

# Lecture 3: 3D scene overview

DHBW, Computer Graphics

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1.2.2023.

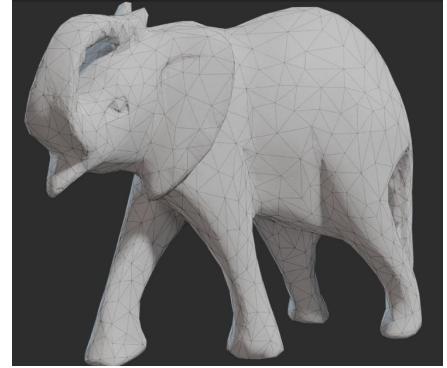
# Syllabus

- 3D scene
  - Rendering
  - Image
- 
- The diagram illustrates the structure of the syllabus. It starts with a list of three main topics: '3D scene', 'Rendering', and 'Image'. A blue rectangular box encloses the first topic. An arrow points from this box to a larger, rounded rectangular box on the right. This second box contains a detailed breakdown of the '3D scene' topic, listing 'Objects', 'Lights', and 'Cameras' under it. Each of these sub-topics has its own bullet point.
- 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

A way of creating, acquiring, representing and manipulating:

- Objects
- Lights
- Cameras

# 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?

- How to use scene elements to create real-world phenomena and objects?
- How do we manipulate 3D models?

# Objects

# Objects: intuition

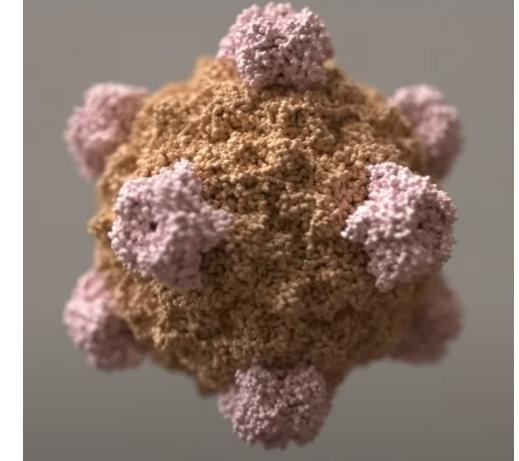
- Depending on application, we would like our 3D scene to contain various objects
- How do we even start with this?



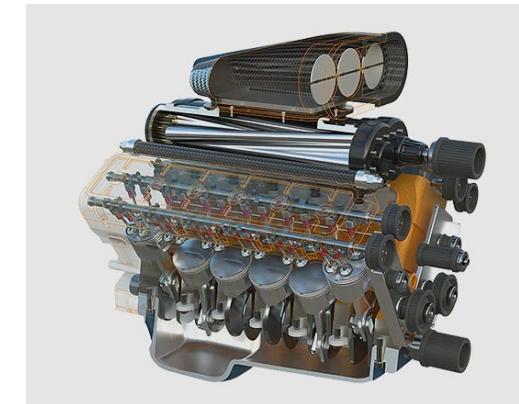
Architecture, Revit: <https://www.autodesk.com/products/revit>



Production examples at dreamworks, OpenVDB: <https://www.openvdb.org/>



Brady Johnston, Visualising viruses:  
[https://www.youtube.com/watch?v=adhTmwYw0iA&ab\\_channel=Blender](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

Decouple real-world phenomena, for 3D modeling and rendering, into:

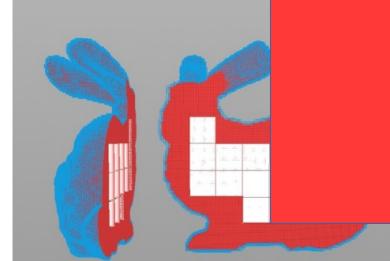
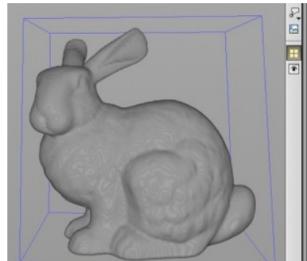
- **Shape: geometry**
  - **Modeling**: object size, form, relative position and proportion to other objects
  - **Rendering**: visibility problem
- **Appearance: material**
  - **Modeling**: achieving desired object appearance
  - **Rendering**: light-surface interaction → shading



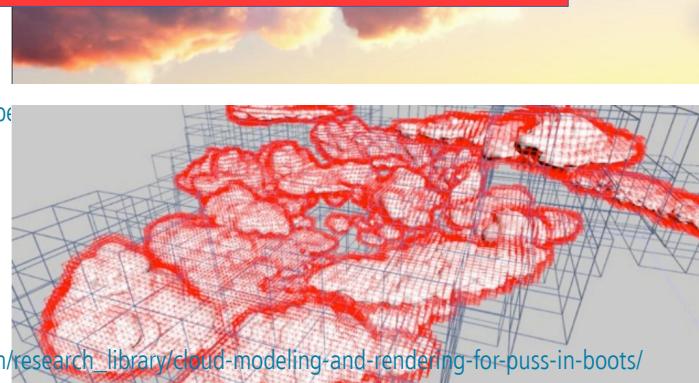
Objects: shape representation

# Shape representation: surface and volume

- Professional rendering/modeling tools support various representations: <https://rman.readthedocs.io/en/latest/representations.html>
- Shape representation can be used to describe:
  - Surfaces
  - Volumes
- Decision on shape representations depends on phenomena that we are modeling



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](https://artifacts.aswf.io/io/aswf/openvdb/openvdb_production_2015/1.0.0/openvdb_production_2015-1.0.0.pdf)

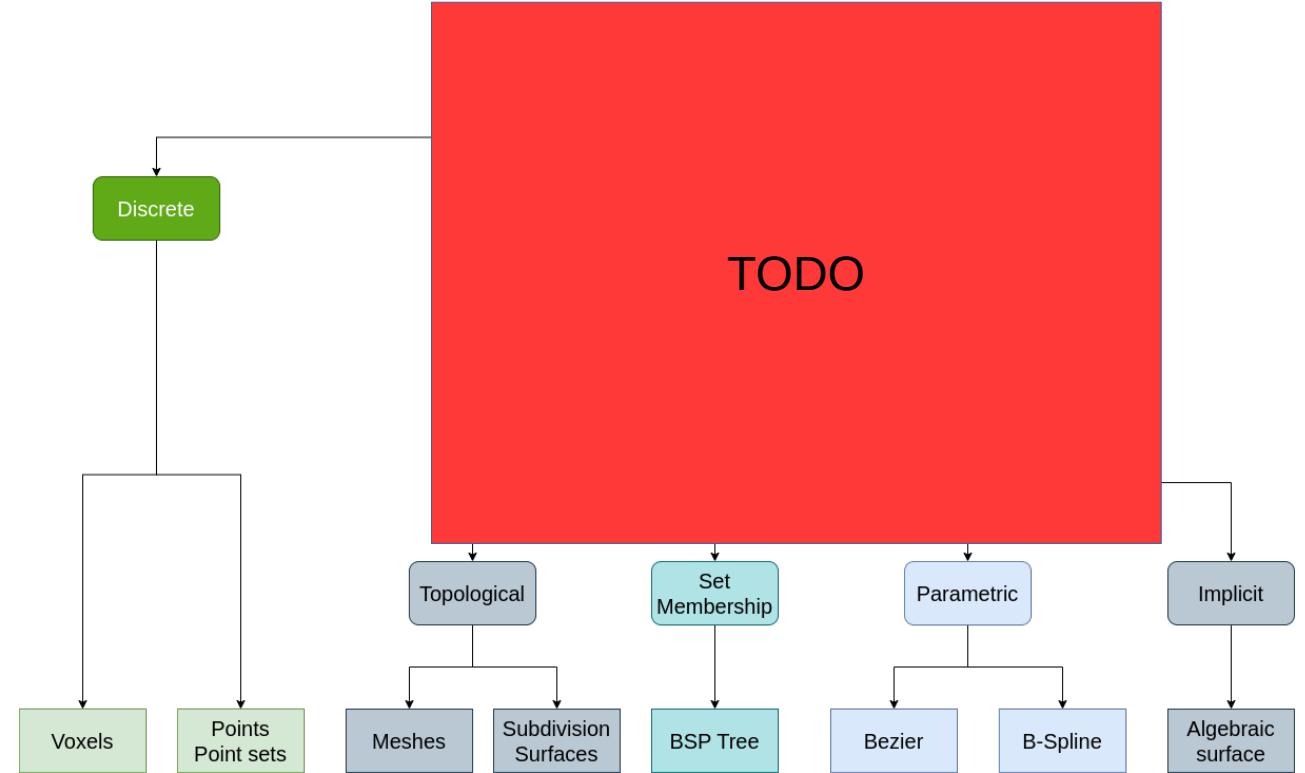


# Object shape representations

- Points
  - Point clouds
  - Particles and Particle systems

- Surfaces:
  - Polygonal mesh
  - Subdivision surfaces
  - Parametric surfaces
  - Implicit surfaces

