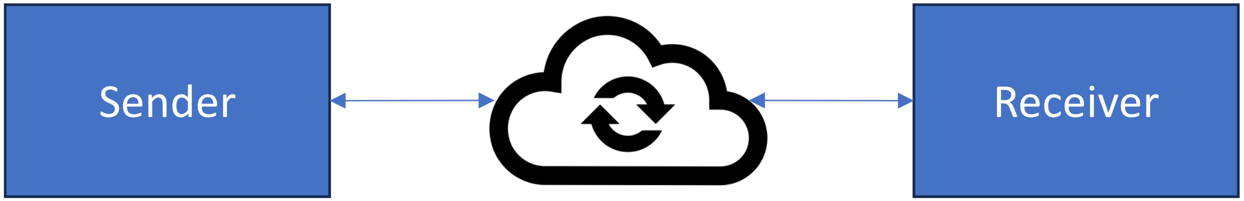
EEC5698
Networked XR Systems

Lecture Outline for Today

- Capturing 3D Videos for Network Transmission
  - Scene Capture
  - Network & Application Interplay
  - Capture Scenarios: Outside-in vs. Inside-out Capture
  - Offline vs. Live Capture
  - Depth Maps, Point Cloud, and Mesh Capture
  - Compute, Bandwidth vs. Latency Trade-offs
- Quiz

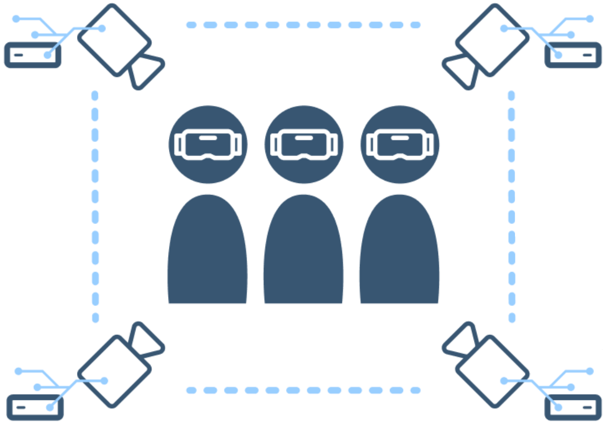
Networked XR System



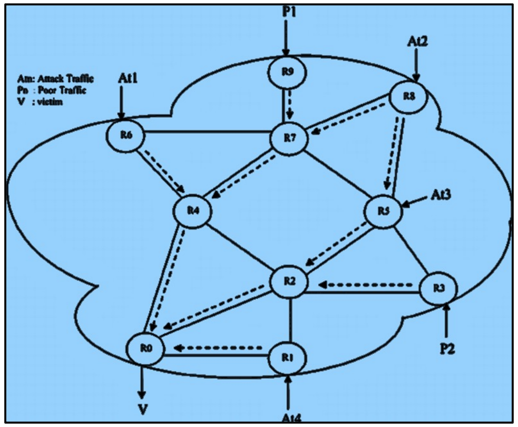
Sender

Receiver

Classical networked system pipeline



Digitize 3D spaces



Network Transport

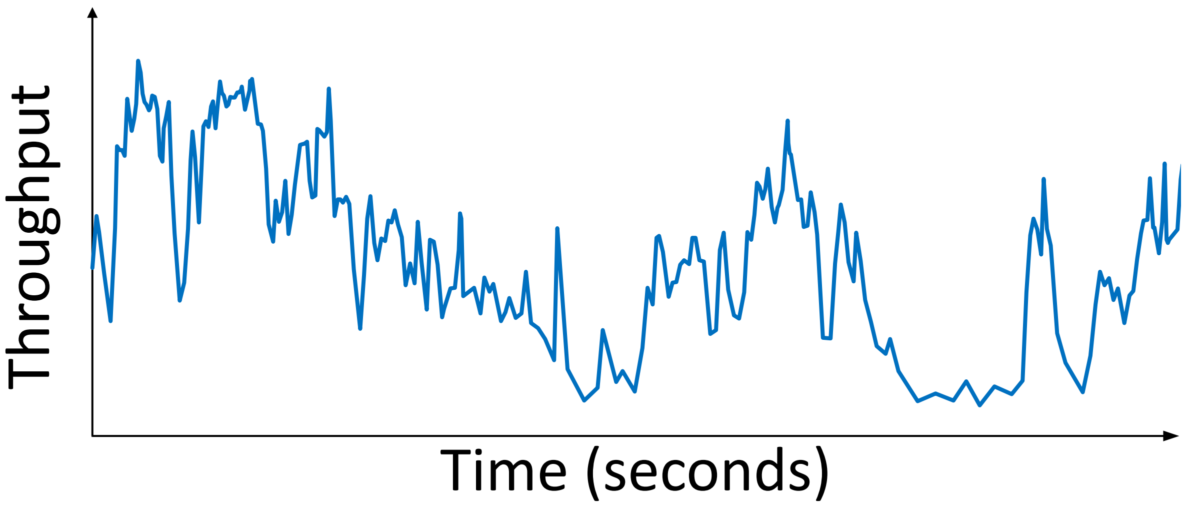
Display Interfaces

Scene Capture

- Storage vs. Network Transmission
- What are the requirements?
  - Storage: Less data is better
  - Network: Low data rate is better (**most of the times**)

Scene Capture

- Data rates should be flexible to change as the network conditions changes – introduces some overhead



Capturing 2D Scenes or Videos

- Mostly mature – work done for nearly 3 decades
- Plenty of hardware to process 2D videos streams
- Still a lot research happening to reduce power consumption
  - Advances in low power image sensors

