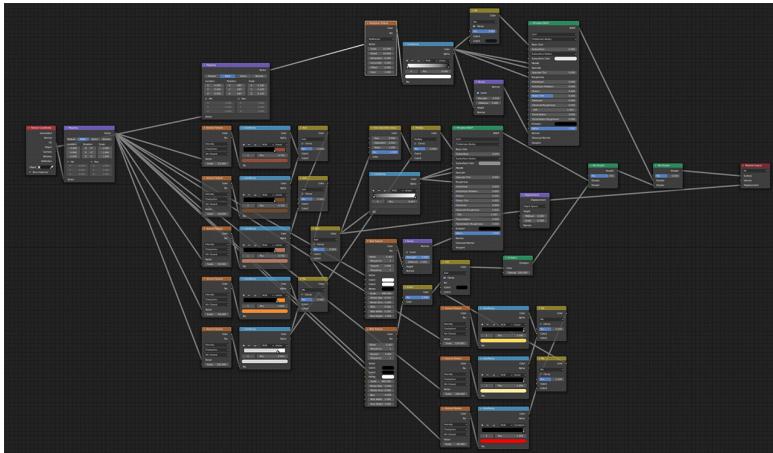
- Extension of 2D image is 3D image, accessed with (u,v,w) coordinates
- Object locations can be used as texture coordinates.
 - Complex problem of finding good 2D parameterize for 3D mesh is not needed
- Volume texture can represent volumetric structure of material such as wood or marble.
- Example: medical imaging data
 - Three dimensional grid is visualized as slices by moving polygon through it or using ray-casting.
- Problem: volumetric image textures are very space demanding



Procedural textures

Procedural textures

Umbrella term for a number of techniques in computer graphics to create 3D models and textures from sets of rules - code segments or algorithms that specify some characteristic of a computer-generated model or effect¹



1. Musgrave, F. K., Peachey, D., Perlin, K., & Worley, S. (1994). Texturing and modeling: a procedural approach. Academic Press Professional, Inc.

https://www.reddit.com/r/blender/comments/khkz98/finished_my_first_nodevember_li/

Procedural textures

- Texture values, instead of image lookup, are evaluated from a function
- Procedural texture defines values for every point in 3D space or 3D surface point → 3D solid textures
 - Parametrization of surface is therefore not needed



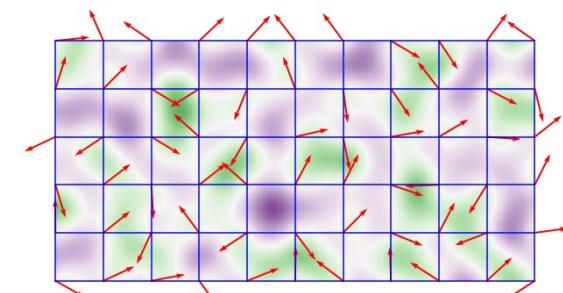
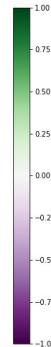
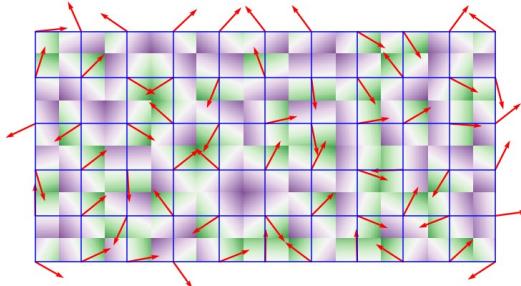
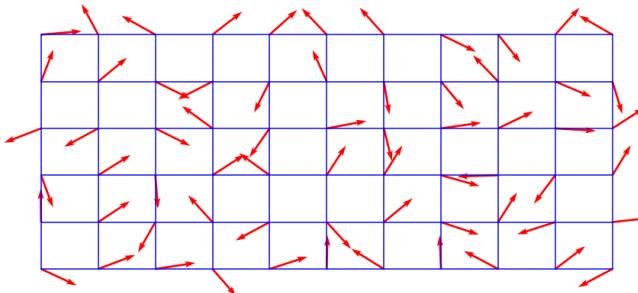
<https://www.rebelway.net/clouds-houdini-tutorial/>

Often based on **noise function**.

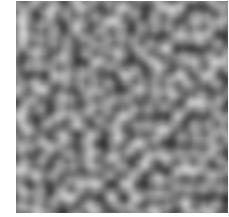
Often used for natural phenomena such as seas, clouds and mountains, etc.

Procedural textures: Perlin noise

- Property: **local changes are gradual, while global changes can be large**
- Most popular noise function upon which wide range of methods is built
- Type of **gradient noise**.
 - N dimensional grid where each grid intersection has associated n dimensional unit length gradient vector
 - To calculate point inside grid:
 - (1) find cell inside which point lies,
 - (2) calculate dot product of vector from this point to cell corner and gradient vector,
 - (3) interpolate dot products

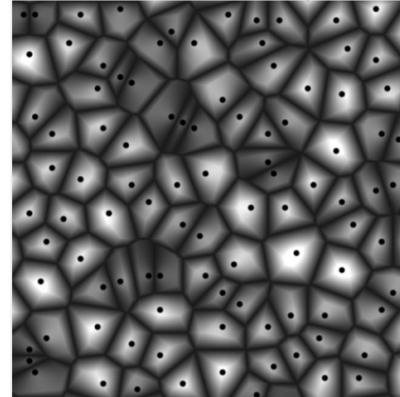
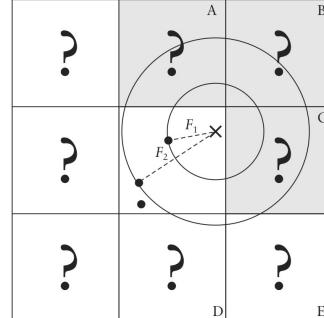
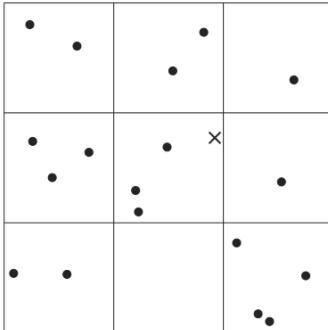


https://en.wikipedia.org/wiki/Perlin_noise



Procedural textures: Cellular texture

- Steven Worley introduced **Voroni-like textures** that can be used for many natural textures: **cells, flagstones, lizard skin, etc.**
 - Another fundamental procedural texture upon which more complex procedural textures are built
- This method is based on **measuring distance from feature points**
 - Space is diced into cubes. Each cube contain random feature points.
 - For current point, find cube inside which lies and check distance to feature points in this and neighboring cubes.
 - First distance is used as value. More combinations with distances are possible.

