EECE5512
Networked XR Systems

Last Class - Recap

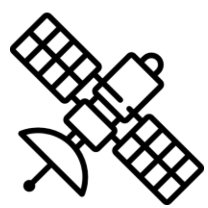
- Sensing Algorithms

Lecture Outline for Today

- Quiz
- XR Data Structures, 3D Representations, formats
  - 2D Videos
  - Stereo/3D Videos
  - Multi-view 2D Videos
  - 2D/Flat 360 Degree Videos
  - Stereo/3D 360 Degree Videos
  - 3D/6-DoF Videos (point clouds, meshes, depth maps)
  - Implicit Neural Representations
  - Gaussian splats

Why XR Data Representations are Important?

Variety of XR display devices
Variety of networks to deliver XR content



Implications across network (bandwidth), display (rendering), user (experience)

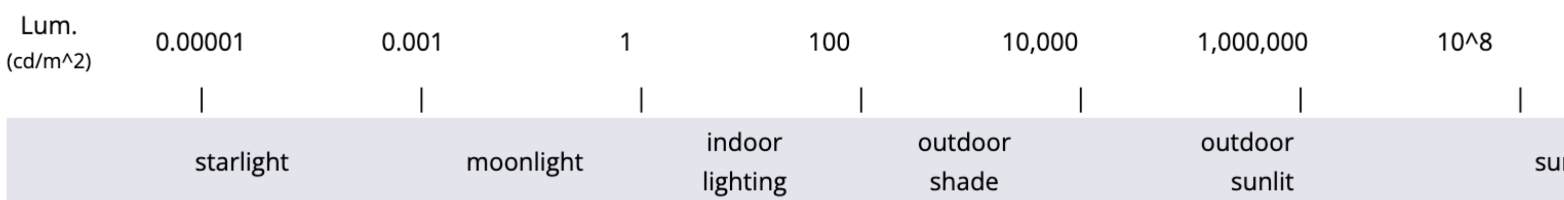
2D Videos

- Fixed data structure
- Color attributes
  - 3 Channels
  - 8 bits each channel
- Color Space Formats
  - RGB – 24 bits
  - YUV (Luma & Chroma)
    - YUV420 – 12 bits
    - YUV422 – 16 bits
    - YUV444 – 24 bits

1080x1920

2D HDR Videos

- High dynamic range – here range is light intensity
- This means that bright objects and dark objects on the same screen can be shown to high degrees of brightness and darkness if the display supports it
- High data rate: 96 bits per pixel, 32 bits per channel
- Dolby vision vs. HDR10
  - Dynamic & Static HDR – for display



2D Videos

- Limitations
  - Not immersive (enough)
    - Cannot pan, tilt or zoom
  - Not interactive
    - Users are passive observers
  - Limited FoV
    - Viewers can only see what the camera captures in small field of view

Stereo Videos

- Captured using two cameras – one per each eye

- Provides depth perception

- More realistic than regular (monocular) 2D videos

Apple rebranded them recently as spatial videos

2D/Flat 360 Degree Videos

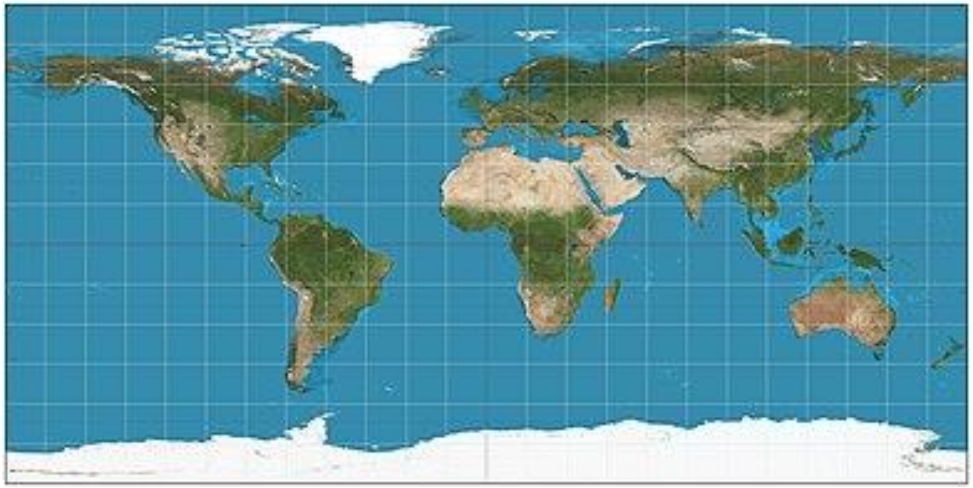
- Flat 360-degree videos are similar to 2D videos
  - RGB or YUV channels
  - Captured using an omnidirectional camera or a collection of cameras.
  - Typically, 360 degrees horizontal, 180 degrees vertical
  - During the playback, the user views a particular viewport

