

Lecture 3: 3D scene overview

DHBW, Computer Graphics

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1.2.2023.

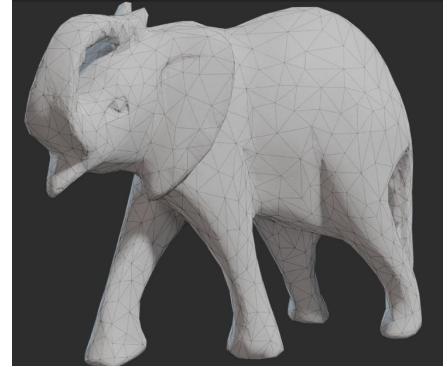
Syllabus

- 3D scene
 - Rendering
 - Image
-
- The diagram illustrates the relationship between the basic components of a 3D rendering pipeline and their detailed sub-components. A blue rectangular box on the left contains the three main items: '3D scene', 'Rendering', and 'Image'. A blue arrow points from the right side of this box to a larger, rounded rectangular box on the right. This second box contains a bulleted list that further breaks down the '3D scene' item into 'Objects', 'Lights', and 'Cameras', each with its own sub-bullets.
- 3D scene
 - Objects
 - Shape representation
 - Material
 - Lights
 - Cameras

3D scene in big picture

Cornerstones of image generation:

- **3D scene modeling**
 - Representing 3D objects, lights and cameras
 - Animation and interaction
- Rendering
 - Creating 2D images from 3D scenes
- Raster image
 - Displaying 2D images
 - Post-processing



3D scene modeling for image synthesis

- Image synthesis: rendering a 3D scene
 - Analogy: taking real world photograph/video
- Elements:
 - **Camera** placed somewhere in space
 - Space contains **objects** with various shapes and materials
 - **Light source** emits light in space



3D scene modeling questions

How do we represent scene elements in a computer?

- Intuitive for user?
- Efficient for rendering?

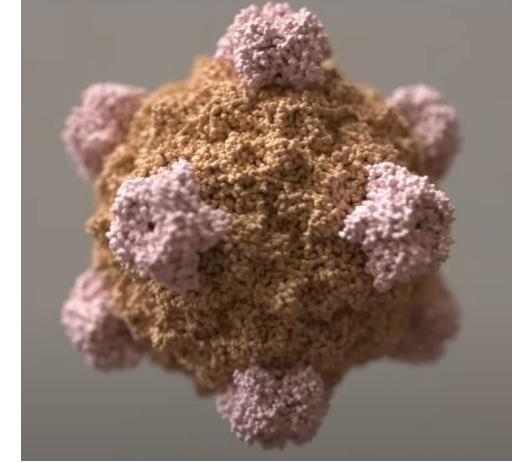
How we create/acquire/manipulate scene elements?

- Objects? Lights? Cameras?
- How to use scene elements to create real-world phenomena and objects?

Objects

Objects: intuition

- Depending on application, we would like our 3D scene to contain various objects
- How do we even start with this?



Brady Johnston, Visualising viruses:
https://www.youtube.com/watch?v=adhTmwYw0iA&ab_channel=Blender



Autodesk Fusion 360:
<https://www.autodesk.com/products/fusion-360/overview>

Objects: shape and material

For 3D modeling and rendering, real-world phenomena is decoupled into:

- **Shape: geometry**

- **Modeling**: process of creating 3D objects by defining size, form, relative position and proportion to other objects
 - **Rendering**: solving visibility problem

- **Appearance: material**

- **Modeling**: process of achieving desired object appearance
 - **Rendering**: calculating light-surface interaction → shading



Objects: shape representation

Object shape representations

- Points
 - Point clouds
 - Particle systems
- Lines/curves
 - Parametric curves
- Surfaces
 - Polygonal mesh
 - Subdivision surfaces
 - Parametric surfaces
 - Implicit surfaces
- Volumetric objects/solids
 - Voxels
 - Space partitioning data-structures



Modeling objects in 3D scene requires different shape representations.

- ▼ RenderMan
- ▼ Geometry
 - Curves
 - NURBS
 - Polygons
 - Subdivision Surfaces
 - Particles
 - Volumes
 - Implicit Surfaces
 - Instancing
 - Aggregate Volumes
 - Modeling Guidelines

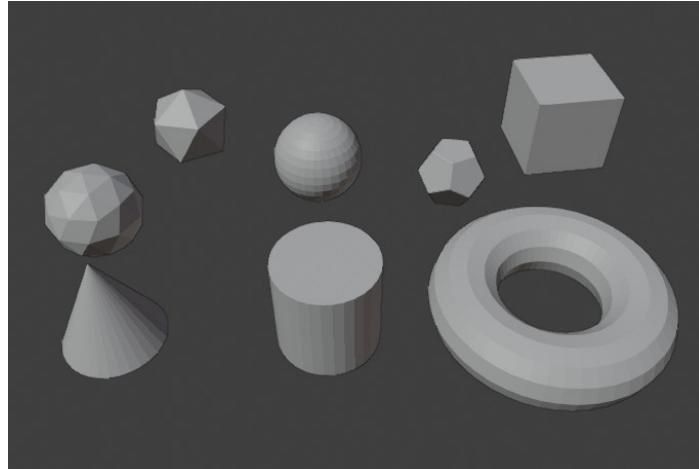
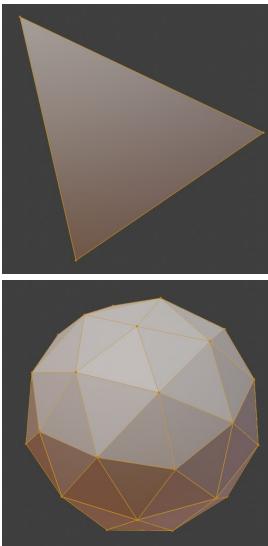
Object shape representations

- Some representations are more convenient for **user and modeling**
 - Example: modeling curved surface (e.g., car) is very hard by using triangles
 - In 3D modeling tools, user is provided with various shape representations to work with
- Some representations are more suitable for **rendering**
 - Having one shape representation for rendering enables more efficient rendering procedures
 - Prior rendering, different representations are transformed into triangles*
- Panel on high performance geometry: modeling vs rendering
https://www.youtube.com/watch?v=CoGo_3C7xR0&t=14103s&ab_channel=High-PerformanceGraphics

* Not all real-world phenomena can be well represented with triangles. Especially volumetric effects such as smoke or clouds. For such cases ray-casting and ray-tracing are often used.

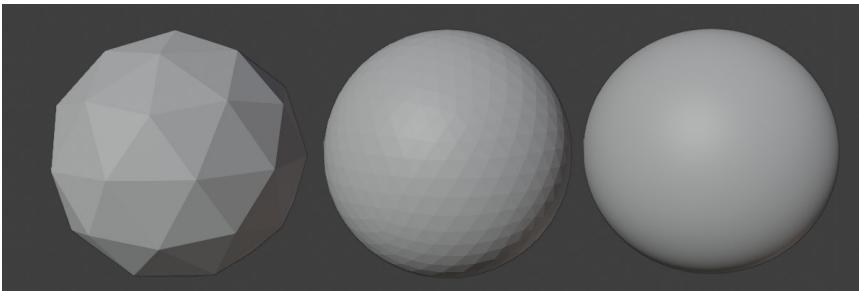
Shape representation 1: triangles

- Simplest way to define surface is using **triangles**
 - Polygons with three points all lying on a plane (co-planar)
 - Widely used surface **shape representation primitive** - especially in rasterization-based rendering engines, e.g. Unity (<https://unity.com/>)
 - **Approximation primitive**: very well approximating various objects, e.g., curved surfaces (with a larger number of triangles)
 - Very **simple**, great properties for **easy calculation**, often used for **efficient rendering** purposes
 - Not intuitive for modeling, thus different shape representations are introduced

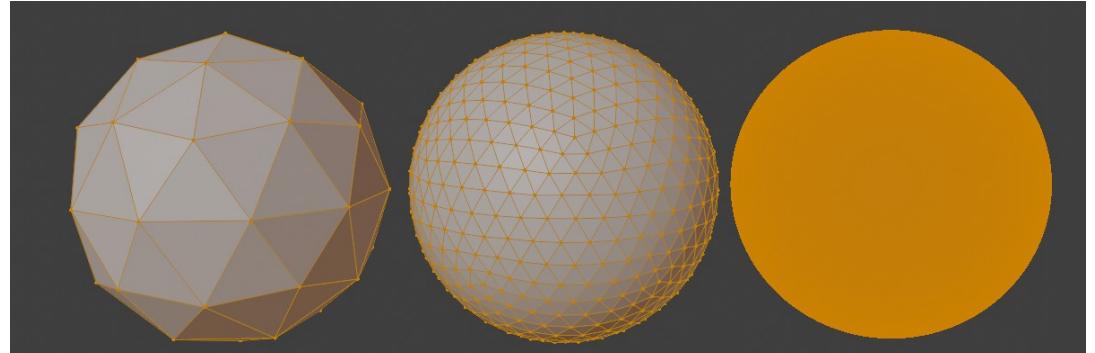


Shape representation 1: triangles

- Different shape representations can be converted to triangles:
 - **Triangulation:** converting shape to triangles
 - **Tessellation:** converting shape to polygons (of any sort)
- Any object can be represented using triangles
 - Higher quality approximation of curved surfaces requires more smaller triangles better fitting surface
 - Amount of details increase realistic representation but also complexity of rendering. Computer graphics often deals with trade-off between visual quality and speed*.