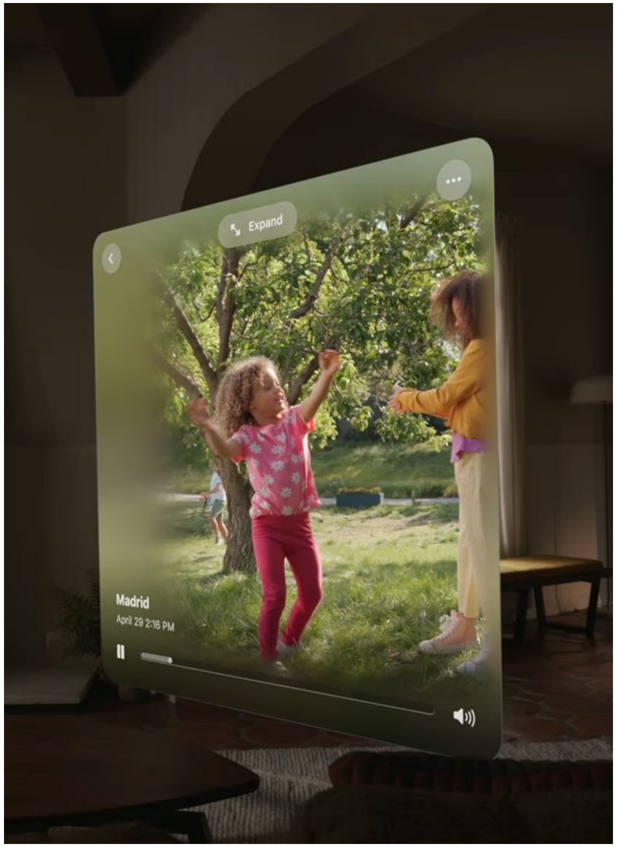
Scene Capture for Network Transmission

- Why transmit over network
  - Share 3D content with others
  - Machine to machine 3D analytics
  - Access 3D movies

  - Many use cases that we saw in the previous lectures

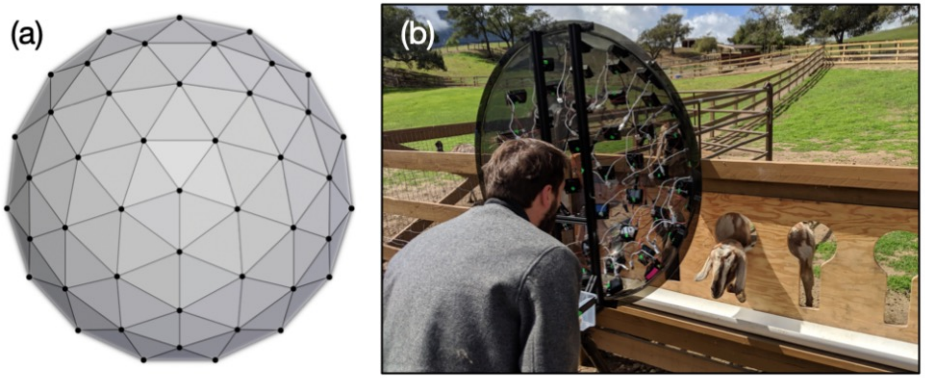
Capture Scenarios

- Inside-out: Mobile Devices or Headsets
    - iPhone Lidar capture or stereo/spatial videos
    - 2 color cameras and a depth camera
    - Or Vision Pro or Quest3 captures



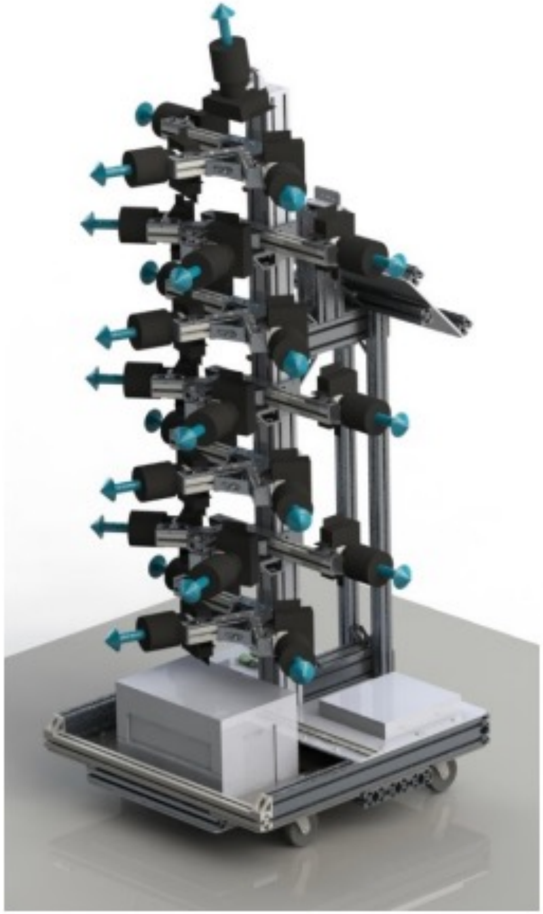
Capture Scenarios

- Inside-out: Multi-camera infrastructure
  - Cameras are placed at vertices of an icosahedral tiling of a 0.92 m diameter hemisphere. This yields an average inter-camera spacing of 18 cm.



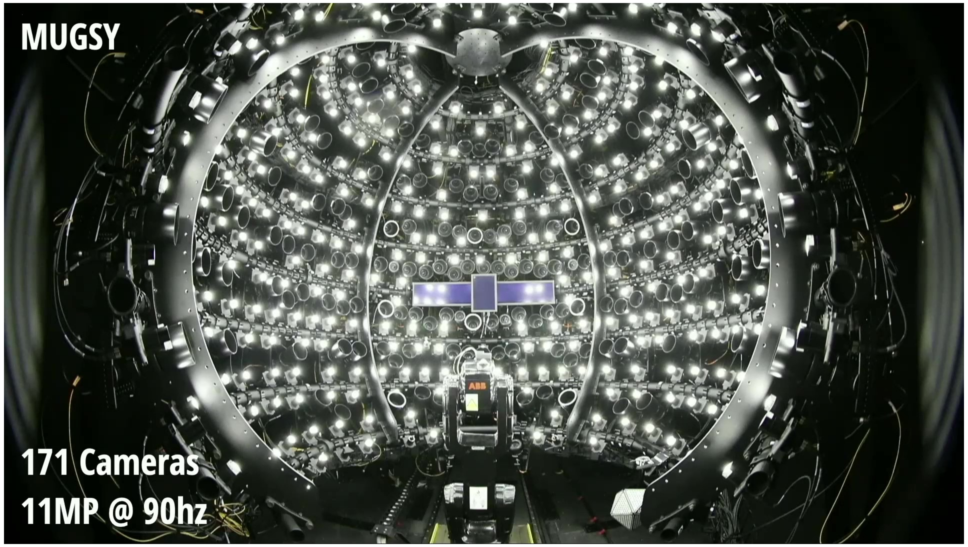
Capture Scenarios

- Inside-out : Multi-camera infrastructure
  - 80×80 cm base with a 1.8 m vertical pole for 22 cameras that are distributed on 7 levels with 3 cameras each, plus one upward-facing camera at the top