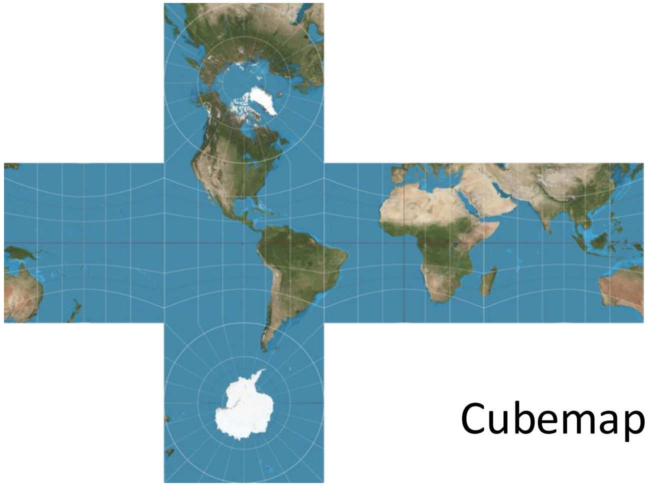
3 degrees of freedom

2D/Flat 360 Degree Videos

- Format
  - Cubmaps are efficient for hardware
  - A lot of pixels are repeated (e.g., top row) for equirectangular format

Equirectangular





Cubemap

2D/Flat 360 Degree Videos

- Display devices
  - Most displays like personal computers, phones, headsets
  - Phones use gyroscope to move around the scene

2D/Flat 360 Degree Videos

- Limitations
  - Limited interaction – no translation
  - A well-known problem – bandwidth inefficient

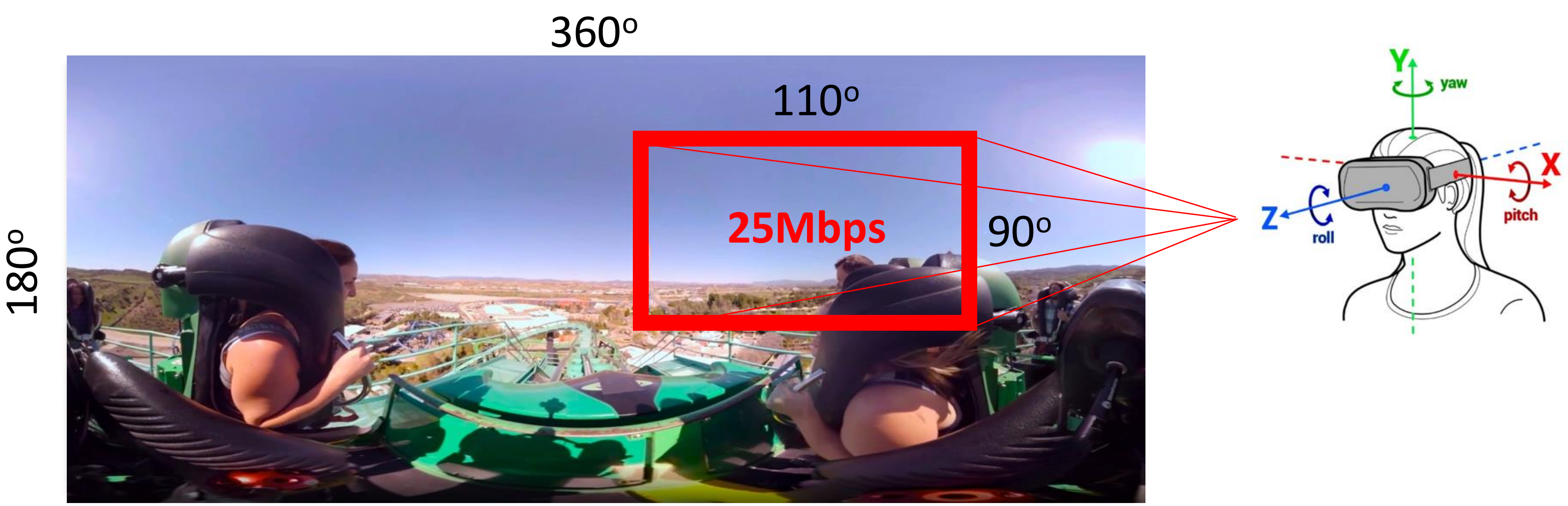


Image from Rollercoaster video

Stereo 360?

- Based on our discussion so far.. What is stereo 360?
- Is it useful? If so, when and where?

