EECE5698
Networked XR Systems

Lecture Outline for Today

XR Data Structures

- 2D Videos
- 2D 360 Degree Videos
- 3D Videos
- View Immersion
- Implicit Neural Representations

Why do we need so many video representations?

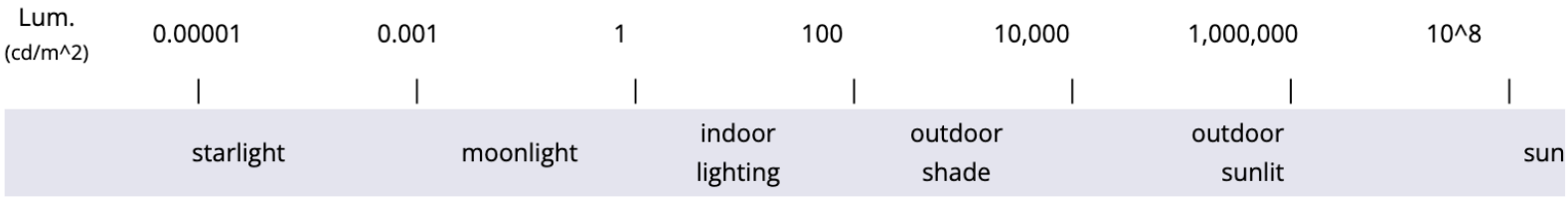
2D Videos

- 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

2D 360 Degree Videos

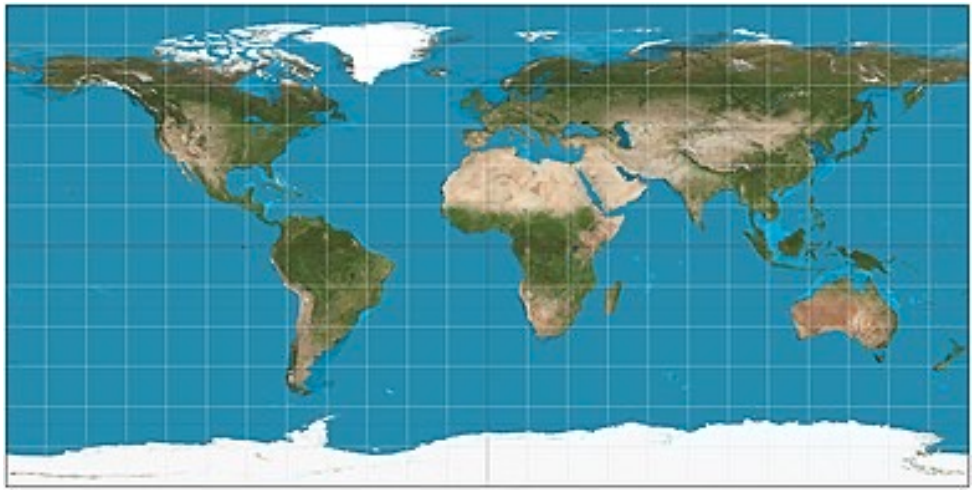
- Pixels are similar to 2D videos
  - RGB or YUV channels
  - Captured using an omnidirectional camera or a collection of cameras.
  - Typically, 360 degrees horizontal, 180 degrees vertical
  - During the playback, the user views a particular viewport

