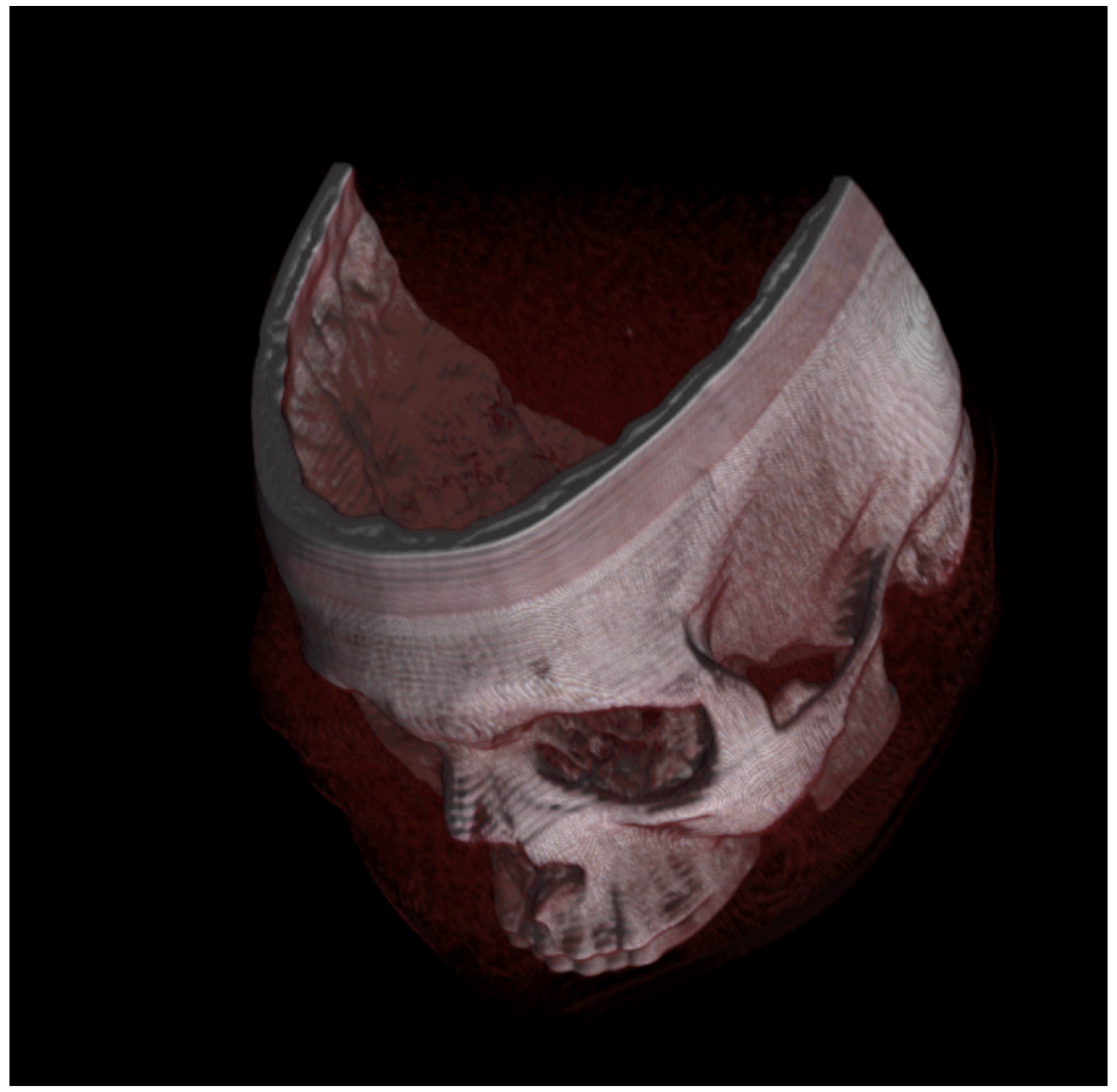
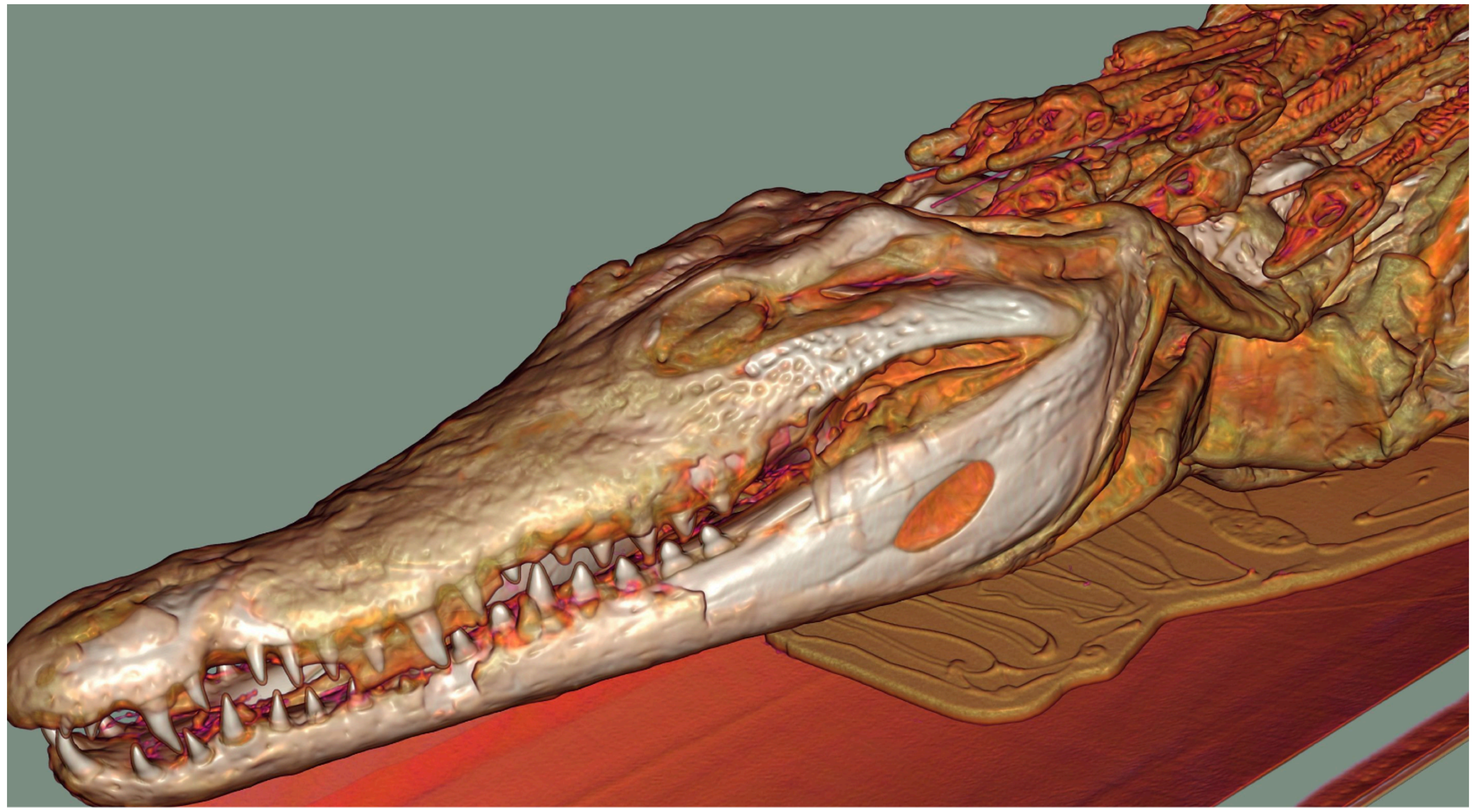
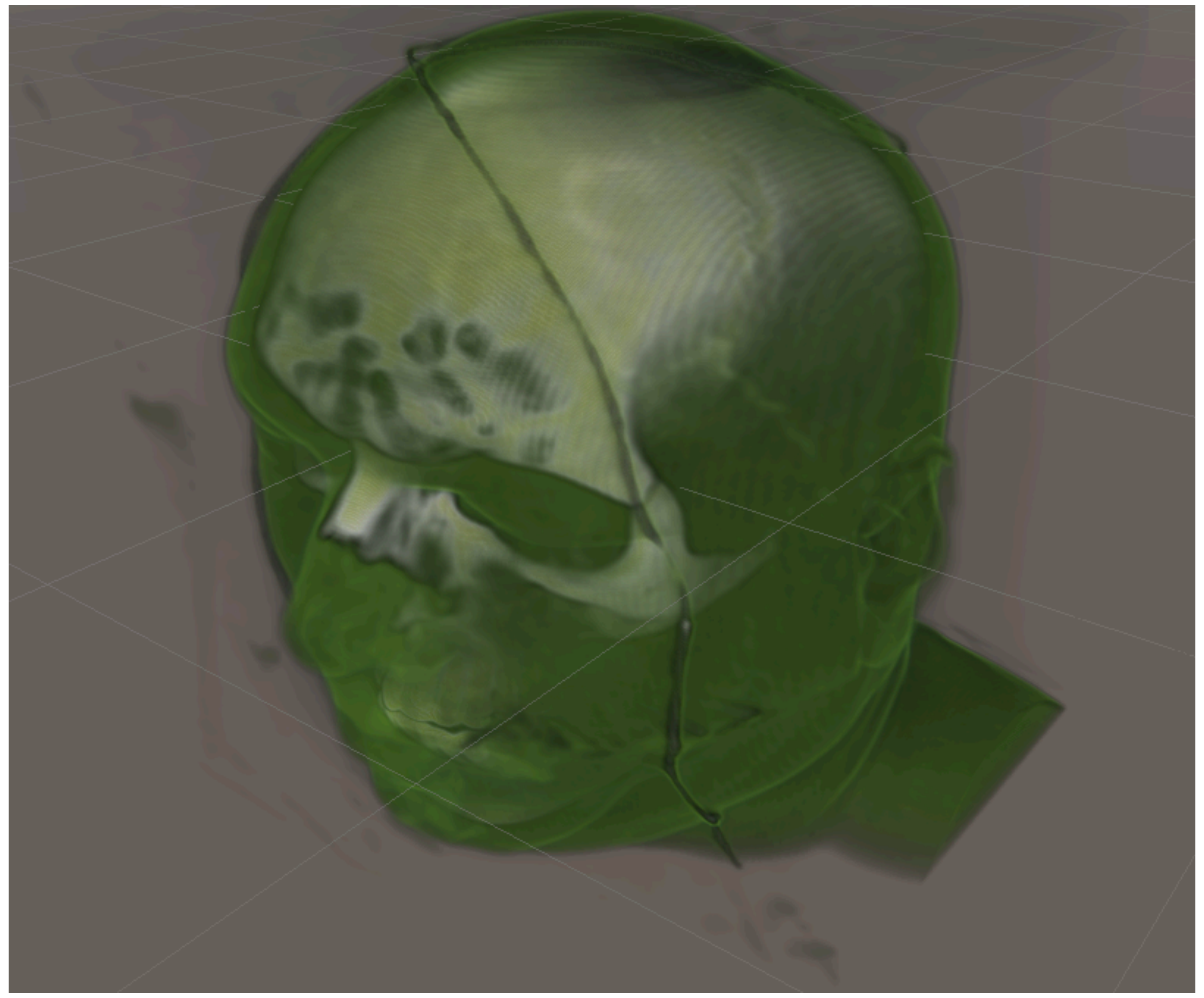