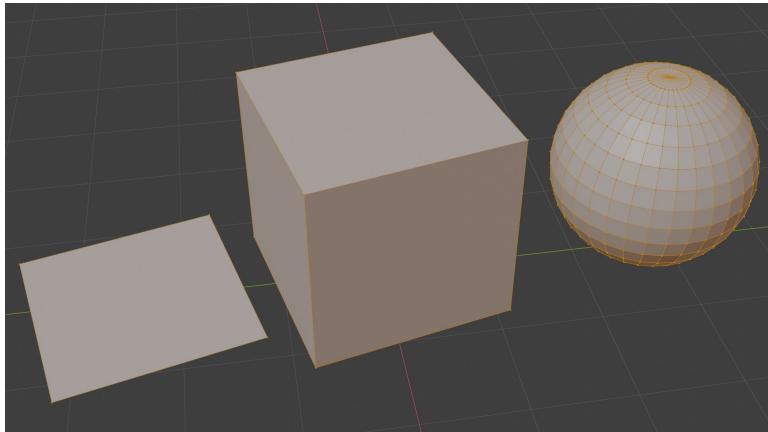
https://www.youtube.com/watch?v=x4RZRs3PD4Q&ab_channel=Udacity



* Finding good tradeoff between visual quality and object complexity is big research field in computer graphics. Note also that distance of viewing plays important role in amount of detail that it has to be represented.

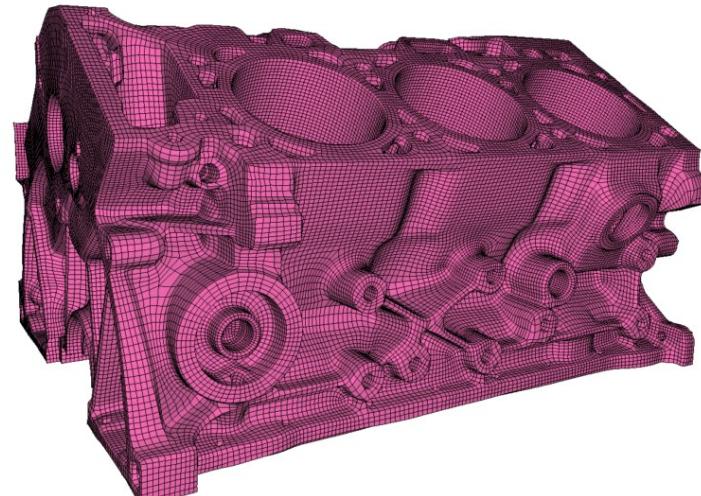
Shape representation 2: quad mesh

- Polygons with four vertices, not necessary co-planar
- Often provided by professional 3D modeling tools
- Often used for modeling (especially hard-surface modeling)



Blender mesh:

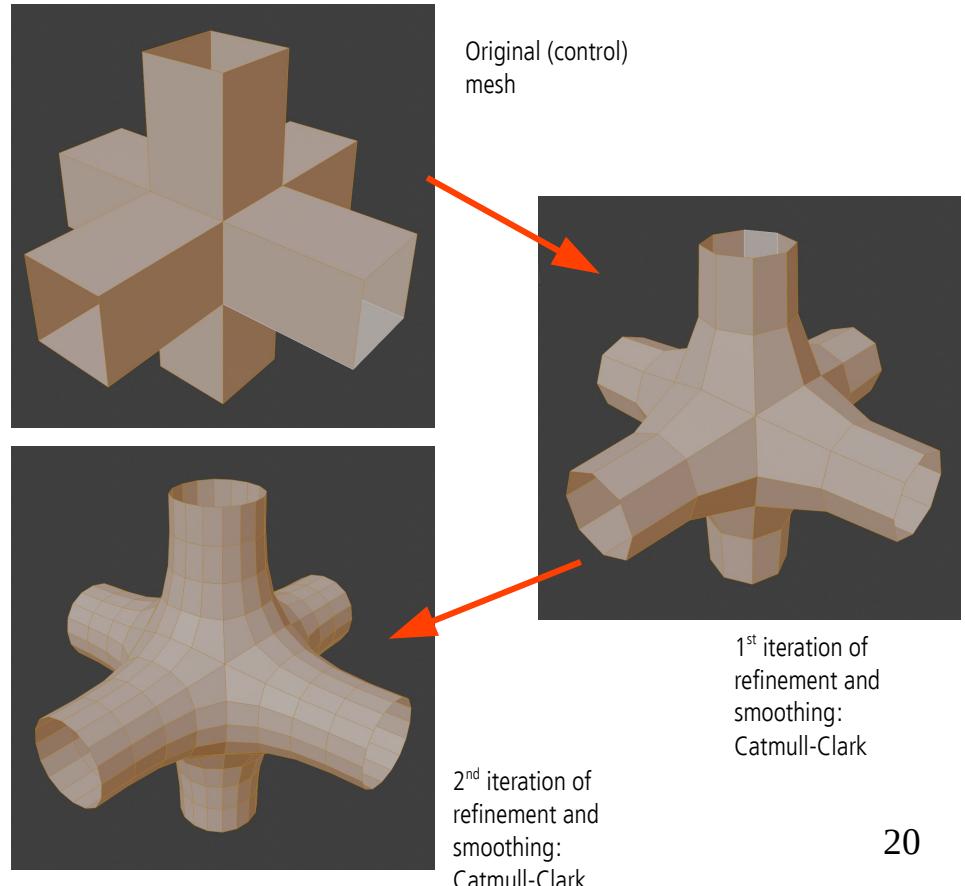
<https://docs.blender.org/manual/en/latest/modeling/meshes/index.html>



<https://geometryfactory.com/products/igm-quad-meshing/>

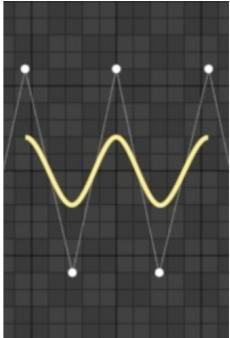
Meshes: subdivision surfaces

- Paradigm for defining **smooth and continuous surfaces** from polygon meshes
- Provides **infinite level of detail**: as many triangles as needed can be generated.
- Approaches:
 - Loop's method
 - Catmull-Clark subdivision

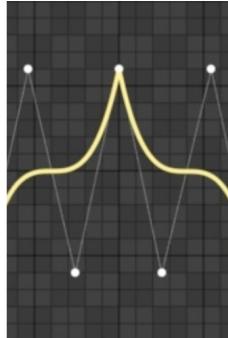


Shape representation 3: Parametric curves

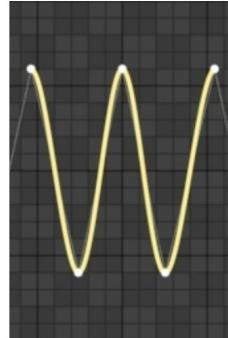
- Useful for modeling large number of thin strands
 - Fur, hair, etc.
- Also used for animation
- Arbitrary, smooth curve shape is determined by control points and parametric equation.
- Methods: Linear, Bezier curve, B-Spline, Catmull-Rom



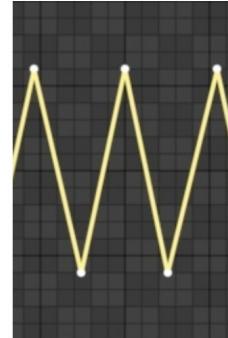
B-Spline



Bezier



Catmull-Rom



Linear



<https://rmanwiki.pixar.com/display/REN24/Curves>

Shape representation 4: parametric surfaces

- Simple shapes can be described mathematically using parametric equations, e.g., spheres, disks, planes
- Equation of sphere with origin C (c_x, c_y, c_z) and radius r :

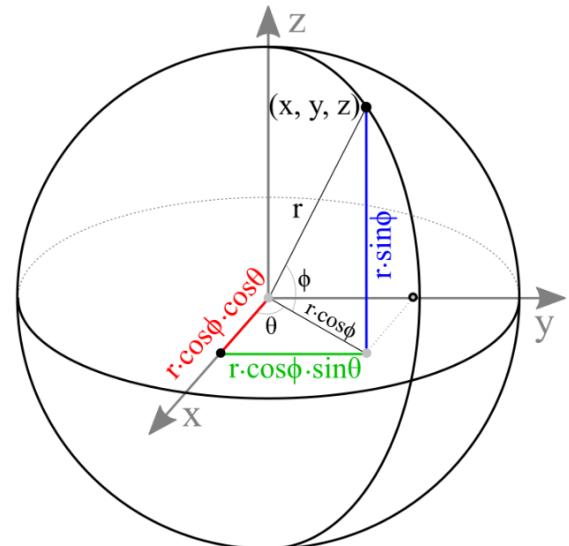
$$(x - c_x)^2 + (y - c_y)^2 + (z - c_z)^2 = r^2$$