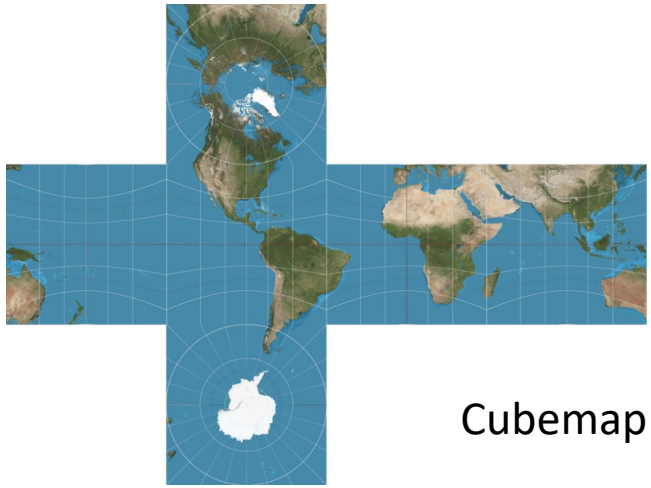
3 degrees of freedom

2D 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 360 Degree Videos

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

2D 360 Degree Videos

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

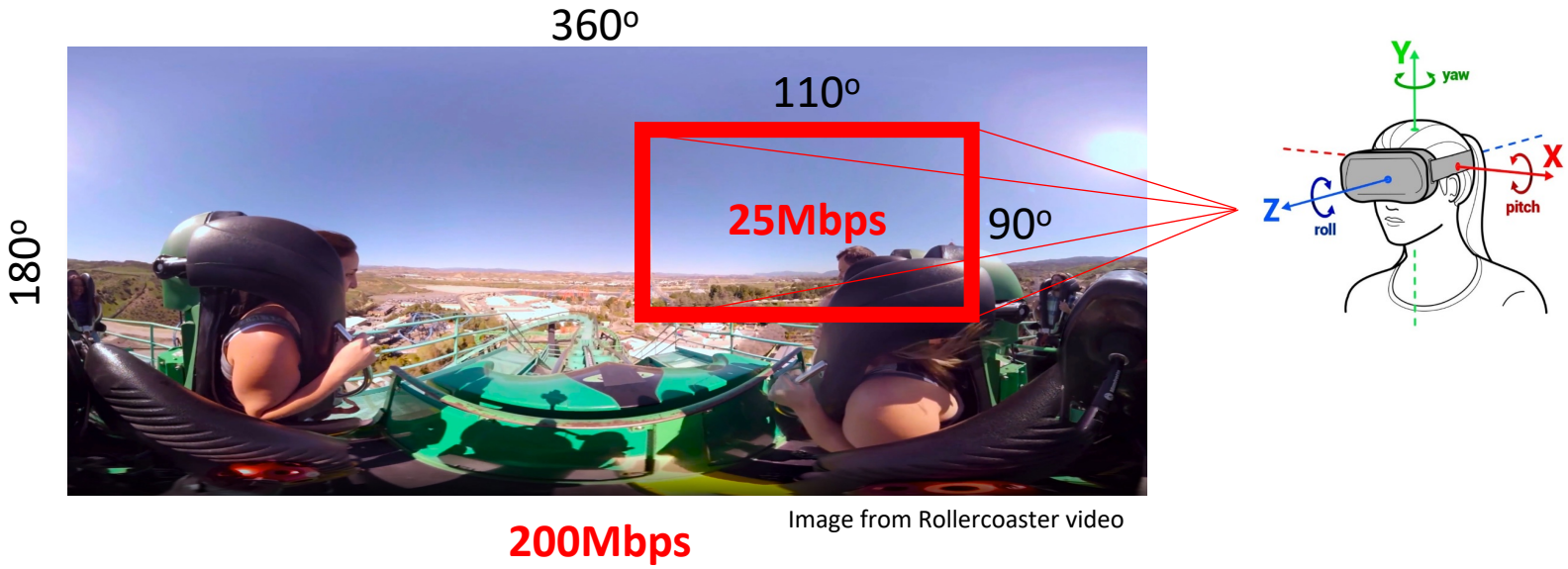


Image from Rollercoaster video

3D 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

Depth Maps

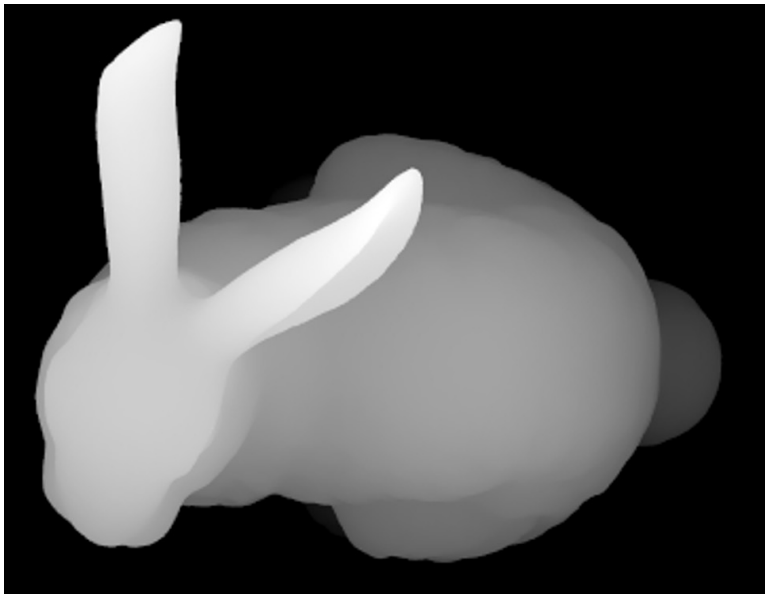
- Depth maps contain information about the distance of objects from a specific perspective or reference point (like a camera lens).