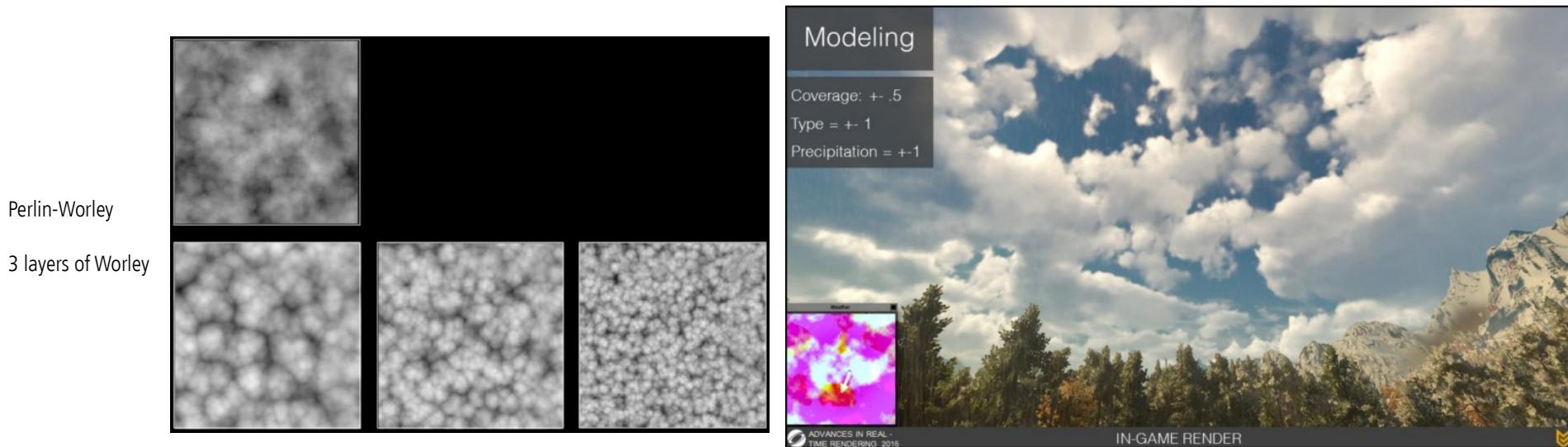


<https://thebookofshaders.com/12/>

1. Musgrave, F. K., Peachey, D., Perlin, K., & Worley, S. (1994). Texturing and modeling: a procedural approach. Academic Press Professional, Inc.

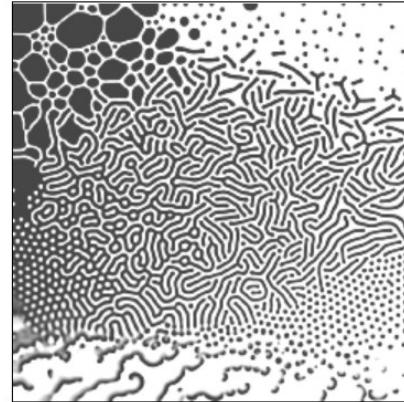
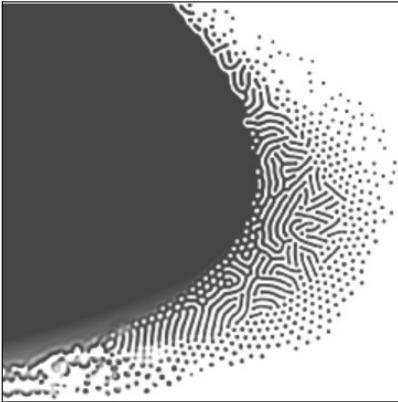
Noise in production

- More complex types of noise are built using Perlin and Worley noise:
 - Fractal noise
 - Simplex noise
- Combining Perlin and Worley noise is often used for more richer details.
- Volume textures are attractive application for procedural texturing since they can be synthesized on the fly

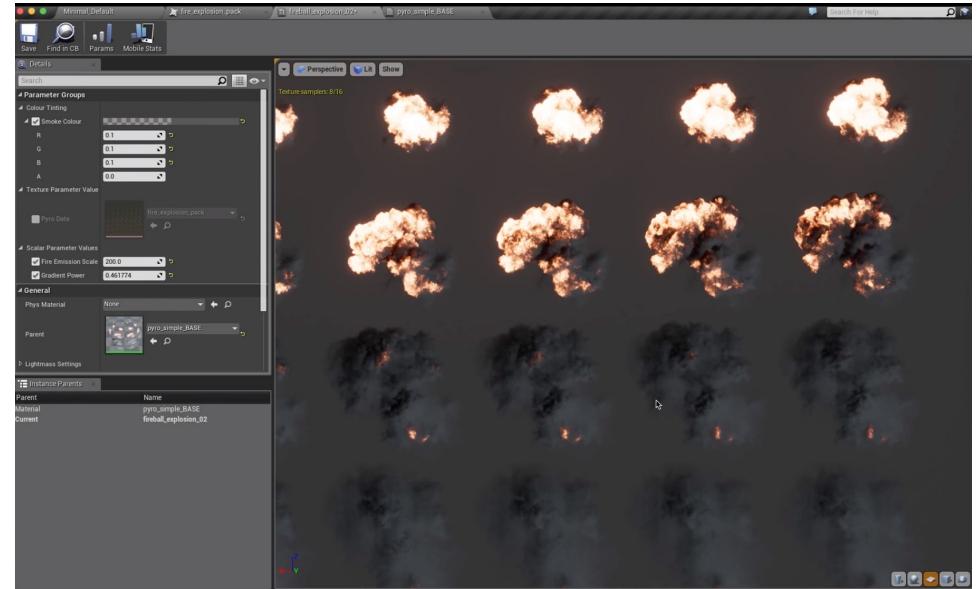


Procedural texture: physical simulation

- Perlin and Cellular textures are mathematical models and phenomenological models for representing natural phenomena
- Physically based simulation can also be used to create textures
 - Reaction-diffusion model
 - Fluid simulation to texture



Reaction-diffusion model: <https://www.karlsims.com/rd.html>

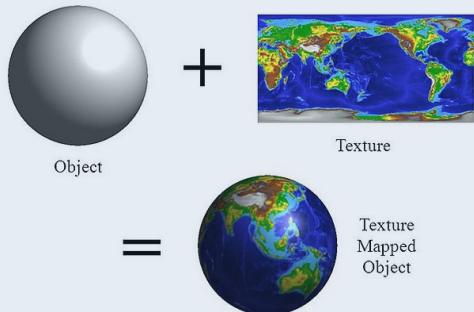


Fluid simulations:
<https://www.sidefx.com/ja/tutorials/channel-packing-pyro-data-using-the-texture-sheets-rop/>

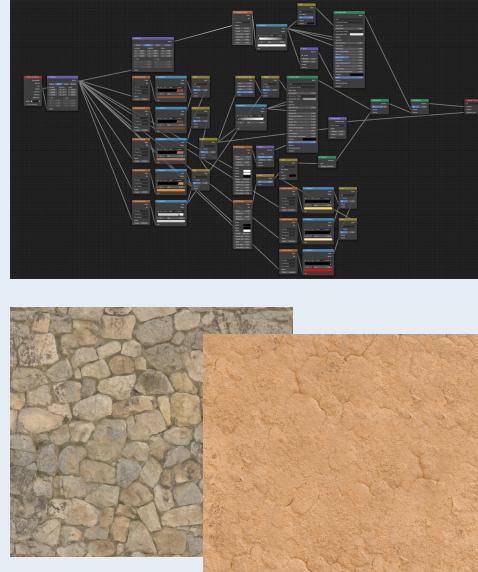
Procedural textures: Antialiasing*

- Procedural texturing is much more popular in offline applications while in real-time rendering image textures are far more common
 - GPUs are extremely efficient with image textures for which antialiasing is also easier
- Antialiasing can be hard for procedural textures
- 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