Capture Scenarios

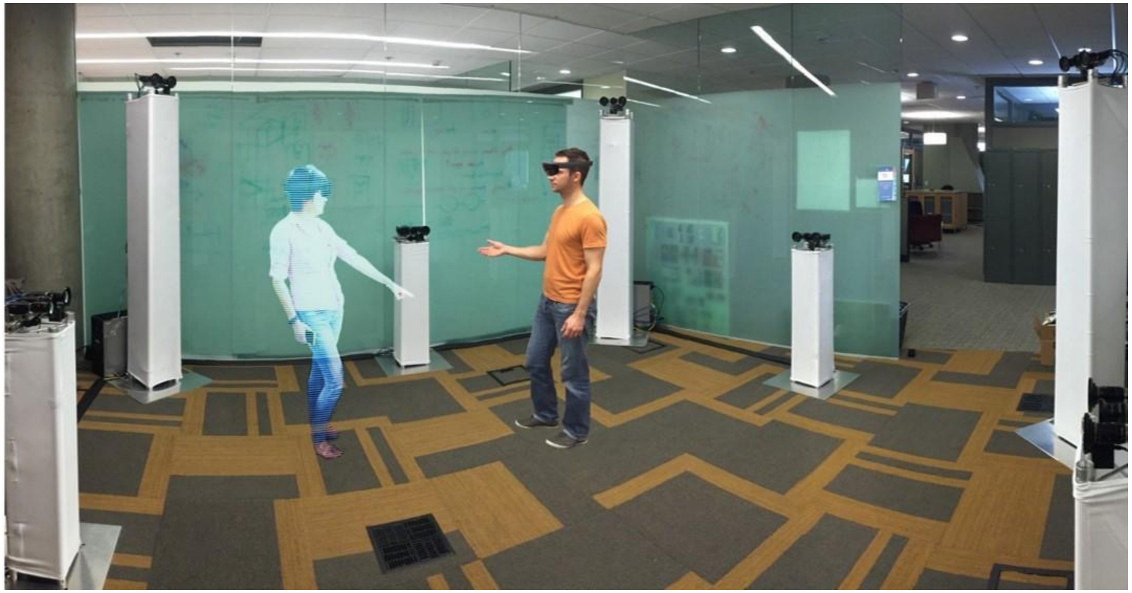
- Outside-in: Multi-camera infrastructure



Meta’s Mugsy

Capture Scenarios

- Outside-in: Multi-camera infrastructure



Live Capture vs. Offline

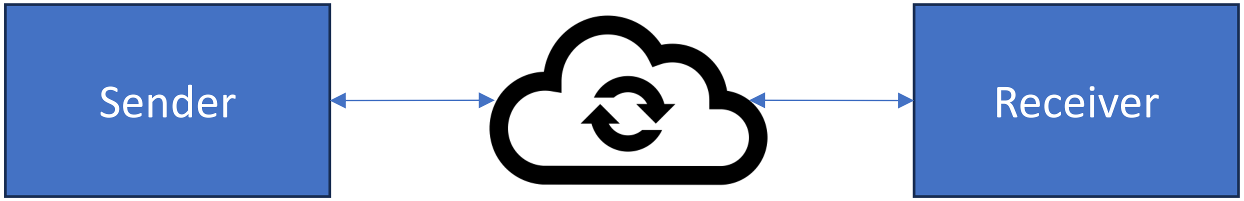
- Offline capture does not pose problems
  - Enough time and resources to process the content
- Live capture has stringent requirements
  - Low latency (<100ms)
  - Trade quality with latency and bandwidth

Live 3D Capture

- Many options
  - Our favorite data structures:
  - Depth Maps
  - Point Clouds
  - Triangle Meshes

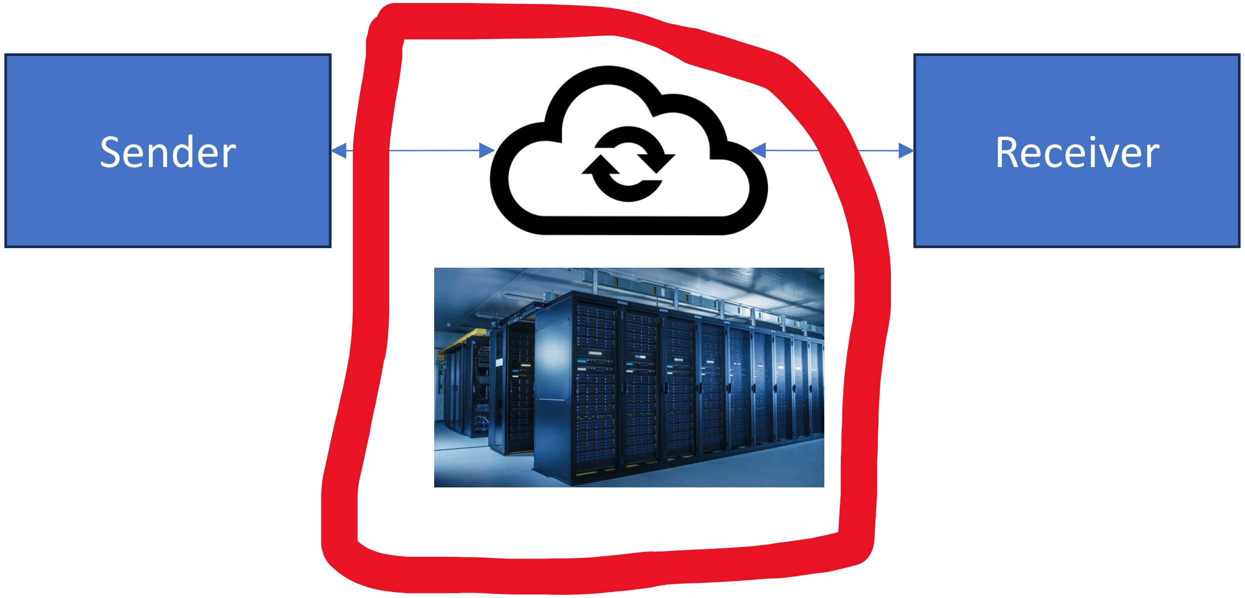
Live 3D Capture

- Different data structures captured at the sender have different implications on the network and receiver device
  - Rendering input: Triangles
  - Where you place the triangle extraction i.e., 3D mesh reconstruction computation matters (particularly for devices like headsets or phones).