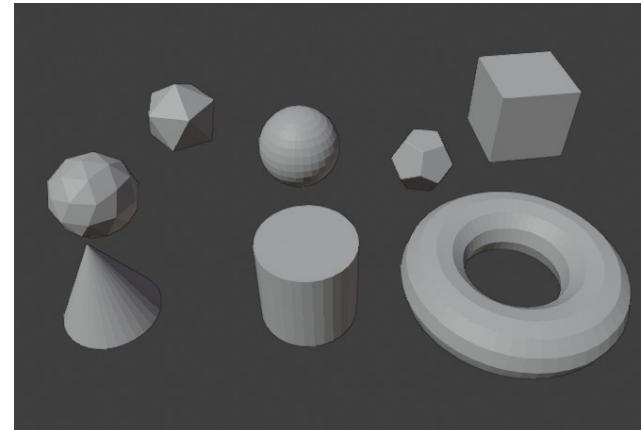
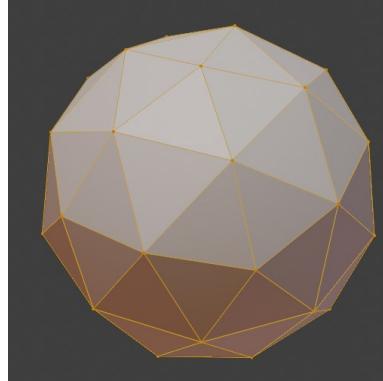
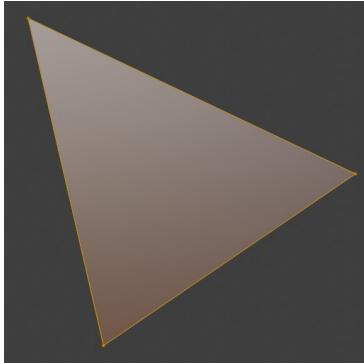
- Volumetric objects/solids
  - Voxels
  - Space partitioning data-structures
- High-level structures
  - Scene graph



Based on:  
<https://www.cs.princeton.edu/courses/archive/spring22/cos426/lectures/Lecture-5.pdf>

# Shape representation 1: triangles

- Simplest way to define surface is using co-planar polygons with three points: **triangles**
  - Widely used surface **shape representation primitive** (especially in game engines, e.g. Unity)
  - It is **approximation primitive**: curved surfaces are approximated with triangles
  - Very **simple**, great properties for **easy calculation**, often used for **efficient rendering** purposes
  - Not suitable for modeling, thus different shape representations are introduced
  - For rendering purposes, often all representations are turned to triangles before/during rendering stage - using very elaborated method called **triangulation**



# Shape representation 1: triangles

- Some shapes do not have flat surfaces! Triangle representation will always have flat surfaces\*.
- If we would like to represent curved surface, we would need smaller triangles which would fit the curved surface better. In this process we are placing vertices on the curved surface.  
Generally, converting smooth surface to triangulated surface – is called **tessellation**.
- Main point to take away is that we can represent any shape using triangles. However, they will never be perfect representations of a real world objects.  
Small enough to display objects in high quality taking into account of rendering time.
  - Amount of details increase realistic representation but also increase rendering time. Computer graphics often deals with trade-off between visual quality and speed\*\*.

TODO

ed mesh

objects  
can be  
ay.

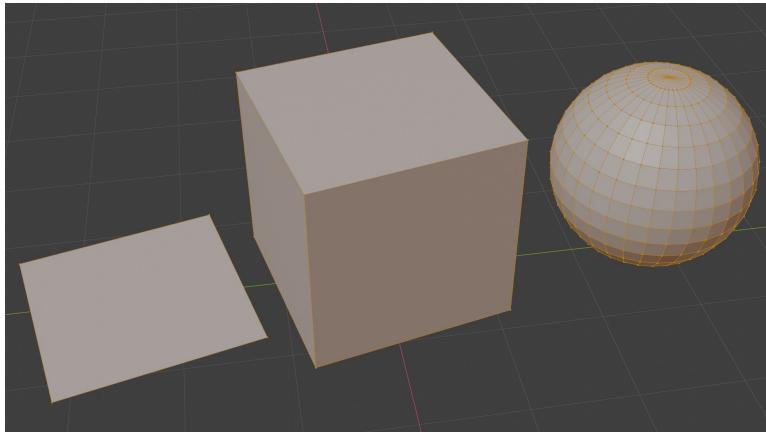
ics often

\* There are methods in rendering which make surface looks smooth although is represented using polygons. This method is called smooth shading and we will discuss it later.

\*\* 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.

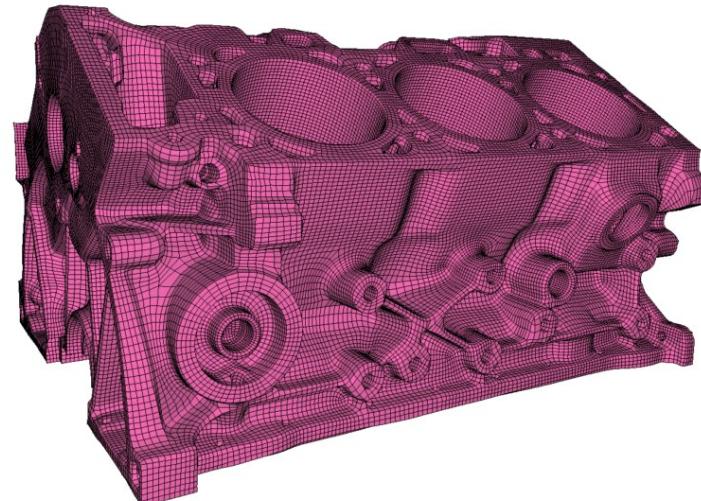
# Shape representation 2: quad mesh

- 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/>

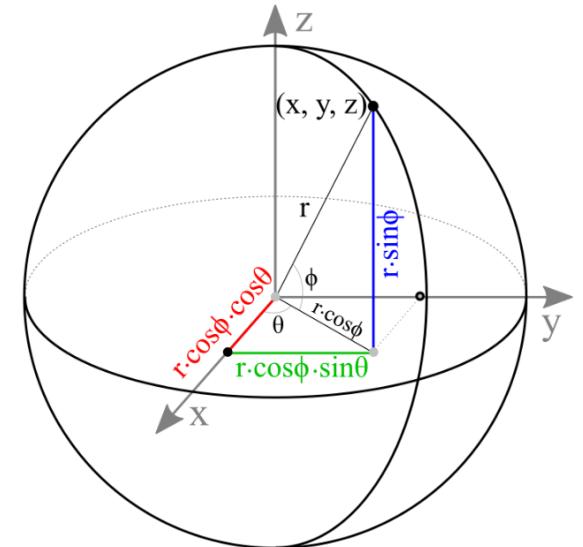
# Shape representation 3: parametric surfaces

- 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:

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

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

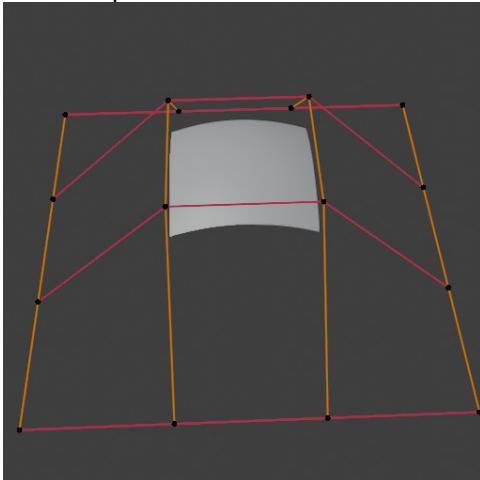
$$z = r \cdot \sin \phi$$



More on spheres in OpenGL:  
[http://www.songho.ca/opengl/gl\\_sphere.html](http://www.songho.ca/opengl/gl_sphere.html)