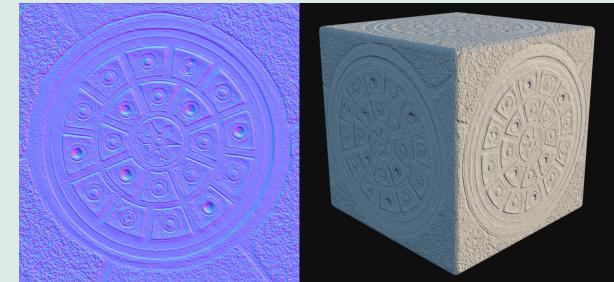
Learning objectives



How to apply textures on objects → **texturing pipeline**



Texturing approaches → **image** and **procedural**

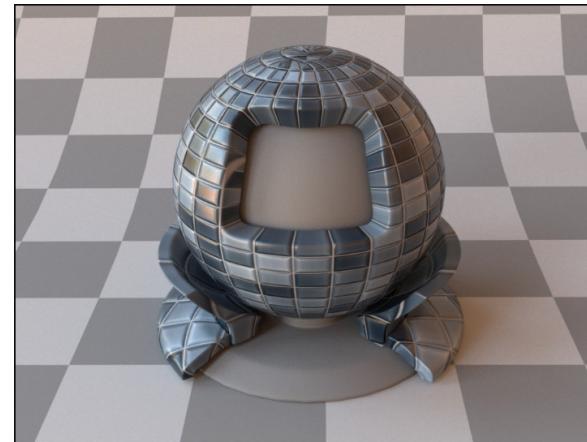


How to use texture for **material modeling** → variation of scattering function parameters and small scale geometry

Textures and material modeling

Usage of texture values

- Texture is used for **varying material parameters** over surface:
 - Scattering function parameters: color, reflectance, roughness, etc.
 - Small scale surface geometry: bumps, irregularities, etc.

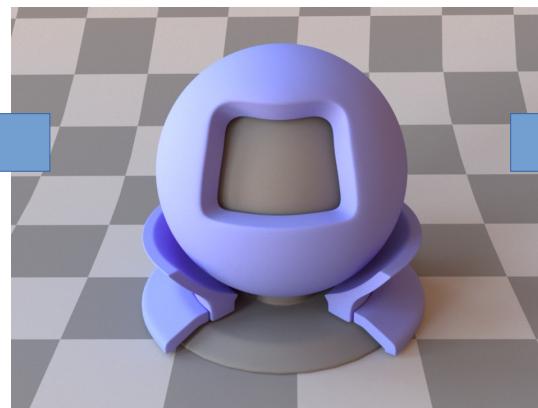


Varying scattering function parameters

- Texture can be used to vary scattering function parameters over surface
- Texture variation of color, reflectance, roughness, etc.



Diffuse scattering model (Lambertian)
with varying albedo (color) parameter
using texture



Diffuse scattering model (Lambertian)
with constant albedo (color) parameter



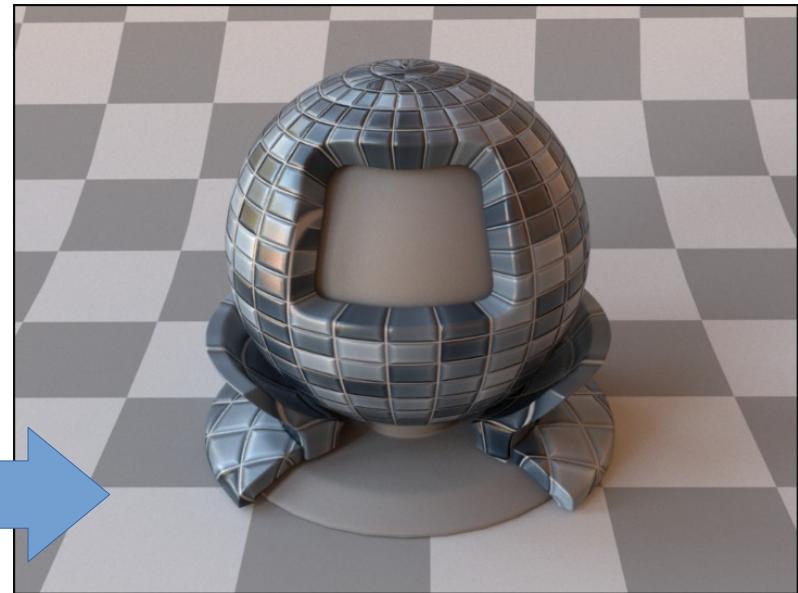
Diffuse scattering model (Lambertian)
with varying albedo (color) parameter
using texture

Varying small scale surface geometry

- Texture can be used to represent small-scale surface details/geometry.
- Texture is employed in shading step during rendering to give more richer 3D appearance than just color
 - Surface doesn't appear smooth



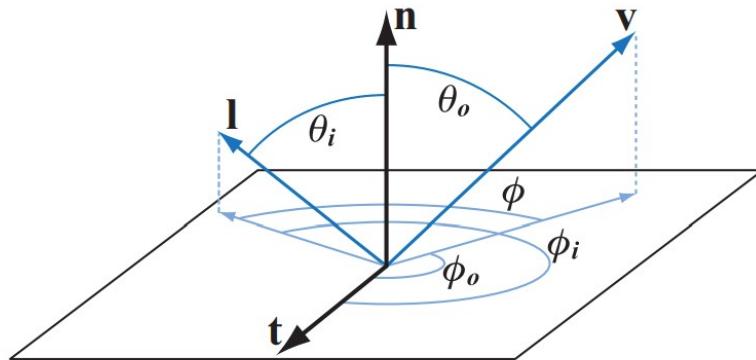
Glossy scattering model (Lambertian) with **varying color parameter using texture**



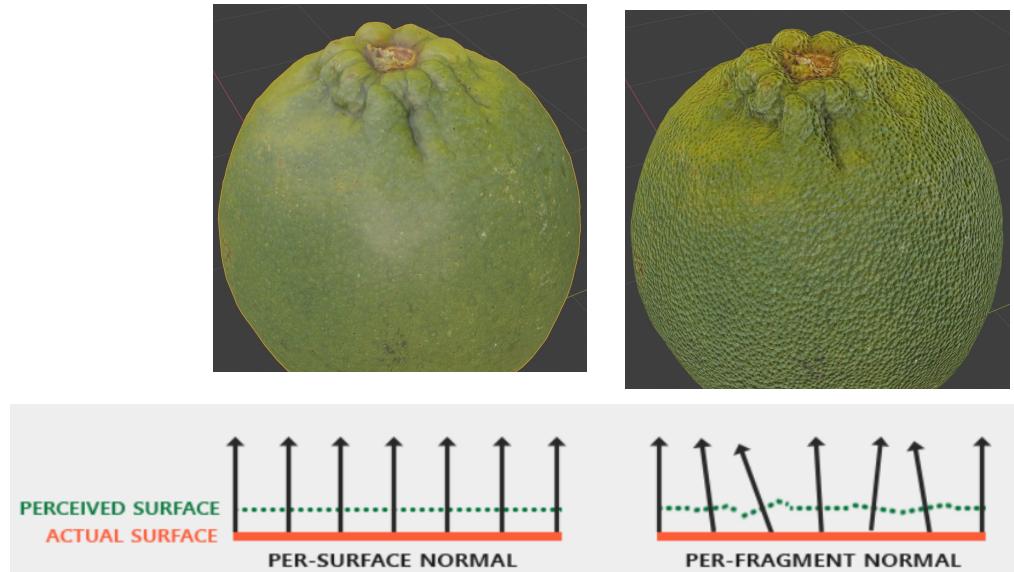
Glossy scattering model (Lambertian) with **varying color and surface details using texture**

Small scale surface geometry

- Texture values are used for perturbing surface or surface normal
 - Perturbing surface or surface normal causes perturbing of BSDF basis and results in variation in light reflection



Besides incoming and outgoing direction, scattering function (BRDF) depends on surface normal.