Capturing Depth Maps

- Possible end-to-end streaming pipelines
  - Cloud based mesh reconstruction
    - In general, many resources – Fast, High Quality
    - Caution on bandwidth requirement

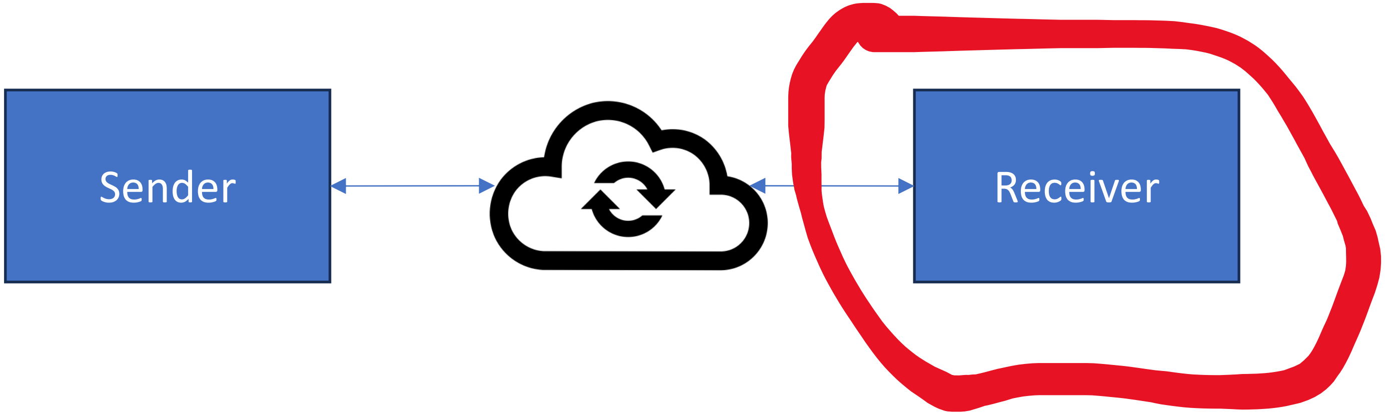


Sender

Receiver

Capturing Depth Maps

- Possible end-to-end streaming pipelines
  - Receiver-side mesh reconstruction
    - Fewer resources – Slow, Low Quality
    - Additional power consumption due to reconstruction computation – bad for XR devices



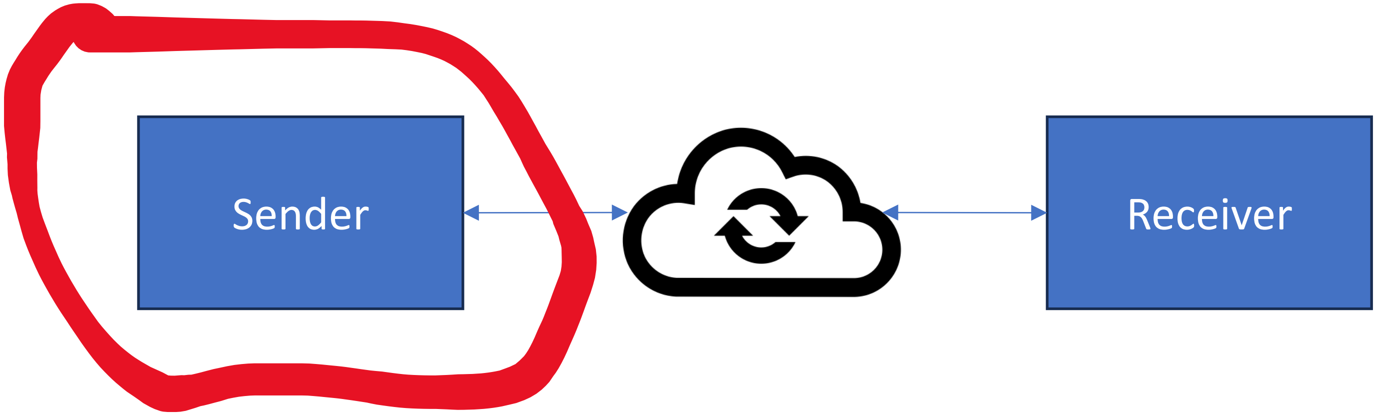
Capturing Point Clouds

- Natively available on the sensor similar to Depth maps (e.g., Lidar)
- Or a depth map can be converted to a point cloud with a simple transformation
  - Very little computation for transformation
  - i.e., sender-side pipeline is not affected as much

- Possible end-to-end streaming pipelines?
  - Similar to Depth maps, including the implications