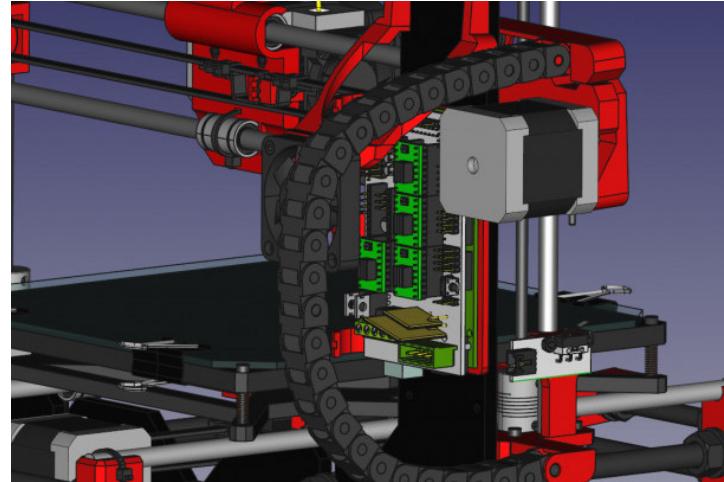
# Shape representation 3: parametric surfaces

- 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:

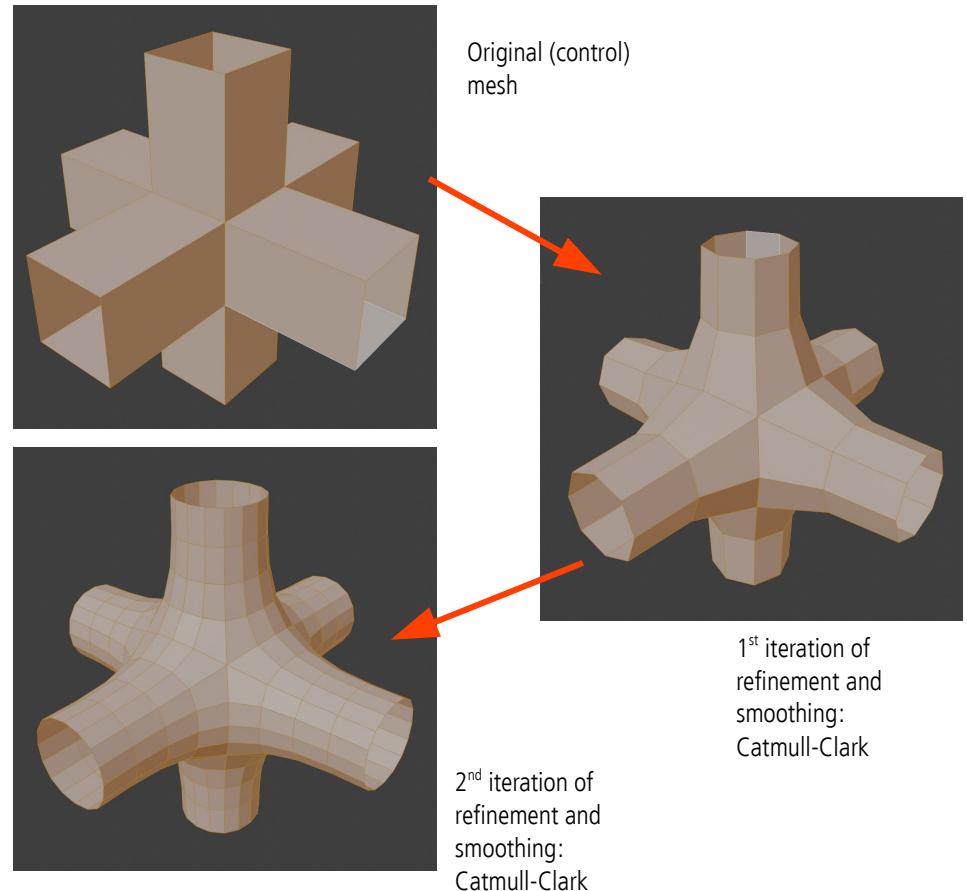
<https://docs.blender.org/manual/en/latest/modeling/surfaces/index.html>



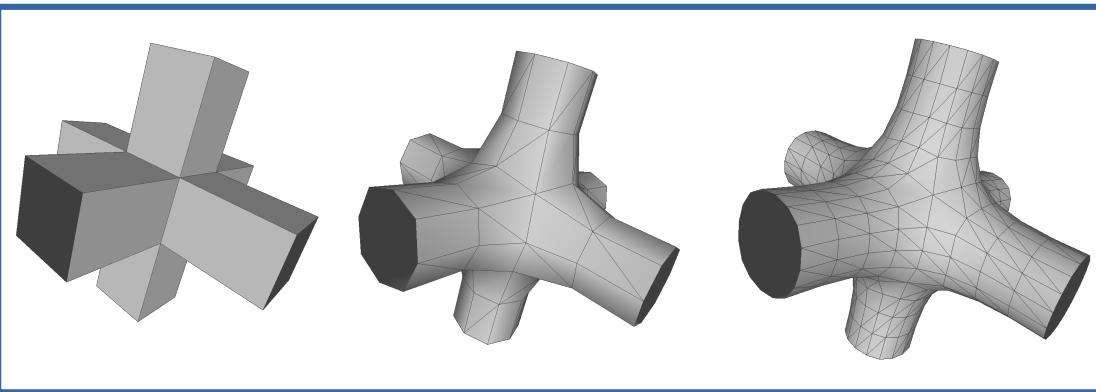
FreeCAD: <https://www.freecadweb.org/features.php>

# Shape representation 4: subdivision surfaces

- Paradigm for defining smooth and continuous surfaces from meshes
- Provides infinite level of detail: as many triangles as needed can be generated. Steps:
  - Process starts with polygonal mesh called **control mesh** (or control cage)
  - First, **refinement phase**, creates new vertices and reconnects to create new smaller polygons
  - Second, **smoothing phase**, computes new positions for some or all vertices in the mesh
- Different subdivision schemes exist depending on methods used in refinement phase and smoothing phase.  
Approaches:
  - Loop's method, Catmull-Clark subdivision, etc.



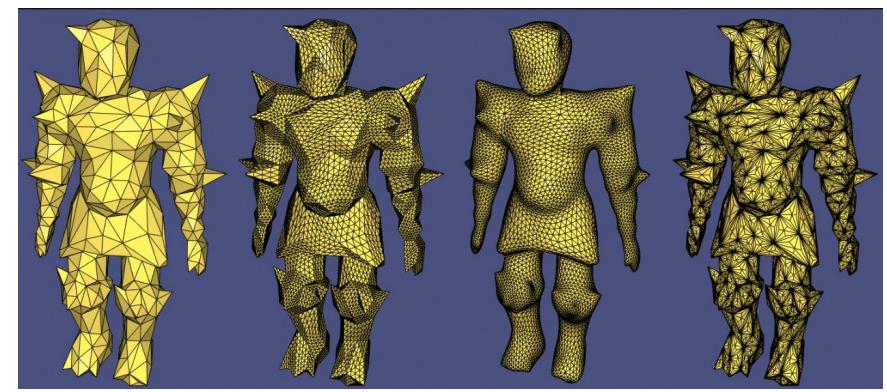
# Shape representation 4: subdivision surfaces



Meshlab loop subdivision:

[https://pymeshlab.readthedocs.io/en/latest/filter\\_list.html#meshing\\_surface\\_subdivision\\_loop](https://pymeshlab.readthedocs.io/en/latest/filter_list.html#meshing_surface_subdivision_loop)

