

Computer image generation overview

Goal of Computer graphics

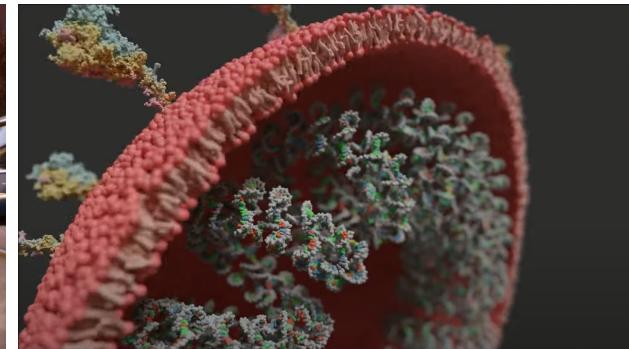
- Any interactive virtual environment, animation, application, development and research in computer graphics → **synthesizing images**



Graphics and computer games
<https://www.rockstargames.com/reddeadredemption2/>



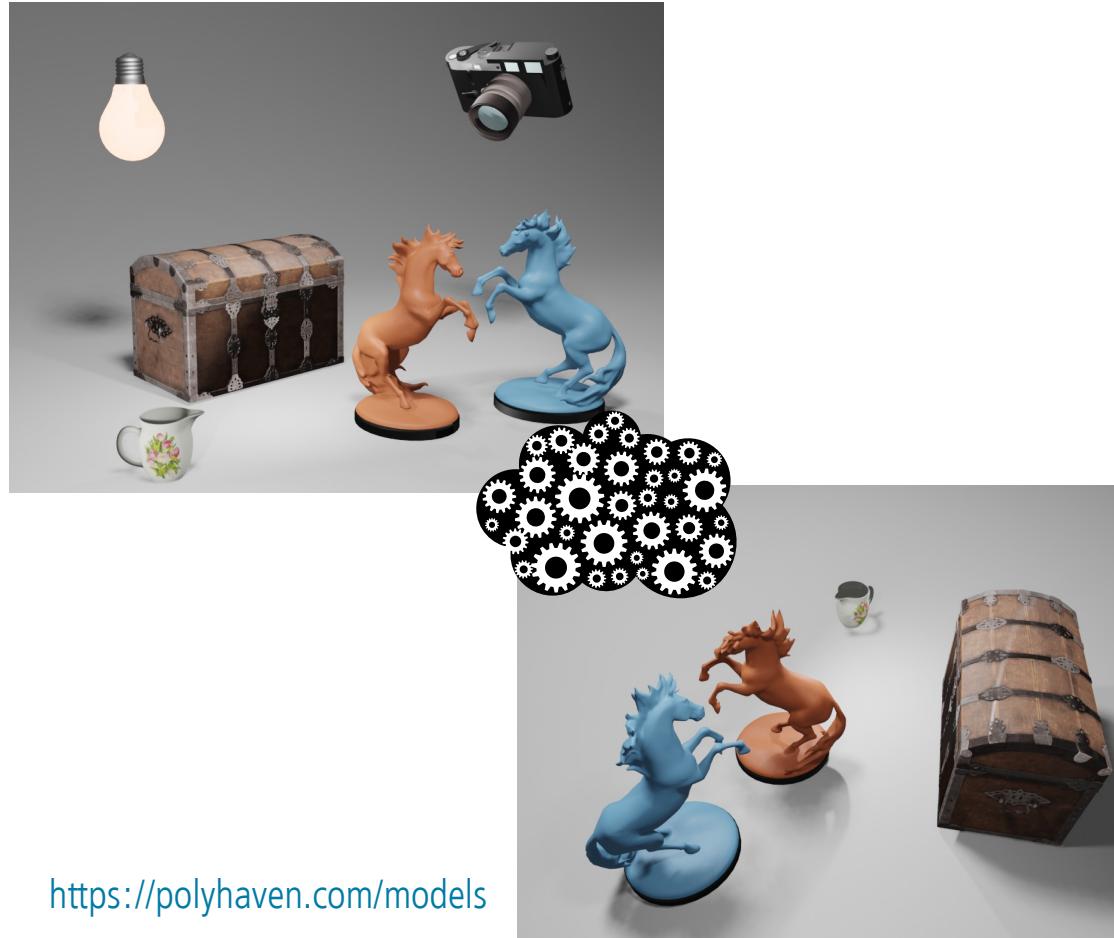
Graphics and animated film
<https://www.pixar.com/soul>



Graphics and scientific visualization
https://www.youtube.com/watch?v=adhTmwYwOjA&ab_channel=Blender

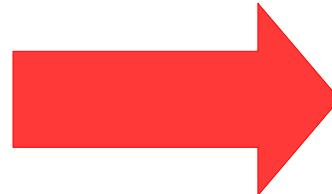
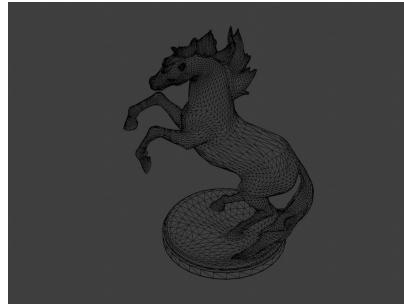
Image synthesis: intuition

- Real world observation/photography:
 - **Source of light** illuminates objects which have different **shapes** and **material**.
 - **Light travels through the space, interacts with objects** and some of it reflects into our eyes or **camera** giving us image of the world around us.



Fundamental image synthesis questions

- How to represent real world objects, lights and cameras in a computer?
- How to generate image based on computer representation of those elements?



Enter computer graphics

- Computer graphics is solving a problem of:
 - Representing real-world in a computer using models
 - Generating (synthesizing) images based on those models

Note: computer graphics

- Art of computer graphics is to decompose real world objects and phenomena into separate models and processes which can be modeled and then again combined into virtual world.
 - All of those parts are deeply intertwined and that one doesn't make sense without another.
 - Example: light and objects. Without light we can't see objects and without objects we can't see light. Nevertheless, we must decompose this phenomena into two models and study them separately

Simplification of a real world

- As in computer science, computer graphics problems are solved using **simulation and approximation**.
 - The complexity of real world objects and phenomena is simulated and approximated to achieve desired outcomes for specific application.
 - Computer graphics simulations and its results (generated image) are **discrete***.

* For example Computer generated image and display device are 2D array of pixels – raster graphics and display (grid of x and y coordinates on a display device).

Pillars of computer graphics

- To synthesize an image:
 - We need a description of a **3D scene** which contains objects and phenomena we want to visualize
 - A way to transform a 3D scene into 2D array of pixels – **rendering**
 - A way of storing 2D array of pixels for raster display – **image**

Modeling and rendering

- Computer graphics R&D is concerned with*:
 - Techniques and methods for modeling of 3D scene
 - Interaction with 3D scene elements is researched in human-computer interaction (HCI) field, closely related to computer graphics
 - Development of rendering algorithms for creating image out of a 3D scene
 - Storing and displaying image.

* Computer graphics is closely related to other fields such as computer vision and image processing.

- Image generation software can be thus split into:
 - **Modeling** – process in which 3D scene is defined: what is rendered
 - **Rendering** – process in which image of 3D scene is generated

Modeling and rendering are intertwined

- Rendering process must “understand” how 3D scene is represented
- Modeling of 3D scene relies on representations which are understood by rendering algorithm

3D Scene Modeling

A start of image generation journey: answering what we render*

* As discussed, but to highlight again, 3D scene modeling and rendering in order to obtain an image is highly intertwined process. For learning purposes in production and as well as in research in development theses processes are separated. Depending on application and teaching the description of whole process can start from rendering as well.

3D scene modeling

- In order to generate an image we need something to render → a 3D scene.
- The real world is made of wide range of objects.
 - For 3D scene modeling, **objects** are described using: **shape and material**
- The reason why we see objects around us is due to light reflecting in our eyes.
 - For 3D scene modeling, we separate objects which generate light - **light sources** and those which only reflect light.
- 3D scene is simulated 3D world from which images can be taken - similarly as photographing a real world. Thus, we also need to simulate a device which is needed for taking images – a **camera** – which also defines from where image is taken.

Pillars of 3D scene

- 3D objects
- Lights
- Cameras

3D space

- To define any object in 3D scene we need to introduce a concept of **3D space**.
 - 3D space is represented with 3 coordinate axis: **Cartesian coordinate system**
 - This main coordinate system is called **world**.