3D 360 Degree Videos

- Allows true 6 degrees of freedom
  - Translation, and Rotation
- Also known as 4D scene – x, y, z + t
- Objects or spaces
- Typically requires multiple cameras to capture 3D videos
- Allows interaction

3D Videos

- Objects

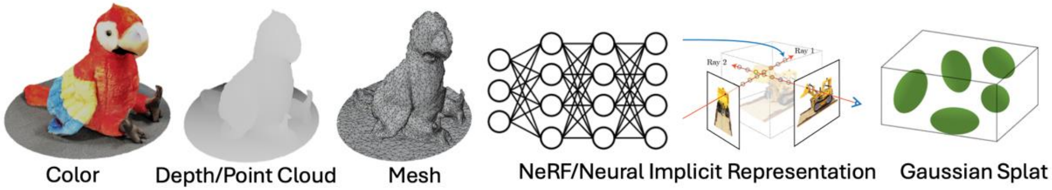
Hologram

3D Videos

- Spaces

3D Videos

- Data Representations
  - Depth Maps
  - Point Clouds
  - Meshes
  - Neural implicit representations (NeRF)
  - Gaussian Splat



3D Representation	Format	Capture	Rendering	Data Rate	Quality
RGB-D	Color + depth images	Fast	Slow	Medium	Medium
Point Cloud	Points (x, y, z) + (r, g, b)	Fast	Slow	High	Low
Mesh	Vertices, edges, faces	Medium	Medium/Fast	Medium/Low	Medium/High
NeRF	Neural network	Slow	Medium/Slow	High	High
Gaussian Splats	3D Gaussians	Slow	Fast	High	High

Depth Maps

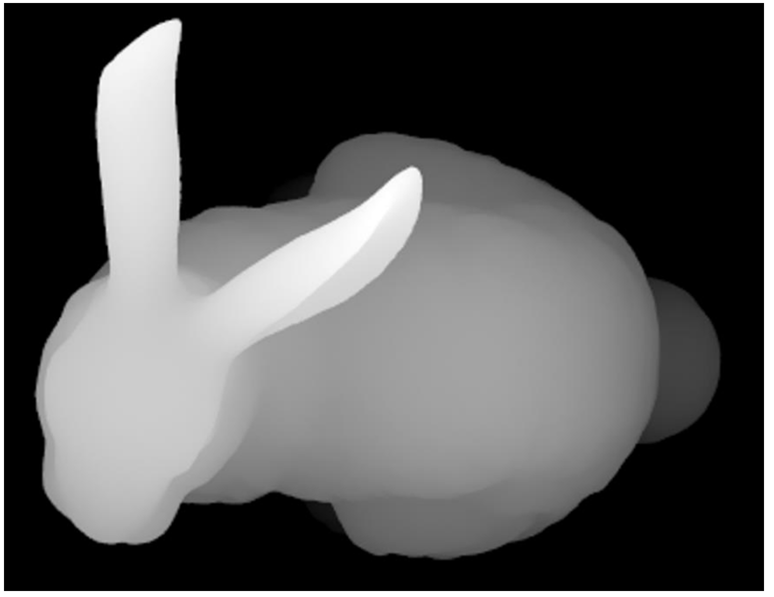
- Depth maps contain information about the distance of objects from a specific perspective or reference point (like a camera lens).
- Each pixel is assigned a value to represent the distance of that pixel from the reference point which creates a 3D representation of the scene for its RGB image or virtual scene.

Depth Maps

- Captured using
  - Depth sensors
    - Stereo Triangulation
    - ToF, Structure light
  - 3D modelling
  - Computer Vision or ML (depth estimation)

Depth Maps

- Typically, the white pixels represent the part of the scene that is closest to the camera lens, and the black pixels represent the part of the scene that is furthest.
- But there's no set standard how to represent the map



Bunny depth map

Depth Maps

- Images – but how many channels?
- Depth maps
  - Do we need 3 channels like RGB?

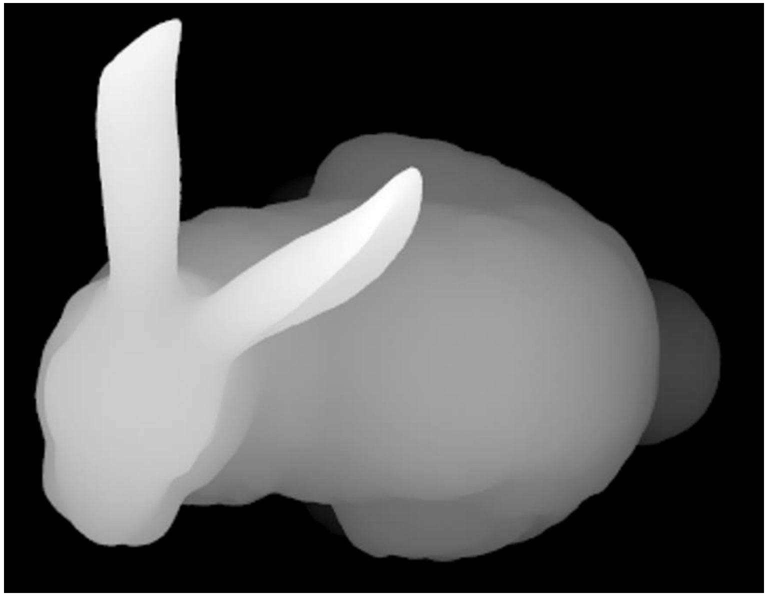
- Bit depth
  - One channel - depth
  - 8 bits – range up to 256 (any unit like meters or cm/mm)
  - 16 bits – range up to 2^16 units etc