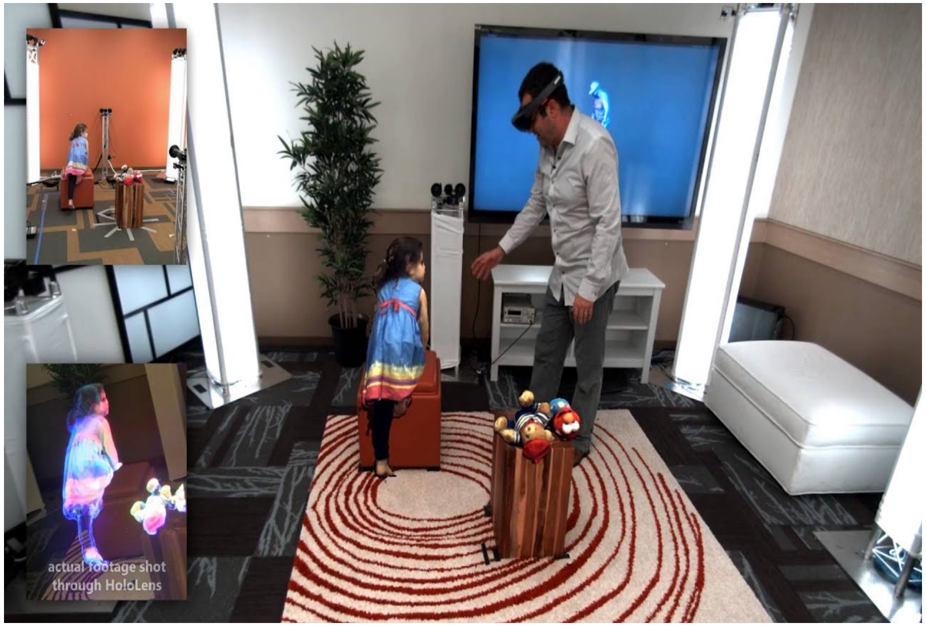
Capturing Meshes

- Meshes are not available natively on the sensor
  - Computation burden on the sender
  - No need for cloud (at least not for reconstruction; for rendering maybe – we’ll talk about that later)
  - Triangle mesh is readily available for receivers – no overhead of reconstruction, less power consumption
  - Sender overhead depending on outside-in or inside-out



Real-world Examples

- Microsoft Holoportation
  - Extracts mesh on the sender-side
  - Outside-in capture
  - Infra heavy
  - Sufficient resources for 3D reconstruction



Real-world Examples

- Google Project Starline
  - 8 Depth videos are streamed
  - Reconstruction computation is placed on the receiver
  - Both sender and receiver have similar computation resources

Real-world Examples

- Apple Vision Pro
  - Sender-side reconstruction
  - 3D reconstruction maybe fast but still consumes power
  - Receivers could be other XR headsets

Live 3D Capture

- Depth Map vs. Point Cloud vs. Mesh

- Outside-in
    - Most scenarios sender has more resources
    - Sender-side reconstruction strikes a good balance

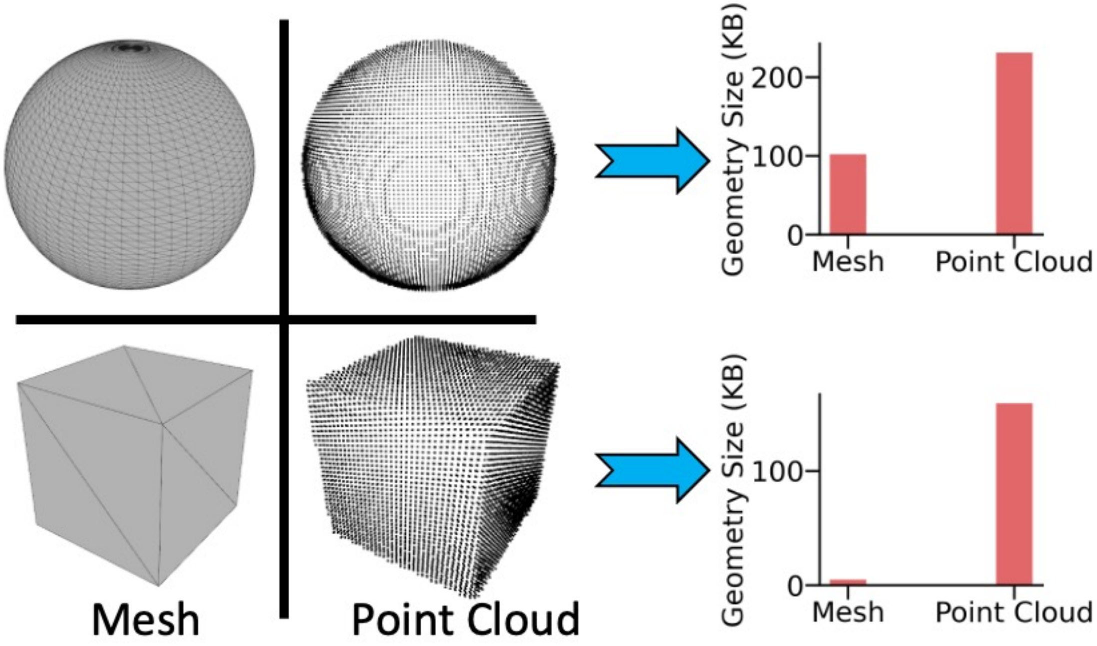
- Inside-out
    - Most scenarios senders do not have enough resources (e.g., phones)
    - Cloud is a good option

Live 3D Capture

- Depth Map vs. Point Cloud vs. Mesh
- Implications on the network?
  - Each data structure has significantly different bandwidth requirement
  - It is unclear which is better – still in experimental research phase, no consensus yet; need to study diverse scenarios.