World coordinate system

- All objects have unique **transform** in this world coordinate system:
 - Position
 - Rotation
 - Scale

Objects in 3D scene

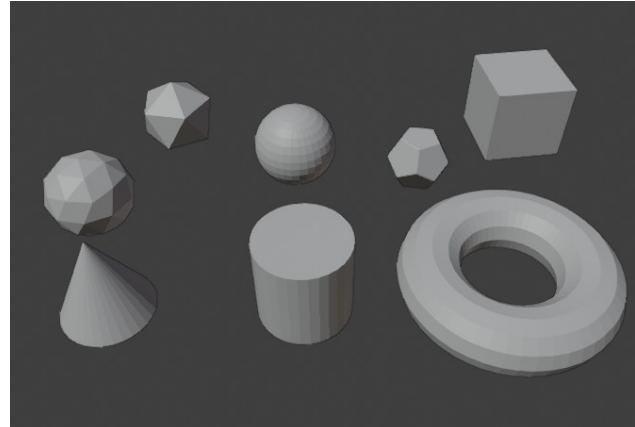
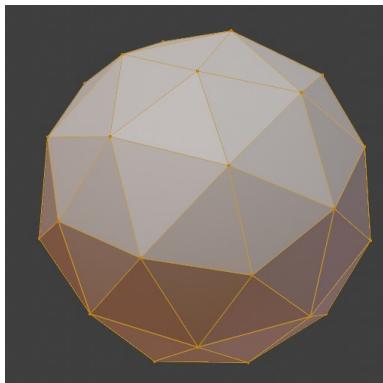
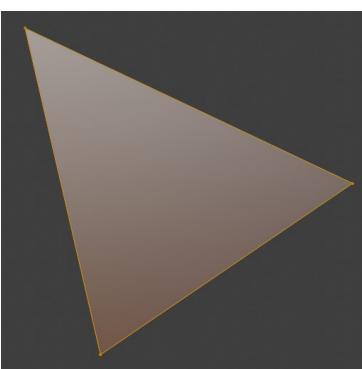
- Modeling 3D scene object is separated into modeling:
 - Object shape
 - Object material

Object shape

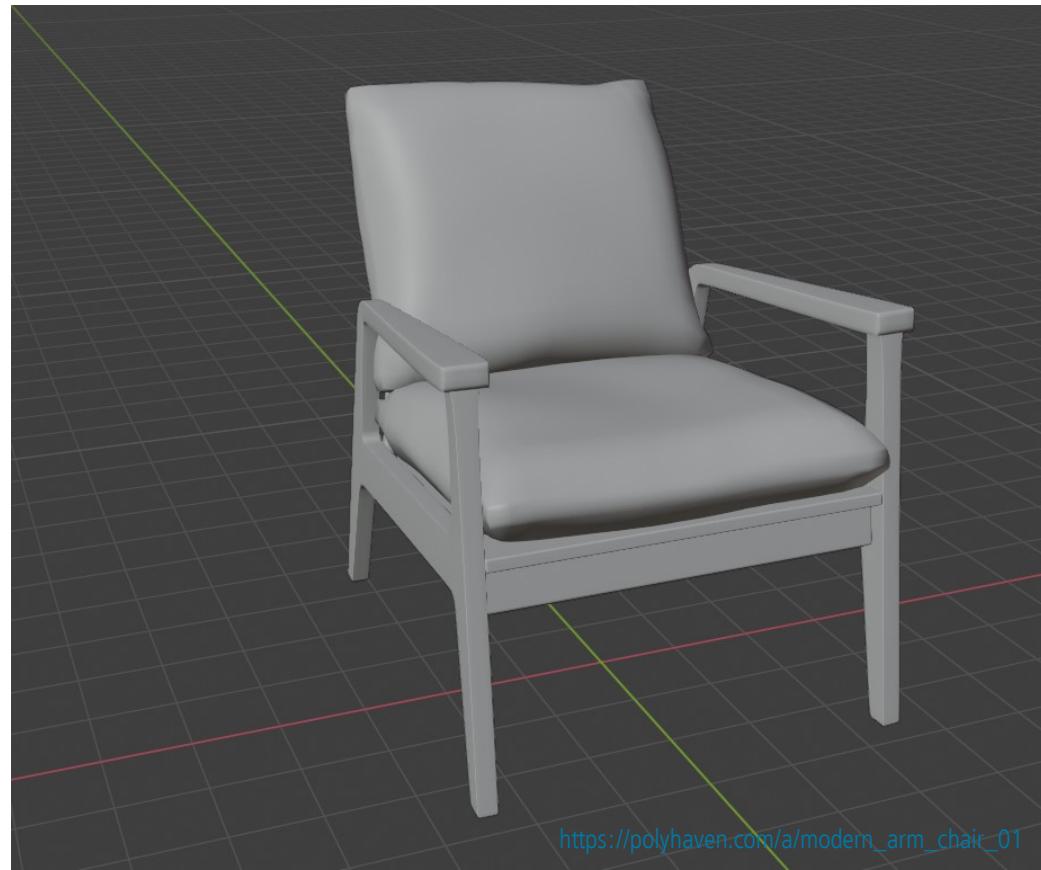
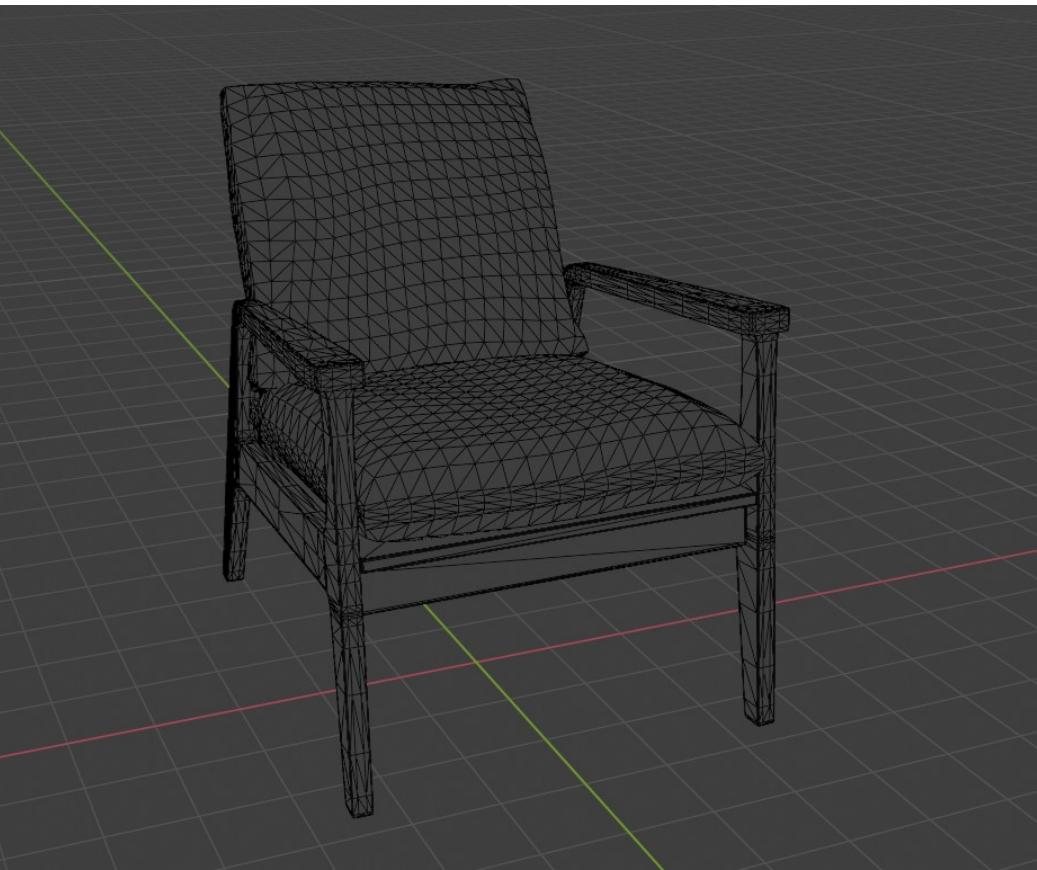
- Define object form, size, etc.
- Place object correctly in the scene with respect to other objects
- Determine which objects are occluded and areas into which shadow is cast by object

Shape representation

- We start by defining **points** (x,y,z) in 3D space.
- To define a **surface**, simplest way is to connect points to form a **polygon**.
 - Most commonly used polygons are **triangles**.



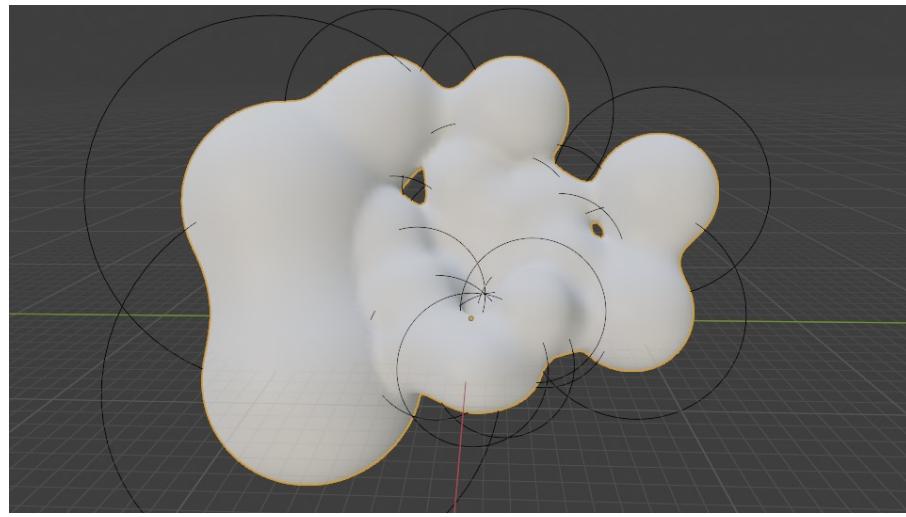
Triangle shape representation



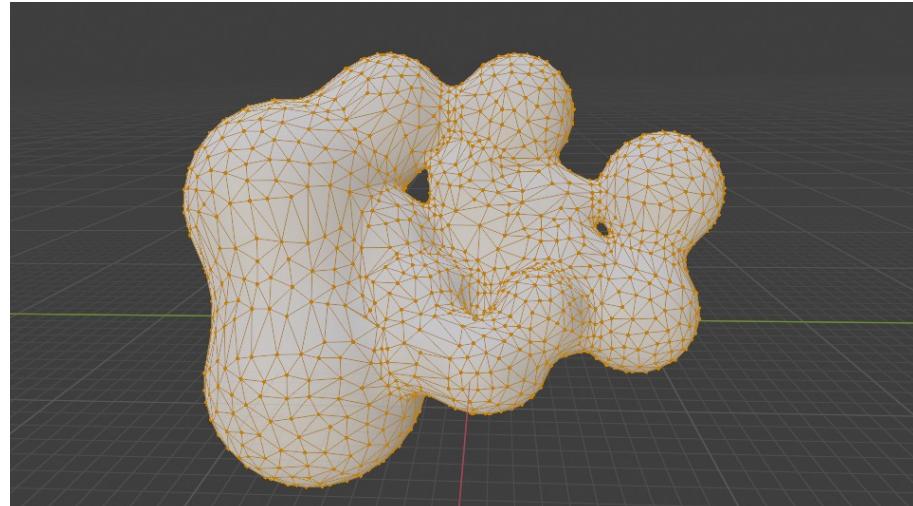


Why triangles?