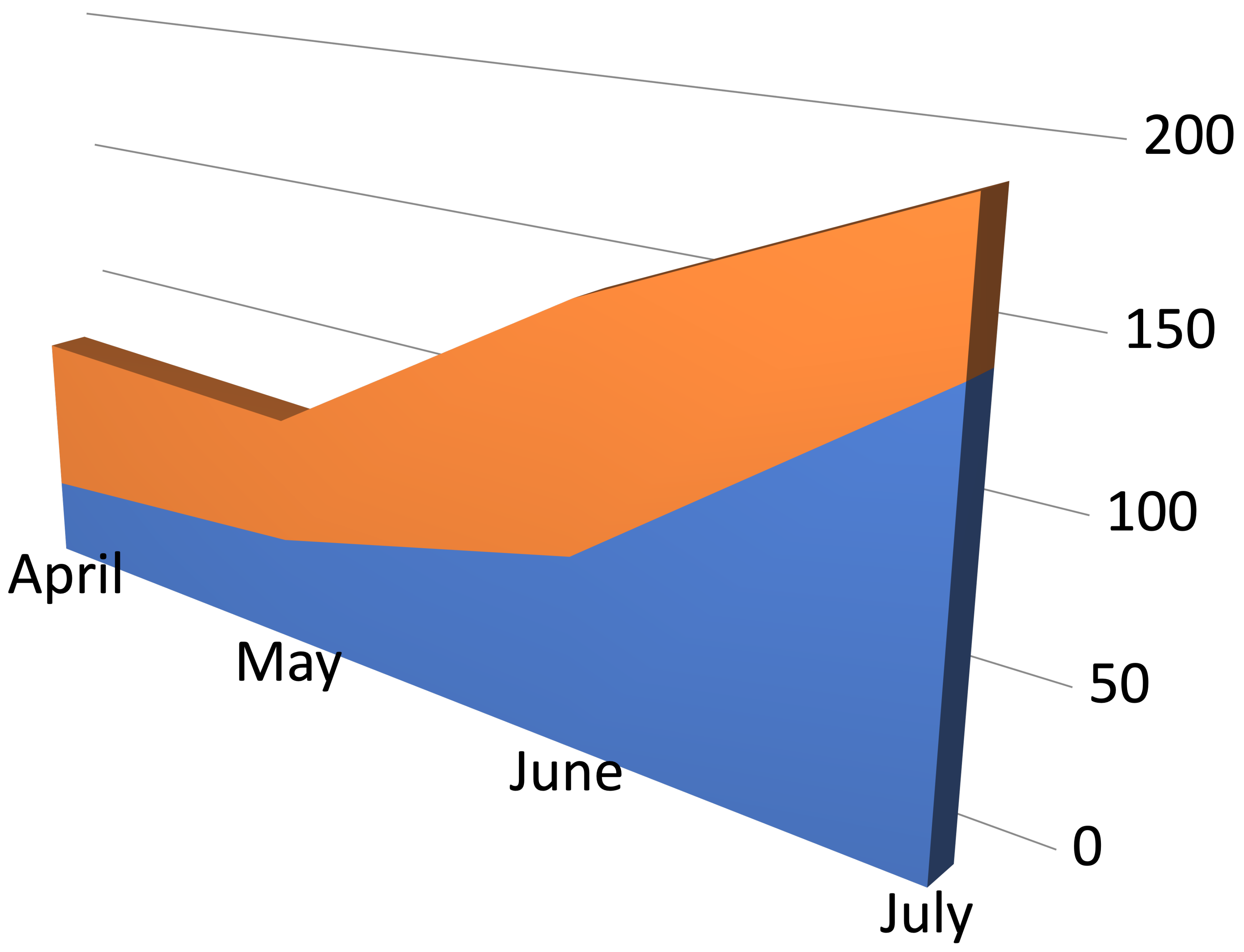
Data Visualization Course: Guest Lecture Stefanie Zollmann