Depth Maps

- Popular Depth Camera or Sensor: ZED
  - Depth can be captured at longer ranges, up to 20m.
  - Frame rate of depth capture can be as high as 100 FPS.
  - Field of view, up to 110° (H) x 70° (V).
  - The camera works indoors and outdoors, contrary to active sensors such as structured-light or time of flight.
  - Stereo triangulation

Depth Maps

- Limitations of this representation
  - Fixed size data structure (i.e., image representation)
  - Inefficient storage of depth
  - Most pixels are not occupied



Point Cloud

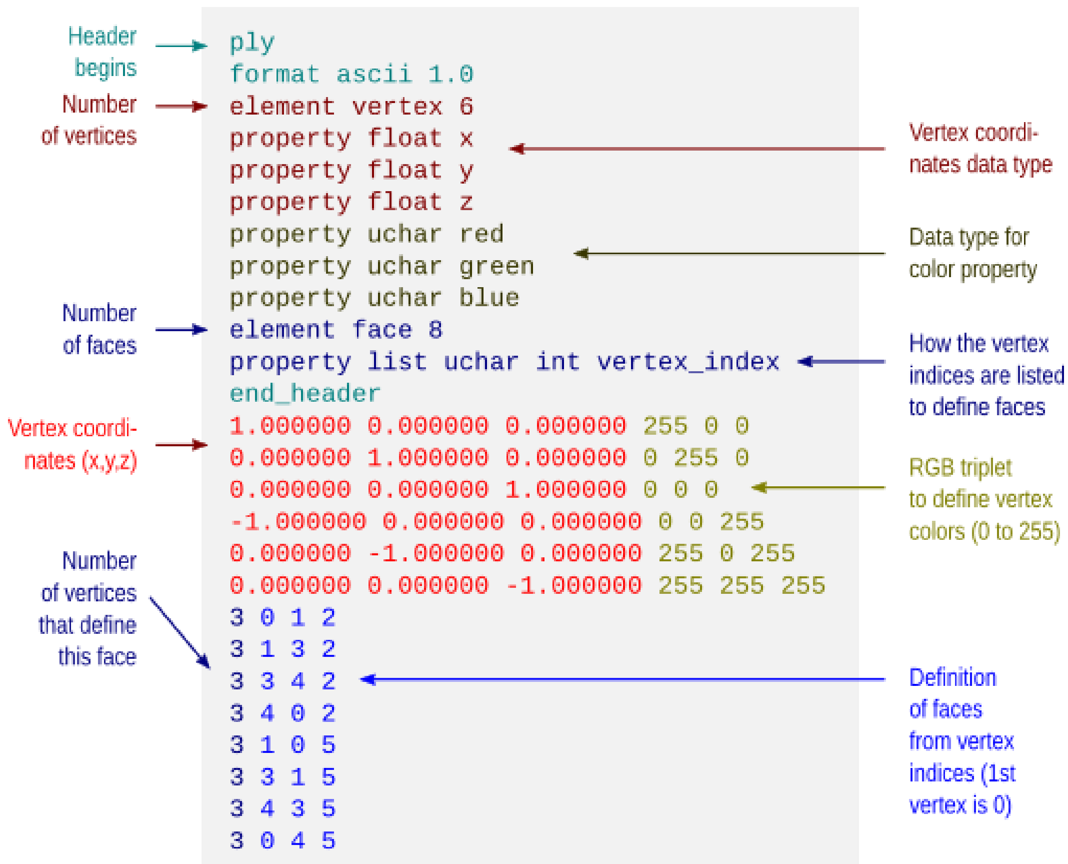
- A point cloud is a discrete set of data points in space.
- Or a set of 3D independent points
- Each Point (X, Y, Z) + Attributes
- Attributes: Color, Alpha, Reflectance

Point Cloud

- Captured using
  - Regular 2D camera array - Photogrammetry
  - Depth sensing - LiDAR scanning, Time of Flight
  - 3D modelling

Point Cloud

- File format (how it is stored in a file)
- .ply



Point Cloud

- Representation
  - Each Point is a floating-point number – 32 bits
  - <X, Y, Z> : 96 bits
  - RGB: 3 channels: 24 bits
  - Also, has other attributes sometimes (light related)

  - Each point: 96 + 24 bits or 15 bytes

- Typically, a point cloud has thousands to millions of points – guess the data rate numbers

Point Cloud

- What is the file size of the point cloud that has 5 million points?