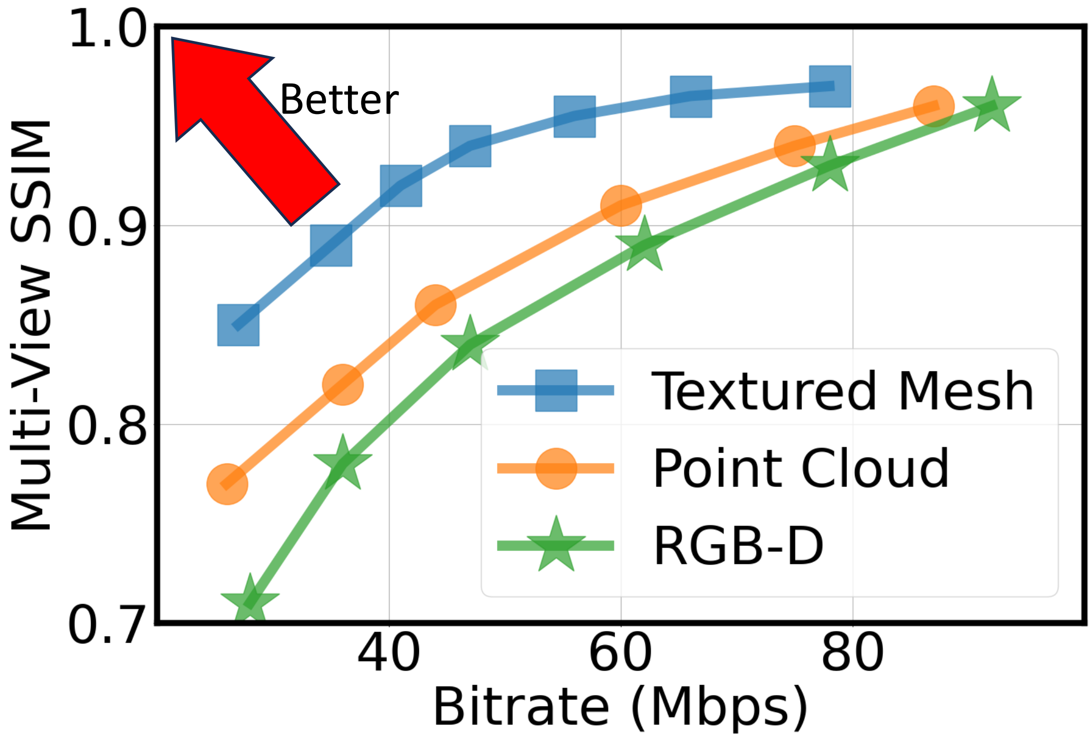
Early Findings

- Mesh is compact



Early Findings

- Mesh requires relatively lower bandwidth for a given final rendering visual quality



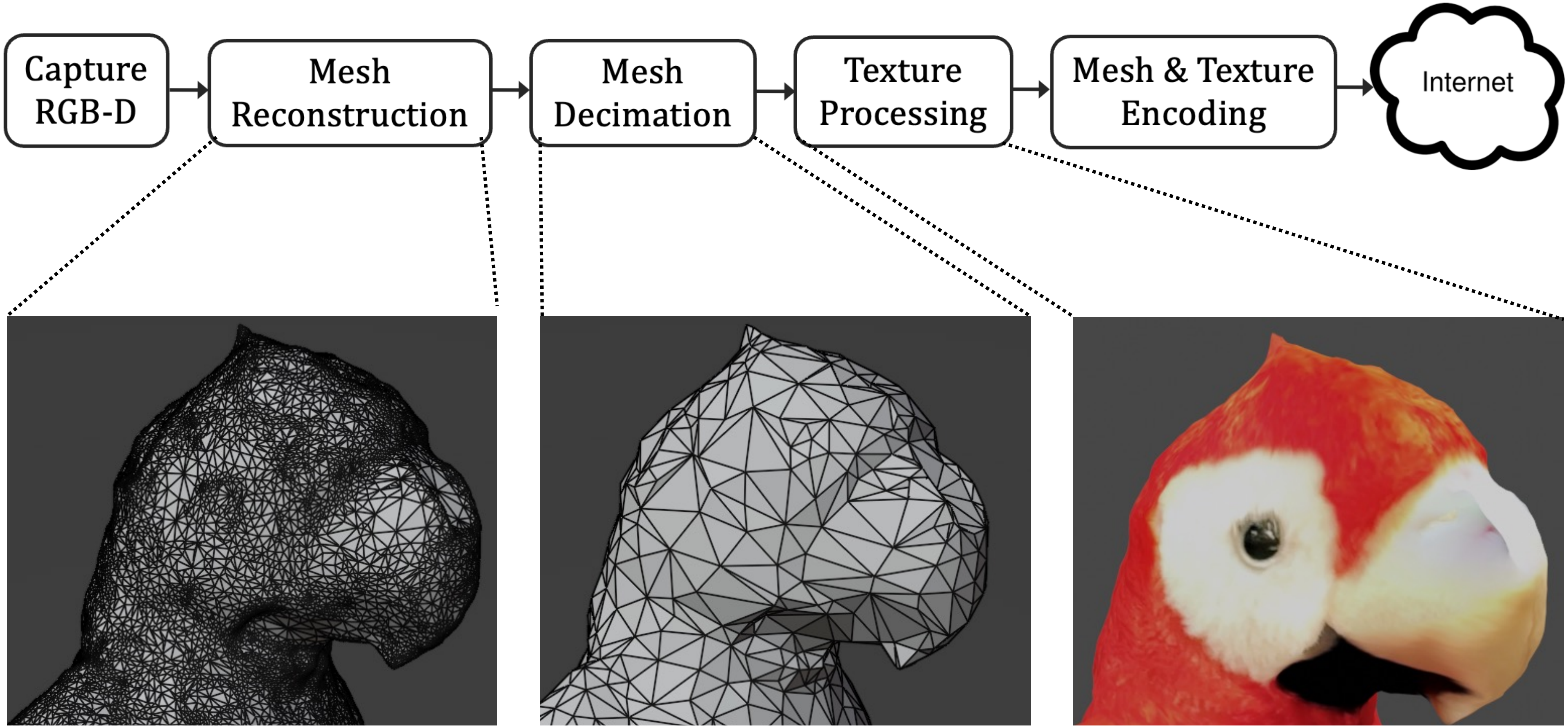
Live 3D Capture

- Depth Map vs. Point Cloud vs. Mesh
- Meshes are generally superior – assuming we can tackle the computation challenge on the sender side
- Several reasons
    - Compact
    - High resolution texture
    - Compatible for rendering hardware - triangles

Live Capture of Meshes

- Texture is given – we can use existing hardware pipelines for 2D videos to capture and stream textures
- Extracting meshes is a complex process
  - Involves a series of computationally expensive reconstruction steps
  - Outside-in scenario: fusing multiple scenes together; adds additional computation