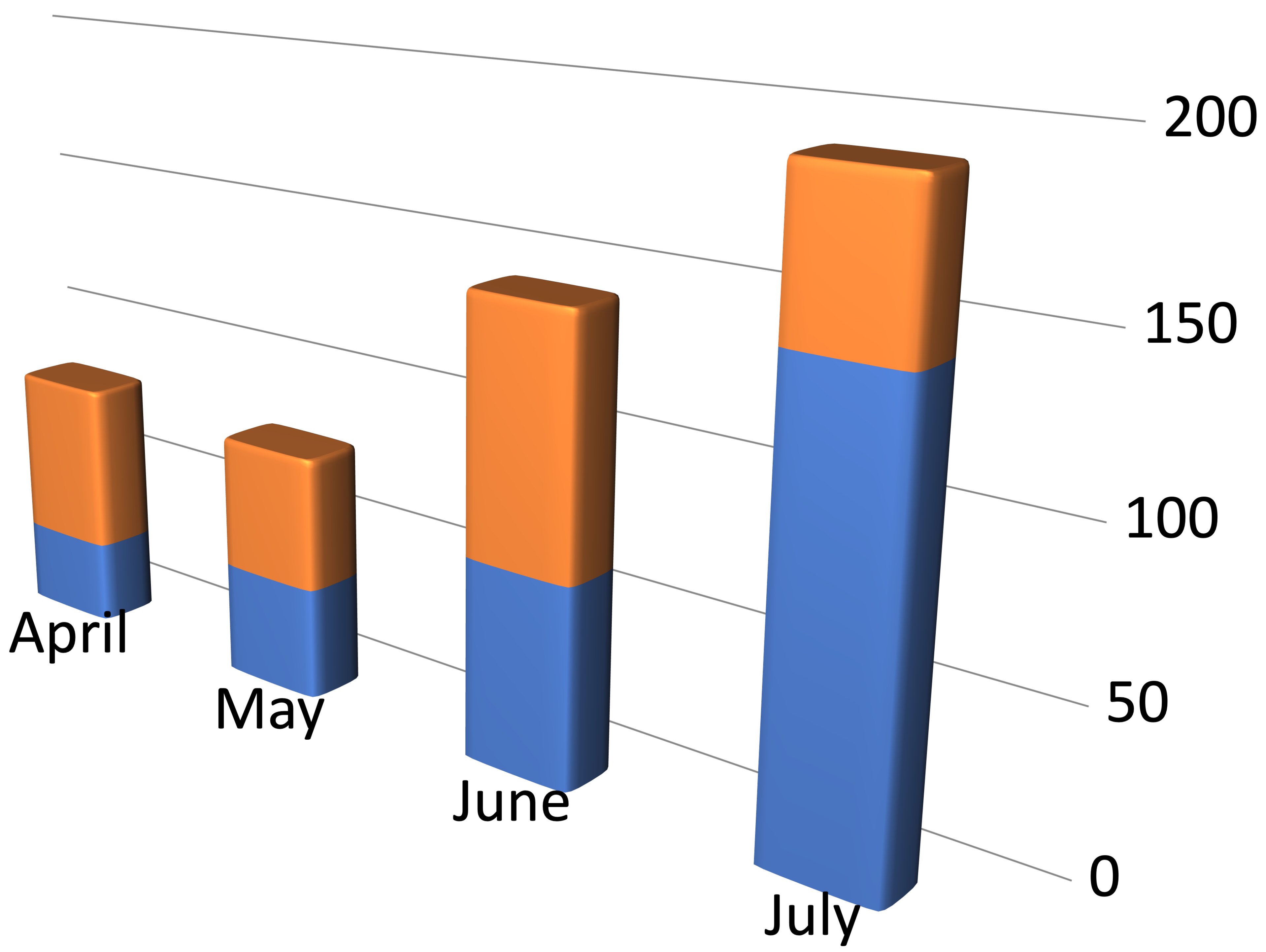




3D Visualisation

Visualisation for 3D or 3D for Visualisation

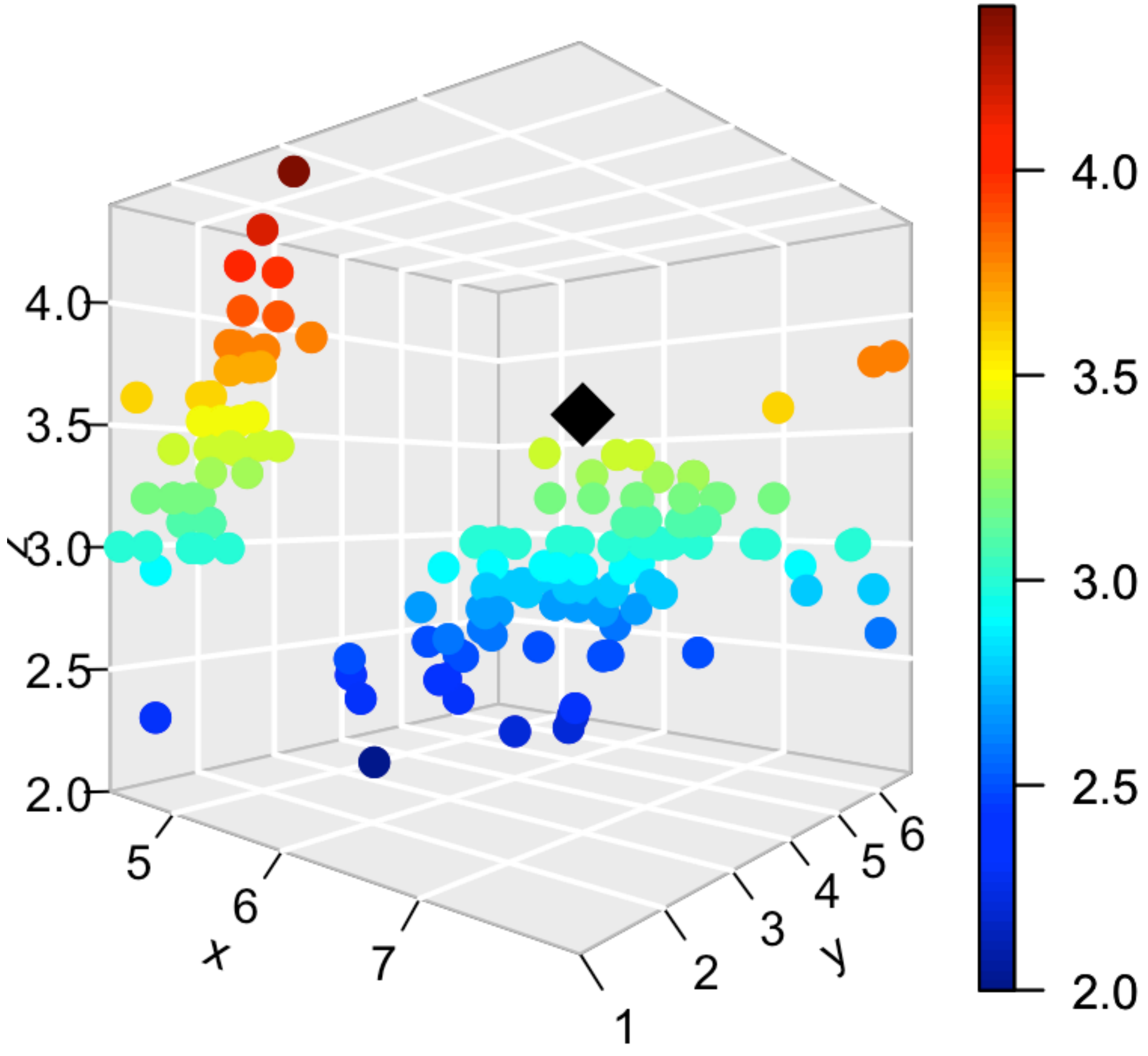
3D Visualisation - Why?





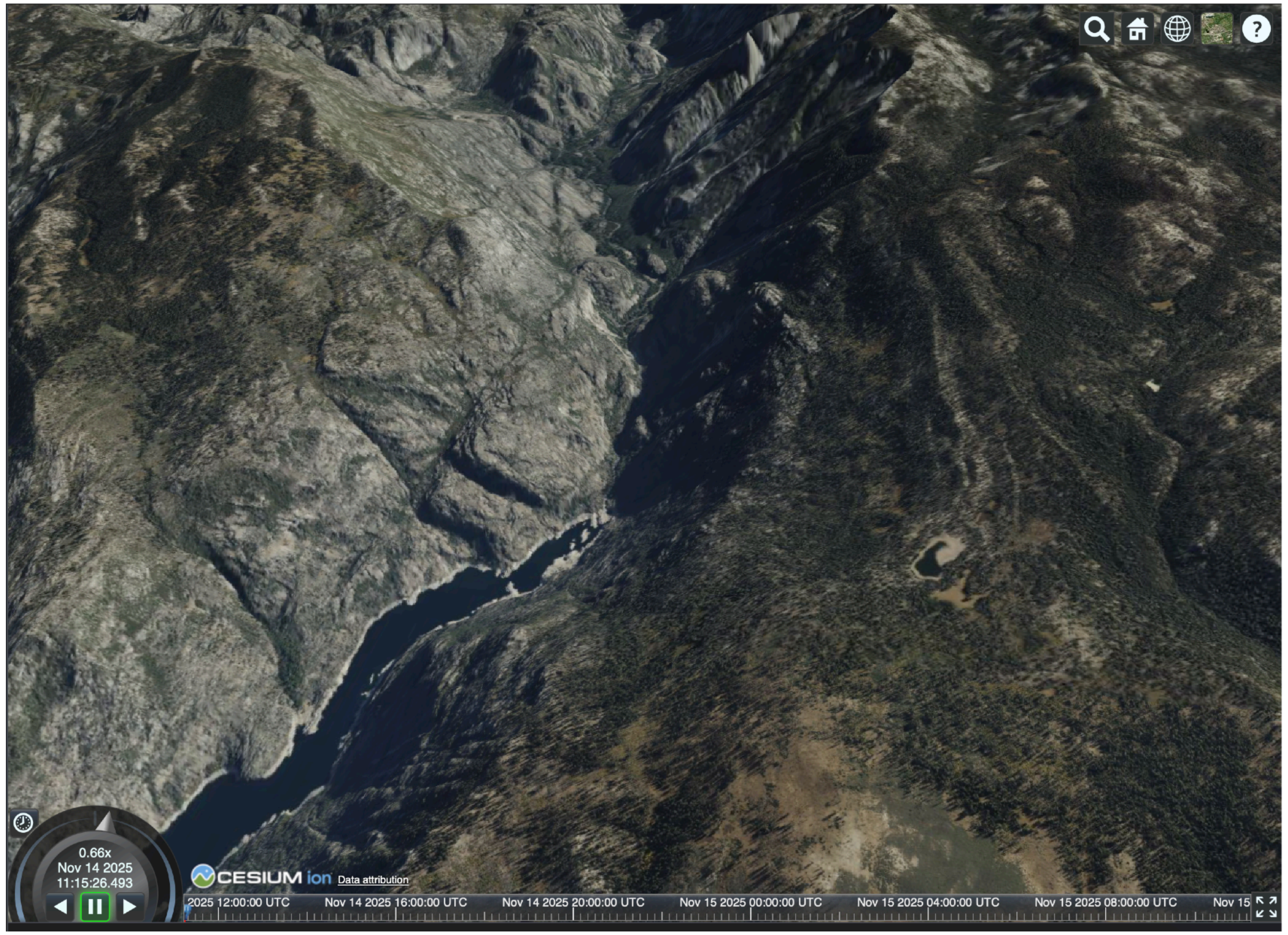
BAD!!!

3D Visualisation - Why?