Point Cloud

Sample data numbers

	queen	longdress	loot	redandblack	soldier
Average number of points (in 300 frames)	1,005,000	834,000	794,000	727,000	1,076,000
Bitrates for transmitting uncompressed video (Mbytes/s)	514.47	542.22	490.61	448.21	681.96

Point Cloud

- Popular sensor – laser scanning
  - 830-grams
  - 100m Range
  - 300,000 Points per Second
  - 360^o Horizontal FOV
  - $30^o \pm 15^o$ Vertical FOV

  - Costly (>$10,000)

Point Cloud vs Depth Map

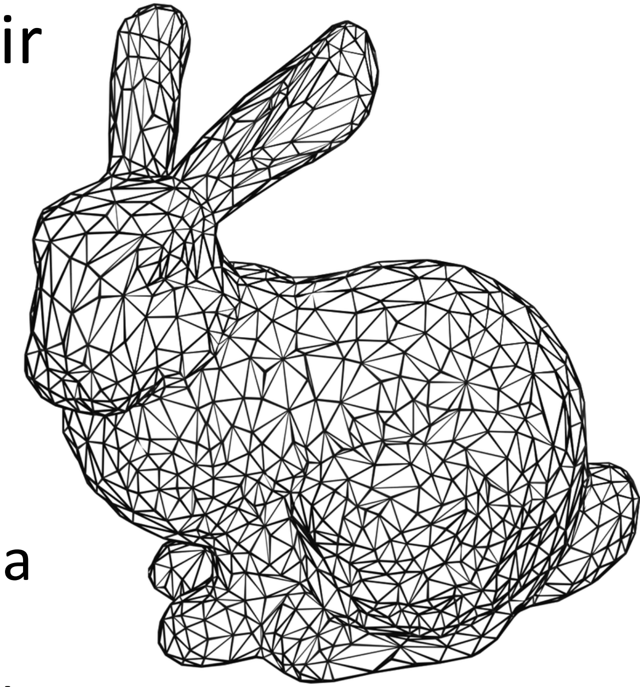
- Both are depth data structures
- A depth map is a 2d image with depth. It only shows the nearest point for each pixel from the direction its oriented.
- A point cloud is a bunch of xyz points, they can be in front of other points.
- Depth map size is fixed while point cloud size varies over time
- Depth map is depth only, while point clouds are often baked with color texture information

Point Cloud

- Limitations
  - Arbitrary data structure
    - Changes number of points in two consecutive frames
    - Creates problems during compression
  - Requires high bandwidth to represent objects or spaces
  - Lacks knowledge of surfaces or requires huge number of points to represent a surface

Mesh

- A set of polygons, connected by their common edges or vertices
- Typically represented by triangles



- Why triangle? Why not other polygons?
  - By definition, a triangle always lies on a single plane, providing a flat surface.
  - This planarity ensures there aren't any distortions when rendering a triangle, making it reliable for building complex 3D shapes.