- Each pixel is assigned a value to represent the distance of that pixel from the reference point which creates a 3D representation of the scene for its RGB image or virtual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

Depth Maps

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

Depth 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?
  - Do we need 3 channels like RGB?

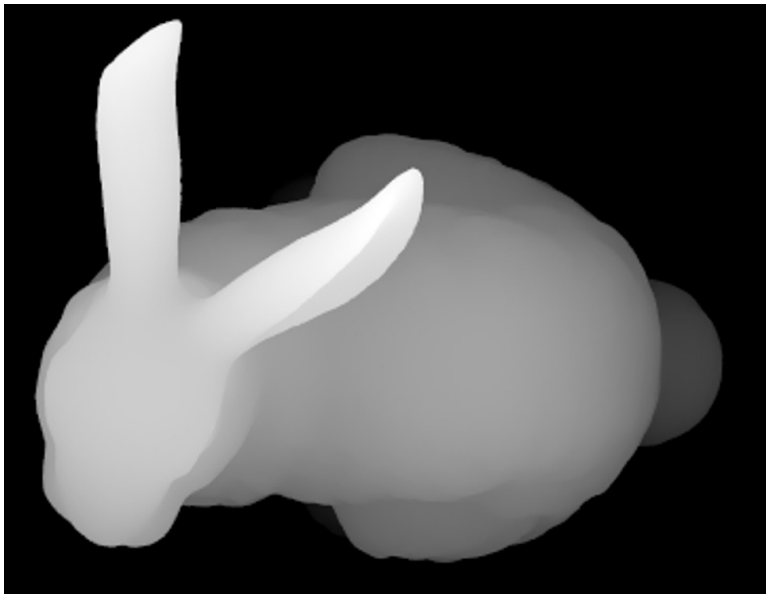
- Bit depth
  - One channel - depth
  - 8 bits – range up to 256 (any unit like meters or cm/mm)
  - 16 bits – range up to 2^16 units etc

Depth Maps

- Popular Depth Camera or Sensor
  - 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