- Are objects that we have seen created using triangles?
 - NO!
- Modeling is often done using different shape representations
 - It is very often that different shape representations are turned into triangles before/during rendering stage - using **triangulation**.
- Triangle is most widely used **primitive** for surface shape representation
 - Simple
 - Efficient for storage and transfer
 - Efficient for rendering



↓ Triangulation



Other shape representations

- Various representations for 3D models exists.
 - Some are better for **modeling** (e.g., implicit surfaces).
 - Other are better for **rendering** (triangulated mesh).

Shape representations for modeling

- In professional software, various shape representations for efficient modeling exist.



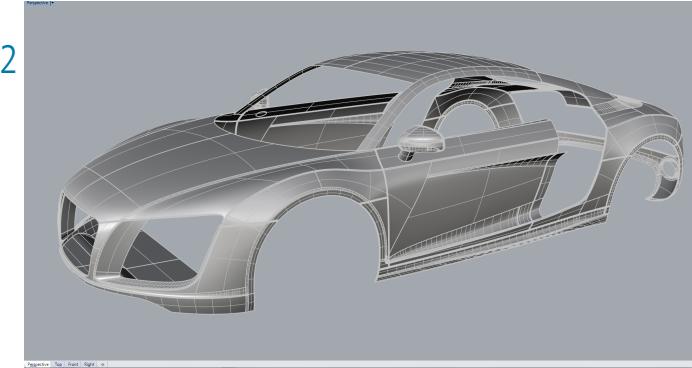
Hair modeling using parametric curves:

<https://developer.nvidia.com/gpugems/gpugems2/part-iii-high-quality-rendering/chapter-23-hair-animation-and-rendering-nalu-demo>



Implicit surface representation:

<https://www.shadertoy.com/view/ld3Gz2>



Parametric surfaces:

<https://forums.cgociety.org/t/audi-r8-v10-2010-nurbs-model-with-rhino-3d/1761843/3>

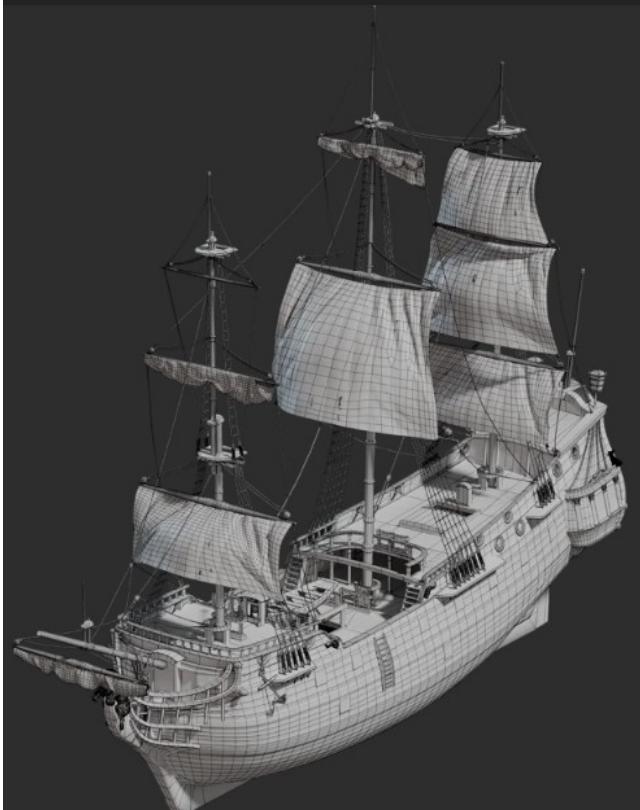
Shape representations for rendering

- Almost always prior rendering, different shape representations are converted to triangulated mesh for efficient rendering.
 - One representation for rendering makes rendering process highly efficient
 - Graphics cards (graphics processing units, GPU) is highly efficient for processing triangles
 - Lot of research and hardware development was focused onto efficient rendering of triangles*.

* It is easy to imagine that different rendering primitive is used. But due to historical events this turned out to be a triangle. What is important to note is that mapping of various representations to triangle mesh is possible and thus it is not important which is the rendering primitive as long as it supports various representations.

Object material

- Material defines how light interacts with object surface → **object appearance**







Material modeling



3D objects: appearance



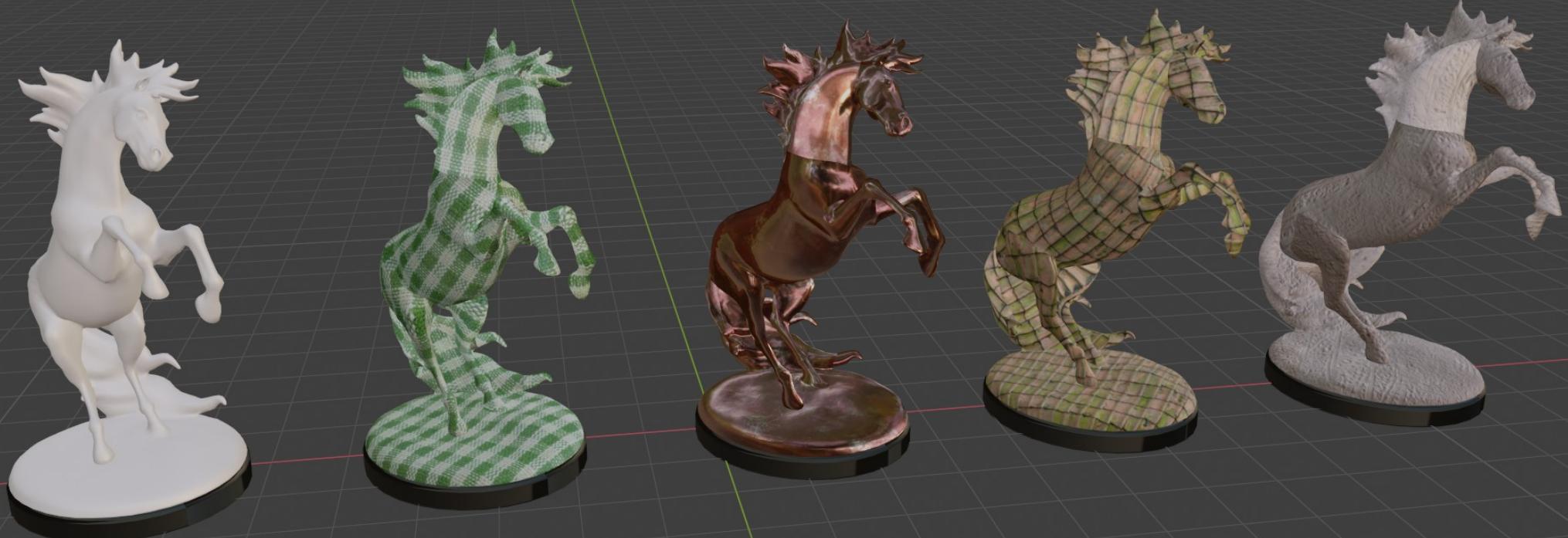
Shape

Shape + Material:
object appearance
greatly depends on
material.



Material and shape

Material and shape can be modeled separately.