Mesh

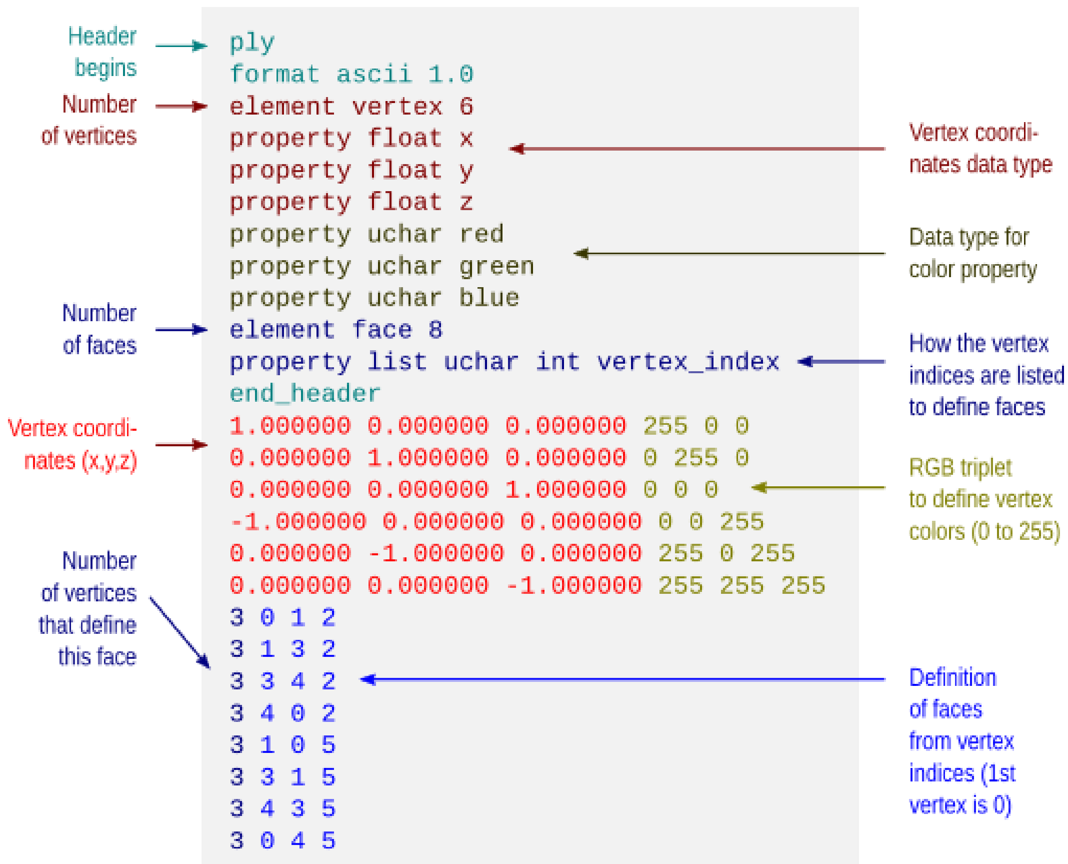
- Capturing mesh data structure
  - No native support from sensors
  - Need to extract mesh polygons from depth maps or point clouds

Mesh

- Data representation
  - Each frame has vertices and connectivity
  - Raw size depends on file format – next slide
  - Color texture is stored independently, so there is also mapping information from texture to polygons