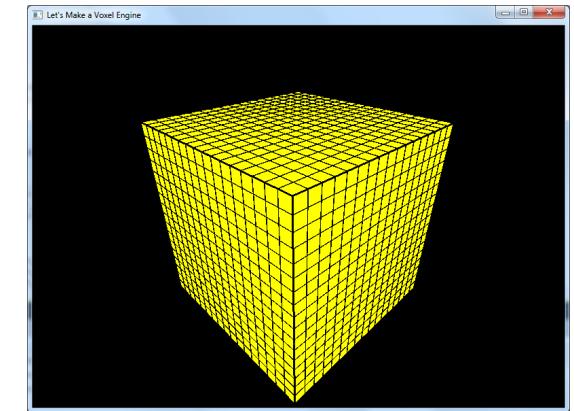
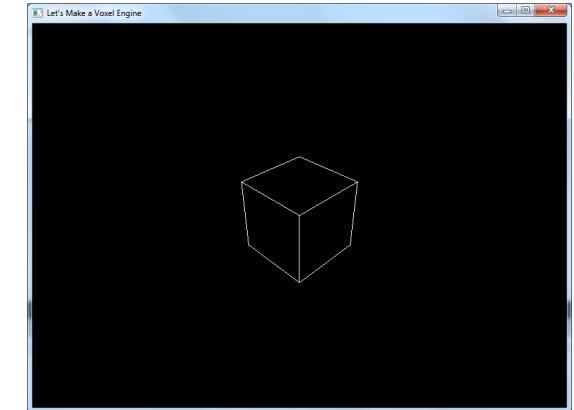
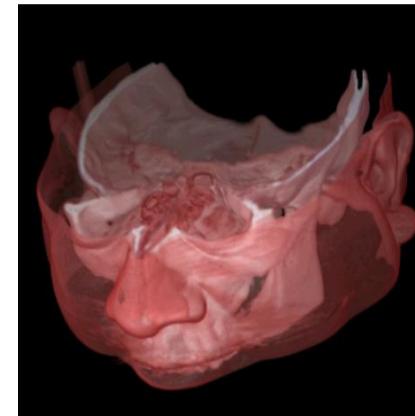
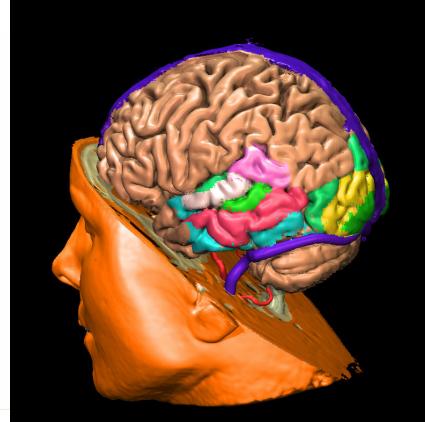
<https://github.com/cnr-isti-vclab/meshlab>



Libigl subdivision: <https://libigl.github.io/tutorial/> (original, upsample, loop and barycentric).

# 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>

<https://github.com/rbguy/GridFluidSim3D>

Voxels in medicine: <https://www.voxel-man.com/3d-navigators/downloads/>  
<http://ablesw.com/3d-doctor/volume.html>

# Shape representation 5: voxels



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

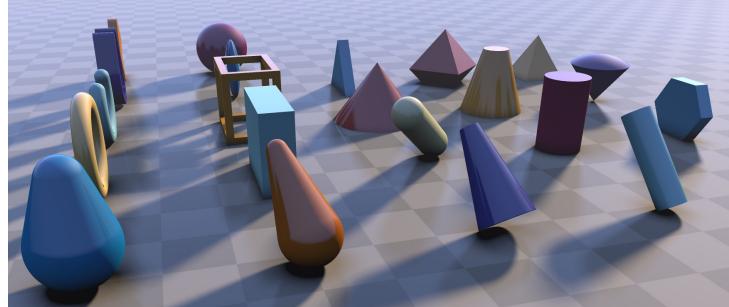
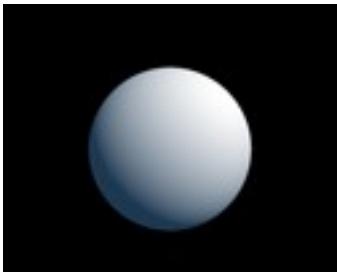


Smoke simulation in Blender:  
<https://docs.blender.org/manual/en/3.4/physics/fluid/index.html>  
[https://www.youtube.com/watch?v=zyIJQHfFQs0&ab\\_channel=Polyfjord](https://www.youtube.com/watch?v=zyIJQHfFQs0&ab_channel=Polyfjord)

- **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 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.
  - Example: sphere centered at origin with radius  $r$ :  $f(p) = \|p\| - r$



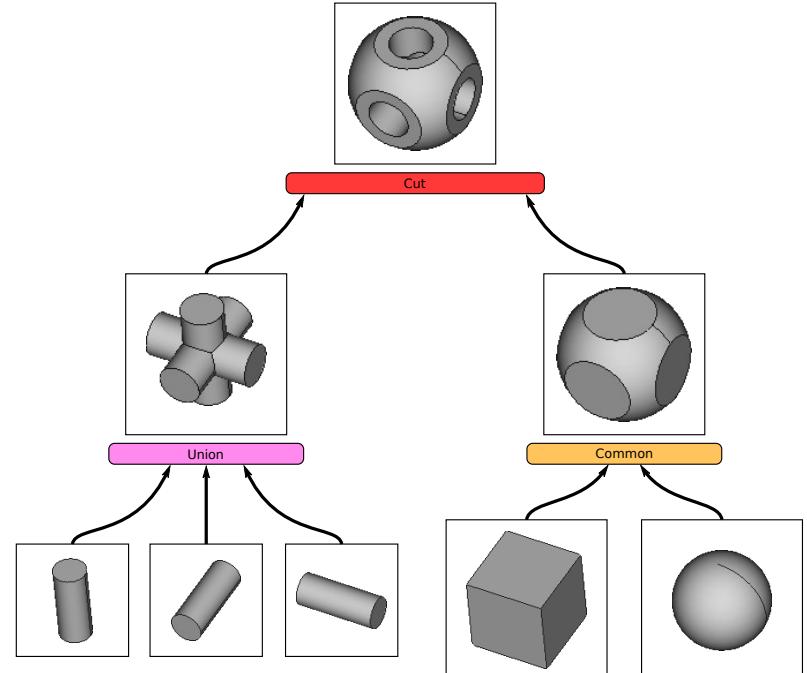
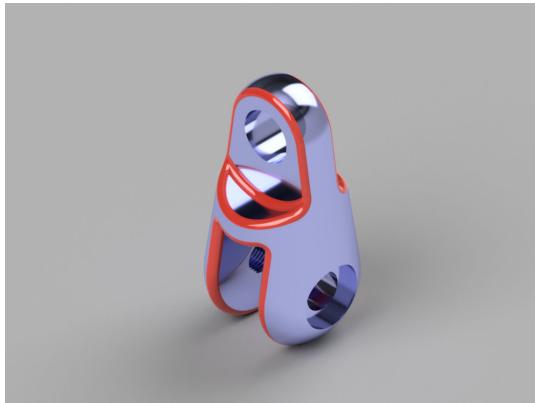
Implicit shape representations:

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

[https://www.youtube.com/watch?v=62-pRVZuS5c&ab\\_channel=InigoQuilez](https://www.youtube.com/watch?v=62-pRVZuS5c&ab_channel=InigoQuilez)

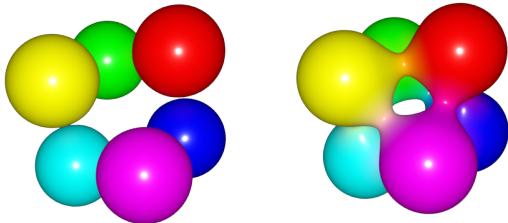
# Shape representation 6: implicit

- 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](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>

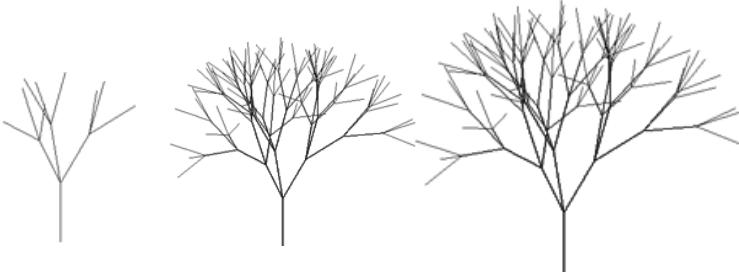


Implicit representation for modeling and rendering:

<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/>

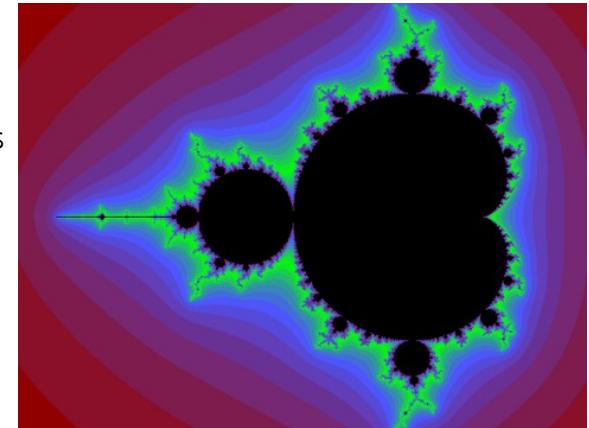


L-Systems: grammar for complex shapes generation using iterations:

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

[https://www.youtube.com/watch?v=0vE8GiXhOWM&t=1248s&ab\\_channel=Houdini](https://www.youtube.com/watch?v=0vE8GiXhOWM&t=1248s&ab_channel=Houdini)