Material

- In computer graphics, material modeling is combination of:
 - Scattering model
 - textures

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



<https://polyhaven.com/textures>

Material



- Uniform material parameters
- Material is defined using only **scattering model***



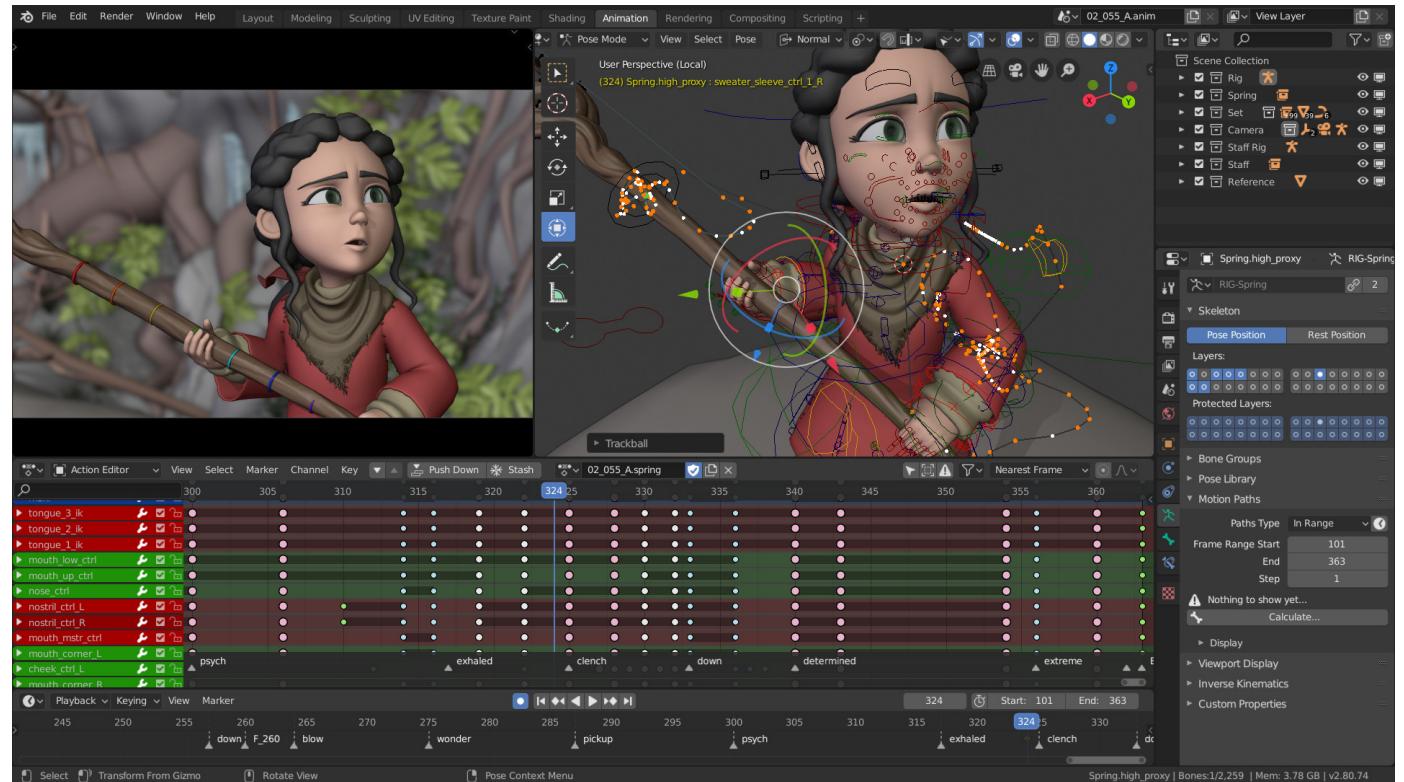
- Varying material parameters
- Material is defined using **scattering function and texture**

Material

- Material defines:
 - How light travels between objects: participating media
 - How light interacts with surfaces: surface scattering
 - How light interacts sub-surface

Creating 3D scene objects

- Interactive modeling using DCC tools



Creating 3D scene objects

- 3D scanning can be used to “import” real object into digital world.



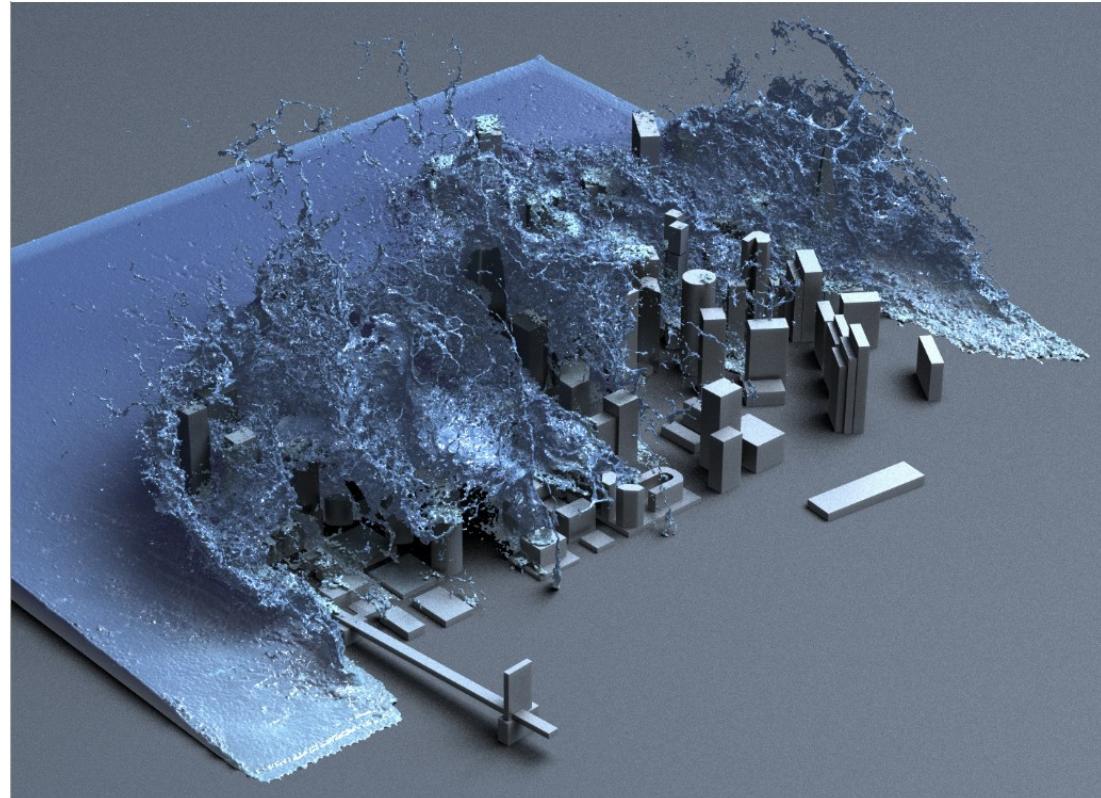
<https://quixel.com/megascans/home/>



<https://www.myminifactory.com/object/3d-print-bust-of-antinous-as-dionysus-50345>

Creating 3D scene objects

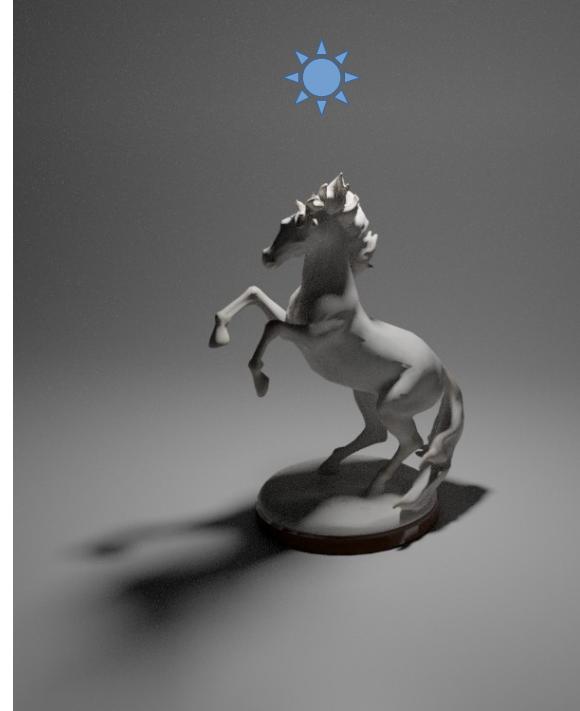
- Simulations
 - Some objects are very hard to model by hand and capture from a real world.
 - Physical simulations are employed to generate shape.



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

Lights

- Light sources define:
 - Position and direction
 - Color and intensity
 - Size and shape