Small-scale geometry: scale of modeling

Macro-features: cover many pixels.

- Represented by **model shape** (e.g., polygonal mesh).
- Example: pillars

Micro-features

- Described with **scattering function and texture**
- Simulates the microscopic response of surface geometry and substance
- Example: glossy and diffuse effects are modeled on micro-scale

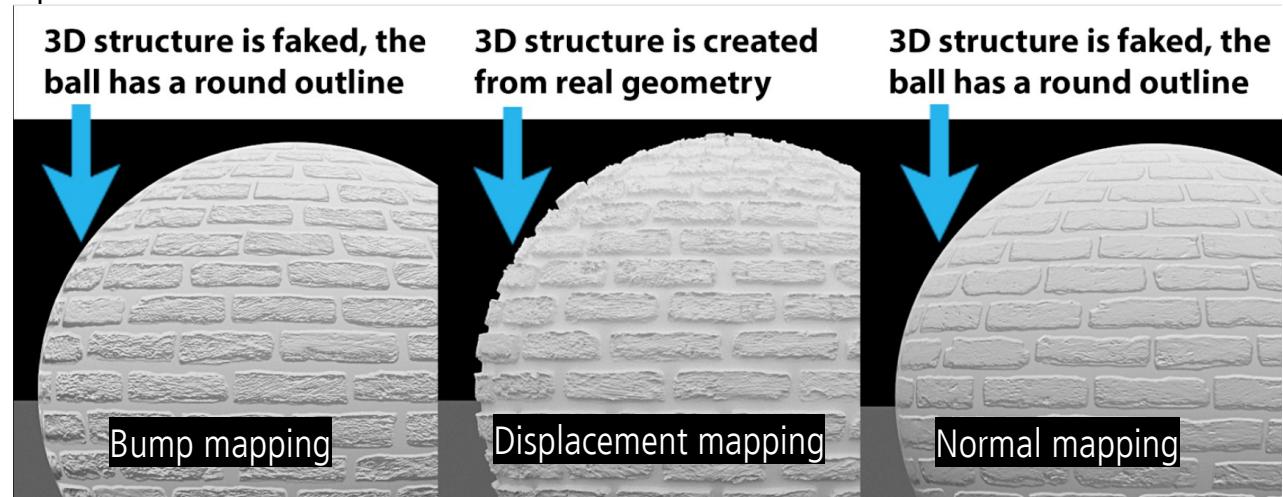


Meso-features: cover few pixels

- Everything between two scales.
- Represents detail that is too expensive for shape representation (e.g., polygonal mesh) but large enough to be observable.
- Example: brick bumps and dents
- For this scale family of **bump mapping methods** is used

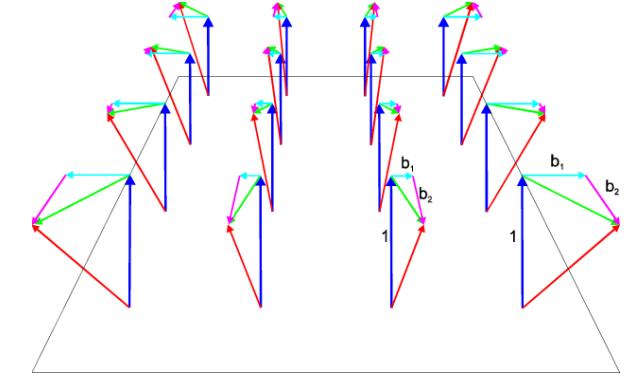
Small-scale geometry variation

- Methods which do not introduce additional geometrical information. Only approximation to achieve desired surface details:
 - Bump, normal mapping
 - Parallax mapping
- Methods which introduce/require additional geometrical information. Give more realistic surface appearance but are computationally expensive:
 - Displacement mapping



Bump mapping

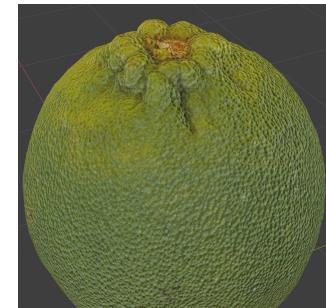
- Idea (**Blinn method**):
 - Surface will appear to have small scale details if normal is slightly perturbed
 - Geometry is not changed!
- Information for perturbing surface normal can be encoded in image texture as color or procedural texture.
- Original bump mapping – **offset vector bump map**
 - Two signed values are stored per texel in image texture – the amount of normal to be varied in u and v image axis
 - Those values are used to scale vectors perpendicular to normal (tangent and bitangent) and are added to normal to change direction