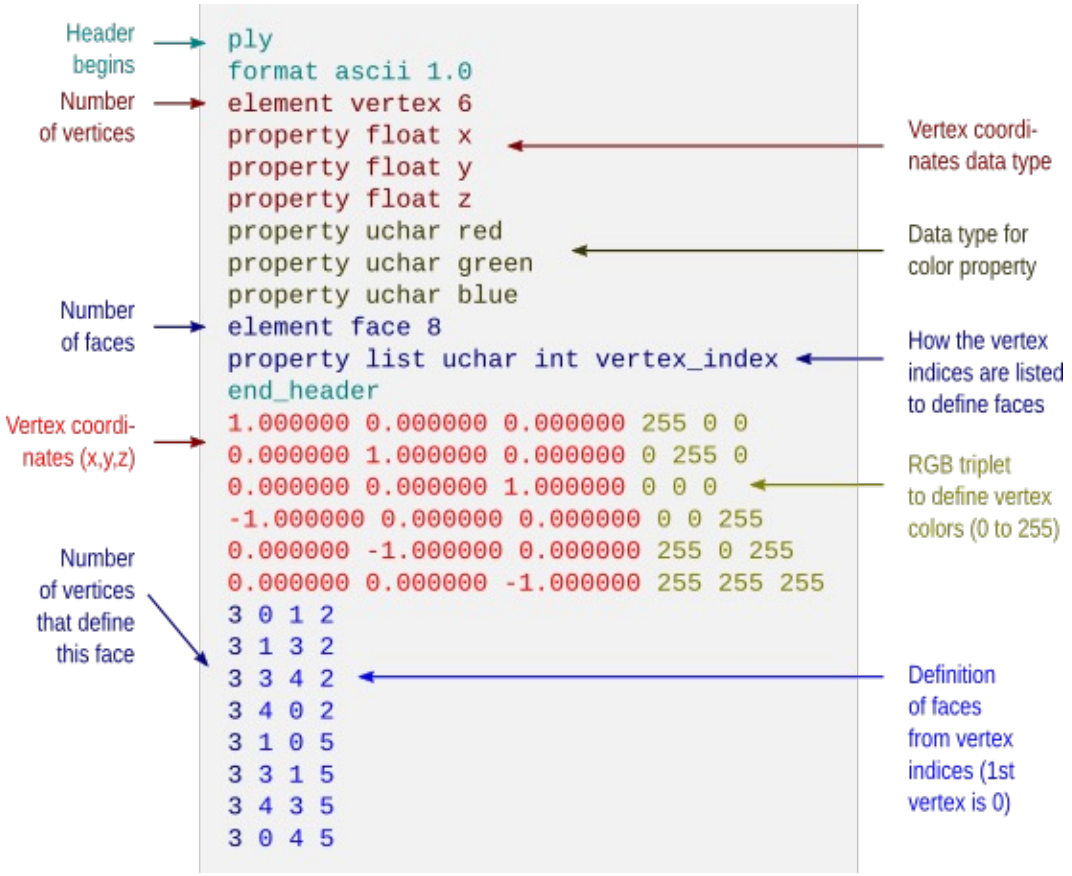
- A point cloud is a discrete set of data points in space.
- Or a set of 3D independent points
- Each Point (X, Y, Z) + Attributes
- Attributes: Color, Alpha, Reflectance

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

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

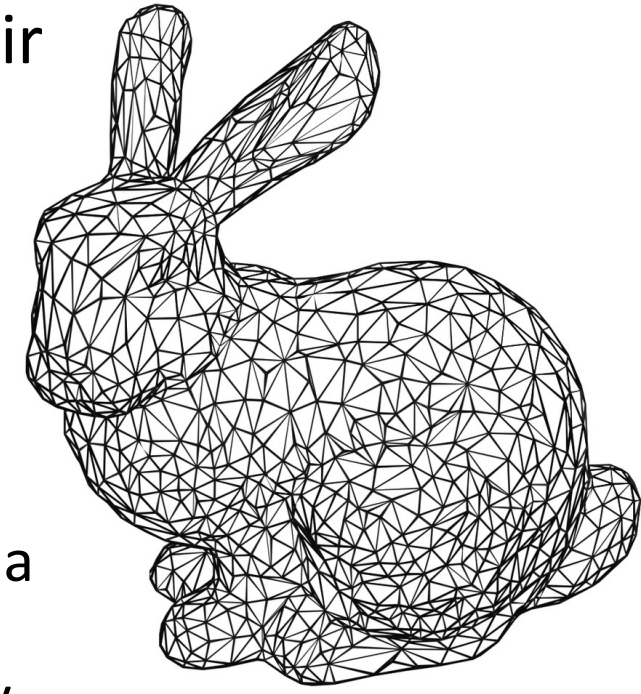
- Both are depth data structures
- A depth map is a 2d image with depth. It only shows the nearest point for each pixel from the direction its oriented.
- A point cloud is a bunch of xyz points, they can be in front of other points.
- Depth map size is fixed while point cloud size varies over time
-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