Light in 3D scene



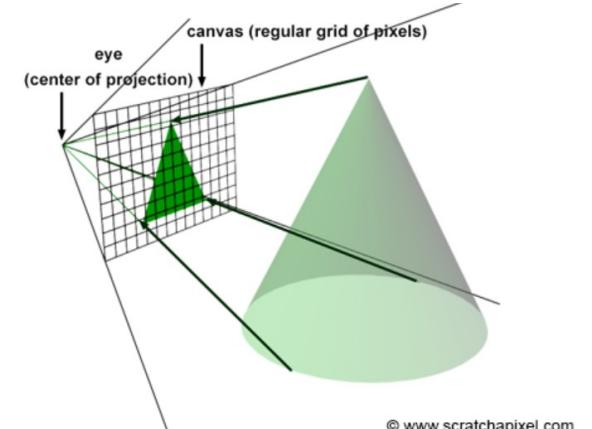
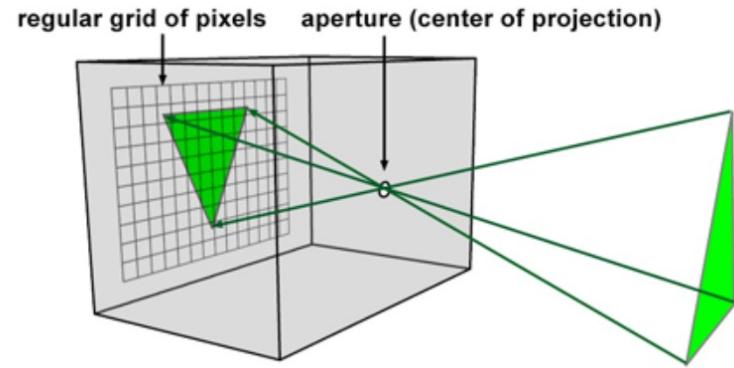
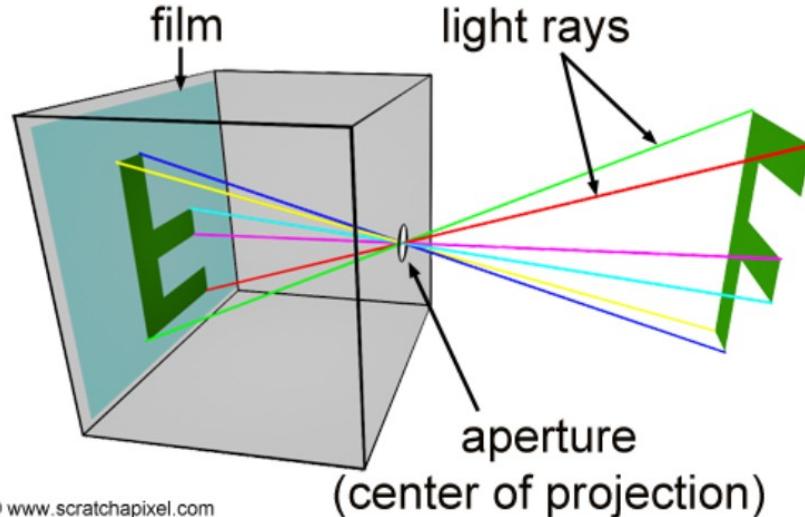
Camera

- Camera defines point of view and it is used to simulate effects of real-world cameras.



Camera

- Fundamental camera model in computer graphics: pinhole camera:
 - Eye (aperture)
 - Focal length
 - Film size



Camera

- Effects

Animated objects

- Introducing a time component into 3D scene and moving/rotating objects and their parts as time goes gives foundations for animation.
- Animation can be predefined, generated at render-time or influenced by interaction
- TODO

Animated objects

- Blender
- Maya
- Houdini

Interaction with 3D scene

- Godot, Unity, Unreal

3D scene: recap

- **3D scene**
 - 3D objects
 - Lights
 - Cameras
- Rendering takes 3D scene information for generating image.
 - 3D scene definition must be done with elements (shapes, material, lights, cameras, etc.) understandable to rendering engine

Rendering

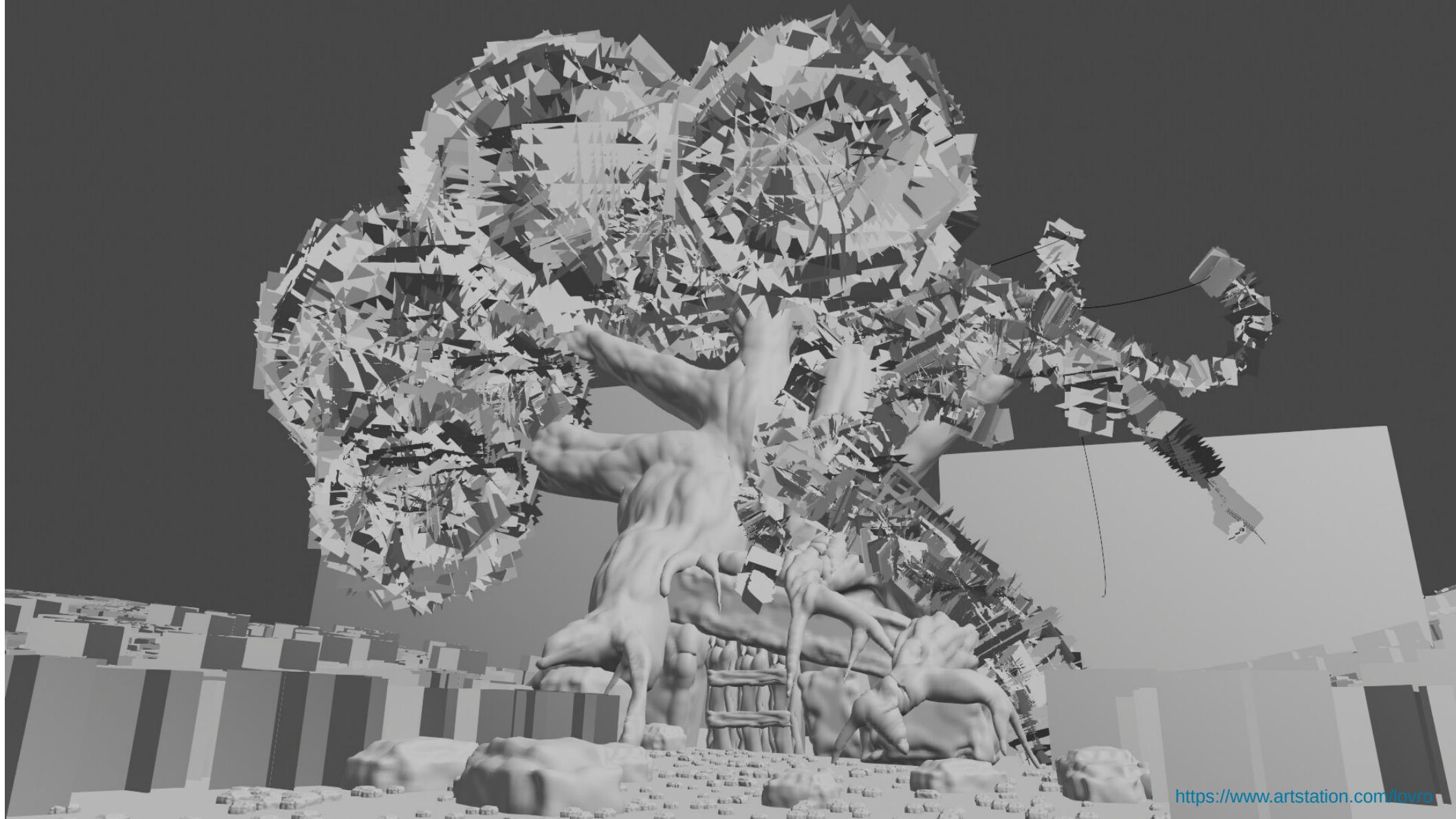
A process of generating image from a 3D scene

Rendering

- Rendering is general term for generating images from a 3D scene.



Scene from: <https://casual-effects.com/data/index.html> (Sponza Palace in Dubrovnik). Rendered in Blender, EEVEE.



<https://www.artstation.com/lovro>







Rendering: photo-realistic images

- Often, goal is to create **photo-realistic** images – images that look like a photograph* of a real world.
 - To make objects appear as they do in real world, we need to simulate laws of physics that are related to appearance – optics, that is, simulating light transport and interaction with objects in 3D scene and camera.



Juan Carlos
Gutiérrez:
<https://appleseedhq.net/gallery.html>

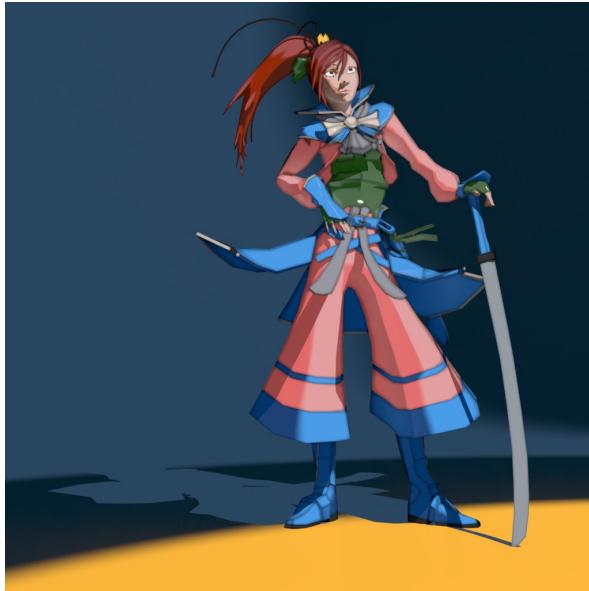


Juan Carlos
Gutiérrez:
<https://appleseedhq.net/gallery.html>

* Note that there is also distinction between images that look like a real photo and that are "correct" like a real photo. In graphics, almost always it is enough to create images that look like a real photo but the way they are produced doesn't necessarily have to be correct in terms of how real world works. Again, this is trade-off between quality and speed and decision depends on application.

Rendering: non-photorealistic images

- On the other hand, creating **non-photo-realistic** (NPR) images* – images that contain wide range of expressive styles, is also often desired.



Enthymeme:
<https://appleseedhq.net/gallery.html>



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

* Specific look of NPR images often comes from exaggerating some characteristics of 3D scene or rendering algorithm. Therefore, it is better to start with photo-realistic rendering and then altering this method to obtain required style in NPR.

- In both cases, image is generated using certain **rendering** method - a simulation of appearance of objects*.