- Arbitrary point on sphere is computed using parametric equations:

$$x = (r \cdot \cos \phi) \cdot \cos \theta$$

$$y = (r \cdot \cos \phi) \cdot \sin \theta$$

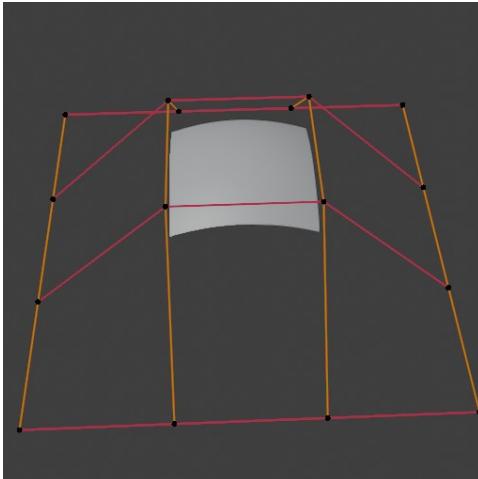
$$z = r \cdot \sin \phi$$



More on spheres in OpenGL:
http://www.songho.ca/opengl/gl_sphere.html 23

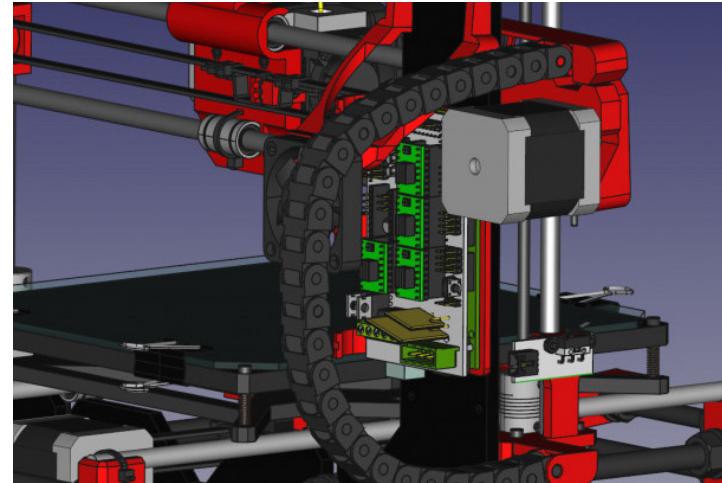
Shape representation 4: parametric surfaces

- More complex surfaces are represented by **points** which define a **control mesh** from which perfect curved surface can be generated using **parametric description**.
 - Note that this kind of representation is much more compact than polygonal mesh.
- Approaches: Bezier patches, B-Spline surfaces, NURBS, etc.
 - Often used in CAD software, e.g., design of objects for manufacturing
- This representation can not be rendered directly. **Tessellation** must be performed prior rendering.



NURBS surface Blender:

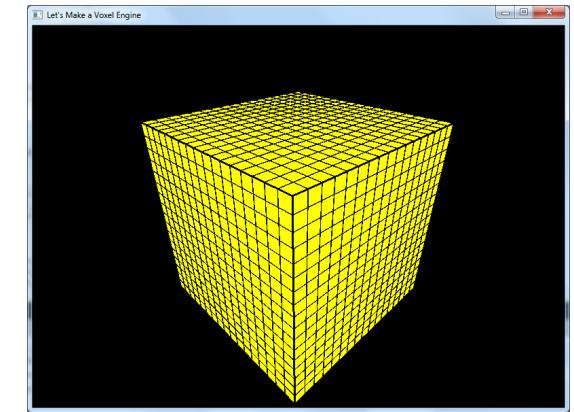
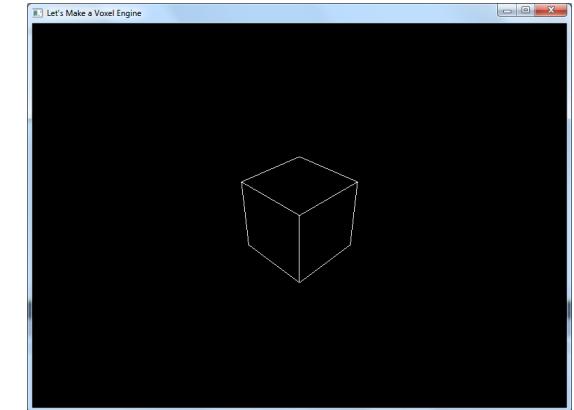
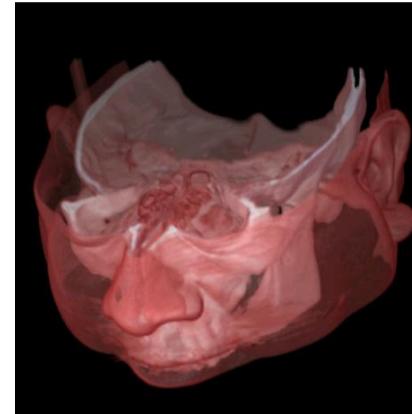
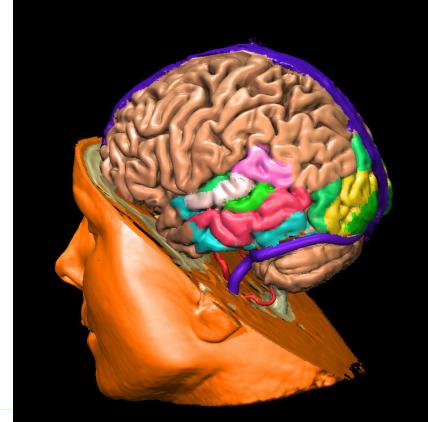
<https://docs.blender.org/manual/en/latest/modeling/surfaces/index.html>



FreeCAD: <https://www.freecadweb.org/features.php>

Shape representation 5: voxels

- **Voxel:** represents volume of space, e.g., cube in 3D uniform regular grid (index of the grid determines voxel location)
- Used for representing **volumetric data** (not only surface as in e.g., polygonal mesh)
 - Example: fluid (smoke or liquid) simulation requires computation on grid of cells – voxels
- Each voxel can contain various information:
 - Density or opacity information, e.g., medical applications, CT acquisition
 - One bit representing if its center is inside or outside surface, e.g., scanning or modeling



Getting started with voxels:
<https://sites.google.com/site/letsmakeavoxelengine/home/water>

Shape representation 5: voxels



Voxel-based modeling: <https://ephtracy.github.io/>



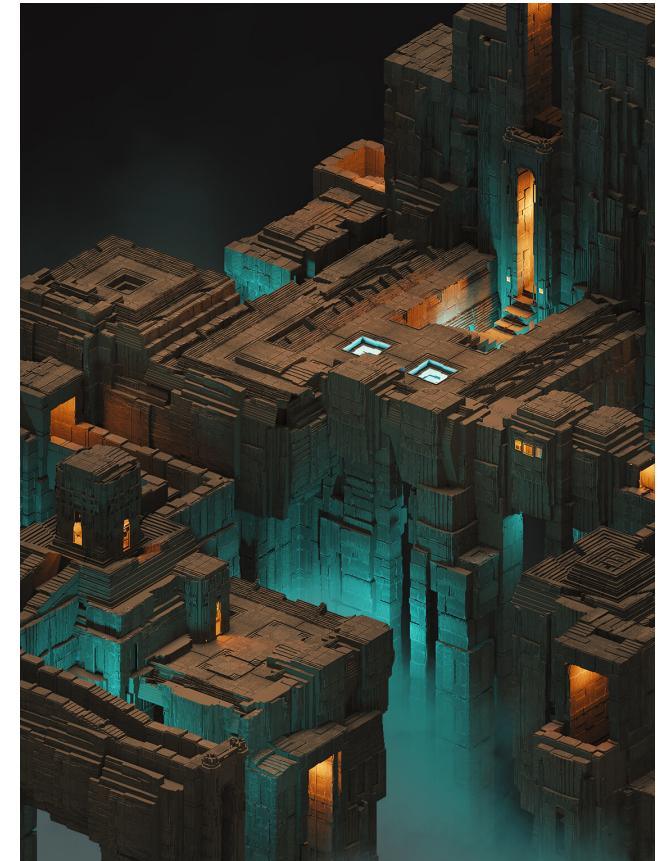
Smoke simulation in Blender:
<https://docs.blender.org/manual/en/3.4/physics/fluid/index.html>
https://www.youtube.com/watch?v=zyIJQHIFQs0&ab_channel=Polyfjord

- **Rendering:** ray-tracing or converting to polygons using marching cubes algorithm.
- Large voxel grids are **memory expensive**.
 - Often, not all voxels in grid are needed and thus memory lighter sparse-voxel representations, e.g., sparse voxel octrees are used:
<https://www.nvidia.com/docs/IO/88972/nvr-2010-001.pdf>

Shape representation 5: voxels



Voxel art: <https://www.artstation.com/madmaraca>



Shape representation 5: voxels



Shape representation: surface and volume

- Shape representation can be used to describe:
 - **Surfaces**, e.g., mesh or parametric surfaces
 - **Volumes**, e.g., voxels