https://www.researchgate.net/publication/228890410_Antialiasing_of_Bump_Maps



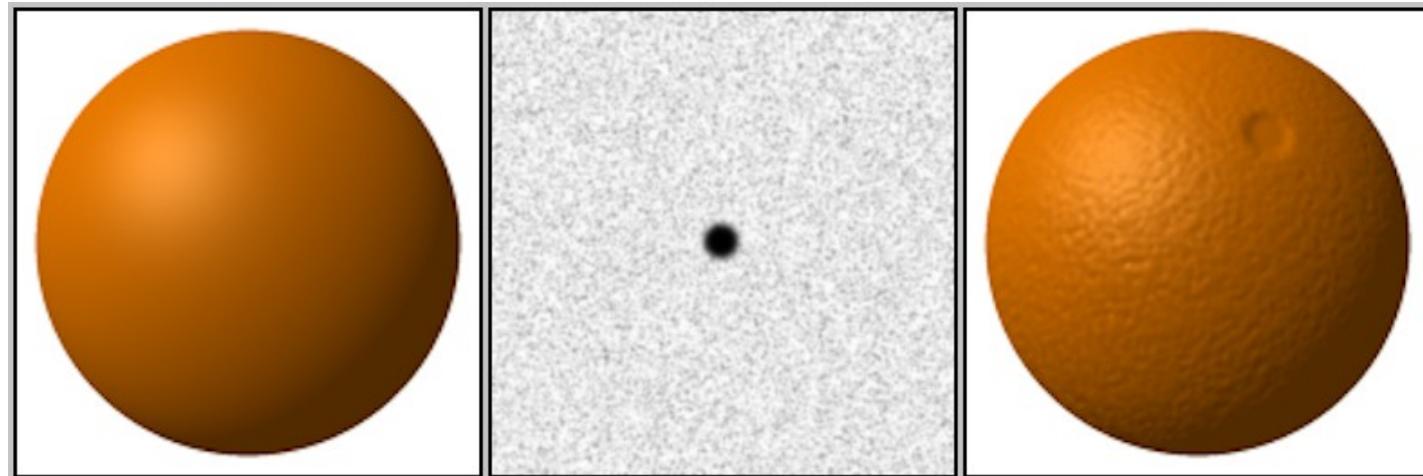
Original surface
normal



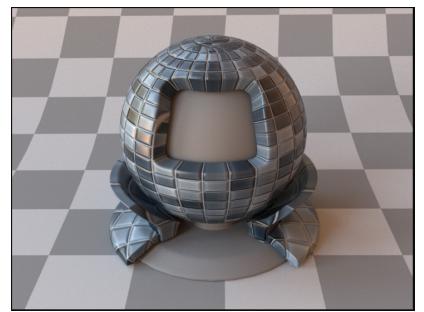
Perturbed surface
normal

Bump mapping

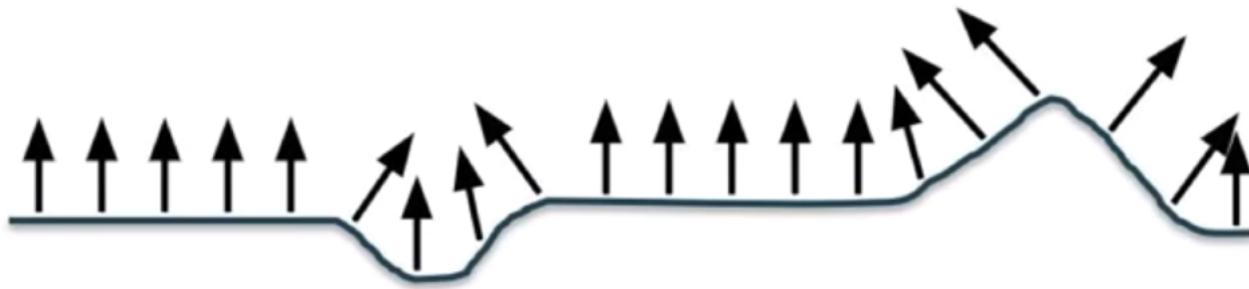
- Modern approach is to use **heightfield** to modify surface normal direction
- **Image texture contains one floating point number per texel representing height**
 - Brighter color: higher values
- Height values are used to derive u and v signed values similar to those in original method – this is done by taking differences between neighboring columns or rows to obtain u and v (e.g., Sobel filter)



Bump mapping



- Actual geometrical details are simulated by just perturbing surface normals
- No additional geometry is added!



Actual surface with actual geometrical details and corresponding normals.

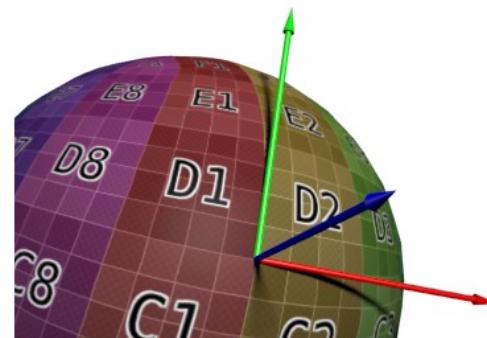
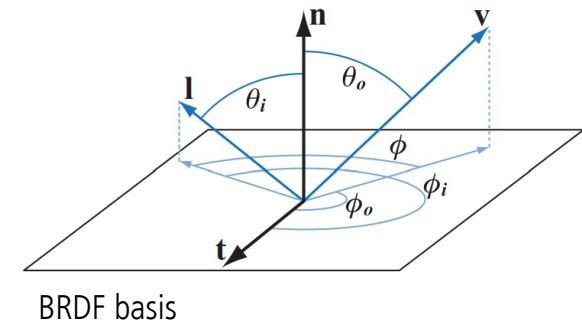


Simulated geometrical details perturbing normals

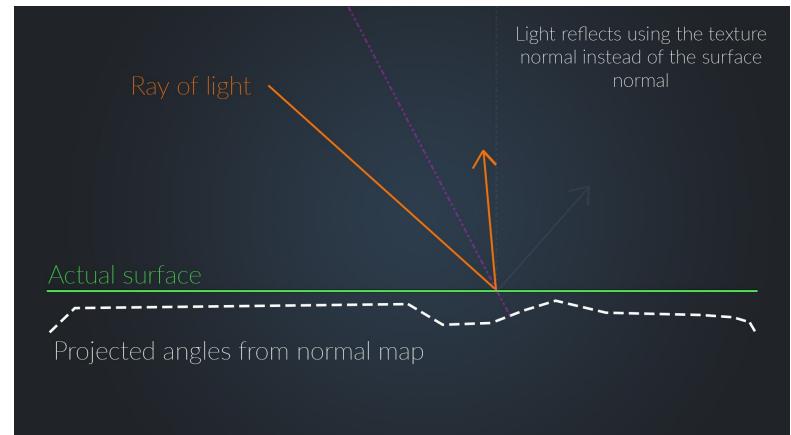
Bump mapping: basis modification

- Perturbing surface normal must be done with respect to some frame of reference: tangent frame
- Scattering model is evaluated on basis created from surface normal
 - Perturbing the basis by perturbing the normal we achieve different incoming light and viewing directions for 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 **anisotropic** surfaces

Re-read



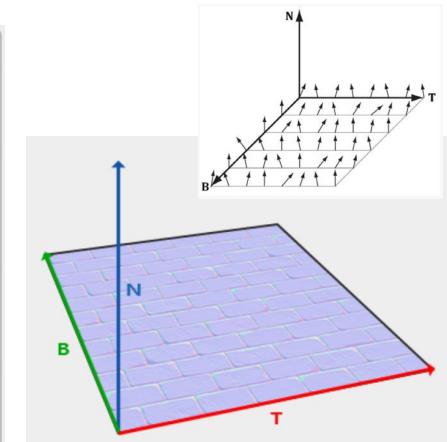
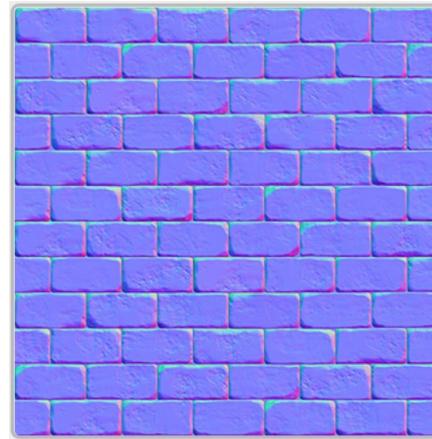
Tangent frame:
<http://www.opengl-tutorial.org/intermediate-tutorials/tutorial-13-normal-mapping/>



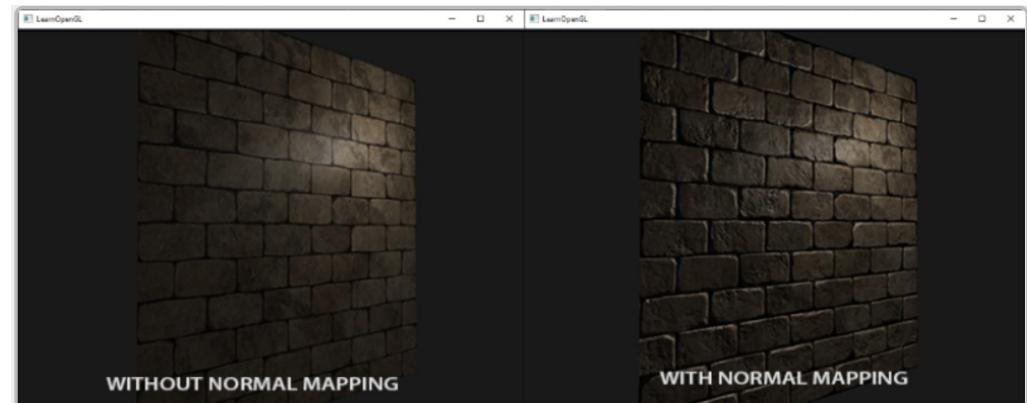
[https://c\(cookie.com/posts/normal-vs-displacement-mapping-why-games-use-normals](https://c(cookie.com/posts/normal-vs-displacement-mapping-why-games-use-normals)