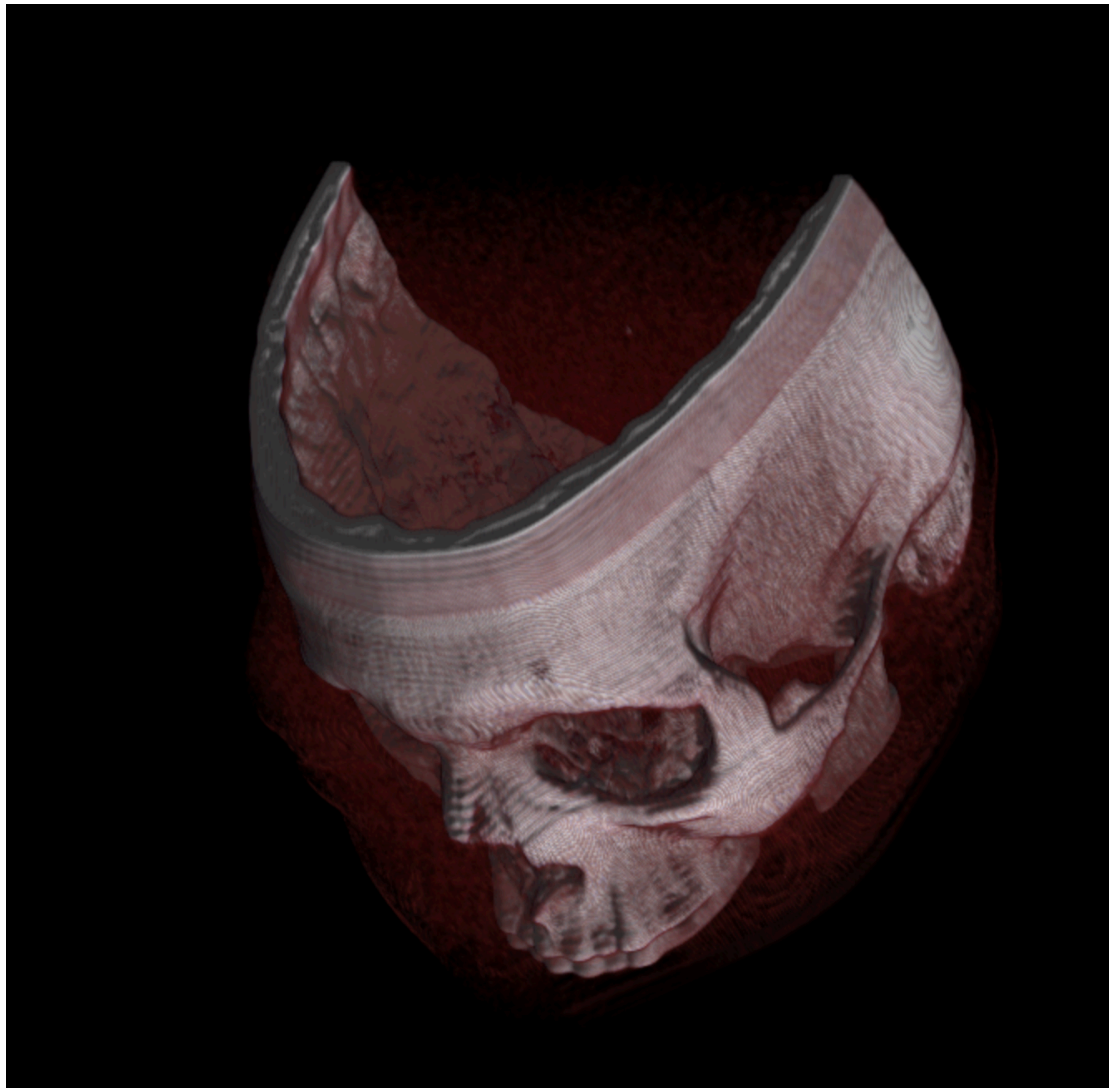
Still bad

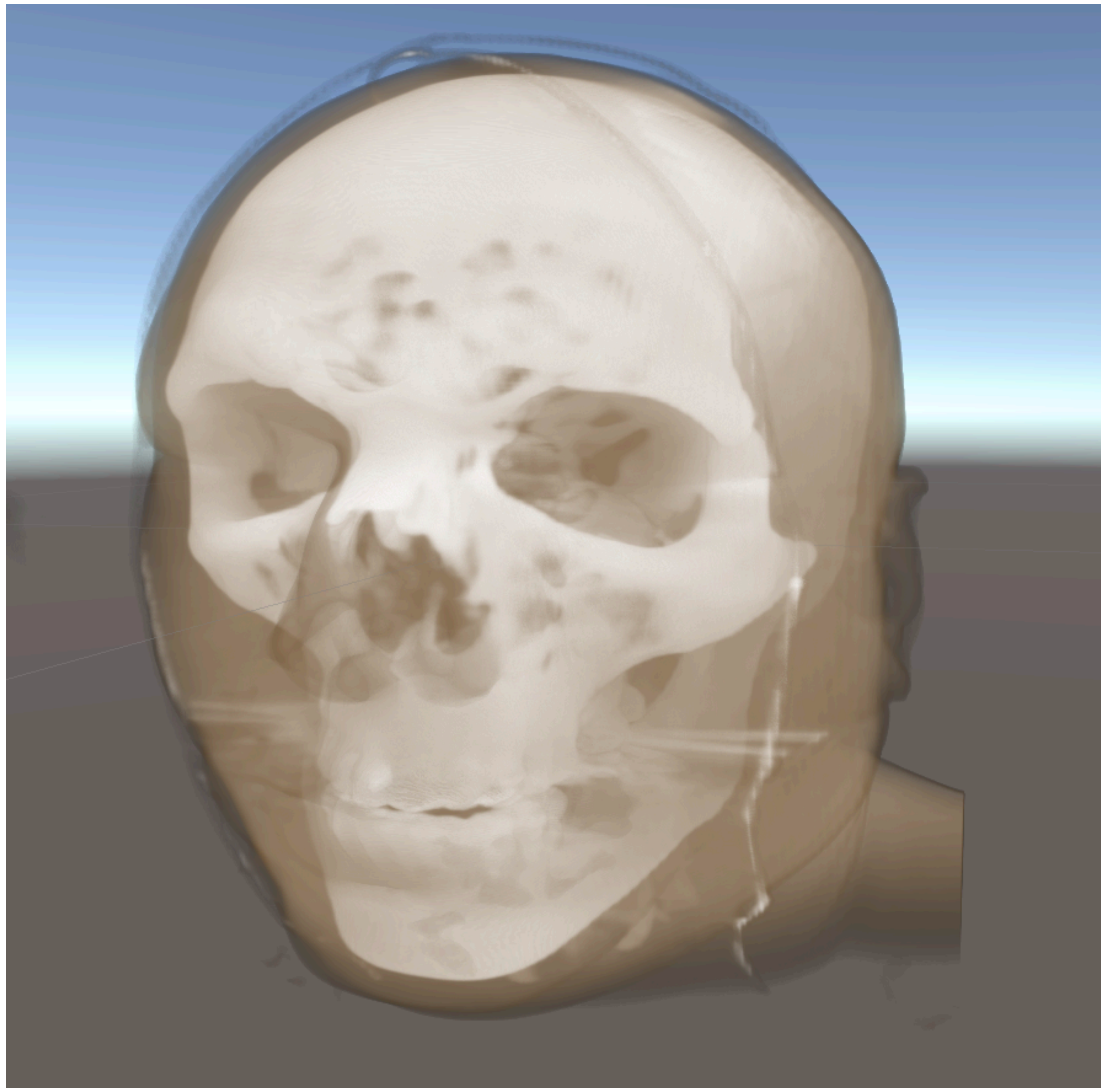
3D Visualisation Examples - Geographic Data



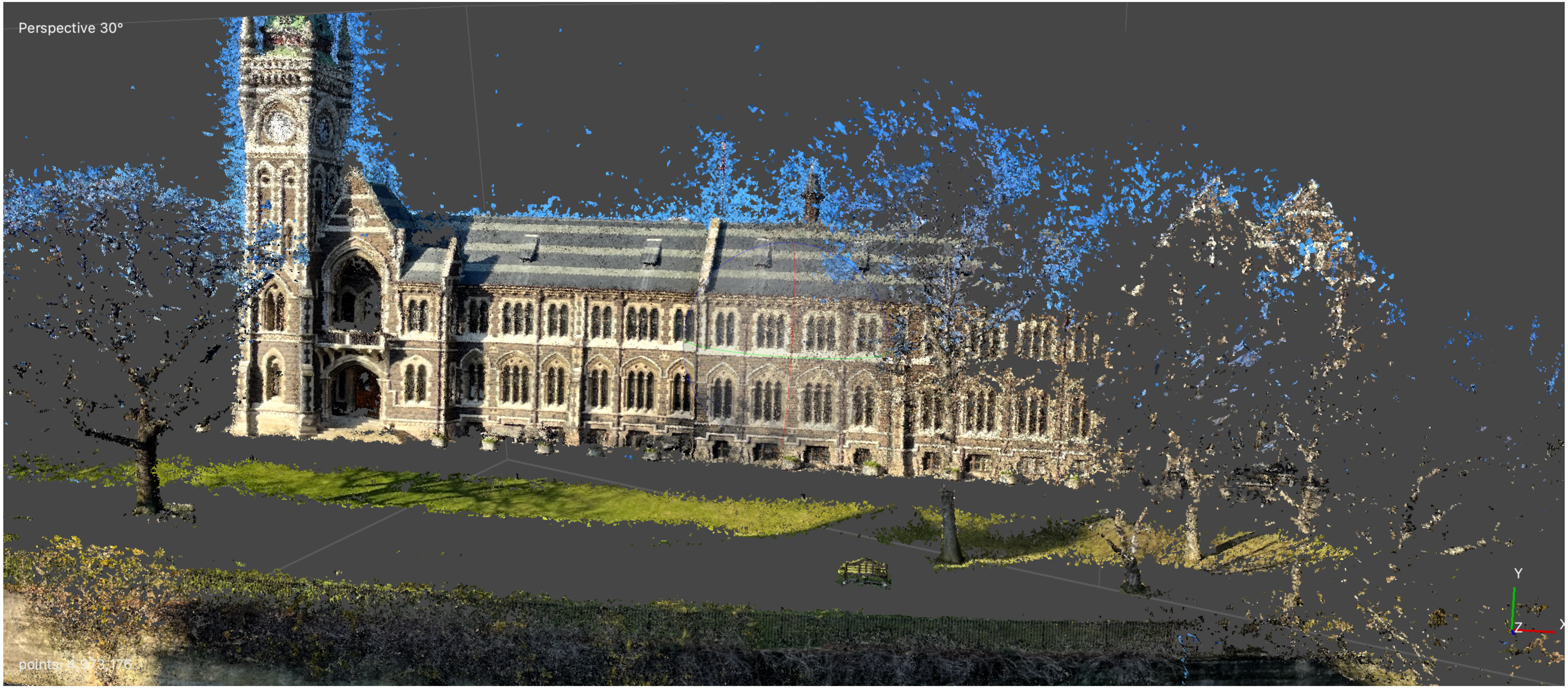
https://sandcastle.cesium.com/?id=cesium-world-terrain