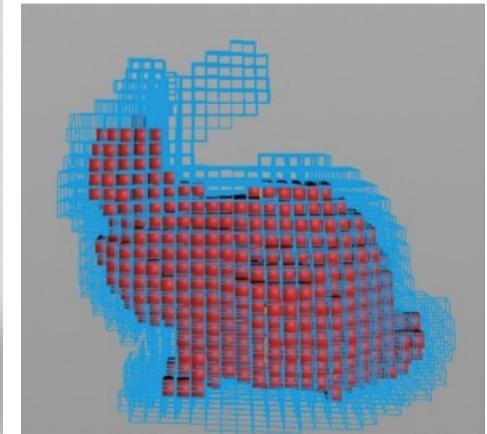
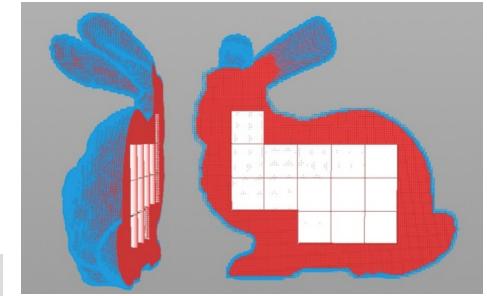


Example: for opaque objects, we don't care about object interior (approximated with material model)

Example: for smoke or other participating media, information inside object is important (e.g., density of smoke)



Volume rendering:
https://help.maxon.net/c4d/s26/en-us/Content/_REDSHIFT_/html/Volume+Rendering.html



Production examples at dreamworks, OpenVDB:
https://artifacts.aswf.io/io/aswf/openvdb/openvdb_production_2015/1.0.0/openvdb_production_2015-1.0.0.pdf

Shape representation 6: implicit

- Point on surface is described with **implicit – signed distance – function (SDF)**:

$$f(x, y, z) = f(p) = 0$$

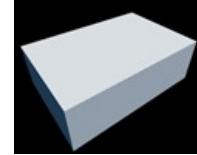
– Point is on surface if $f(p) = 0$. If $f(p) < 0$ then p inside, otherwise p is outside

- Simple shapes** can be defined using SDFs: cubes, spheres, etc.

```
float sdSphere( vec3 p, float s )  
{  
    return length(p)-s;  
}
```



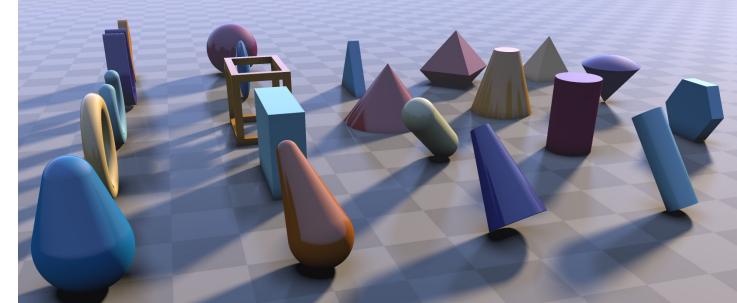
```
float sdBox( vec3 p, vec3 b )  
{  
    vec3 q = abs(p) - b;  
    return length(max(q,0.0)) + min(max(q.x,max(q.y,q.z)),0.0);  
}
```



Implicit shape representations:

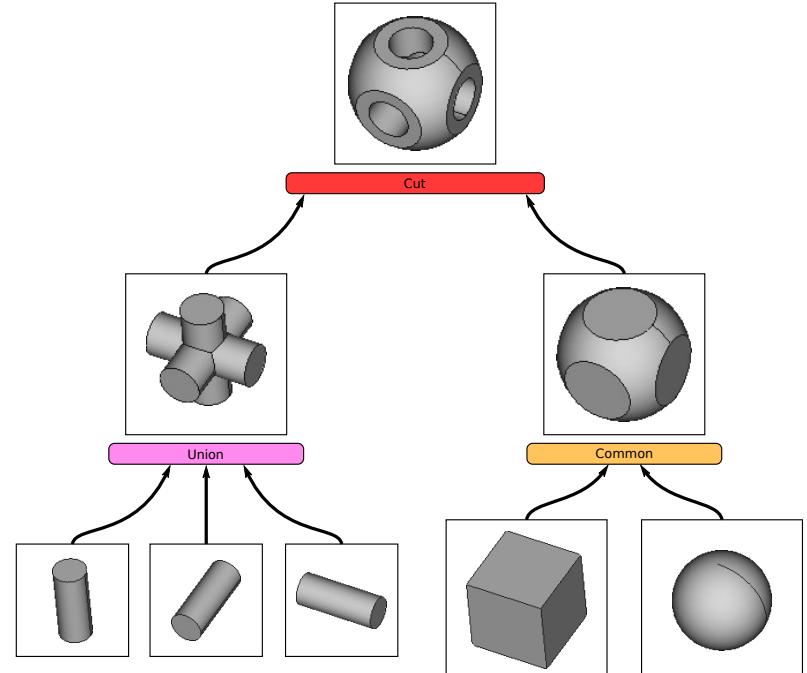
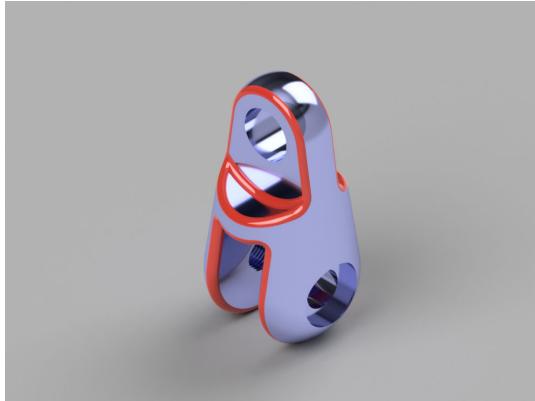
<https://iquilezles.org/articles/distfunctions/>

https://www.youtube.com/watch?v=62-pRVZuS5c&ab_channel=InigoQuilez



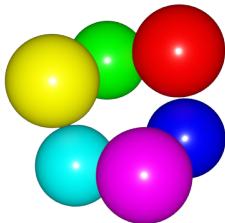
Shape representation 6: implicit

- Modeling with SDFs is done using **constructive solid geometry** operations: addition, subtraction, etc.
- Rendering
 - Converted to triangulated mesh using marching cubes algorithm
 - Ray-tracing (simple ray-implicit shape tests)
- Often used in engineering and CAD modeling environments



https://wiki.freecadweb.org/Constructive_solid_geometry

Shape representation 6: implicit



Good for representing organic objects (metaballs):

<https://rmanwiki.pixar.com/display/REN24/Implicit+Surfaces>

<https://docs.blender.org/manual/en/latest/modeling/metaballs/introduction.html>

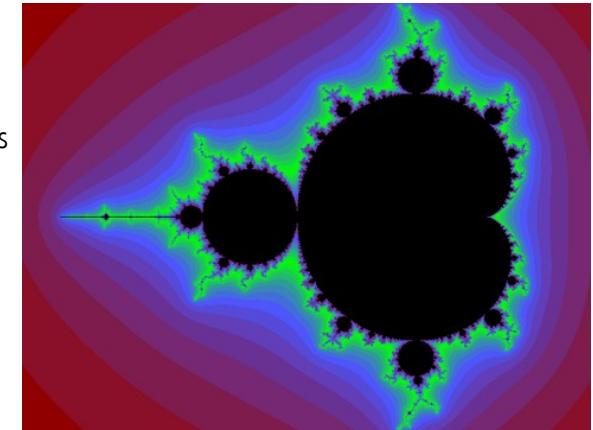
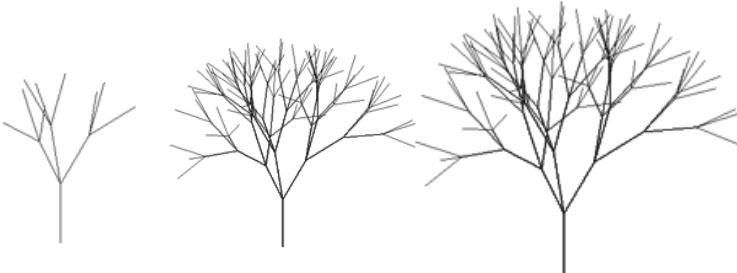


Implicit representation for modeling and rendering:

<https://www.gdcvault.com/play/1025316/Advanced-Graphics-Techniques-Tutorial-GPU>

Shape representation 7: fractals

- Irregular geometrical shapes with symmetrical property
 - Complex, natural phenomena such as clouds, mountains, trees, vegetation, galaxies can be represented using fractals
- Generative art: <http://blog.hvidtfeldts.net/>



I-Systems: grammar for complex shapes generation using iterations:

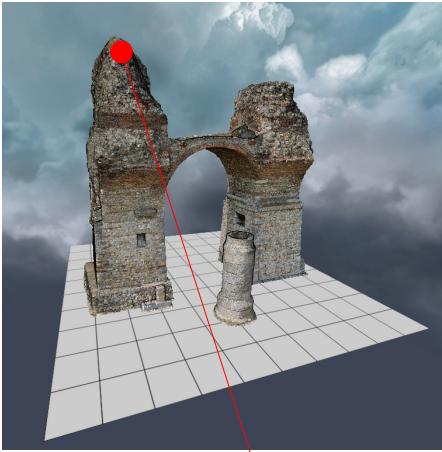
<https://www.sidefx.com/docs/houdini/nodes/sop/lsystem.html>

https://www.youtube.com/watch?v=0vE8GiXhOWM&t=1248s&ab_channel=Houdini

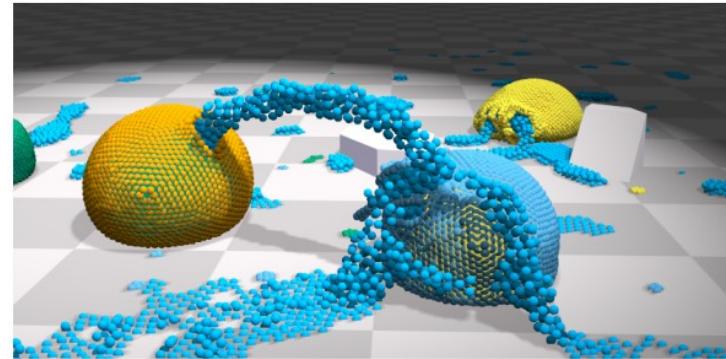
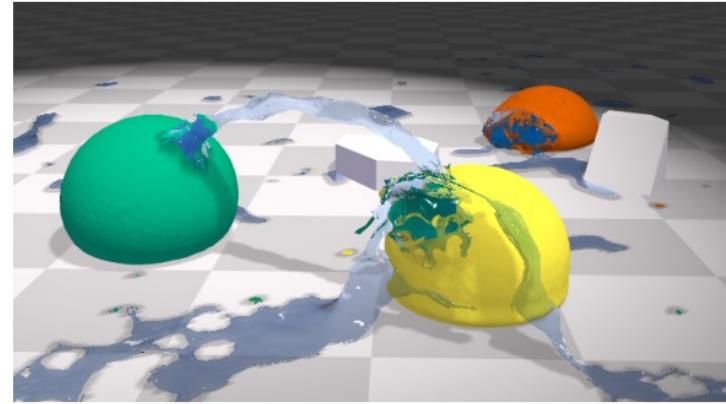
https://www.jonathanrpace.com/project_trees.html

Mandelbrot: <https://www.mandelbulb.com/>
<https://www.geeks3d.com/20091116/exploration-of-the-real-3d-mandelbrot-fractal/>

Shape representation 7: Point clouds



Scanned real-world
objects can be stored as
point clouds



Unified physics for real-time applications using points:
https://mmacklin.com/uppfra_preprint.pdf

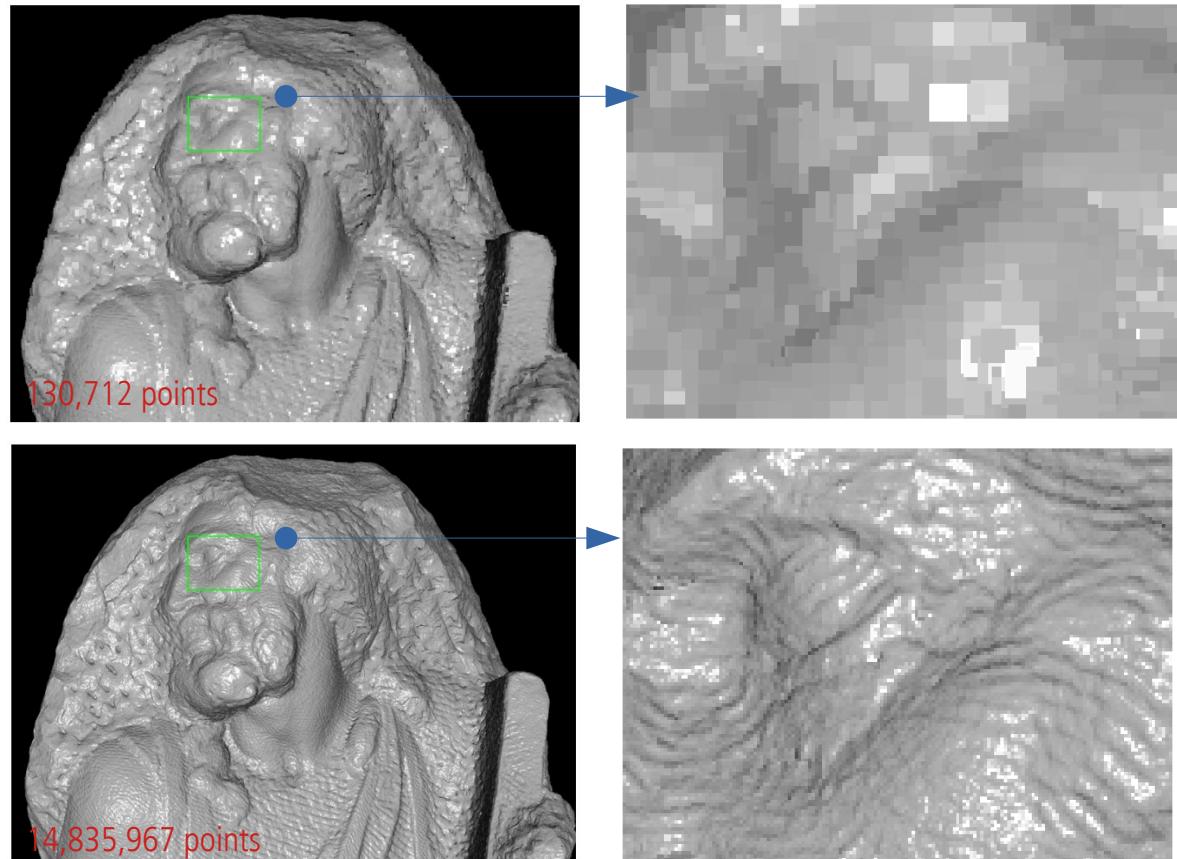
Shape representation 7: Point cloud

- Point clouds rendering:
 - **Splat** – shape with radius
 - **Surfels** – point based surface element*
 - Conversion to mesh



Points and implicit surfaces:

https://www.youtube.com/watch?v=u9KNtnCZDMI&ab_channel=MediaMolecule



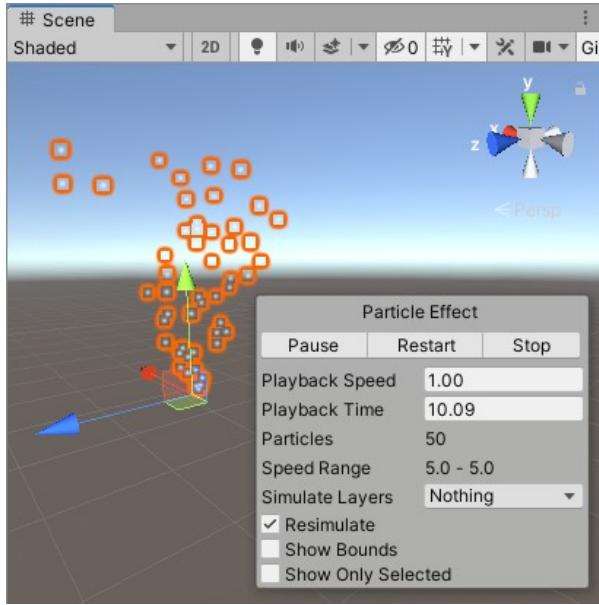
Qsplat: <http://graphics.stanford.edu/software/qsplat/>

* Surfels:

<https://vcg.seas.harvard.edu/publications/surfels-surface-elements-as-rendering-primitives>

Shape representation 8: particle systems

- Collection of small objects that are set into motion using some algorithm.
 - Often, **billboards** – image that are always oriented towards camera is used as particle particles
- Applications: simulation of fire, smoke, water, FX, etc.



<https://docs.unity3d.com/ScriptReference/ParticleSystem.html>



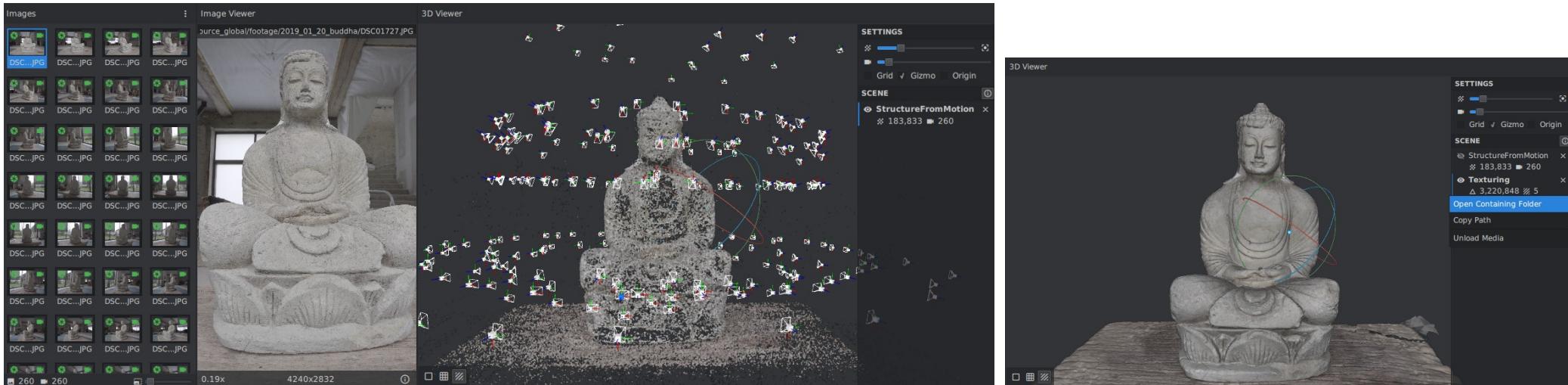
https://developer.valvesoftware.com/wiki/Particle_System_Overview

Various shape representations?