Normal mapping

- Normal vectors are 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 (R, G, B) image texture
 - For PNG images, 8bit unsigned int is used.
Therefore, conversion $[-1, 1] \rightarrow [0, 255]$ is performed
- Normal map are often defined in **tangent space**
 - Color of normal map is determined with (x, y, z) directions of encoded vectors



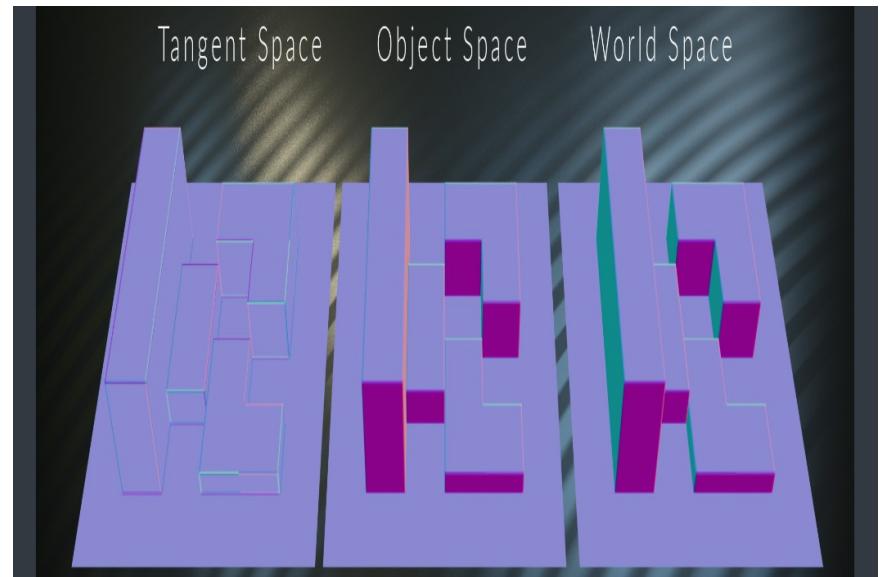
<http://ycpcs.github.io/cs470-fall2014/labs/lab12-2.html>



<https://learnopengl.com/Advanced-Lighting/Normal-Mapping>

Normal map types

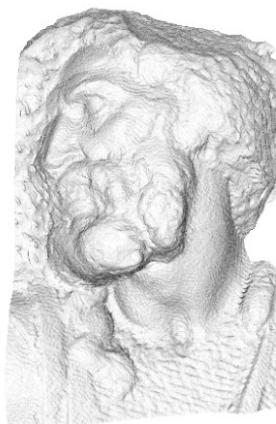
- **Tangent space:** based on tangent direction of face.
Normal map can be then maximally reused for different objects, transformations and deformations.
 - Blue: normal direction
 - Red: left/right tangent direction
 - Green: up/down tangent direction
- **Object space:** based on entire object rather than each face individually
 - Faster to compute, tied to particular model which can not be deformed
- **World space:** based on global coordinates
 - Object must not be rotated
 - Useful for large, static environment objects



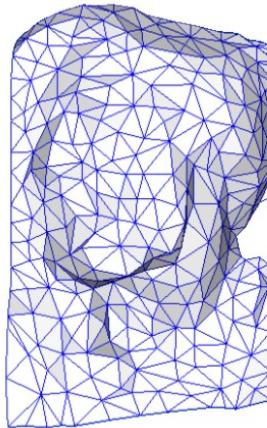
<https://cgcookie.com/posts/normal-vs-displacement-mapping-why-games-use-normals>

Normal mapping

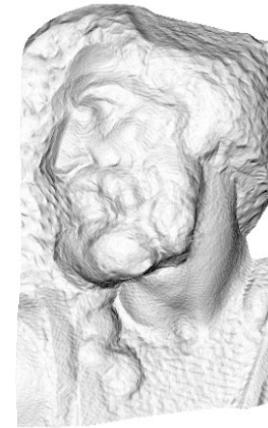
- Advantage of normal (and bump) mapping is that complex geometry can be represented in cheap way.



original mesh
4M triangles



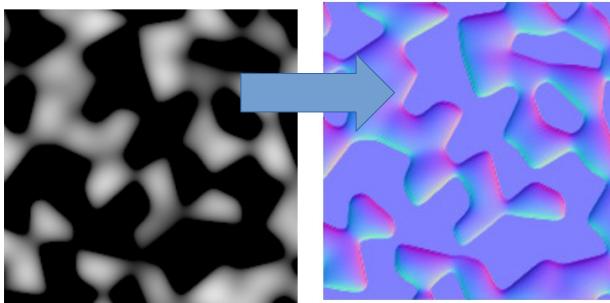
simplified mesh
500 triangles



simplified mesh
and normal mapping
500 triangles

<https://helpx.adobe.com/substance-3d-painter/using/baking.html>

Creating bump/normal maps



Normal map can be derived from height map.

Scanning heights from real world and converting them to normal map.

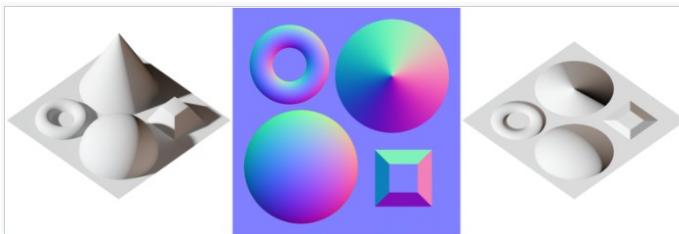
Image editing/painting software: converting photo textures into normal maps, procedural normal map images, hand-painting normal maps

<https://docs.gimp.org/2.10/en/gimp-filter-normal-map.html>



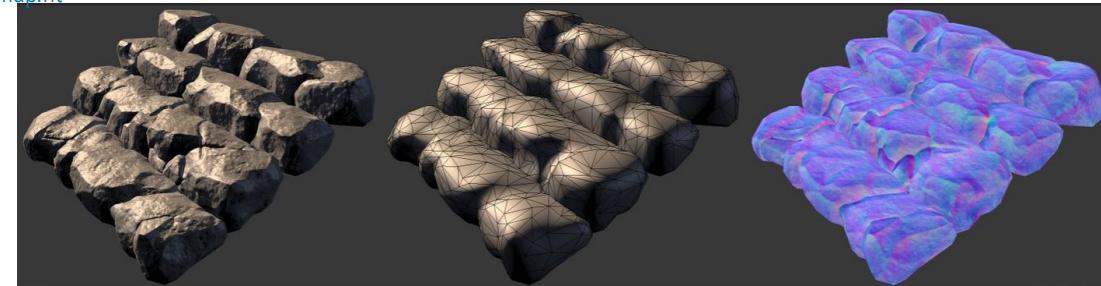
edit

https://docs.krita.org/en/reference_manual/brushes/brush_engines/tangen_normal_brush_engine.html