3D Visualisation Examples - Medical Datasets



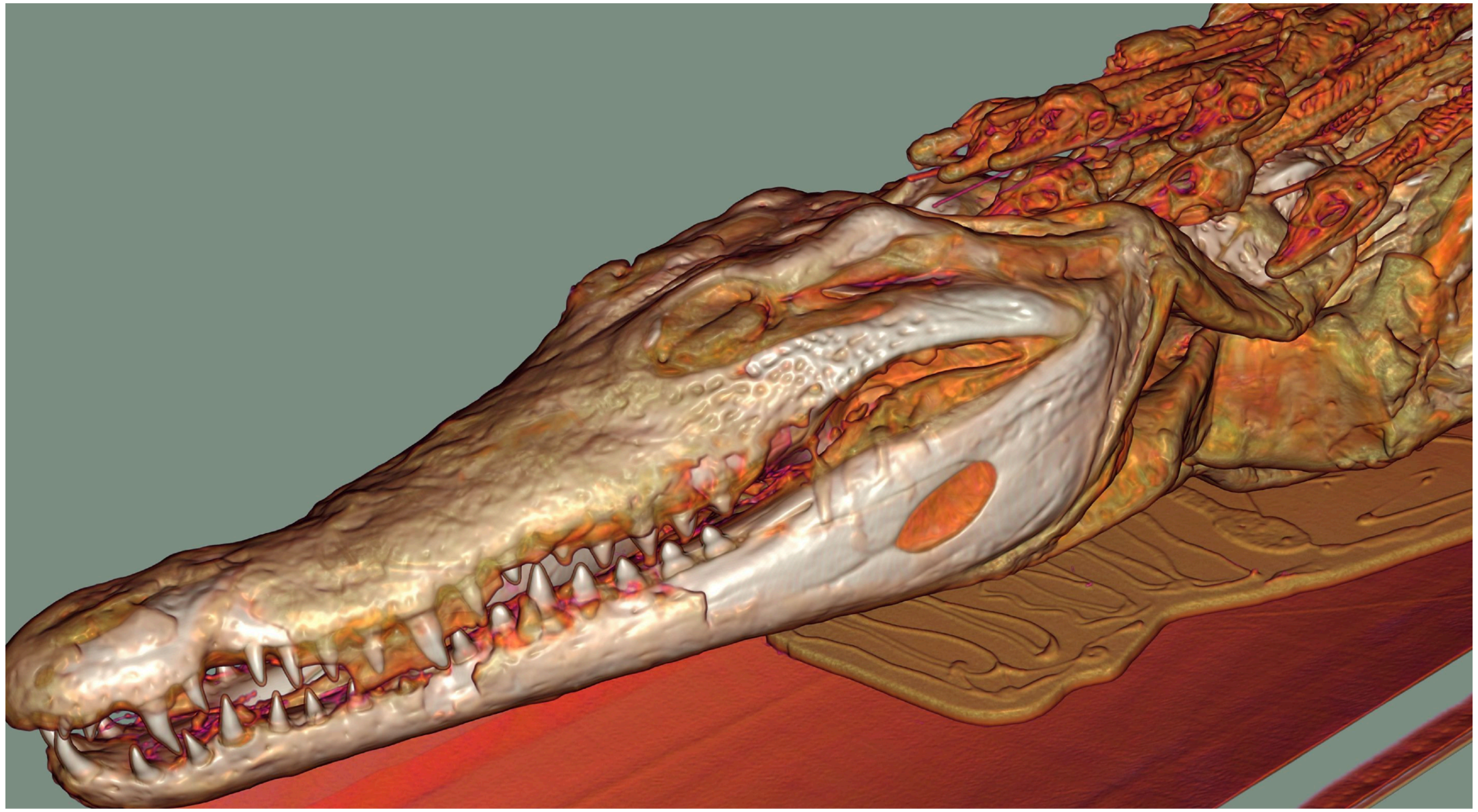


3D Visualisation Examples - Photogrammetry



Why 3D Visualisation?

- Many scientific domains produce 3D datasets:
  - Medicine (CT, MRI)
  - Fluid dynamics, CFD
  - Geoscience & atmospheric models
  - Photogrammetry
  - Molecular structures
- 2D projections can obscure:
  - Spatial correspondence
  - Internal structures
  - Occluded surfaces

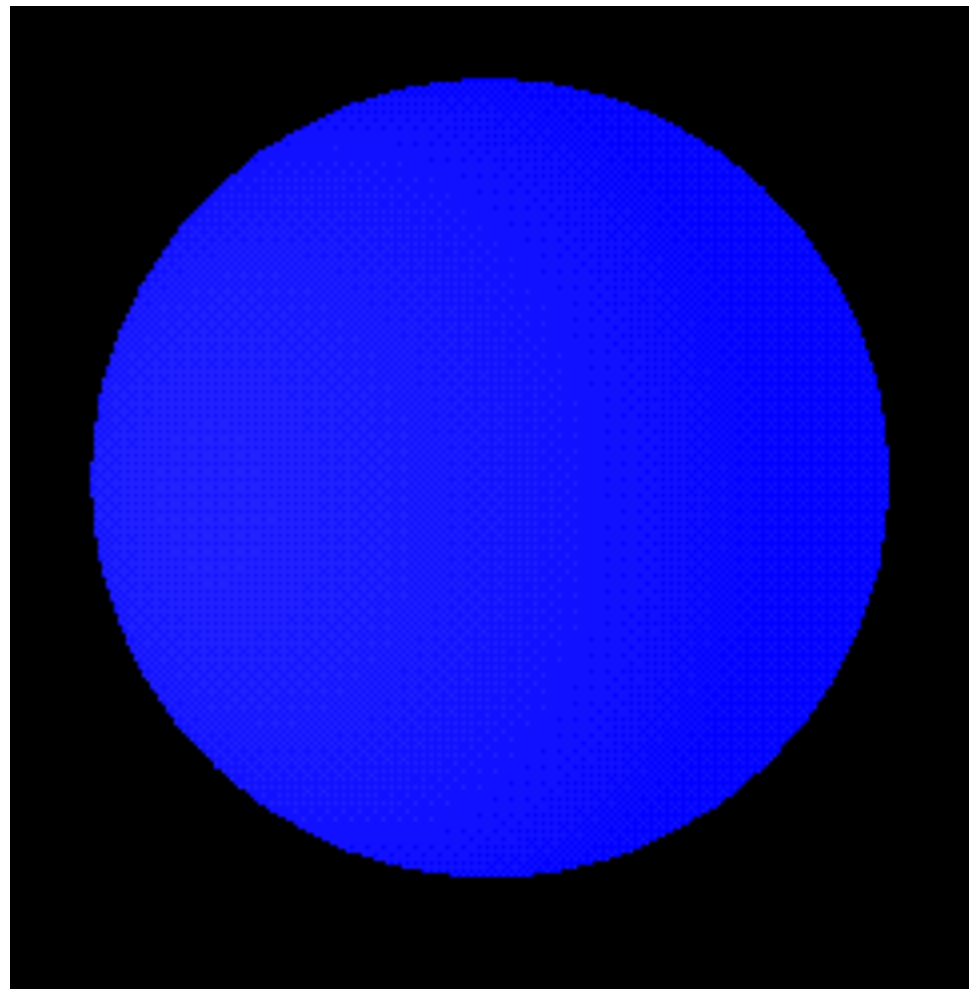


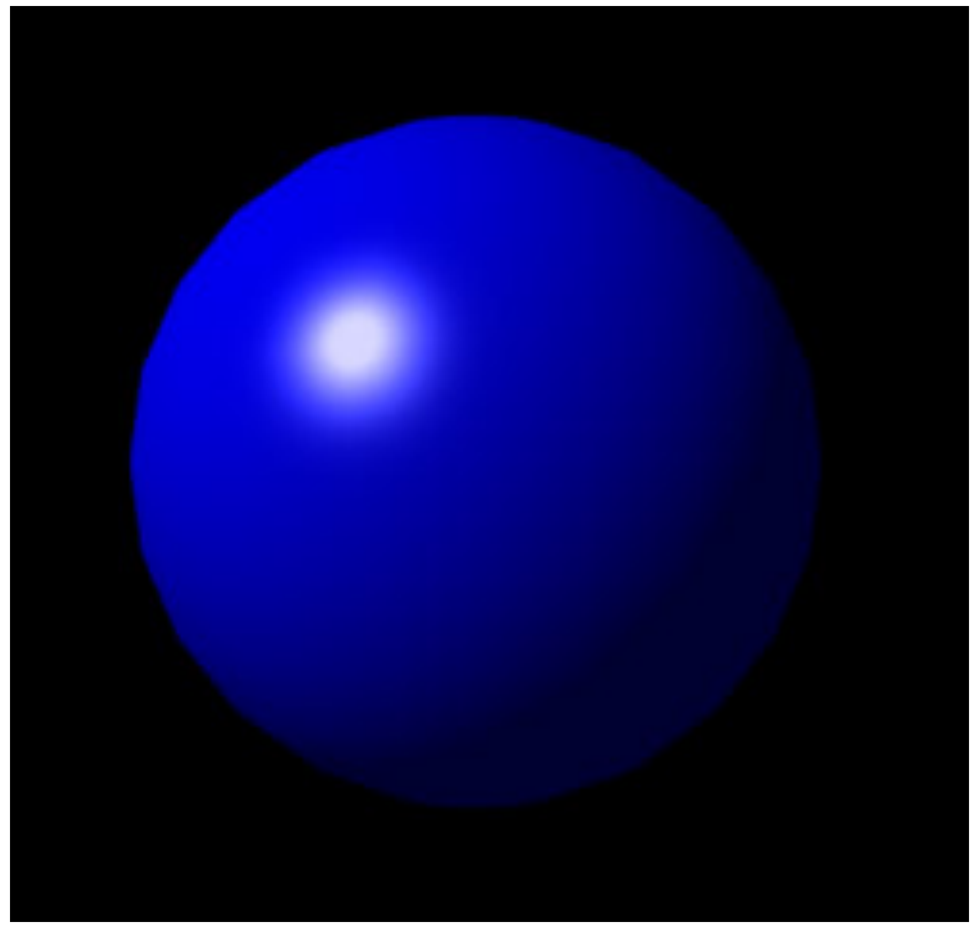
Why is 3D Visualization Challenging?