Live Capture of Meshes



Capture RGB-D

Mesh Reconstruction

Mesh Decimation

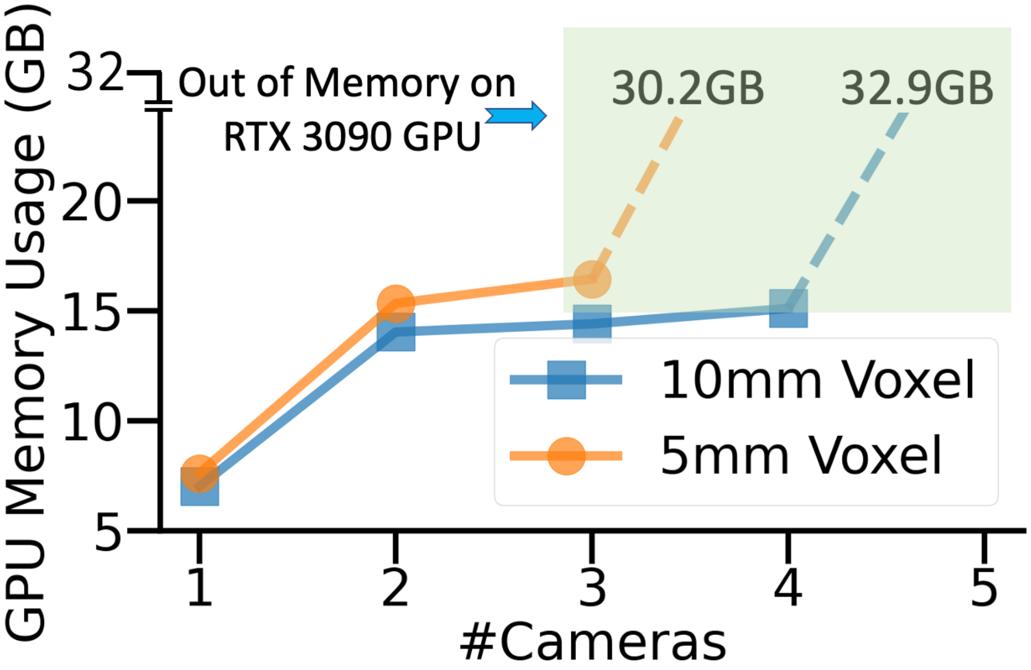
Texture Processing

Mesh & Texture Encoding

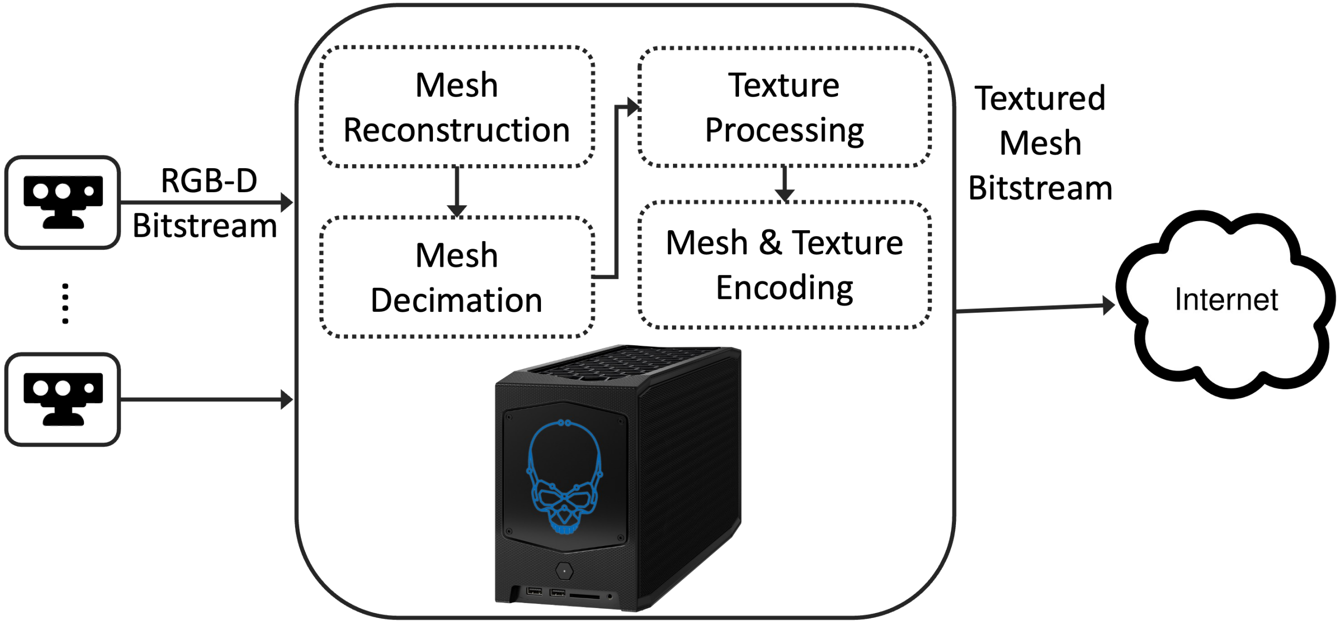
Internet

Live Capture of Meshes

- Single camera vs. multi camera reconstruction
  - GPU memory runs out of memory quickly
  - Depends on the voxel resolution
  - What is voxel?