Normal map baked from geometry

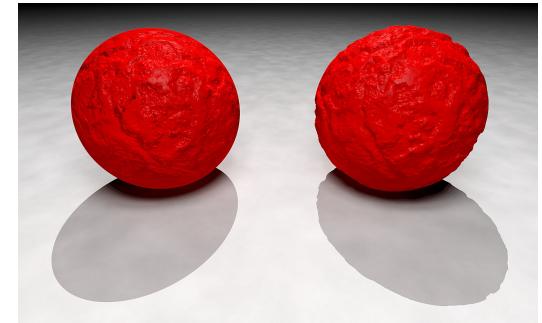
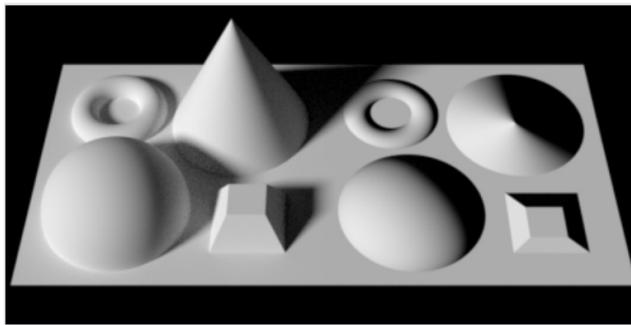
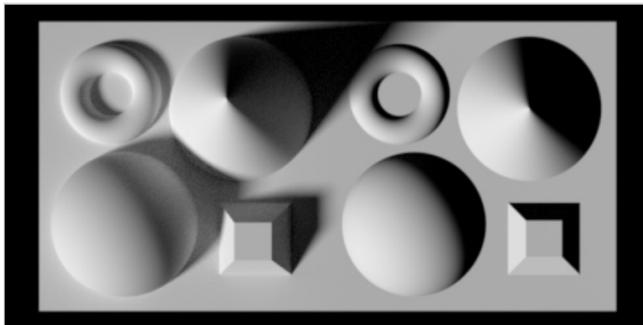
https://en.wikipedia.org/wiki/Normal_mapping



- Baking normal maps from high quality 3D models (often done for real-time graphics applications)
http://wiki.polycount.com/wiki/Normal_map

Bump and Normal mapping: practical notes

- Relationship between normal and shaded color is not linear*. Therefore, filtering of normal maps for **anti-aliasing** requires additional work.
- 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.



Comparison of real geometry and normal mapped geometry https://en.wikipedia.org/wiki/Normal_mapping

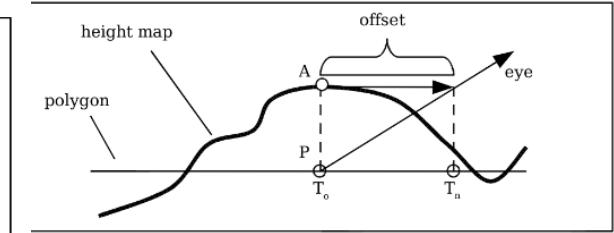
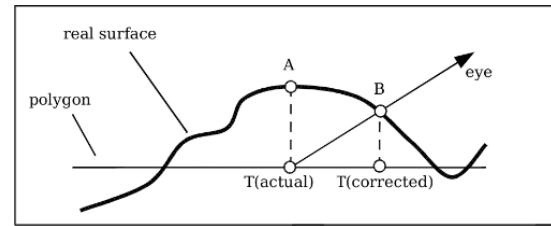
Normal mapped surfaces do not have real geometrical deviation
https://en.wikipedia.org/wiki/Bump_mapping

* 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 lambertian shading is based on dot product with normal which is linear operation.

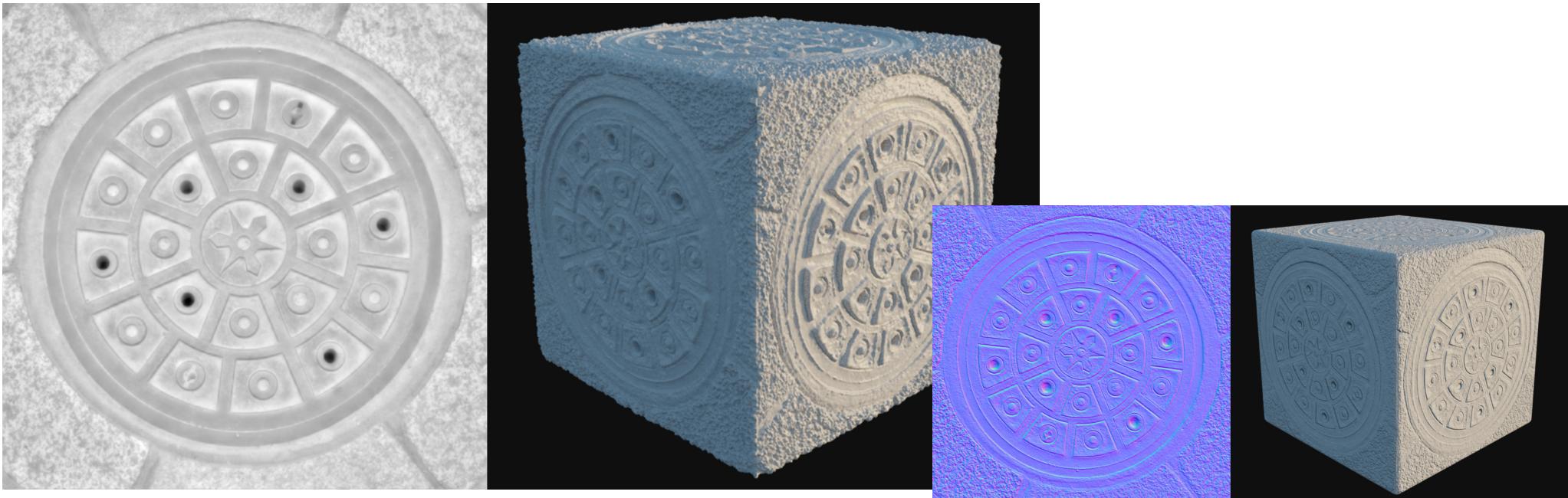
** Generally, when light falls on surface with bumps, multiple scattering, masking and shadowing effects happen which are not possible with normal mapping.

Parallax mapping

- Bump and normal mapping never shift location with the view angle, nor block each other
- Parallax: positions of objects move relative to one another as the observer moves
- Parallax mapping: approximation technique which is offsetting texture coordinates based on height: what should have been seen in pixel by examining the height of what was found to be visible.
 - Also known as virtual displacement mapping
- When viewing surface at a given pixel, height value is retrieved at that location and used to shift the texture coordinate to retrieve a different part of the surface. Amount of shift is based on retrieved height and angle of the eye to the surface
- Enhancement: **parallax occlusion mapping or relief mapping**: ray-marching is used along view vector until approximate intersection point on height-field texture

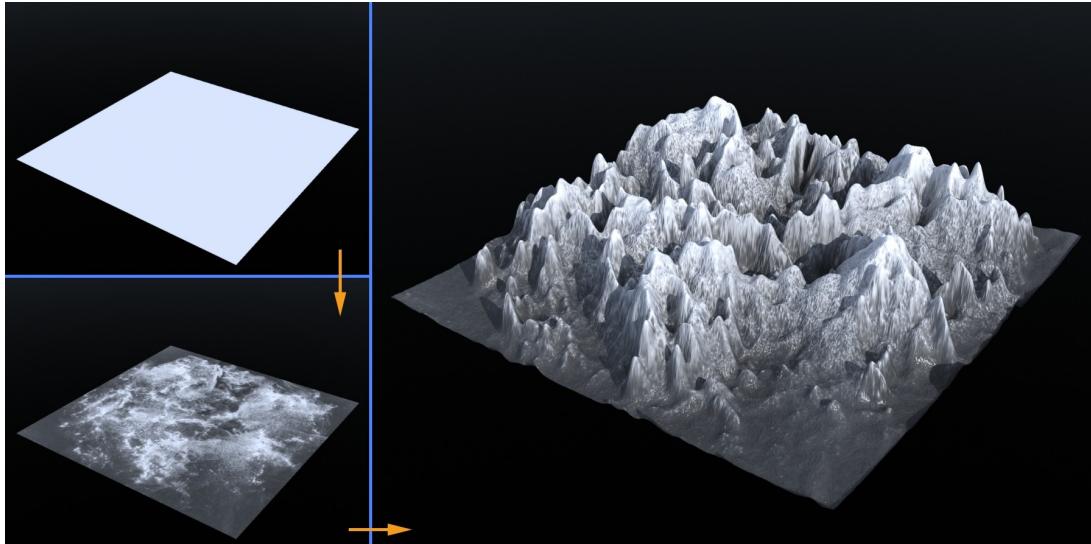


<https://github.com/marcusstenbeck/tncg14-parallax-mapping/tree/master/documents>