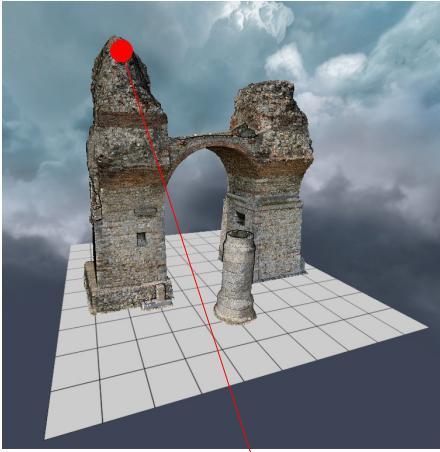
[https://www.jonathanrpace.com/project\\_trees.html](https://www.jonathanrpace.com/project_trees.html)



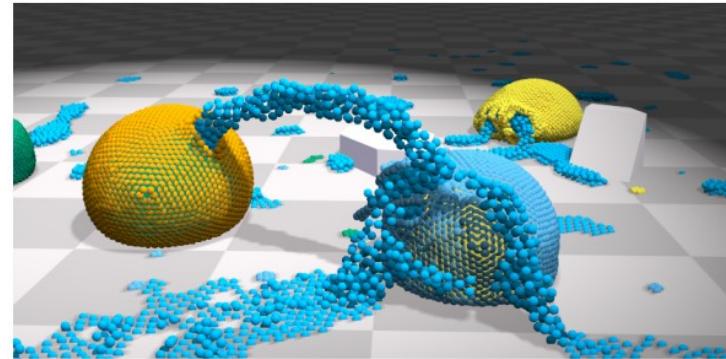
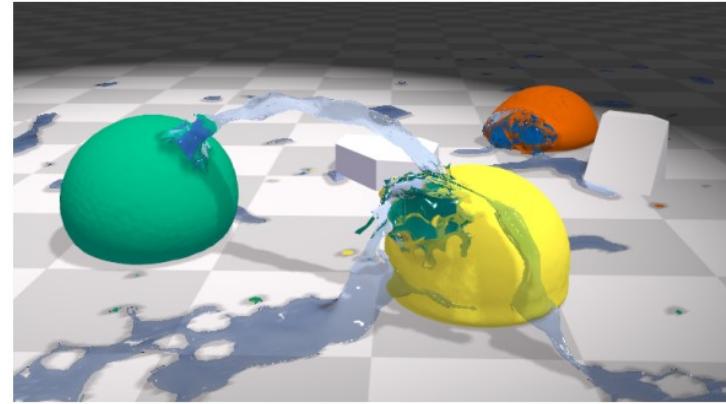
Mandelbrot: <https://www.mandelbulb.com/>

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

# Shape representation 8: Points



Scanned real-world  
objects can be stored as  
**point clouds**



Unified physics for real-time applications using points:  
[https://mmacklin.com/uppfra\\_preprint.pdf](https://mmacklin.com/uppfra_preprint.pdf)

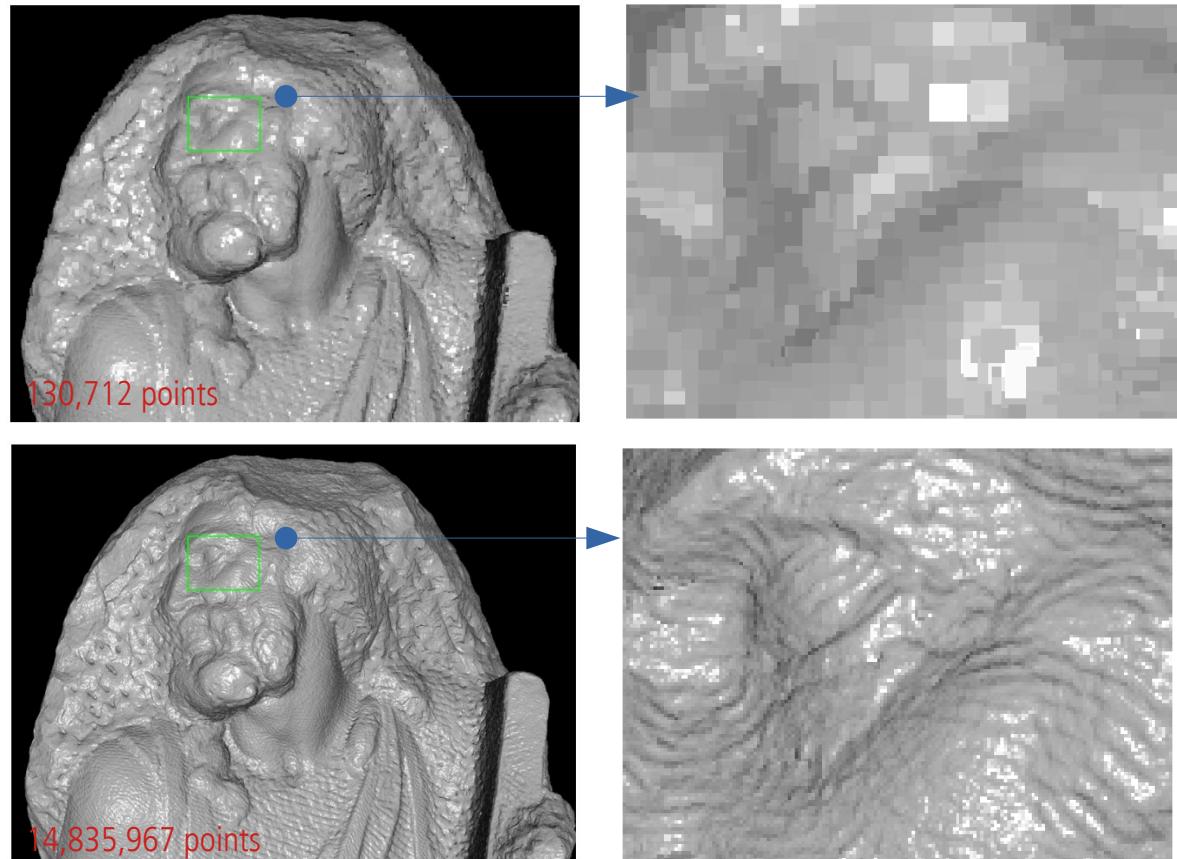
# Shape representation 8: Points

- 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](https://www.youtube.com/watch?v=u9KNtnCZDMI&ab_channel=MediaMolecule)



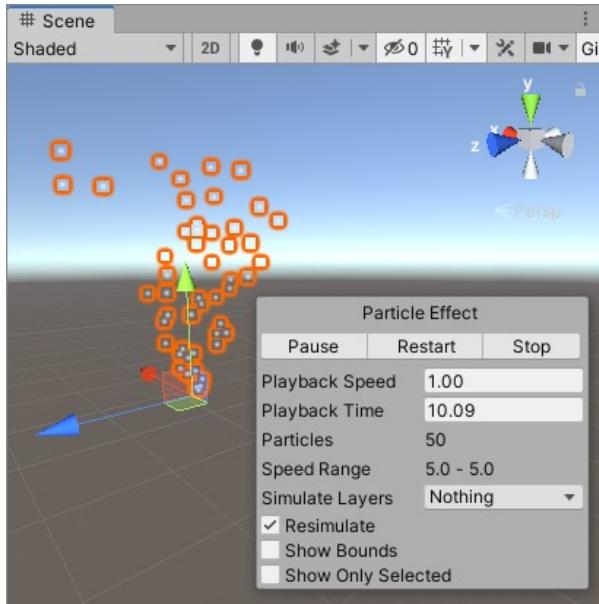
Qsplat: <http://graphics.stanford.edu/software/qsplat/>

\* Surfels:

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

# Shape representation 9: 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>



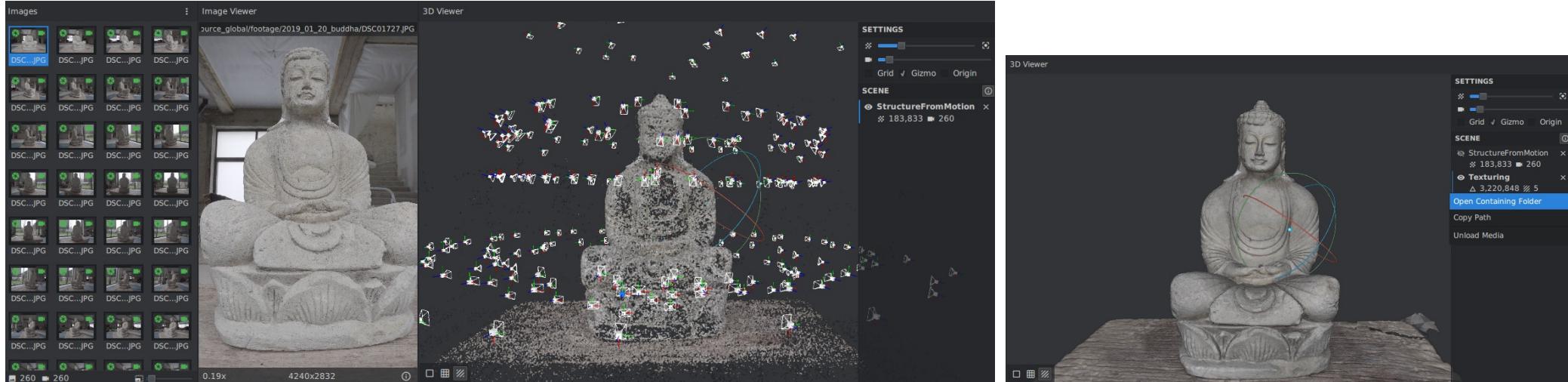
[https://developer.valvesoftware.com/wiki/Particle\\_System\\_Overview](https://developer.valvesoftware.com/wiki/Particle_System_Overview)

# 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

# Various shape representations?

- 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>

# Various shape representations?

- Modeling: Sculpting
  - Mesh, voxels, implicit representations



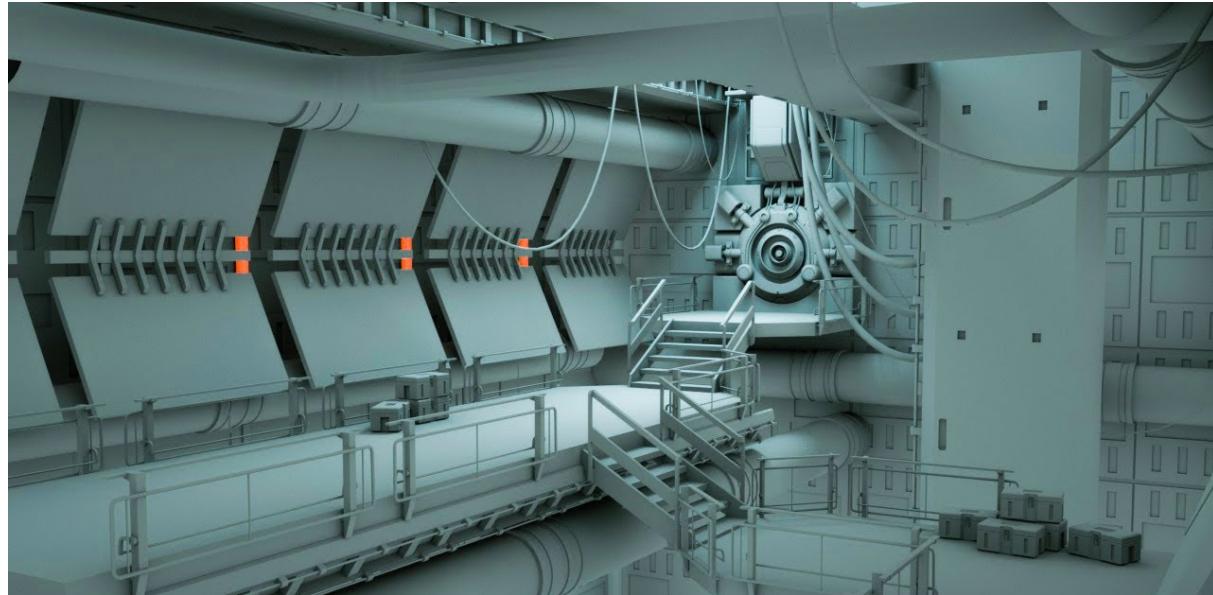
Jasmine, Zbrush,  
<http://pixologic.com/zbrush/gallery/?year=2018>



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

# Various shape representations?

- Modeling: hard-surface modeling
  - Quad mesh



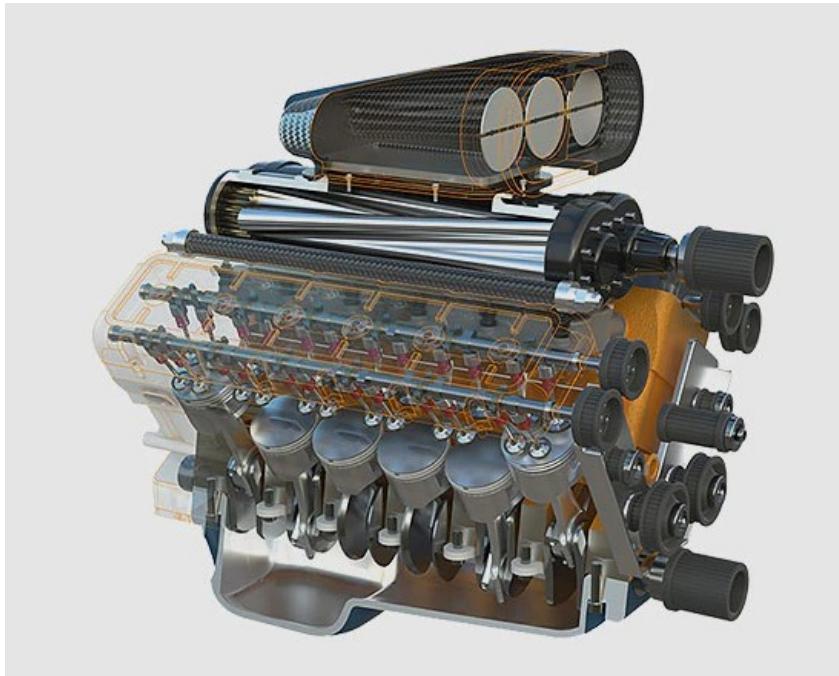
Hard surface modeling:

<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](https://www.youtube.com/watch?v=1qVbGr_ie30&ab_channel=JoshGambrell)