- User (modeling) point of view: shape representations must be intuitive and flexible to use and cover different applications
 - Acquisition, modeling, animation, texturing, analysis, etc.
- Rendering point of view: efficient visibility calculation

Applications

- Acquisition:
 - Photogrammetry (reconstructing from photographs)
 - Point clouds, meshes
 - Scanning: CT, MRI, Kinect



Photogrammetry: given object images, point cloud and mesh are constructed: <https://sketchfab.com/blogs/community/tutorial-meshroom-for-beginners>

Applications

- Modeling: Sculpting
 - Mesh, voxels, implicit representations



Jasmine, Zbrush,
<http://pixologic.com/zbrush/gallery/?year=2018>



Blender, <https://www.blender.org/features/sculpting/>

Applications

- Modeling: hard-surface modeling
 - Quad mesh



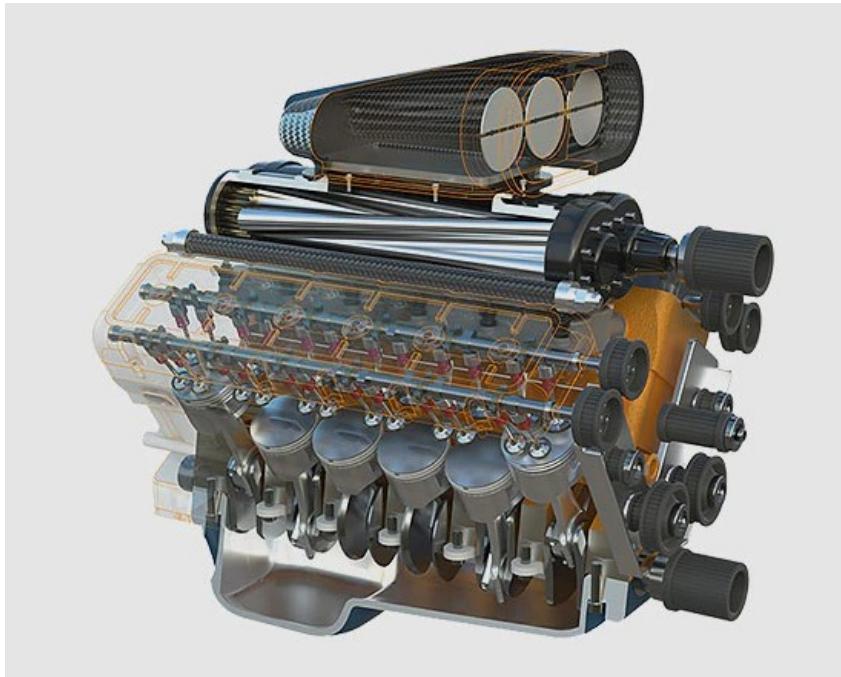
Hard surface modeling:

<https://www.sidefx.com/tutorials/houdini-modelling-tutorial-175-houdini-hard-surface-modelling-tutorial/>

Hard surface modeling: https://www.youtube.com/watch?v=1qVbGr_ie30&ab_channel=JoshGambrell