Mesh

- File format - .ply



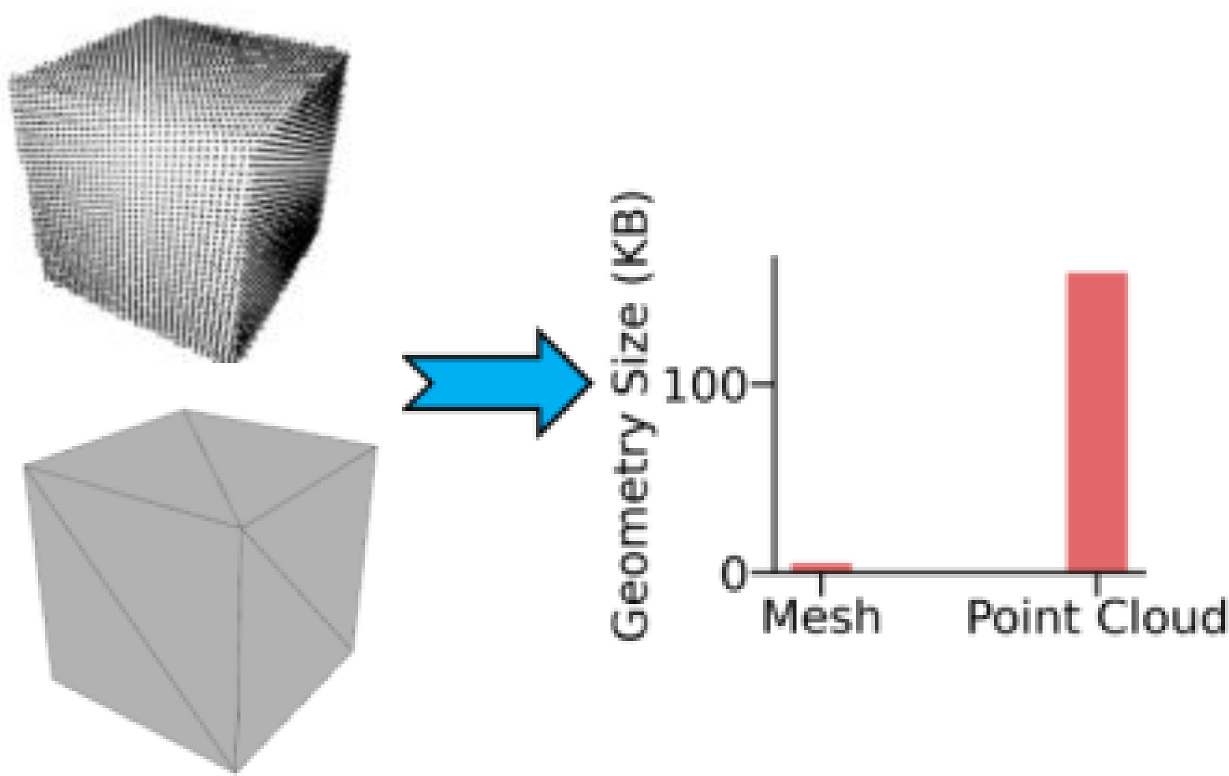
Mesh

- File format - .obj

```
# List of geometric vertices, with (x, y, z, [w]) coordinates, w is optional and defaults to 1.0.
v 0.123 0.234 0.345 1.0
v ...
...
# List of texture coordinates, in (u, [v, w]) coordinates, these will vary between 0 and 1. v, w are optional
and default to 0.
vt 0.500 1 [0]
vt ...
...
# List of vertex normals in (x,y,z) form; normals might not be unit vectors.
vn 0.707 0.000 0.707
vn ...
...
# Parameter space vertices in (u, [v, w]) form; free form geometry statement (see below)
vp 0.310000 3.210000 2.100000
vp ...
...
# Polygonal face element (see below)
f 1 2 3
f 3/1 4/2 5/3
f 6/4/1 3/5/3 7/6/5
f 7//1 8//2 9//3
f ...
...
# Line element (see below)
l 5 8 1 2 4 9
```