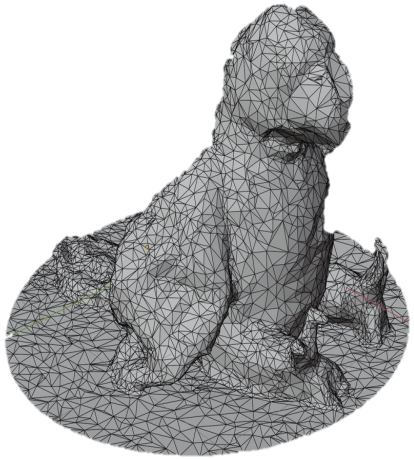
- Why triangle? Why not other polygons?
  - By definition, a triangle always lies on a single plane, providing a flat surface.
  - This planarity ensures there aren't any distortions when rendering a triangle, making it reliable for building complex 3D shapes.

Mesh

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

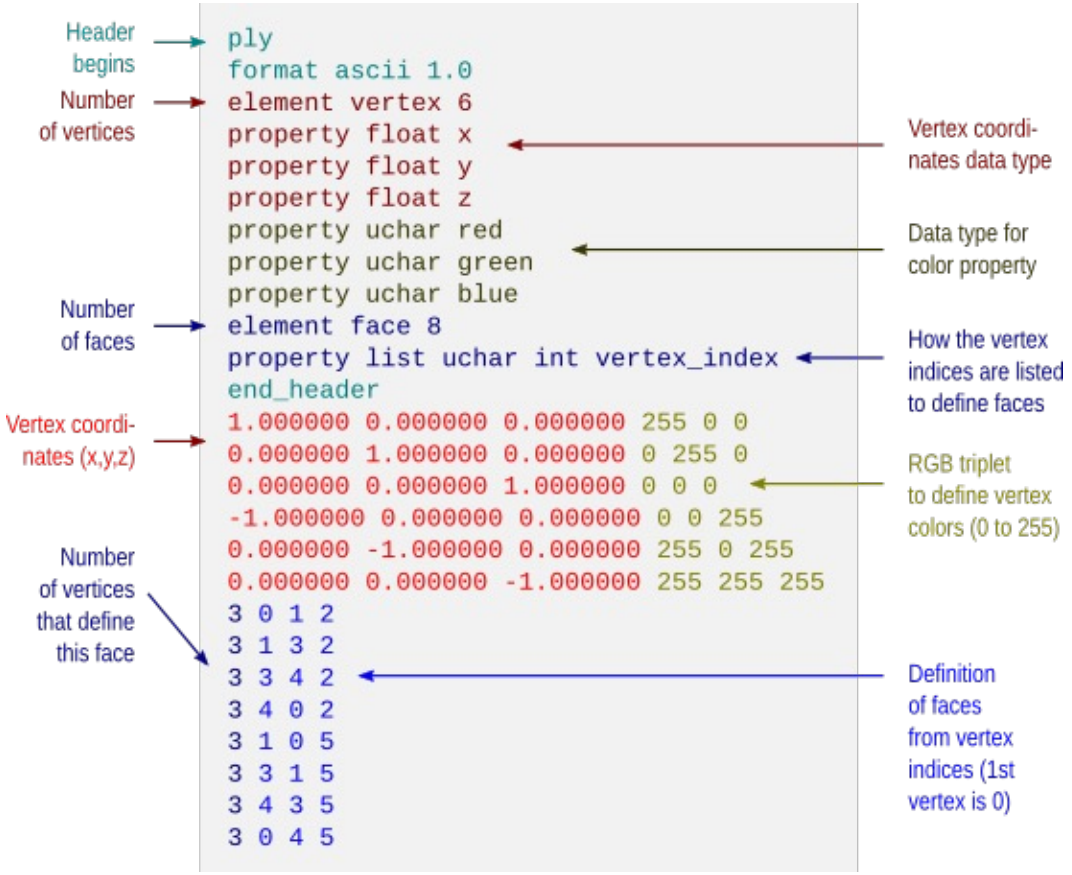
Mesh

- Data representation
  - Each frame has vertices and connectivity
  - 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