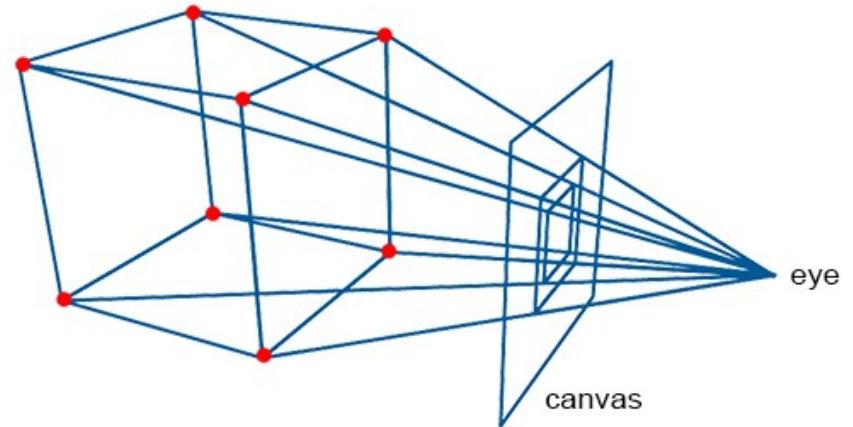
* Note that the realism/style of image, next to rendering, also depends on the way how 3D scene is simulated as well as its complexity. This is another example showing how rendering and modeling of 3D scene are intertwined processes.

Rendering: simulating visual system

- **Foreshortening effect:** objects that are further appear smaller than those which are closer
- Important for photo-realistic rendering since it simulates how our visual system works
 - It defines shape and size with respect to the distance to the eye.

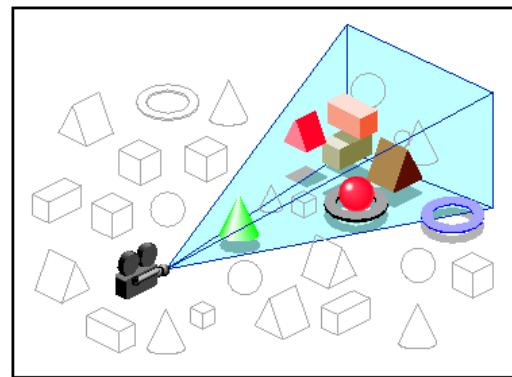
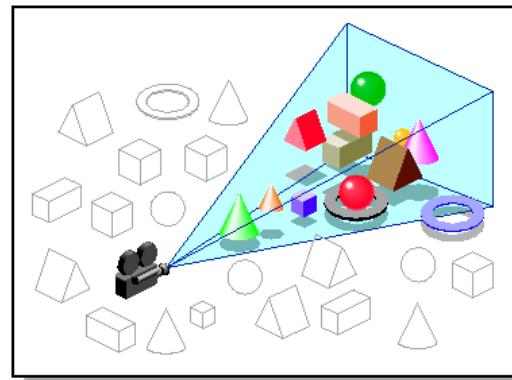
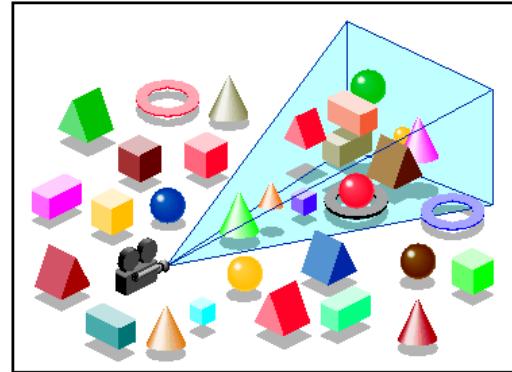
Foreshortening effect: trace rays from corners of objects to eye and intersecting them with imaginary canvas that lies in between → perspective projection.

Direct result of such method is called **wireframe rendering**.



Rendering: visibility problem

- Camera placed at certain point of view covers only small portion of 3D scene
- **Visibility problem***: determine if two points in 3D scene are visible (not obstructed)
 - Determine which objects are visible from camera
 - Determine which surfaces are visible to each other in 3D scene
- Solving the visibility relies in object **shape information**
- Solution to visibility problem in computer graphics can be solved using two main methods:
 - Rasterization**
 - Ray-tracing

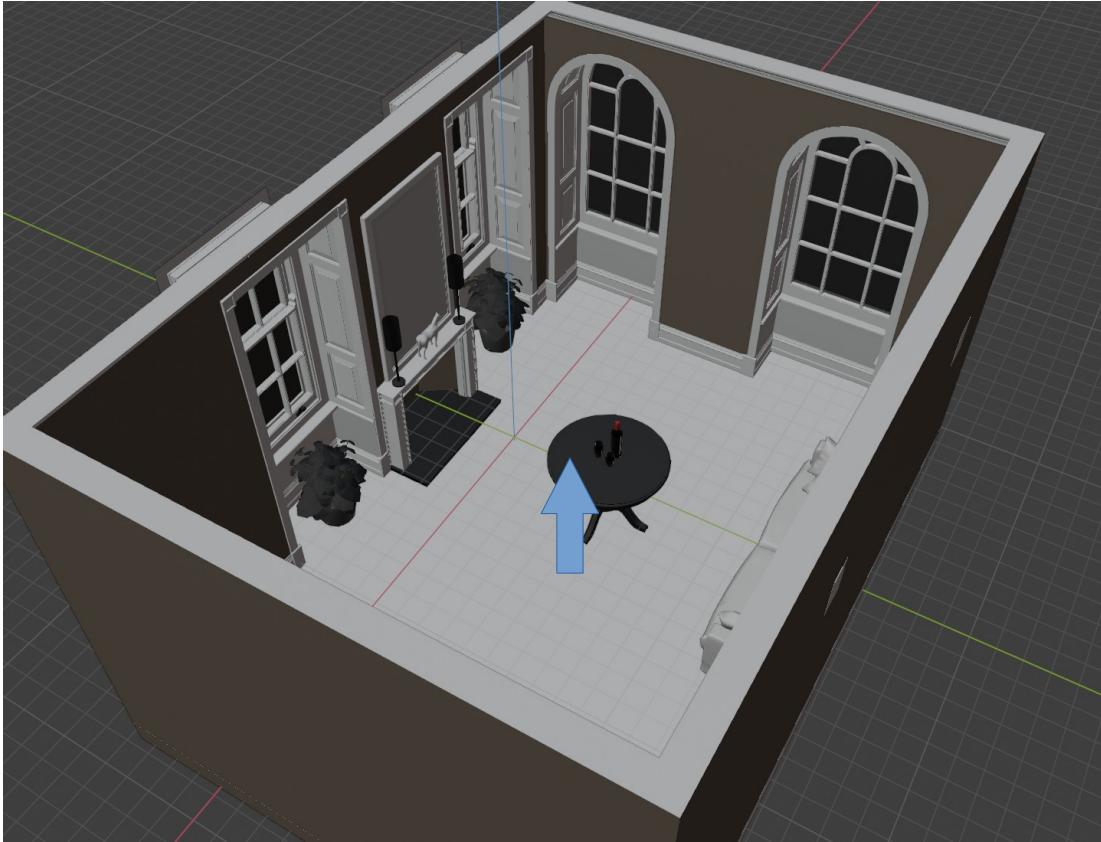


https://techpubs.jurassic.nl/manuals/nt/developer/Optimizer_PG/gi_html/ch05.html

* Also known as: hidden surface elimination, hidden surface determination, hidden surface removal, occlusion culling and visible surface determination

** This is umbrella term and some popular methods are painter's algorithm and z-buffer. Almost all GPUs use an algorithm from this category.

Rendering: visibility problem



Rendering: appearance

- Once visibility problem is solved; which geometry is visible from certain viewpoint, **appearance of object** is calculated
 - Appearance: The look of objects in terms of color, texture and brightness.
- Object appearance depends on:
 - Object shape and material
 - Illumination
 - Camera viewpoint
- Appearance of object is simulated using **shading**

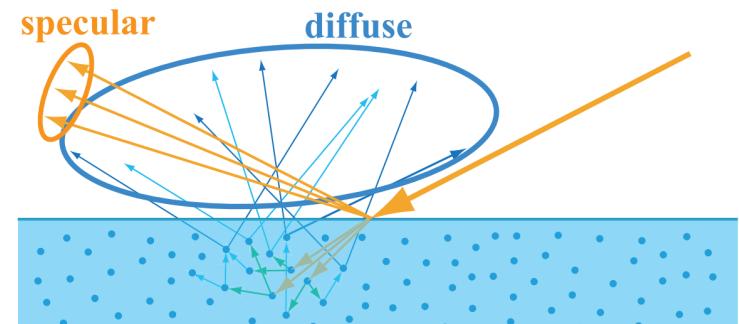
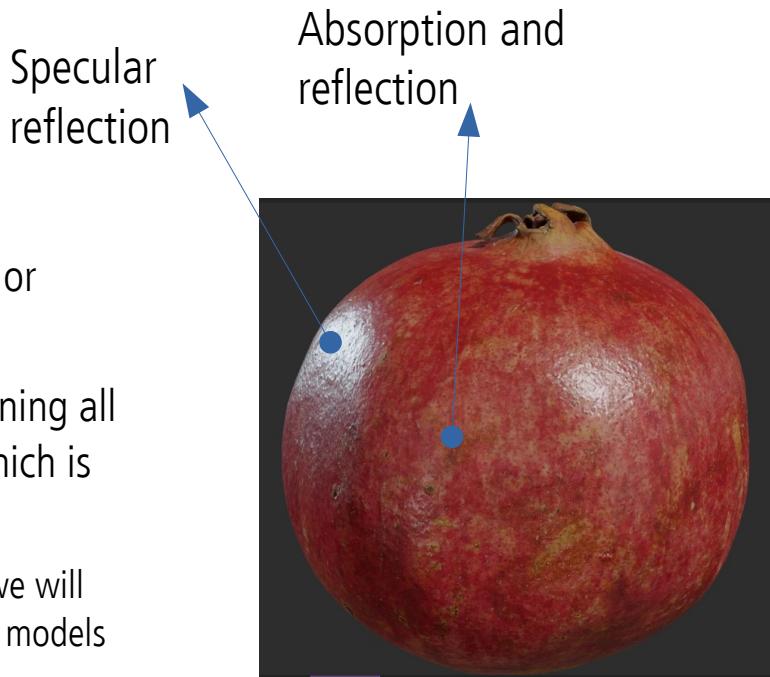


Rendering: shading

- **Shading** defines interaction of light with object material
 - Gathering light falling on surface → **light transport**
- Implementation of mathematical model which simulates light interaction with surface is called a **shader**.
- Real-world light-matter interaction is complex topic.
 - In CG there is always trade-off between quality of image and rendering speed.