- Occlusion:
  - 3D scenes naturally hide parts of the data from view
- Perspective distortion & depth ambiguity
  - Users struggle to perceive depth accurately without additional cues
- Navigation complexity
  - Manipulating a 3D viewpoint adds cognitive load
- High data sizes
  - Volumetric data can become very large and requires optimised rendering (GPU rendering)
- There is a need for specialised techniques rather than simply extending 2D visualisations into 3D

Depth Cues & Perception

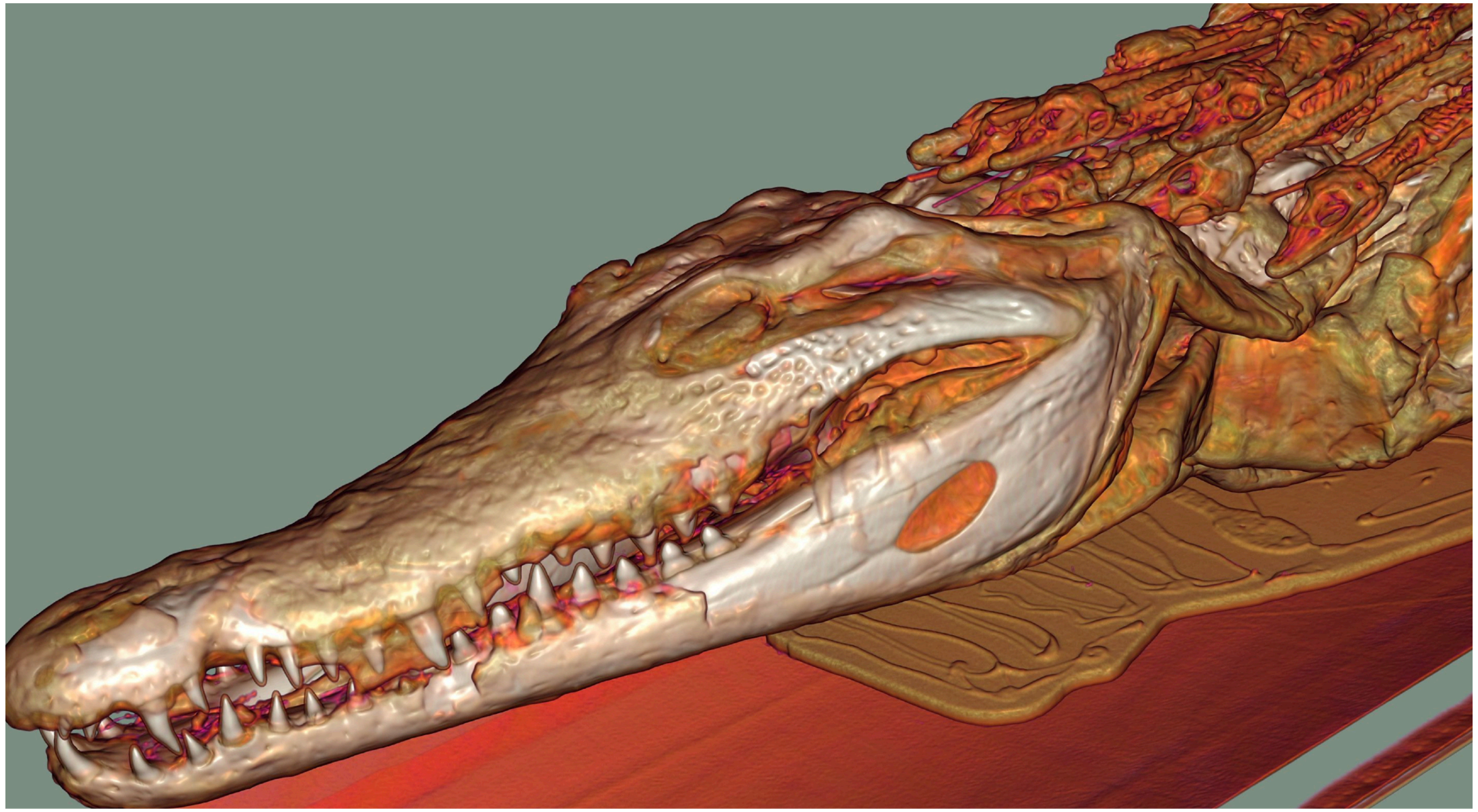
- Shading (Phong, Blinn–Phong)
  Essential for conveying shape on surfaces
- Shadowing & occlusion techniques
  Improve depth perception and reveal structure
- Color coding, transparency, and transfer functions -> Important in volume visualisation
- Cutting planes and slicing
  Reduce clutter and reveal occluded internal structures



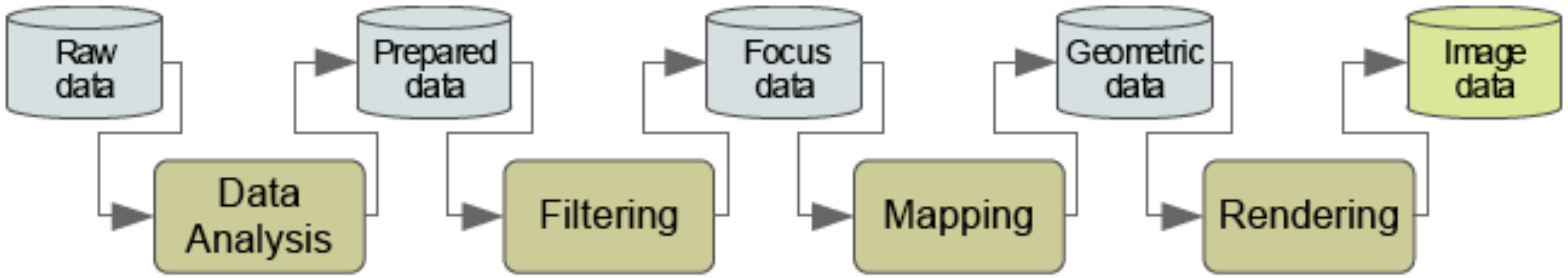


3D Visualisation

- 3D Visualization is the process of transforming complex (sometimes abstract) 3D data into an intuitive graphical representation
- Goal: Gain insight -> not just make pretty pictures
- Why 3D?
  - Intuitive Perception: Our brains are built for 3D
  - Spatial Relationships: Understand "what's next to," "inside of," or "behind" something else
  - Data Density: We can encode more information (x,y,z + color, size, opacity)



(3D) Visualisation Pipeline



https://infovis-wiki.net/wiki/Visualization_Pipeline

- 3D Example:
  - Data (Raw Data): Raw CT scan - a huge file of numbers.
  - Filtering (Data Prep): Smooth the data to reduce noise/Filter out irrelevant information (e.g. air)
  - Mapping ("Artistic" Step): Decide what the data looks like -> map data values to visual properties
    - Density values to colour
    - Density values to opacity
    - Specific density (like bone) to a surface (an isosurface)
  - Rendering (Creating the Picture): Creates final 2D image (calculating lighting, shadows, and perspective)

3D visualisation is not always better

- Effective when spatial or volumetric relationships are critical
- Ineffective when projection or occlusion obscure structure
- Hybrid approaches (e.g., linked 2D–3D views) often outperform pure 3D

3D Data Types and Representations

Data type	Representation	Visualization techniques
Scalar fields	Volumetric grids (voxels)	Volume rendering, isosurfaces
Vector fields	Flow data (velocity, wind)	Streamlines, glyphs, particle tracing
Geometric Data	Meshes, point clouds	Surface rendering, shading
Multivariate spatial data	Geometry + attributes	Color mapping, texture, transparency

How do 2D Concepts map to 3D Visualisation

Concept	In 2D Visualization	In 3D Visualization
Data–space mapping	(x, y) ➝ pixel position	(x, y, z) ➝ voxel or vertex position
Mark encoding	Shape, color, size	Geometry, material, illumination
Projection	Orthographic, map projection	Perspective projection, camera transforms
Interaction	Pan, zoom, filter	Orbit, flythrough, slicing, selection in depth