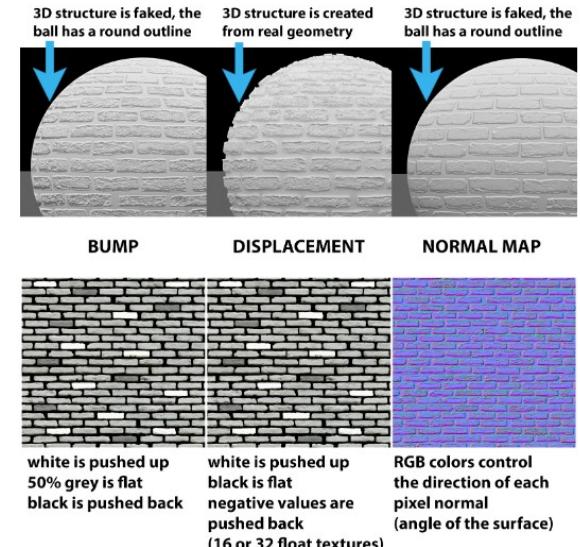
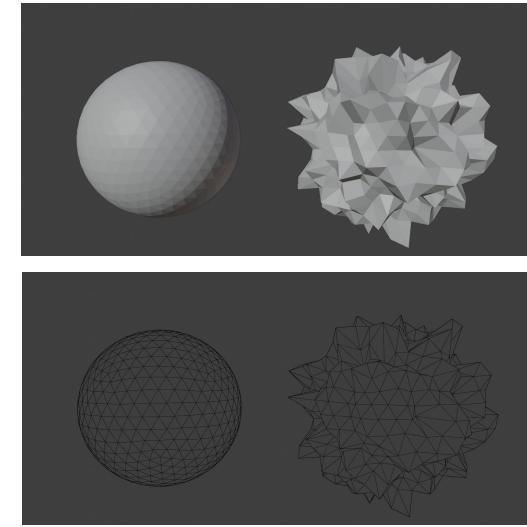


Displacement mapping

- This method changes the locations of actual geometry vertices in a mesh using height texture information.
 - Height map for displacement mapping can have negative values
- Most computationally expensive technique since requires fine geometry
 - Geometry must be subdivided prior or during rendering before displacement mapping
 - Modern GPUs support on-the-fly tessellation (tessellation shader) for subdivision of base geometry
- Good for modeling larger geometry features such as terrains.



https://ca.wikipedia.org/wiki/Displacement_mapping



<https://garagefarm.net/blog/how-displacement-maps-work-and-how-to-optimize-them-in-v-ray-part-1>

Note on small scale geometry

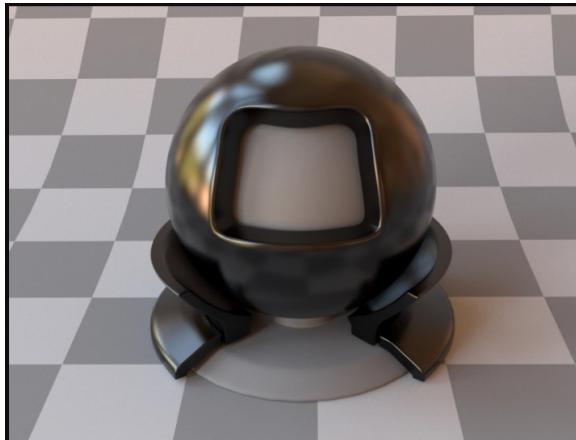
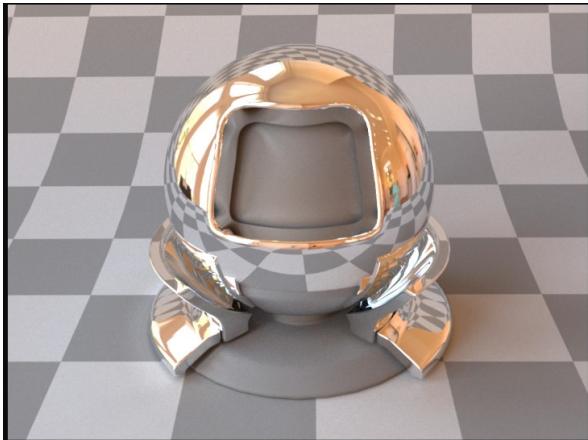
- Note that texture is often used to represent small scale geometry which is expensive to represent and render directly.
- However, there are rendering/representation techniques which enable modeling and rendering of high quality geometry without need for normal, bump, parallax or displacement mapping.



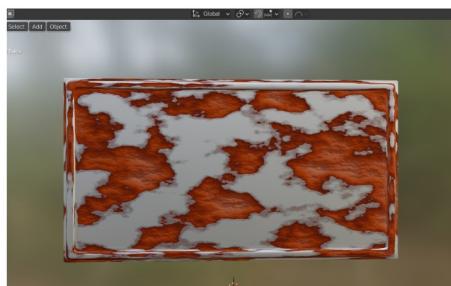
<https://docs.unrealengine.com/5.0/en-US/nanite-virtualized-geometry-in-unreal-engine/>

Distributing materials

- Texture is also used to **distribute different materials** over surface
 - Texture can be used as a “mask” which determines which scattering function and shading calculations will be performed where



<https://mitsuba2.readthedocs.io/en/latest/generated/plugins.html#textures>



<https://blender.stackexchange.com/questions/231205/how-do-i-combine-these-two-textures>

Texture modeling and texture application

Re-read
simplify

- When we talk about textures in computer graphics, we can separate the work in creating/modeling a texture and applying it to a shape. These two processes are often blurred.
- Reminder: we said that material modeling (which includes texture) can be performed separately of modeling 3D shapes.
 - Creation of texture is often separated from 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 space 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

Links and examples

Practical note: textures

Re-read
simplify

- Generally, outside of computer graphics field, term texture is overused.
- 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.

Exploring textures

Examples and links

- Industry standard texturing tool:
<https://www.adobe.com/products/substance3d-painter.html>
- Textures are often used for layering materials (RTR 9.12)
- Procedural texturing
- Texture mapping
- <https://www.realtimerendering.com/#texture>

Practical insights

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

Examples?

Summary

- Questions: https://github.com/lorentzo/IntroductionToComputerGraphics/tree/main/lectures/8_texture
- Texture is used to vary material properties over surface
- Texturing pipeline
 - Projection, corresponding, value obtain and transform
- Image textures
 - Aliasing and mip mapping
- Procedural textures
 - Noise functions
- Material variation
 - Scattering function parameters variation
 - Small scale geometry: bump, normal, parallax and displacement mapping

Create questions

Literature

- <https://github.com/lorentzo/IntroductionToComputerGraphics>