# Various shape representations?

- Modeling: curved surfaces
  - Parametric surfaces

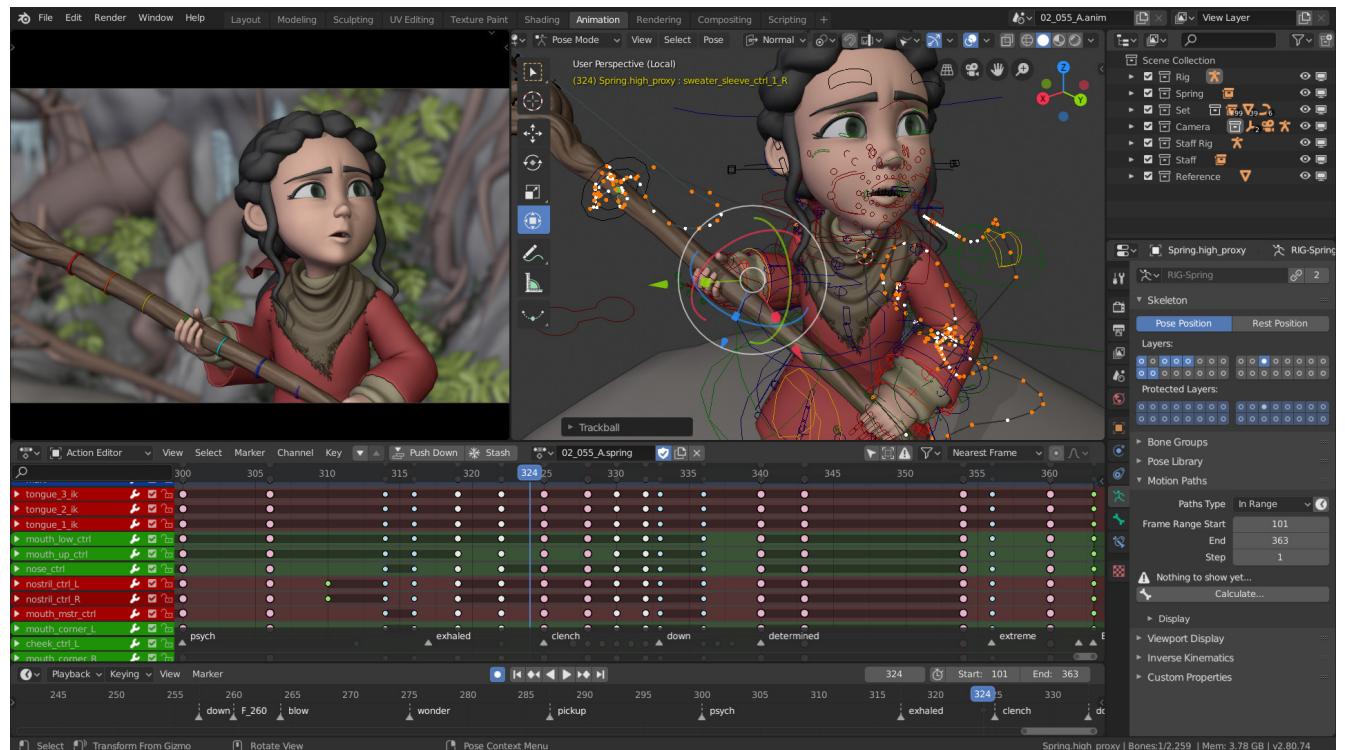


Renderman NURBS: <https://rmanwiki.pixar.com/display/REN24/NURBS>

# Various shape representations?

Animation: manual

- Meshes, parametric surfaces

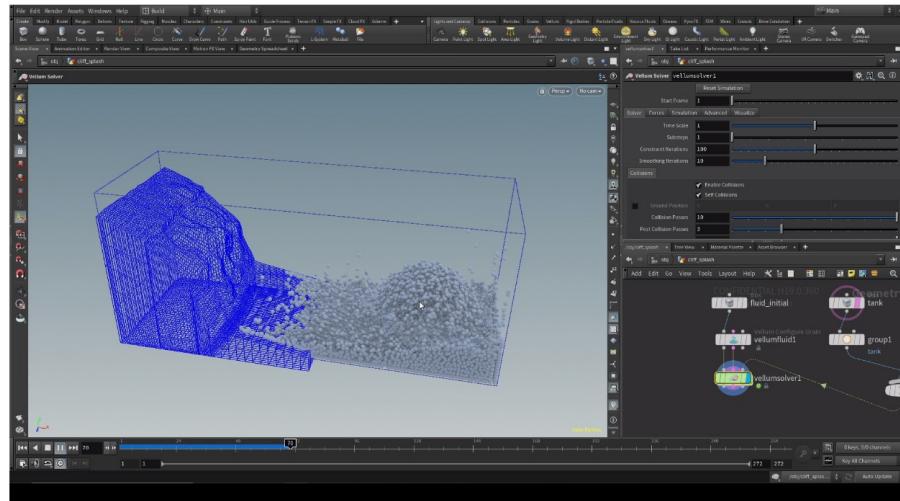


<https://www.blender.org/features/animation/>

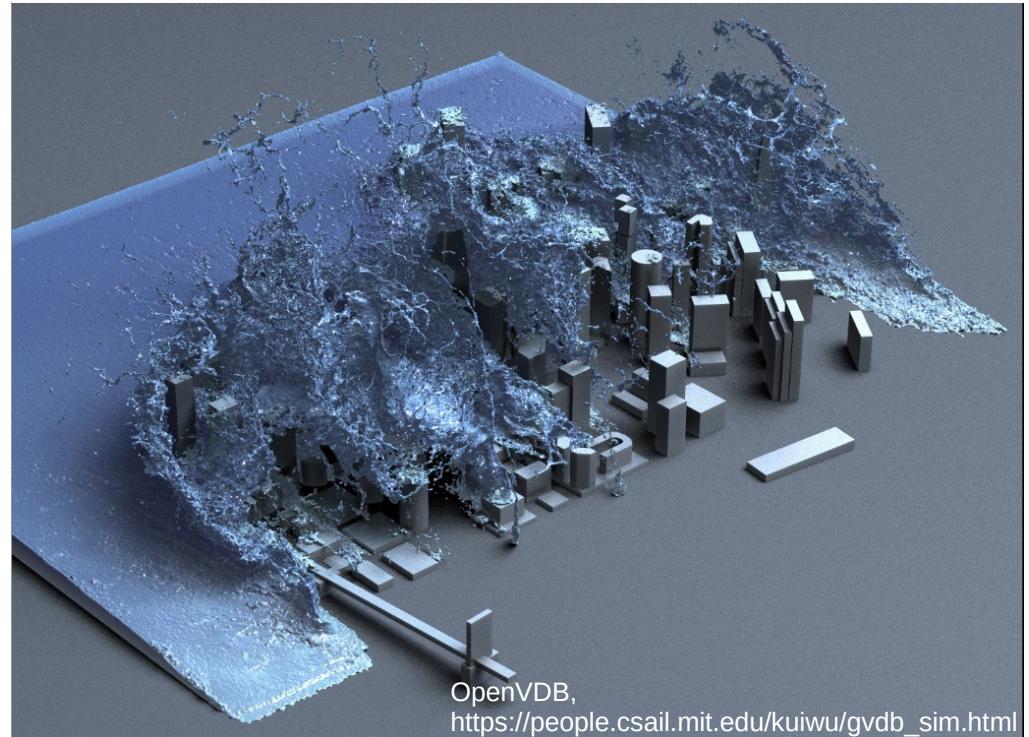
# Various shape representations?

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](https://people.csail.mit.edu/kuiwu/gvdb_sim.html)

# 3D models: various representations?

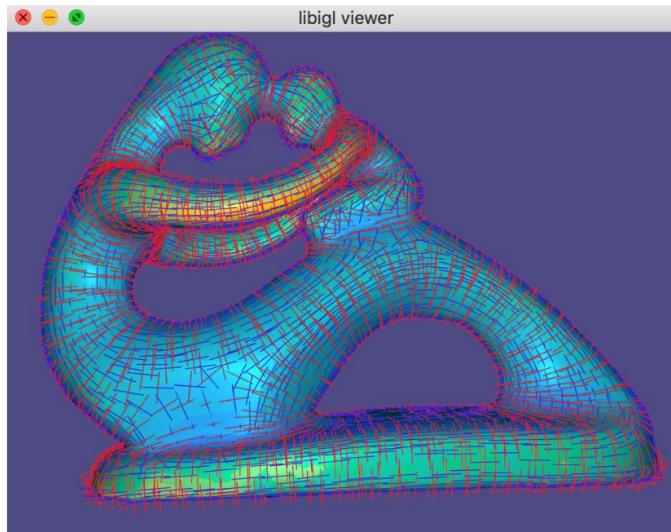
- **Rendering:** efficient visibility sol  
– Triangles, implicit surfaces



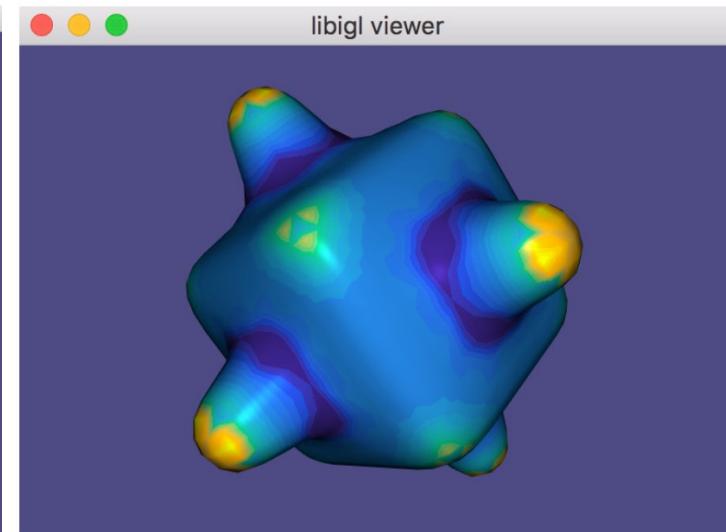
TODO

# Various shape representations?

- Analysis and processing
  - Meshes



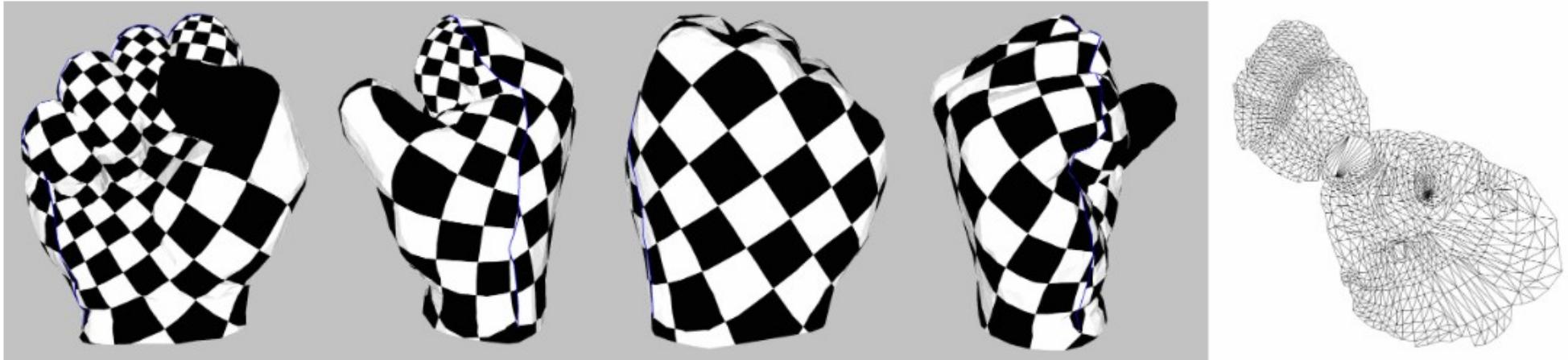
Libigl: principled curvature directions vectors (<https://libigl.github.io/>)