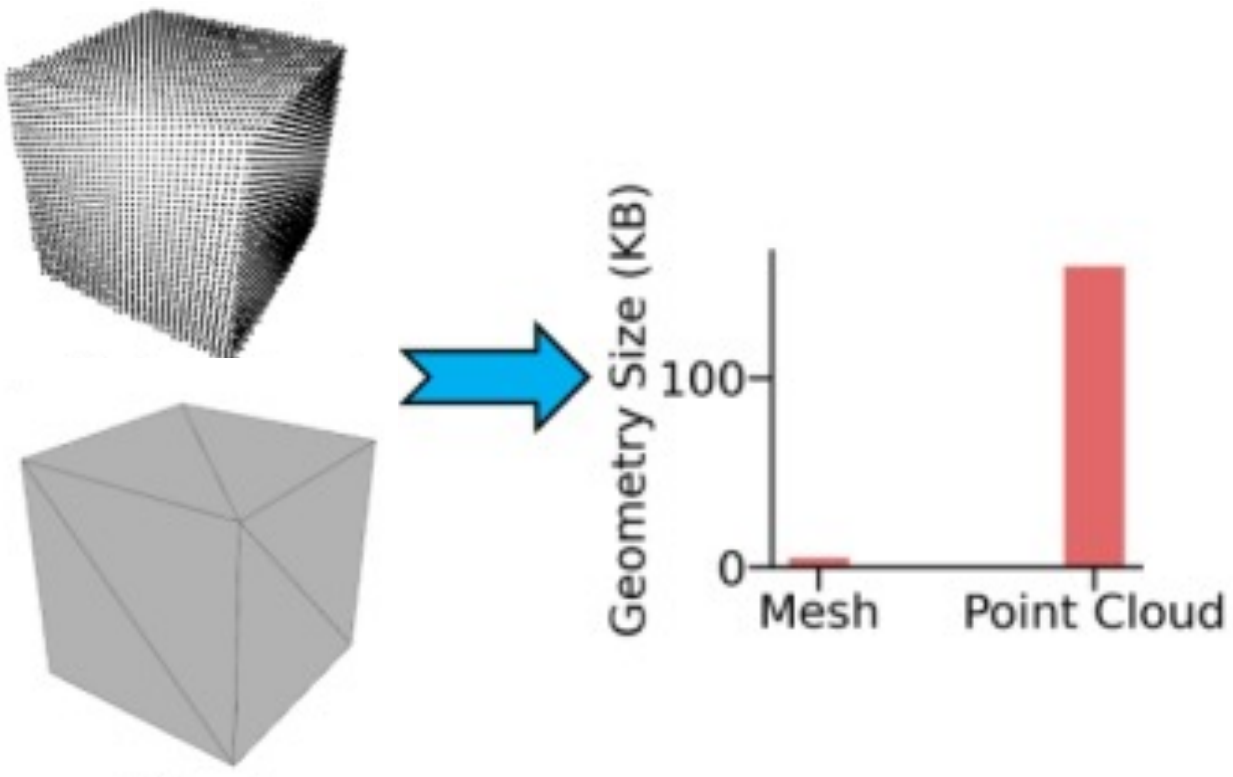
Mesh

- 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
```

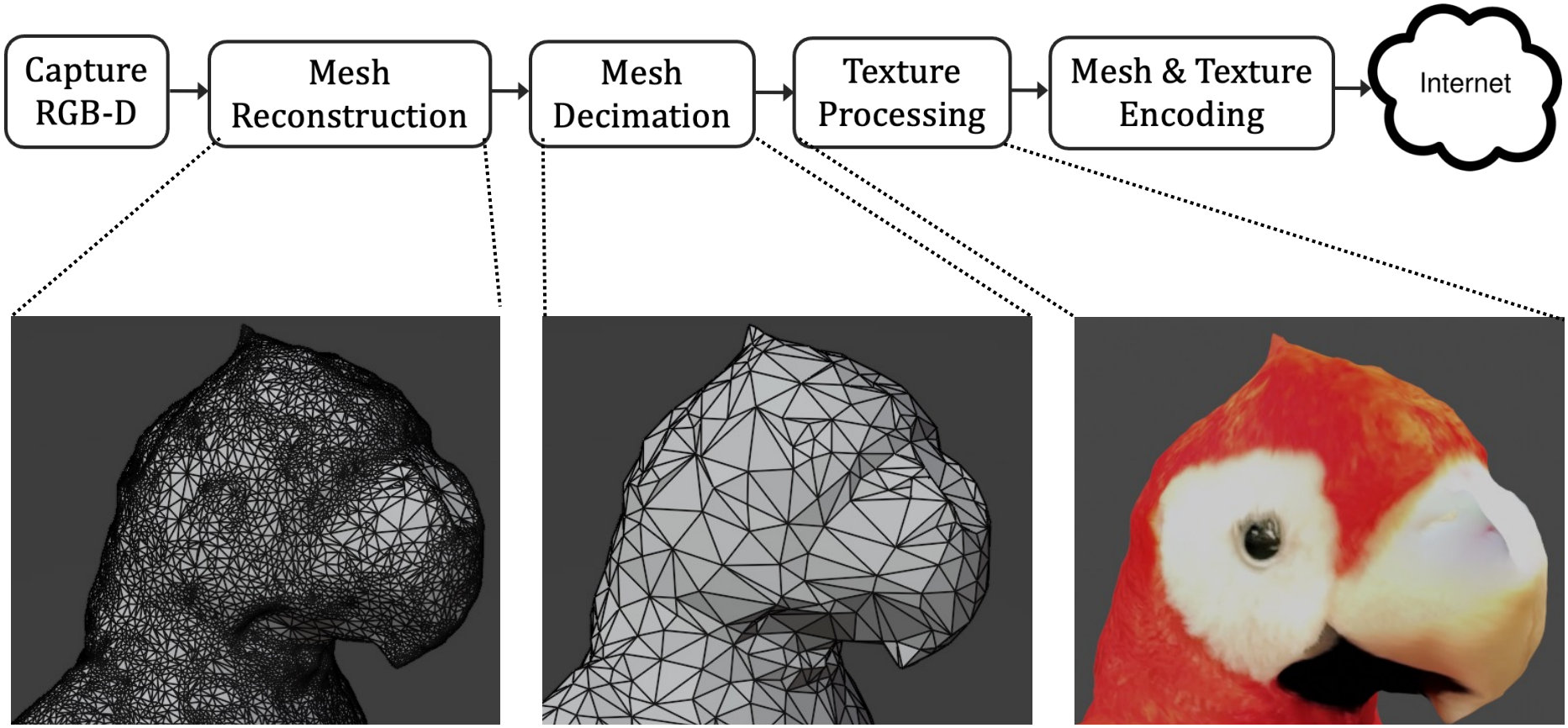
Mesh vs. Point Cloud

- Meshes are much more compact



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

View Immersion

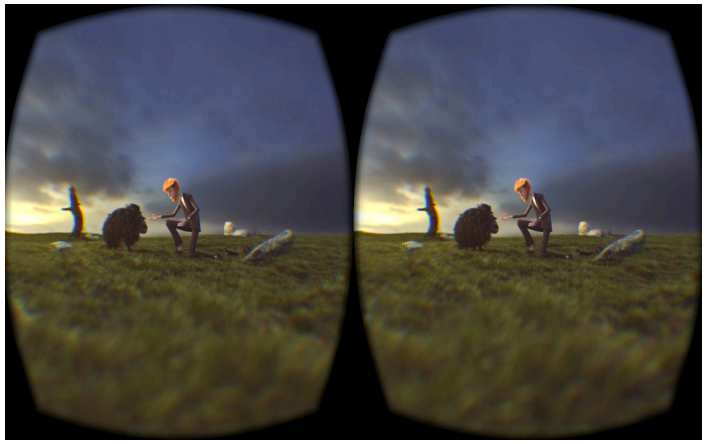
- Monocular
- Stereoscopic
- Multi-view

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 to get in real-time

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

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