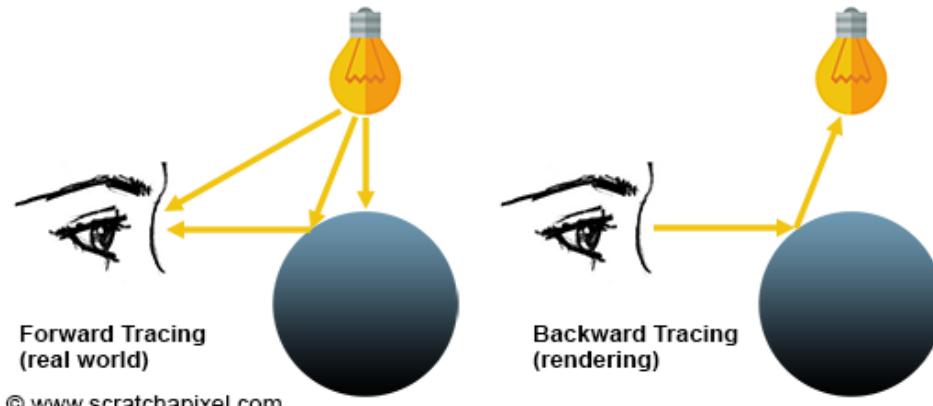
Rendering: shading

- When light comes in contact with an object it can be: absorbed or reflected
- **Absorption** gives objects their unique color. If white light (containing all colors) falls onto object which absorbs all colors except red – which is reflected, we perceive this object as red.
 - Color of object is one foundational material information of object as we will see later. It can be defined directly or indirectly using physically-based models which calculate color.
- **Reflection**. Light which is not absorbed is reflected. Direction of reflection depends on:
 - Surface orientation → **surface normal** vector.
 - **Scattering** – a model which describes what happens with light at small scale. This model can have uniform parameters or varying parameters – giving textured look



Rendering: light transport

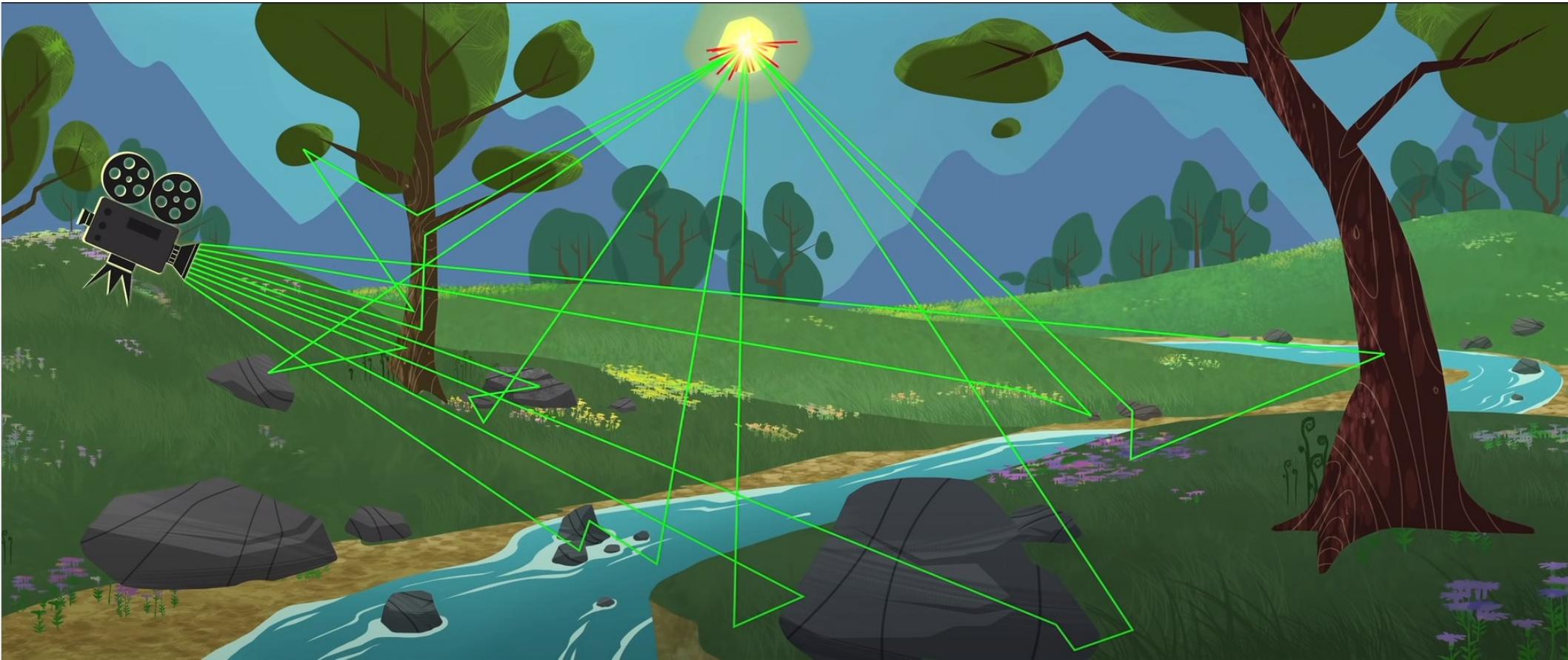
- Crucial information for shading is amount of light falling on surface → **light transport**
- Light is emitted from light sources, reflects from objects and eventually might fall into camera → **forward tracing**
 - Extremely expensive to calculate complete light behavior in whole scene.
- **Backward tracing:** starting from camera, find visible objects and incoming light from there