Applications

- Modeling: curved surfaces
 - Parametric surfaces

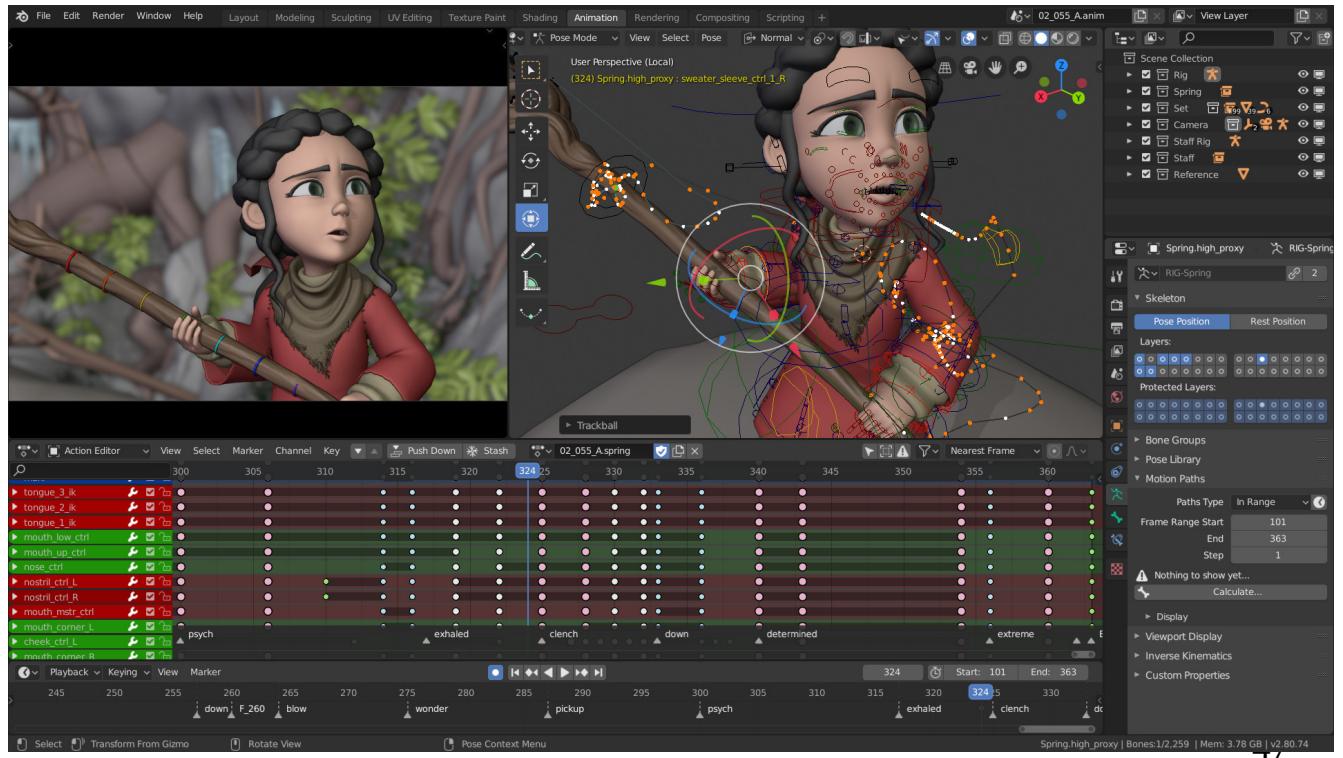


Renderman NURBS: <https://rmanwiki.pixar.com/display/REN24/NURBS>

Applications

Animation: manual

- Meshes, parametric surfaces

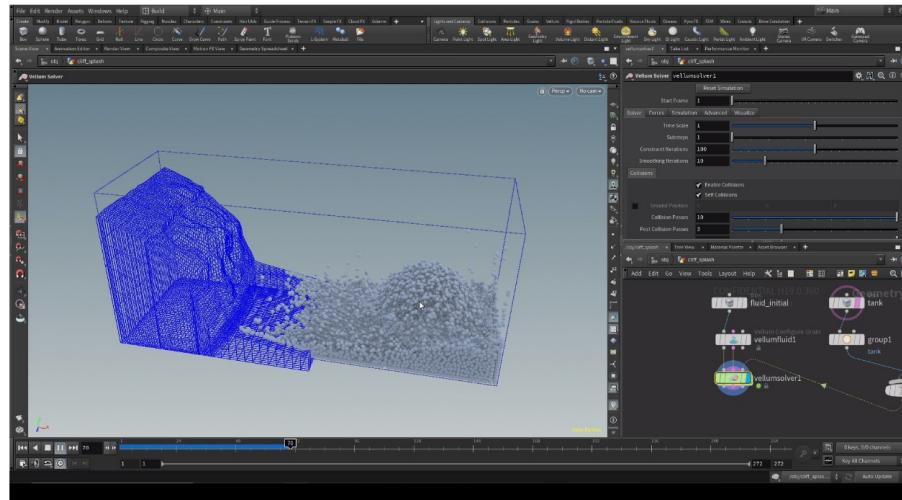


<https://www.blender.org/features/animation/>

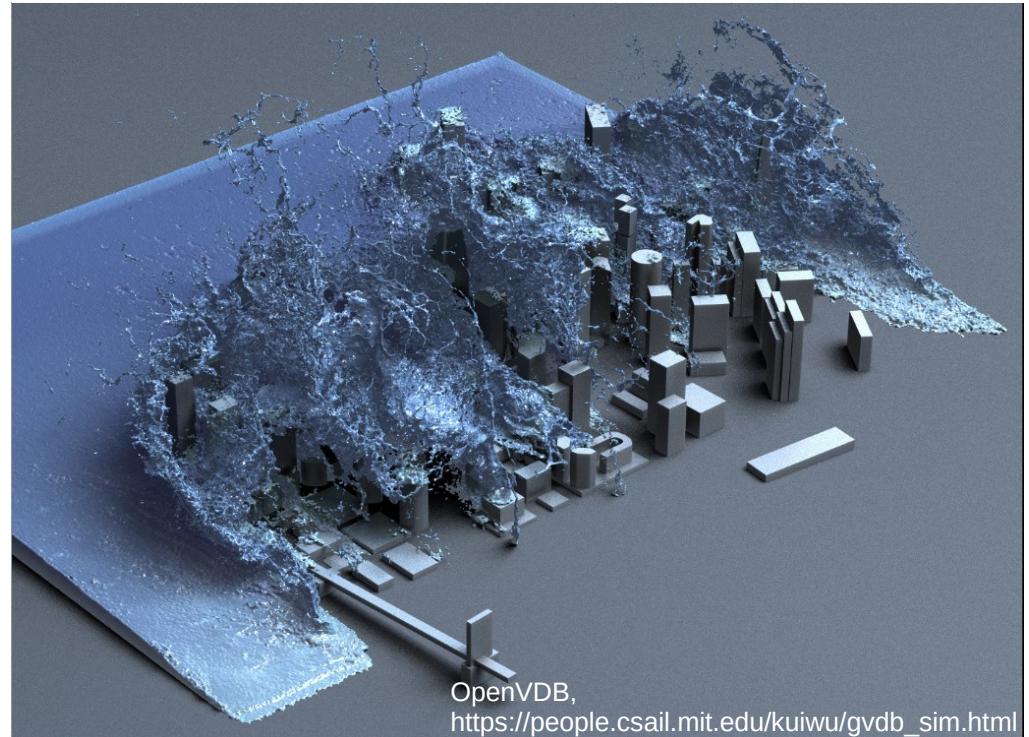
Applications

Animation: procedural, simulation

- Voxels, points



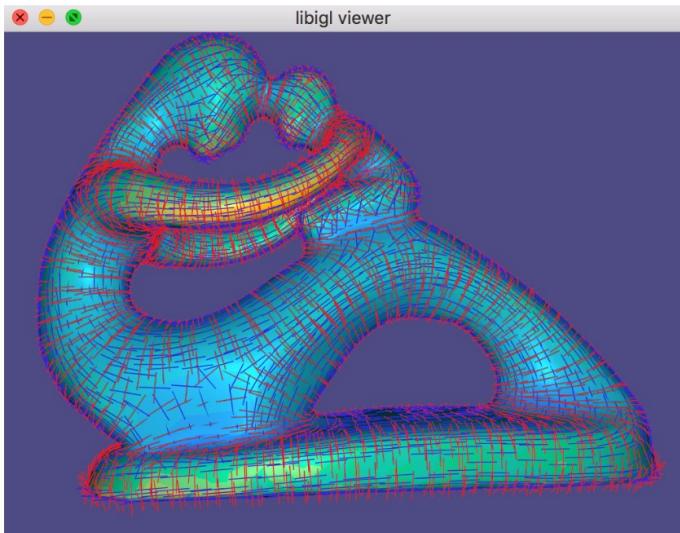
Houdini,
<https://www.sidefx.com/tutorials/h19-vellum-fluids-starter-pack/>



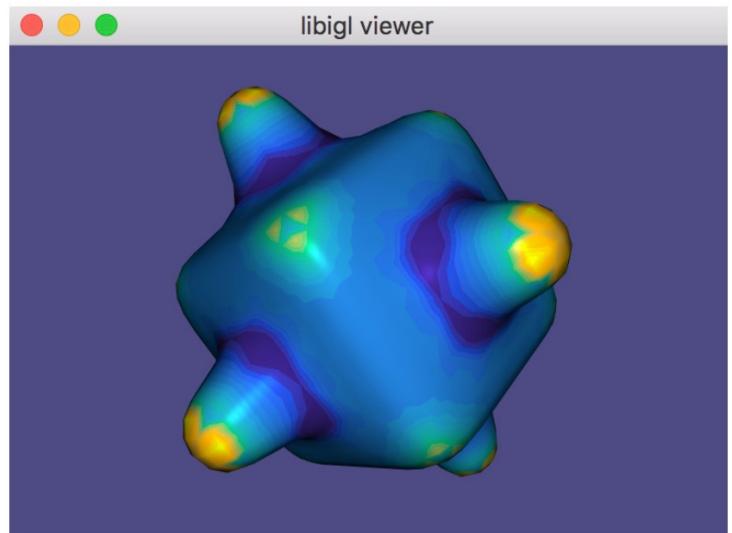
OpenVDB,
https://people.csail.mit.edu/kuiwu/gvdb_sim.html

Applications

- Analysis and processing
 - Meshes



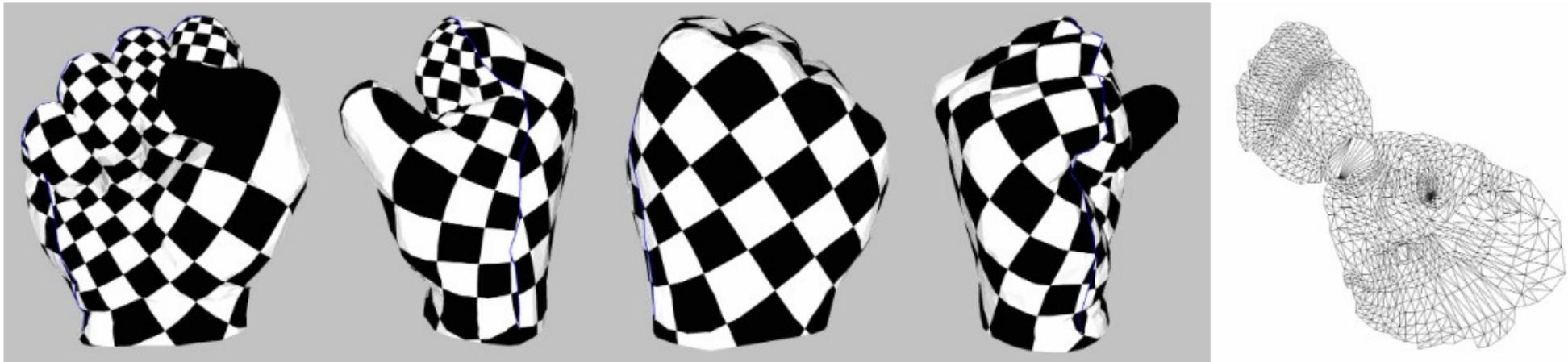
Example: principled curvature directions vectors (libigl: <https://libigl.github.io/>)



Example: Gaussian curvature visualization using pseudo color (libigl: <https://libigl.github.io/>)

Applications

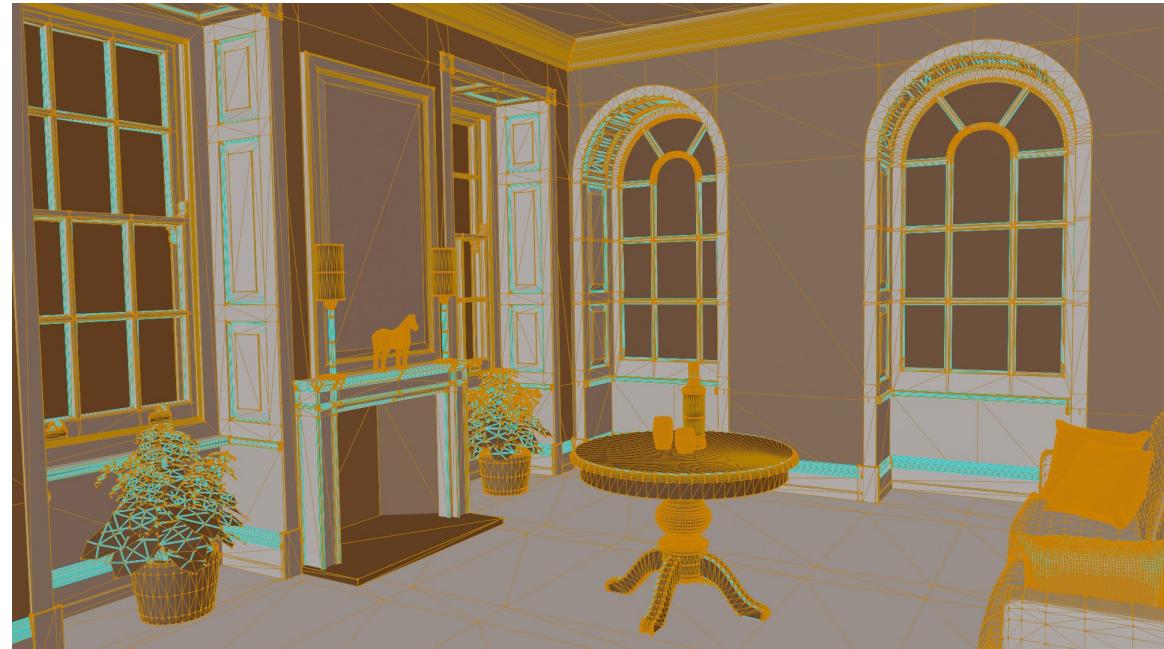
- **Texturing:** parameterization
 - Mesh, parametric surfaces, implicit surfaces



Mesh representations require surface parametrization for texture application. CGAL: Least Squares Conformal Maps (<https://www.cgal.org/>)