Important Fundamentals

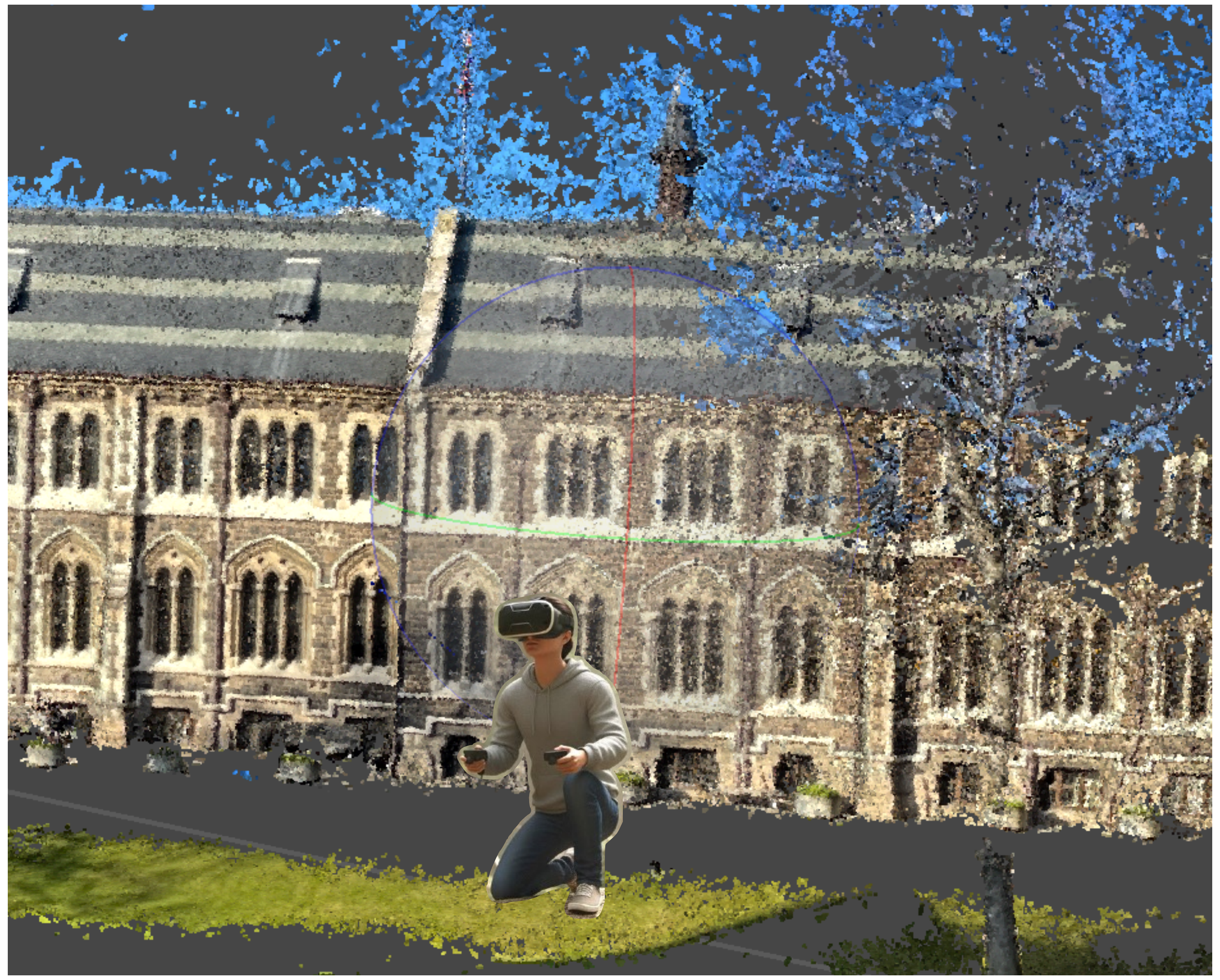
- Camera model: viewpoint, field of view, projection type
- Lighting model: how shading conveys shape and depth
- Transparency and volume rendering: controlling visibility of interior structures
- Interaction metaphors: orbit, slice, 3D selection

Interaction

- Basic Interaction: Zoom, Pan, Rotate:
  - Needed because of occlusion: 3D objects may hide behind other 3D objects
- Data Interaction:
  - Slicing: "virtual knife" to cut open a 3D model
  - Brushing: Selecting data in one view (e.g., a 3D scatter plot) and seeing it highlight in another (a 2D histogram).
  - Editing: Changing the Transfer Function

Display

- Screen (Standard): “2D window into the 3D world”
- Virtual Reality (VR):
  - Immersive: Users are inside data
  - Used for complex data exploration, simulations
- Augmented Reality (AR):
  - Contextual
  - Overlaying data onto real world
  - Used in engineering, medicine, or architecture



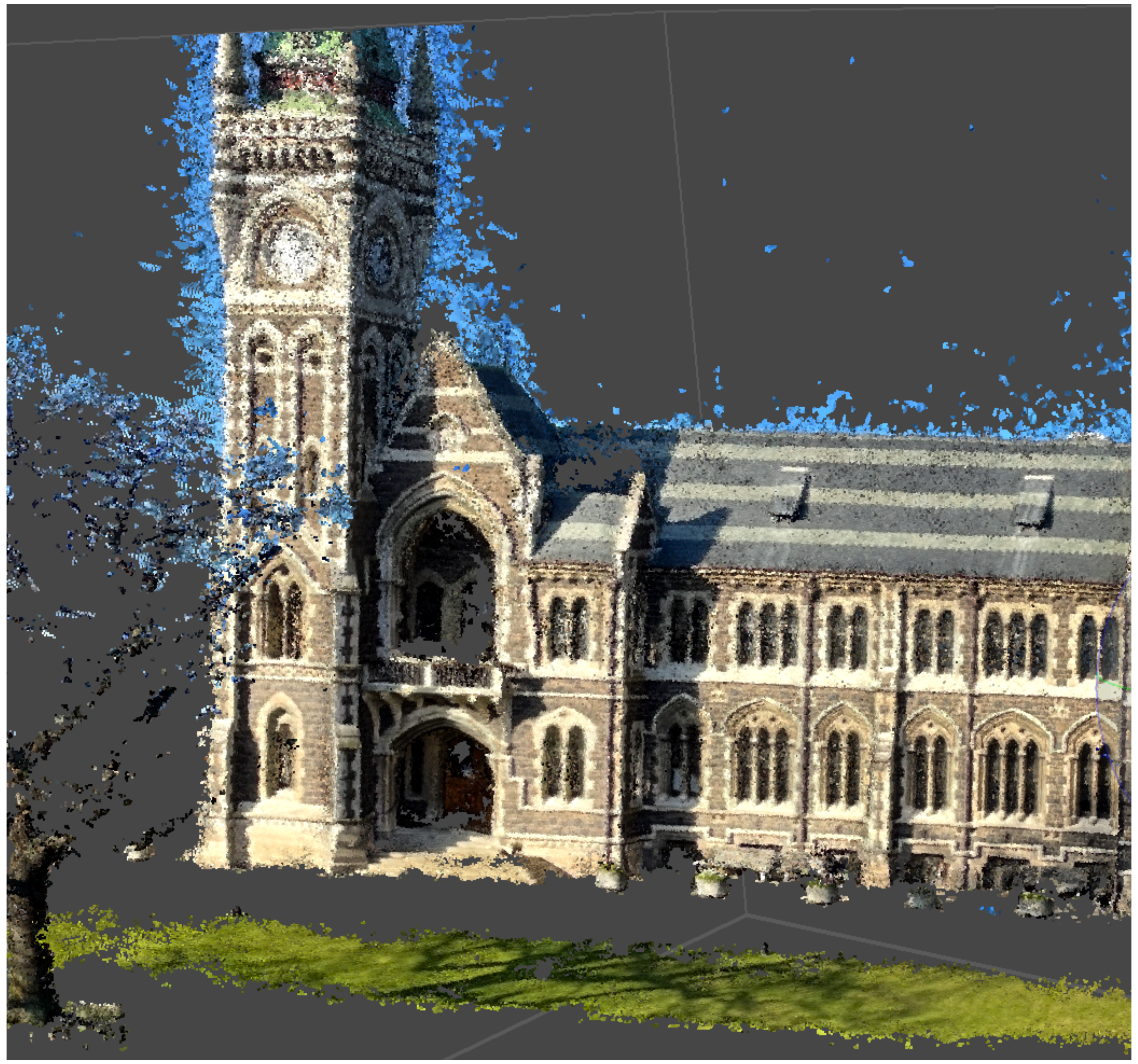
Key Concept: Projection (Going from 3D to 2D)

Perspective Projection

- Perspective Projection
  - Things farther away appear smaller
  - Mimics how the human eye works
  - Use:
    - Games, movies, realistic visualisation
- Orthographic Projection
  - Size does not change with distance
  - Parallel lines remain parallel
  - Use: Technical blueprints, CAD, engineering design (where measurements are key)

Rendering Techniques: Point clouds

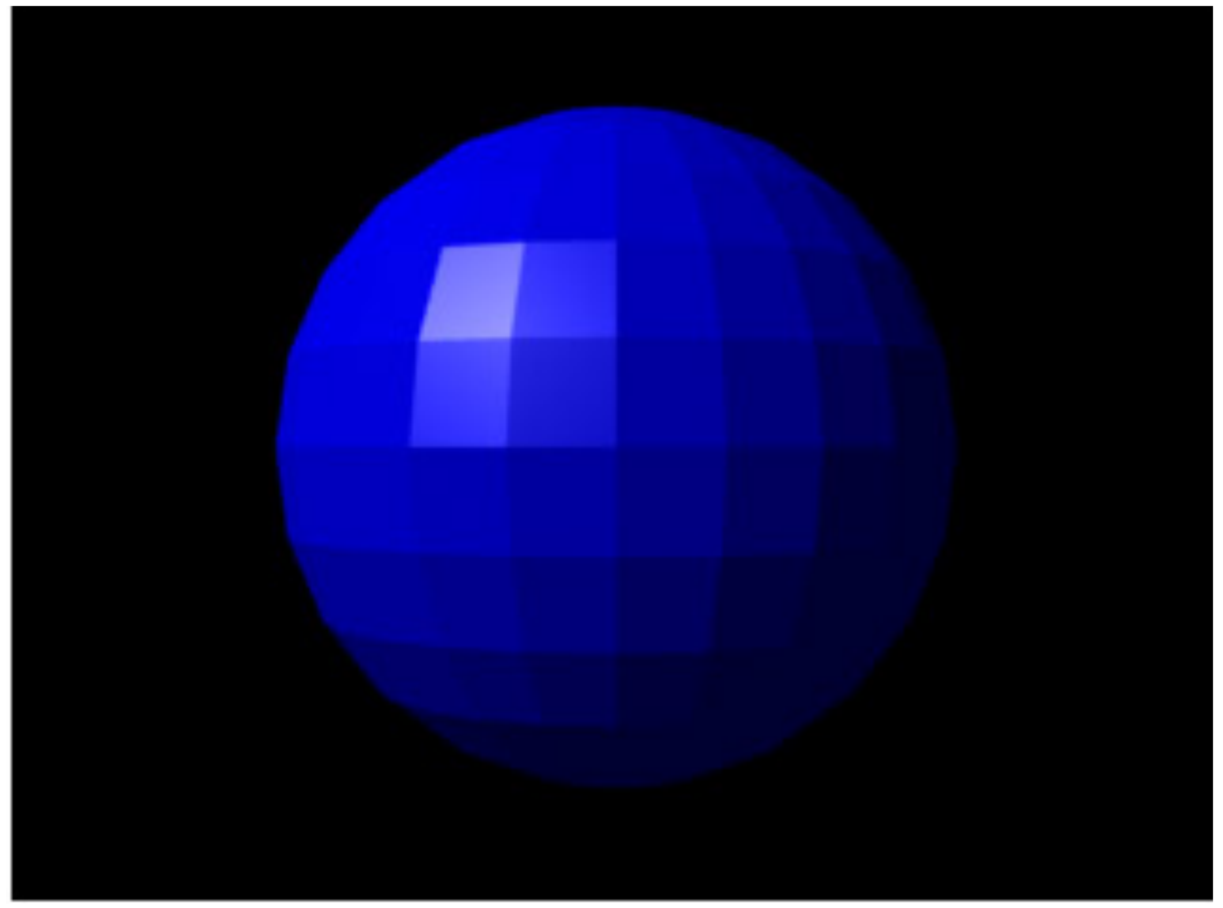
- Techniques include:
  - Point-based rendering/splatting
  - Density estimation & smoothing
  - Normal estimation for shading
  - Multi-scale representations (octrees, kd-trees)
- Points are easy to display but can be hard to interpret without local surface reconstruction or splatting