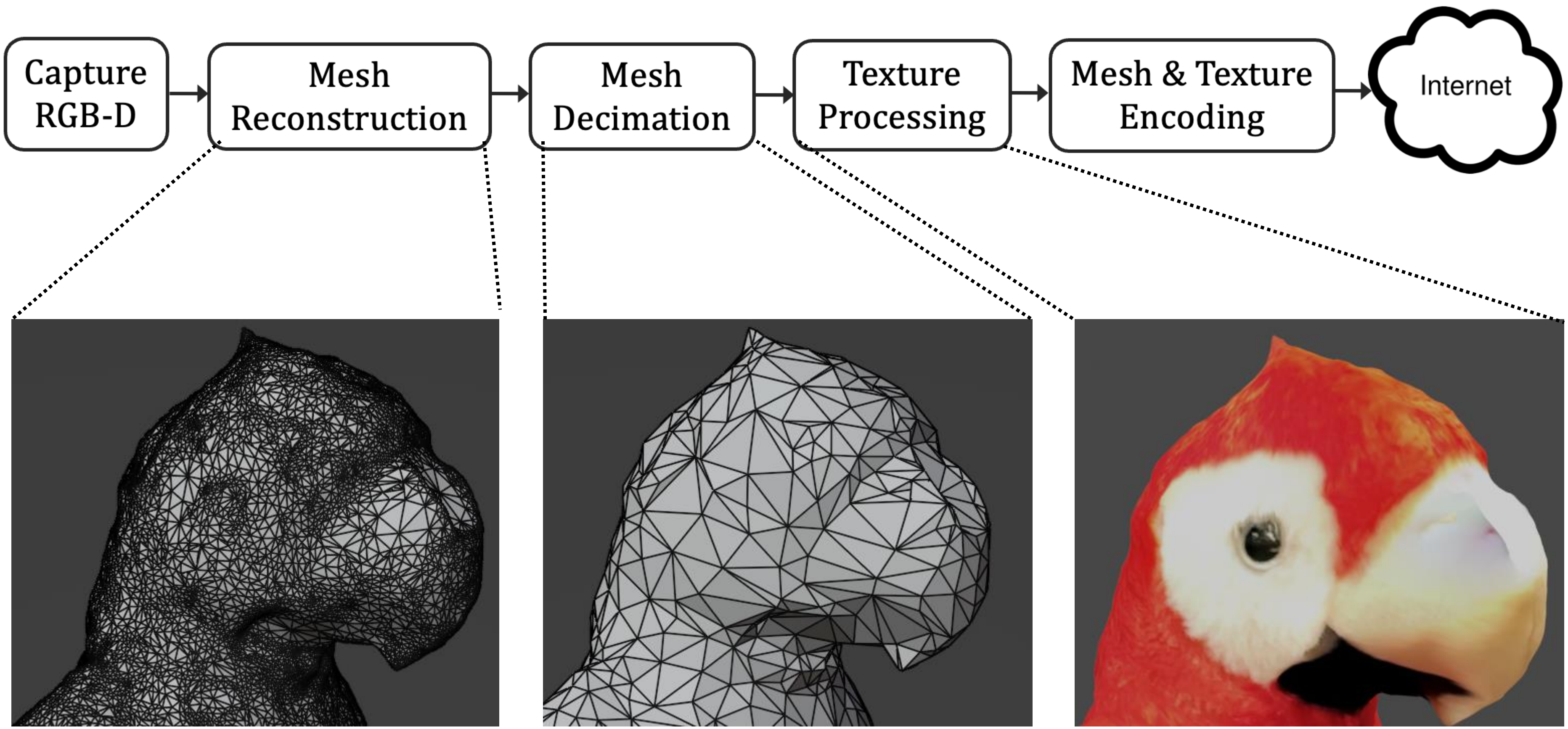
Mesh vs. Point Cloud

- Meshes are much more compact (raw files)



Mesh

- But extracting meshes is computationally intensive task, unlike point clouds that are readily available



Recap: 3D Data Structures

- Depth Map vs. Point Cloud vs. Mesh
  - Depth maps and point clouds are simple, easy to manipulate, quickly available
  - Meshes are compact and requires significantly less bandwidth, but are computationally heavy to extract
  - Depth maps are fixed in size while the other two have arbitrary sizes
  - Meshes define surfaces while the other two not
  - Meshes are approximate 3D data structures while the other two represent accurate points

Quiz

View Immersion

- Monocular
- Stereoscopic
- Multi-view

View Immersion

- Mono or monocular
  - Single camera
  - Simple, low cost
- Limitations
  - No depth perception

View Immersion

- Stereo or Stereoscopic
  - 2 cameras
- Depth perception depends on the baseline
- Limited by small field of view

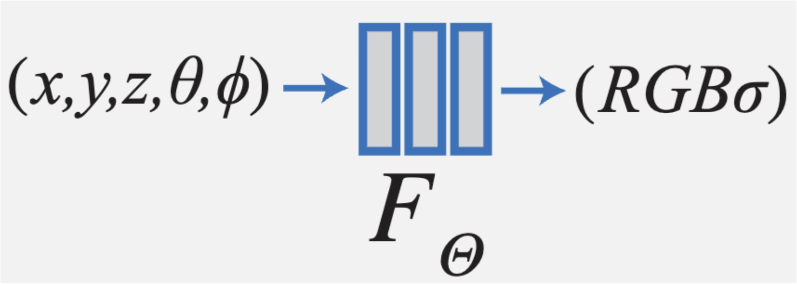
Apple spatial videos

View Immersion

- Multi-view videos
  - Typically, tens to hundreds of cameras are deployed to get full 3D 360^o view of the scene of interest
  - Highest level of immersion
  - Costly
  - Very infra heavy
  - Bandwidth heavy
  - Compute heavy
  - Hard (almost impossible) to get in real-time/live

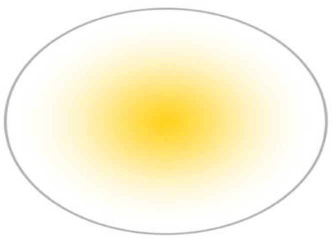
Implicit Neural Representation

- A fully-connected neural network that can generate novel views of complex 3D scenes, based on a partial set of 2D images.
- Set of weights
- To render a view, need to query the neural network by inputting the pose info

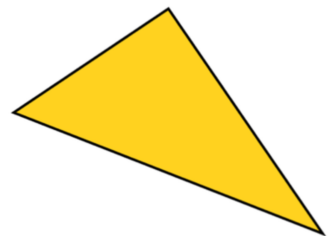


https://www.matthewtancik.com/nerf

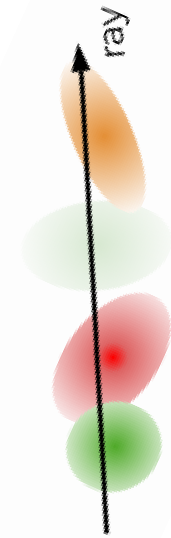
Gaussian Splats



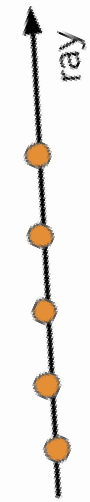
Scene is represented with a number of gaussian distributions



Mesh is made up of triangles



Gaussian Splat



NeRF

- **Position**: where it's located (XYZ)
- **Covariance**: how it's stretched/scaled (3x3 matrix)
- **Color**: what color it is (RGB)
- **Alpha**: how transparent it is (α)

Summary of the Lecture

- XR Data Structures
  - 2D videos
  - 360^{o} videos
  - 3D videos
    - Depth Map
    - Point Cloud
    - Mesh
  - View-immersion
    - Mono
    - Stereo
    - Multi-view
  - Implicit neural representations

Next up: Capturing XR content for network transmission