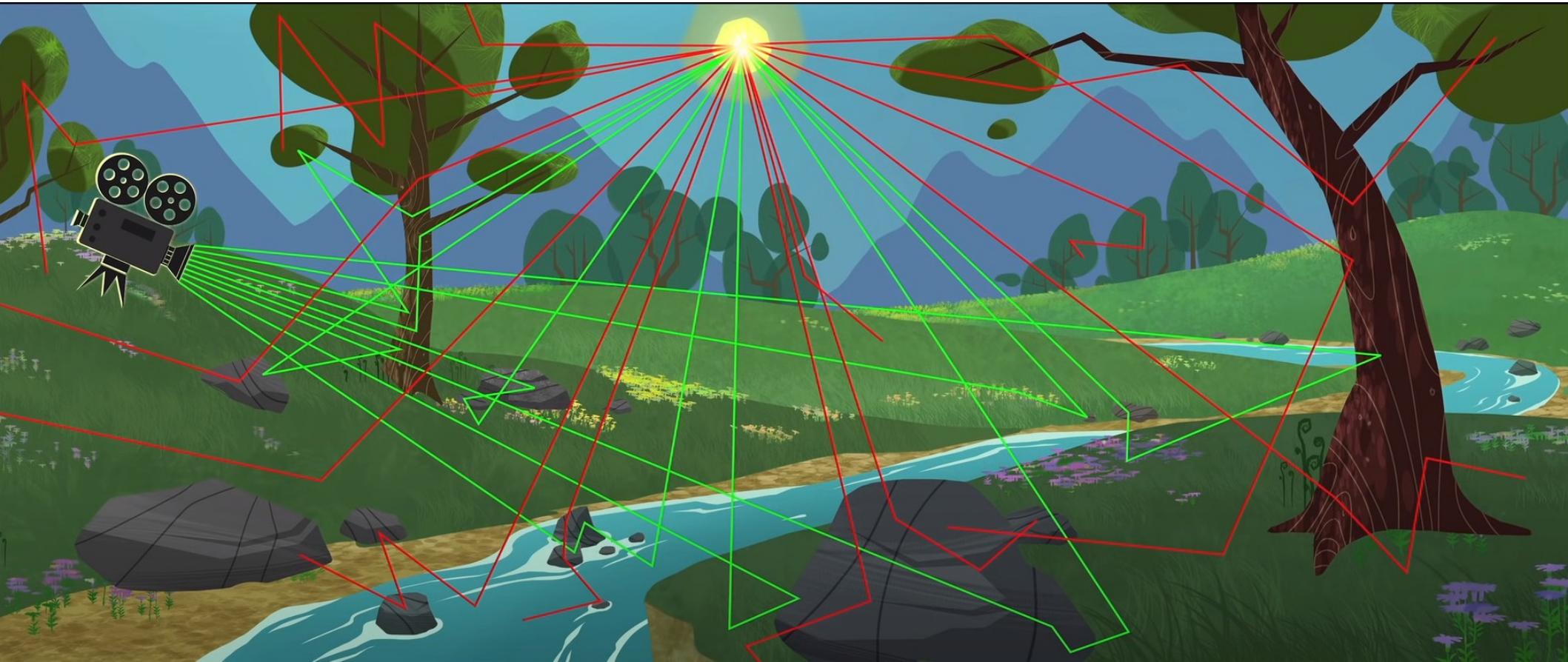
Forward tracing



Backward tracing

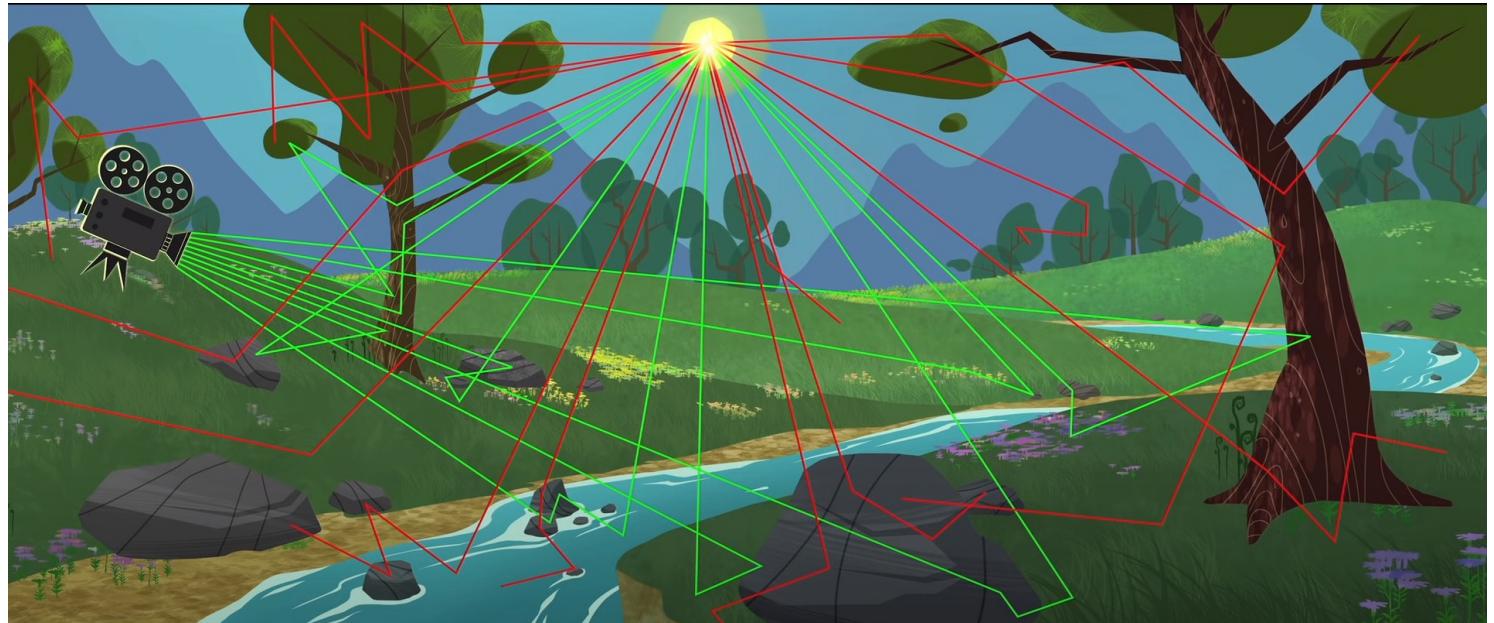


Forward tracing is expensive!



Forward tracing

- Object surface which is visible from camera might receive light from any light source or surface which is facing.
- Amount of light which falls into camera is extremely small. Thus rendering employs light transport only for visible surfaces starting from the camera and only for relevant light paths.

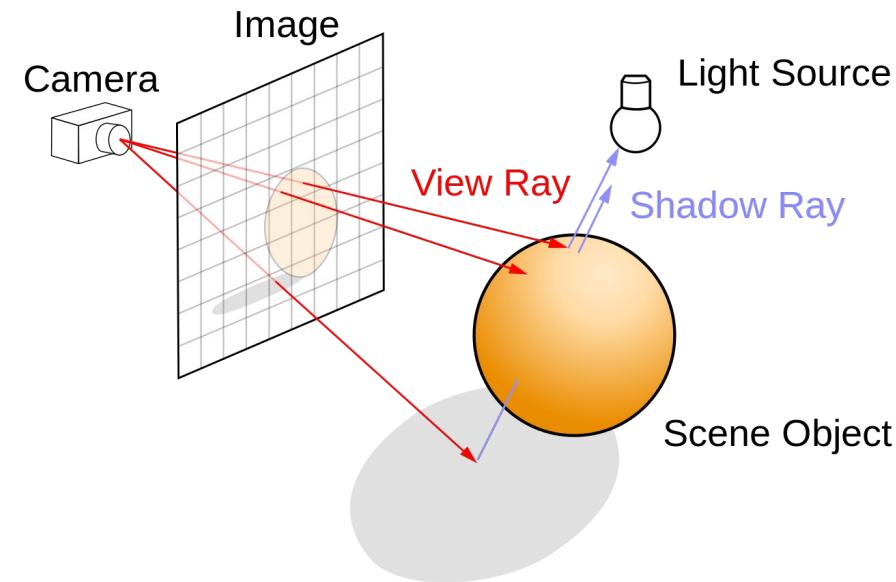


Local and global illumination

- Taking in account only light from light sources → **direct (local) illumination**
- Taking in account light reflected from other objects → **indirect illumination**
- Simulating direct and indirect illumination → **global illumination**

Rendering: recap

- Rendering:
 - Solving **visibility problem**: what is visible from camera point of view
 - Perspective projection
 - Object shape
 - **Shading**: calculating appearance of visible objects
 - Material and shape of object
 - Viewing direction
 - Light falling on the object: **light-transport** (again, visibility problem)

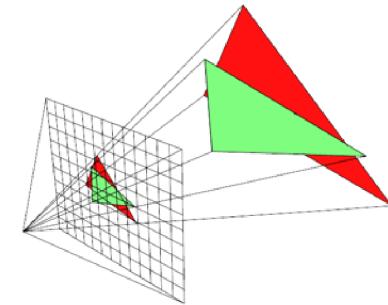


Practical rendering

- In practice, rendering is implemented using
 - Rasterization
 - Ray-tracing
- These two methods are essentially solving visibility problem
- Shading is influenced by this choice since it depends on visibility problem

Rasterization

- Visibility problem is solved by projecting object on surface of canvas from given point of view
 - Project point P onto screen to compute P'
 - Perspective projection matrix
- Object-centric approach

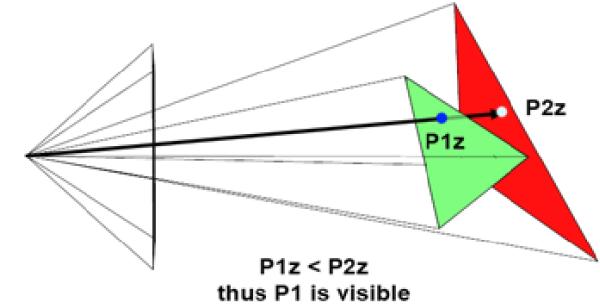


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```
for T do in triangles  
    for P do in pixels  
        determine if P inside T  
    end for  
end for
```

Ray-tracing

- Trace rays from camera for each pixel on canvas and intersect objects in the scene → closest objects are visible ones
 - Perspective camera
- Image-centric approach



© www.scratchapixel.com

```
for P do in pixels
    for T do in triangles
        determine if ray through P hits T
    end for
end for
```

Scene

Blender, WorkBench
Scene: Crytek Spinoza
<https://casual-effects.com/data/index.html>

Rasterization-based render



Blender, EEVEE
Scene: Crytek Spinoza
<https://casual-effects.com/data/index.html>

Ray-tracing-based render

Blender, Cycles
Scene: Crytek Spinoza
<https://casual-effects.com/data/index.html>

Rasterization vs ray-tracing

- **Rasterization** can quickly determine visibility but has limited shading capabilities when it comes to light transport
 - Geometry (object shape) is projected onto canvas and large amount of information is lost
 - Mainstream method for used by graphic cards and in real-time rendering
- **Ray-tracing** has advanced shading possibilities when it comes to light-transport but it is slow
 - Shadows, soft shadows, reflections, refractions, volumetric scattering, etc.
 - Easier to create photo-realistic images
 - Often requires acceleration-structure for solving visibility problem

- Give short practical intro in rasterization and raytracing.
- Raytracing: simple renderer rendering spheres
- Rasterization: opengl rendering cube

Tech demo
Raytracer
rasterization

Image
A result of 3D scene rendering

Image

- Array of pixels
- Display device

Merging all together
3D scene, rendering and Image

- 3D scene, rendering and resulting image are highly intertwined elements of image synthesis
- Now that big picture has been discussed, following lectures will dive deeper into each of these topics.

What have we learned?

- Map of computer graphics:
 - 3D scene
 - Rendering
 - Image