Applications

- **Rendering:** efficient visibility solving
 - Triangles, implicit surfaces



Objects: material

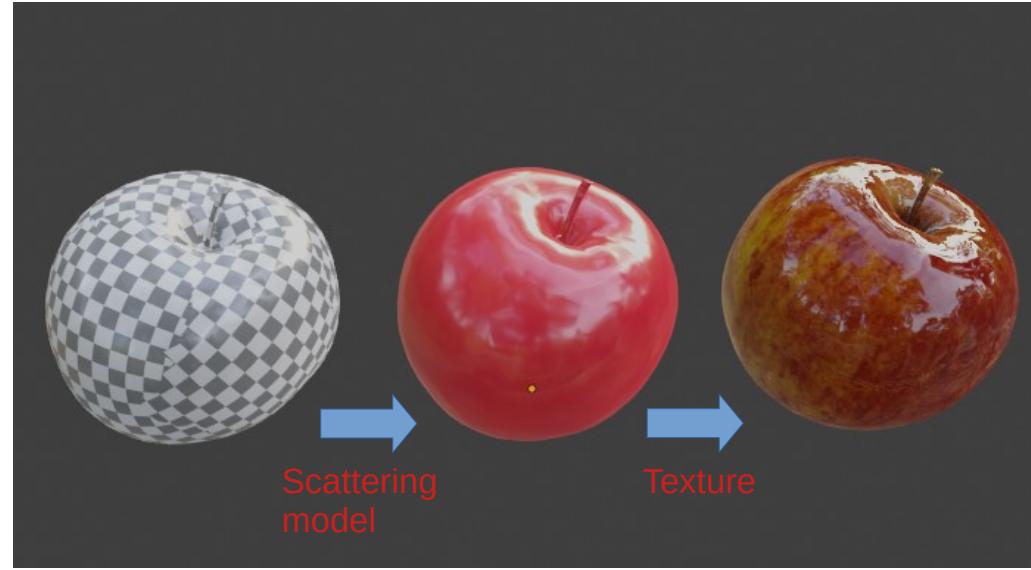


Objects: material

- **Modeling:** achieving desired appearance
 - Color, reflectivity
 - Surface patterns
- **Rendering:** crucial **shading** information; light-surface interaction
 - Scattering function
 - **Texture:** variation of scattering function properties

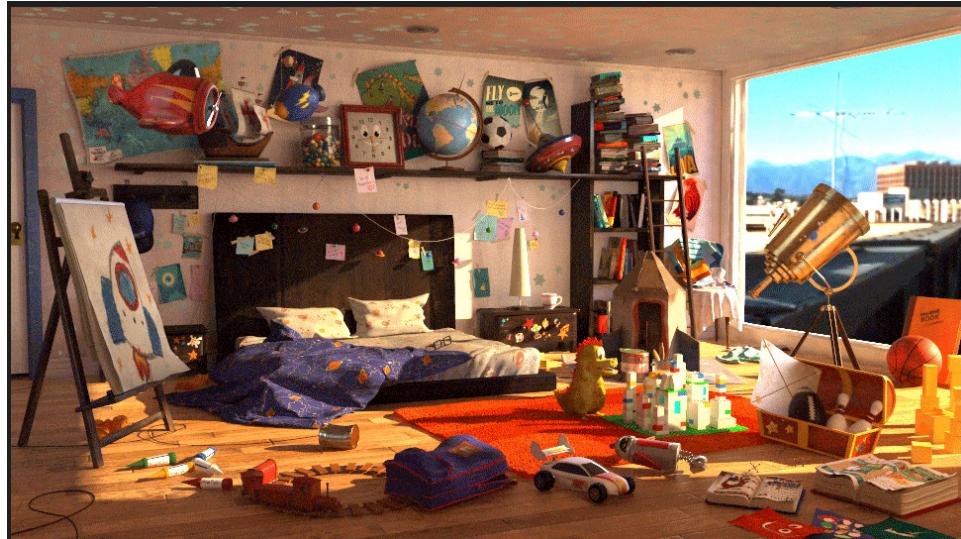


Scattering function: <https://appleseedhq.net/gallery.html>



Texture: <https://polyhaven.com/textures>

Lights

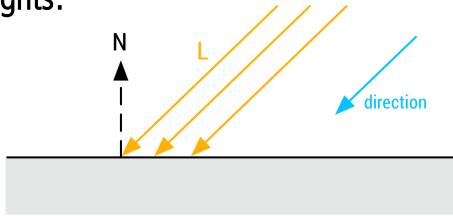


<https://discover.therookies.co/2018/06/24/learn-how-to-light-and-render-like-a-pixar-artist/>

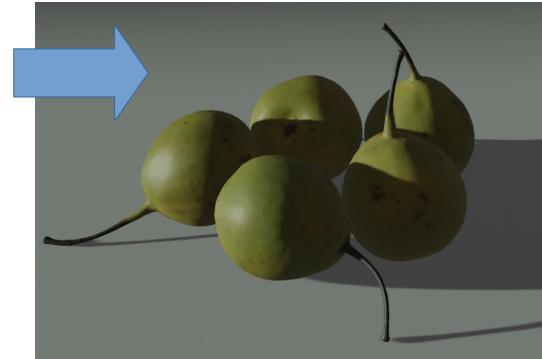
Lights: non-physical lights

Directional lights:

- Direction
- Intensity
- Color

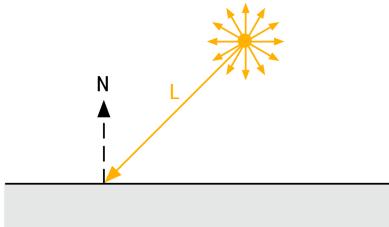


Real-world counterpart: sun



Point lights:

- Position
- Intensity
- Color



Real-world counterpart: light bulb



Lights: physical lights

- Next to position, intensity and color, physical light define:
 - **Shape** and **size**



Area light size determines softness of shadows (left: small area light, right: large area light) https://www.pbr-book.org/3ed-2018/Light_Sources/Area_Lights 57

Lights: environment light

- Besides local or directional lights, scene can be illuminated from all directions using **environment illumination**.
- Real-world image can be acquired and wrapped around 3D scene → **environment mapping**.



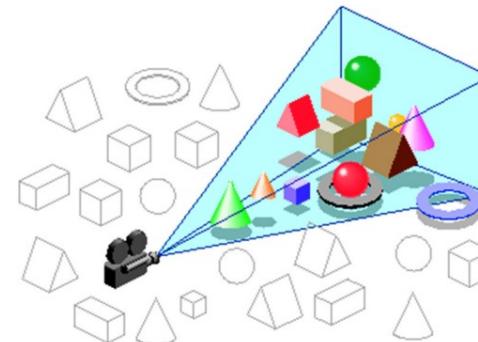
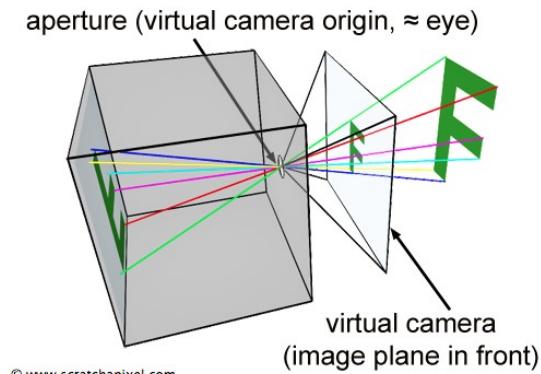
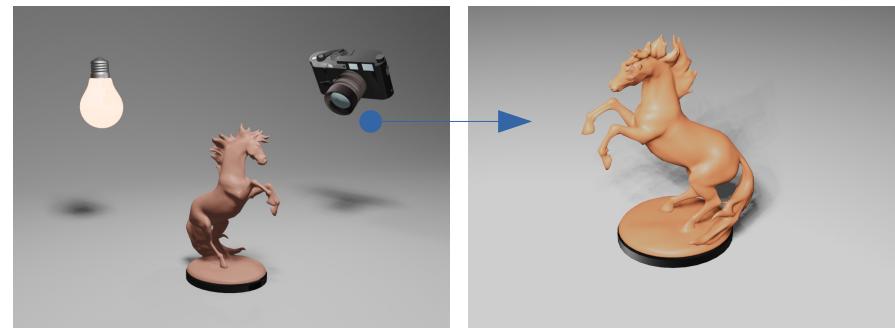
Cameras



Camera model determines portion of visible scene and simulates real-world camera effects:
depth of field, bokeh, motion blur, etc. <https://rmanwiki.pixar.com/display/REN24/Cameras>

Camera

- Position and orientation determines portion of visible scene
- Pinhole camera model elements:
 - Aperture (eye)
 - Film (image) plane
- Pinhole camera model parameters:
 - Focal length
 - Film size
- Viewing frustum
 - Only objects inside viewing frustum are visible in final image



Camera

- Camera represents first step in image generation process where light from scene is **exposed** to the film plane
- Realistic camera models simulate **lens system** next to aperture and film plane.
- Exposition (**exposure**) is achieved using:
 - Aperture → depth of field
 - Shutter speed → motion blur
 - Sensitivity (gain) → noise



<https://photonify.com/3-steps-for-adjusting-the-depth-of-field-on-your-camera/>

<https://petapixel.com/exposure-triangle/>

<https://actioncamera.blog/2017/02/22/the-exposure-triangle/>

<https://www.shutterbug.com/content/give-photos-dramatic-perspective-motion-and-blur-simple-photoshop-technique-video>

Summary/questions

- https://github.com/lorentzo/IntroductionToComputerGraphics/tree/main/lectures/3_3d_scene_overview

Literature

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