Live Capture of Meshes



RGB-D Bitstream

Mesh Reconstruction

Mesh Decimation

Texture Processing

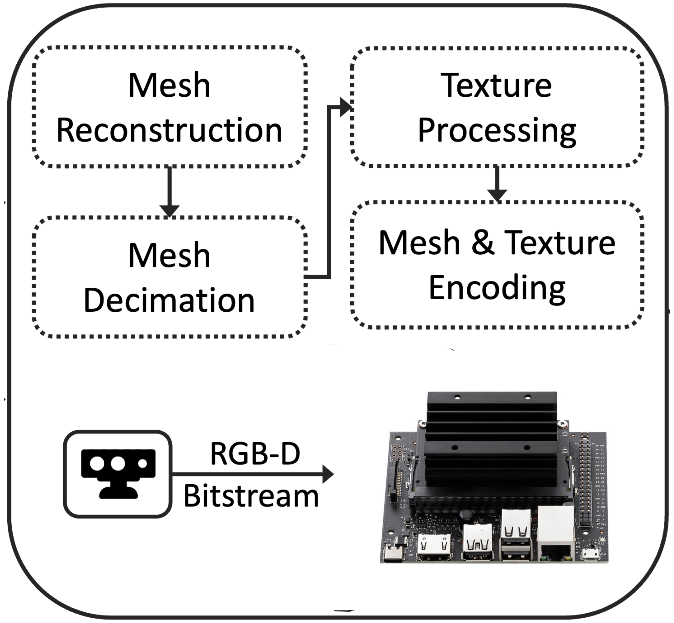
Mesh & Texture Encoding

Textured Mesh Bitstream

Internet

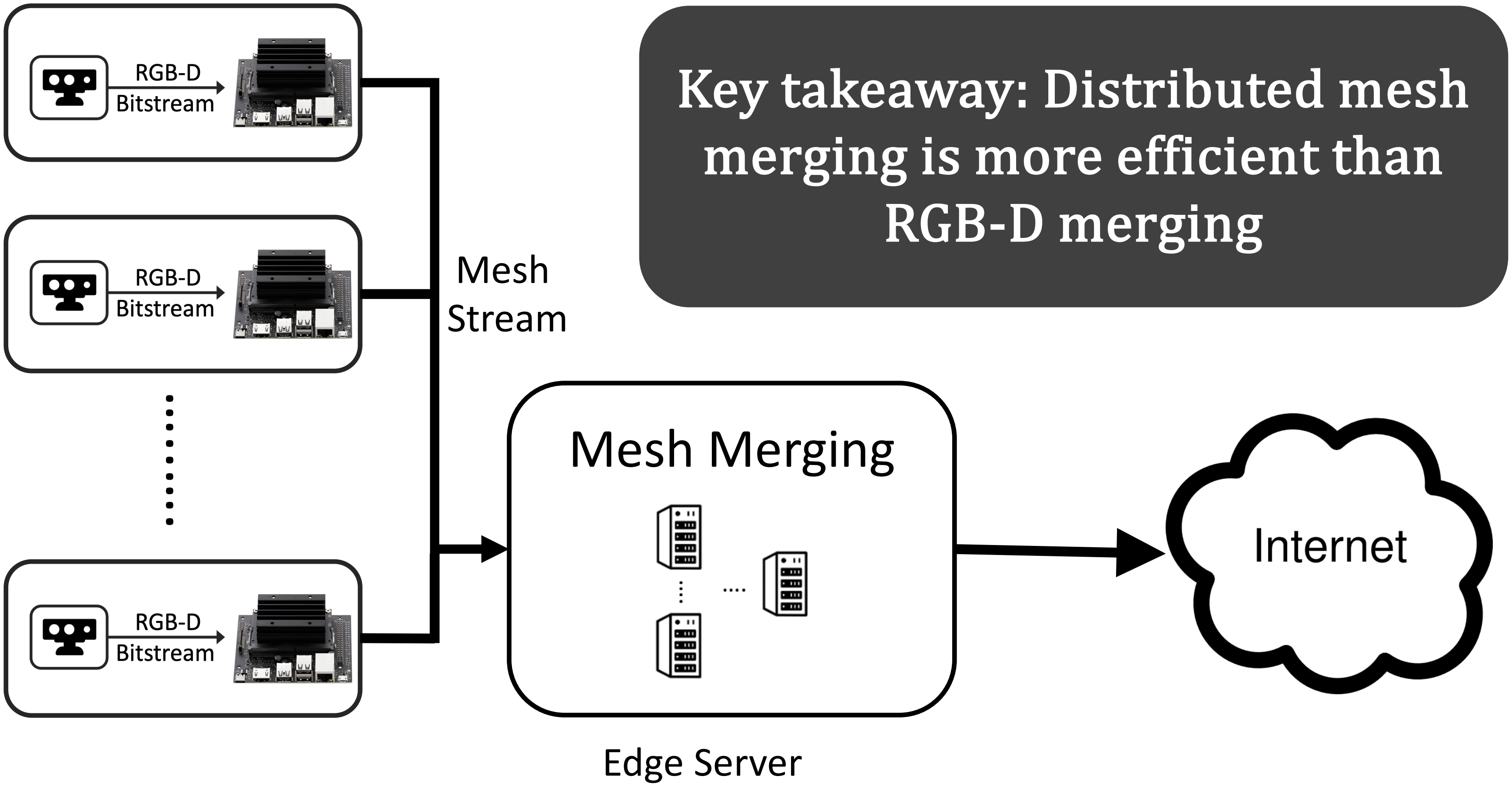
Centralized Textured Mesh Creation Server

Live Capture of Meshes



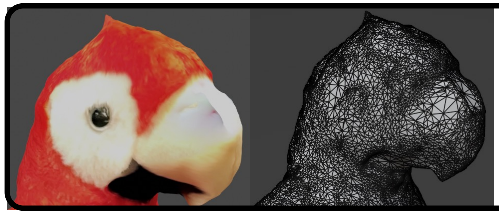
Live Capture of Meshes

Key takeaway: Distributed mesh merging is more efficient than RGB-D merging



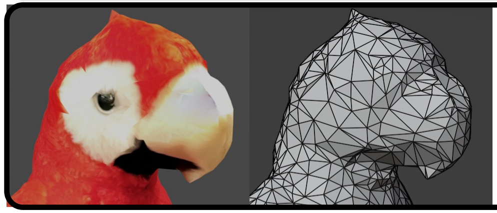
Live Capture of Meshes

- Texture vs. Mesh bandwidth



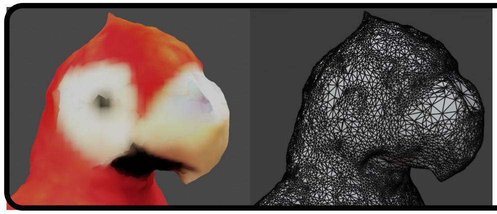
Original texture
Original mesh

164MB



Original texture
Low-res mesh

8.2MB



Low-res texture
Original mesh

8.2MB

Summary of the Lecture

- Scene Capture
    - Computation, bandwidth, latency implications
- Capturing different 3D Data Structures
- Sender, Cloud and Receiver-driven Pipelines
- Distributed Mesh Reconstruction

Next Up: Compression Fundamentals

Quiz