Libigl: Gaussian curvature visualization using pseudocolor (<https://libigl.github.io/>)

# Various shape representations?

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



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

# Objects: material

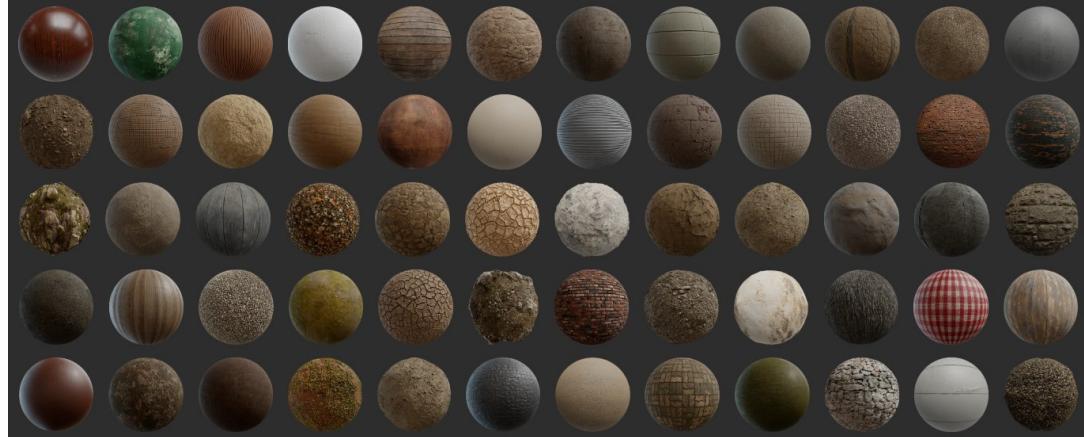
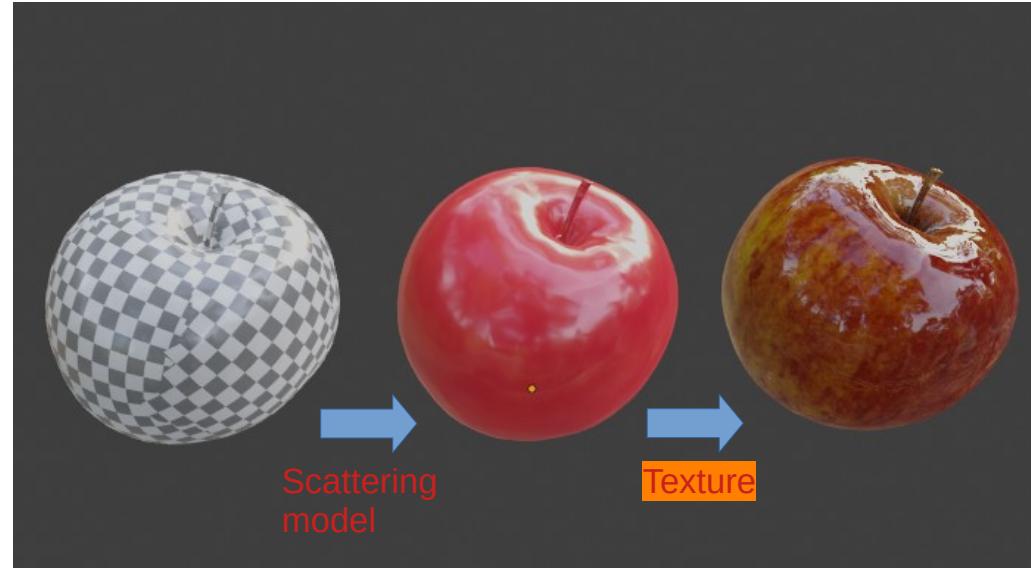


# Objects: material

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

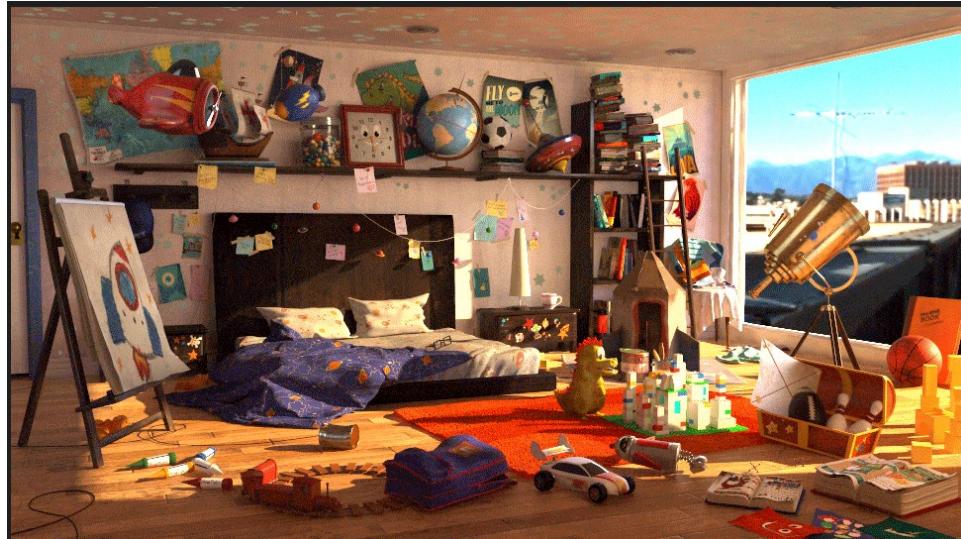


Scattering function: <https://appleseedhq.net/gallery.html>



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

# Lights

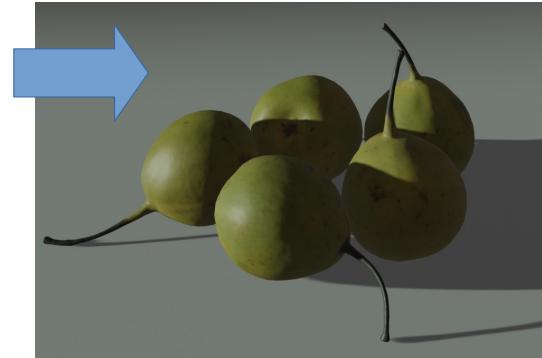
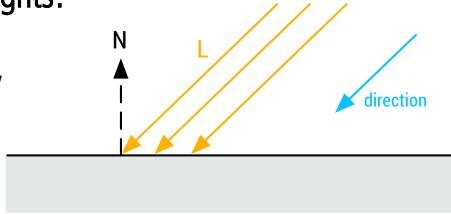


<https://discover.therookies.co/2018/06/24/learn-how-to-light-and-render-like-a-pixar-artist/>

# Lights: non-physical lights

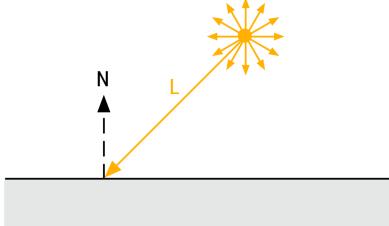
Directional lights:

- Direction
- Intensity
- Color



Point lights:

- Position
- Intensity
- Color



# Lights: physical lights

- Position, shape, size, intensity, color



Add example of  
Area light  
e.g. neon light street

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](https://www.pbr-book.org/3ed-2018/Light_Sources/Area_Lights)

# Lights: environment light



# 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>

# Cameras

- Pinhole camera model
  - Focal length
  - Film size
- Portion and amount of visible scene
- Advanced:
  - Lenses: depth of field
  - Shutter speed: motion blur



# Literature

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