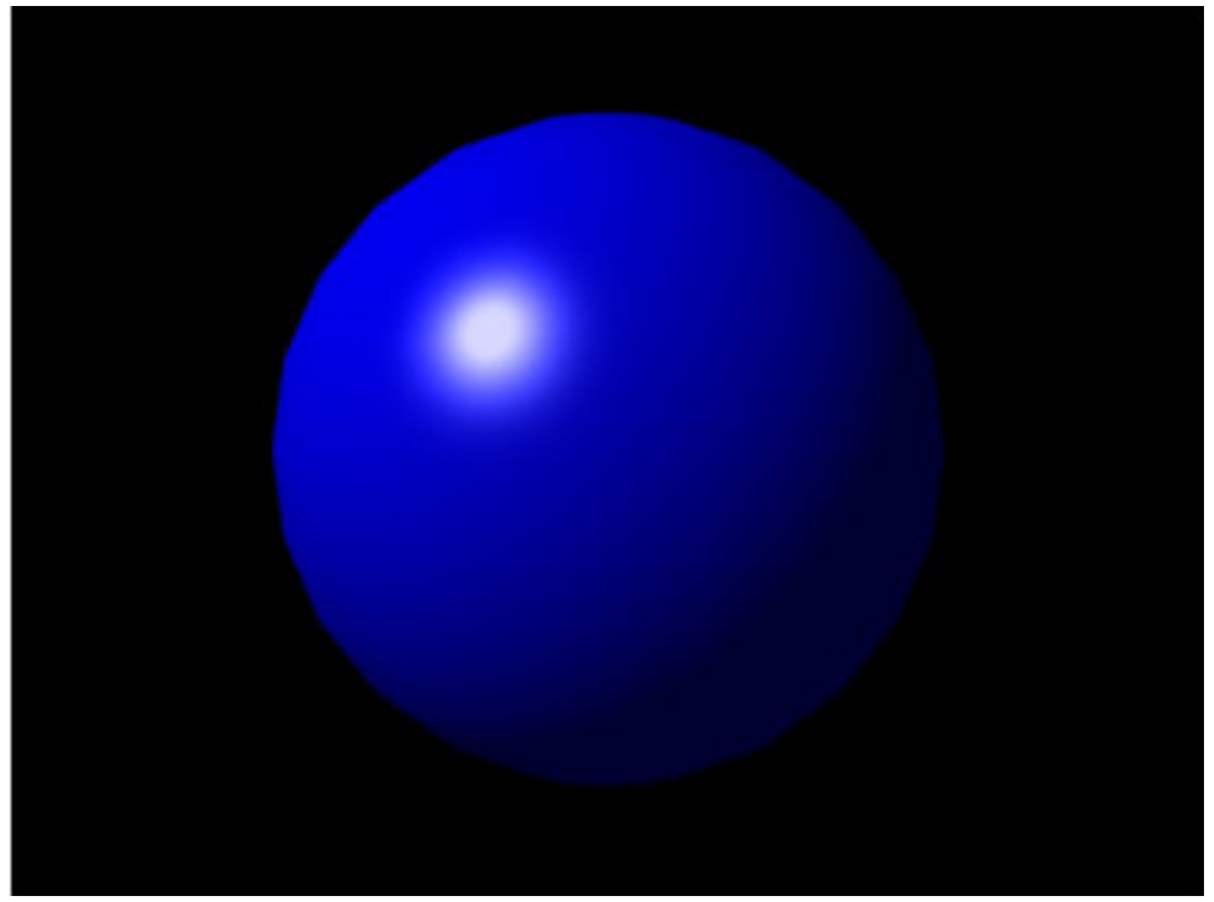


Visual Computing: Interactive Computer Graphics and Vision

Rendering Techniques: Surfaces

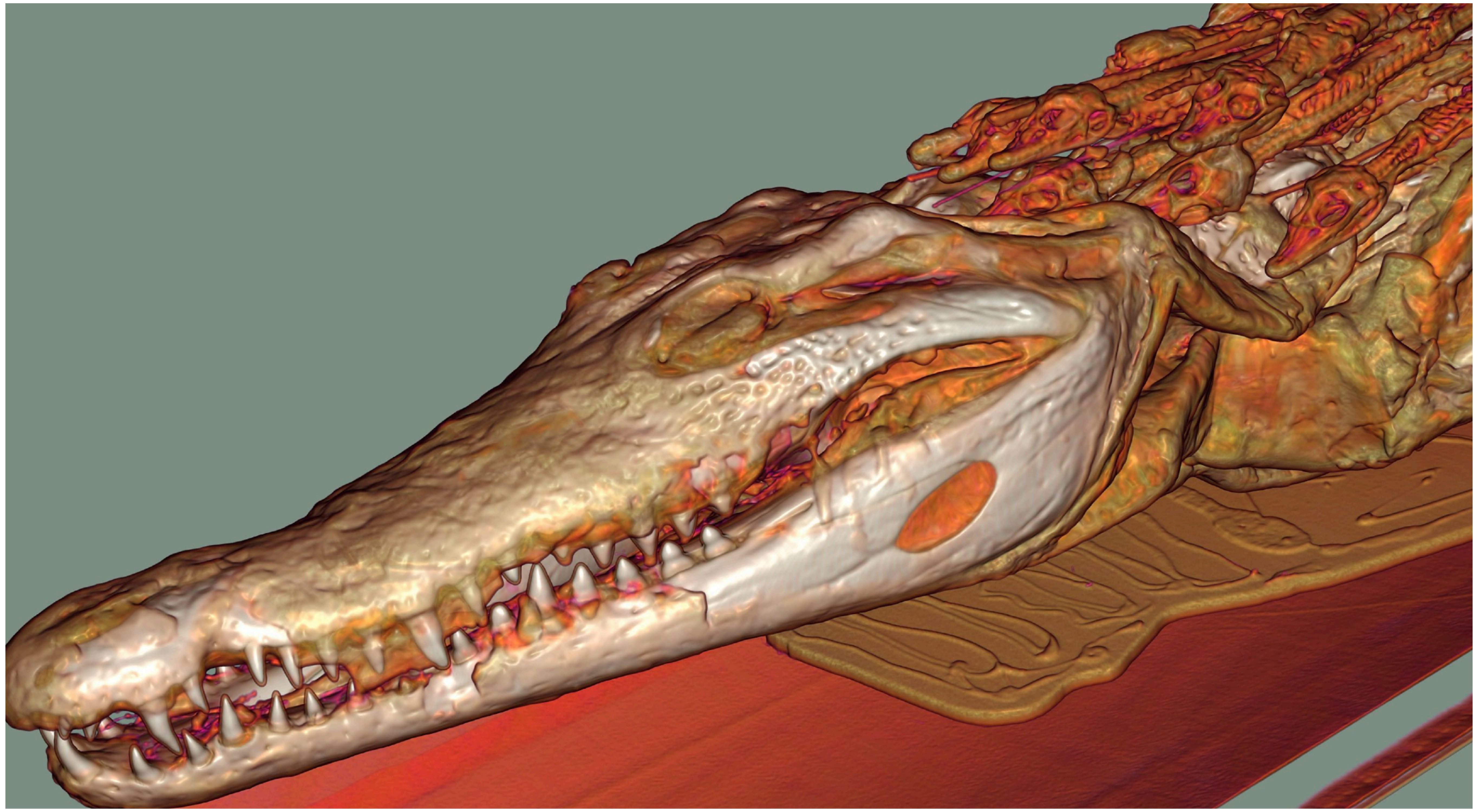
- How we draw Polygonal Meshes:
  - Wireframe: Show only the edges. Good for seeing structure
  - Flat Shading: Each polygon gets one solid color based on its angle to the light. "Blocky" look
  - Smooth Shading (Gouraud/Phong):
    - Calculates lighting at each vertex and blends it across the face
    - Creates illusion of a smooth, curved surface
  - Texturing: "Wallpapering" the mesh with a 2D image to add detail (like brick, wood, or skin)



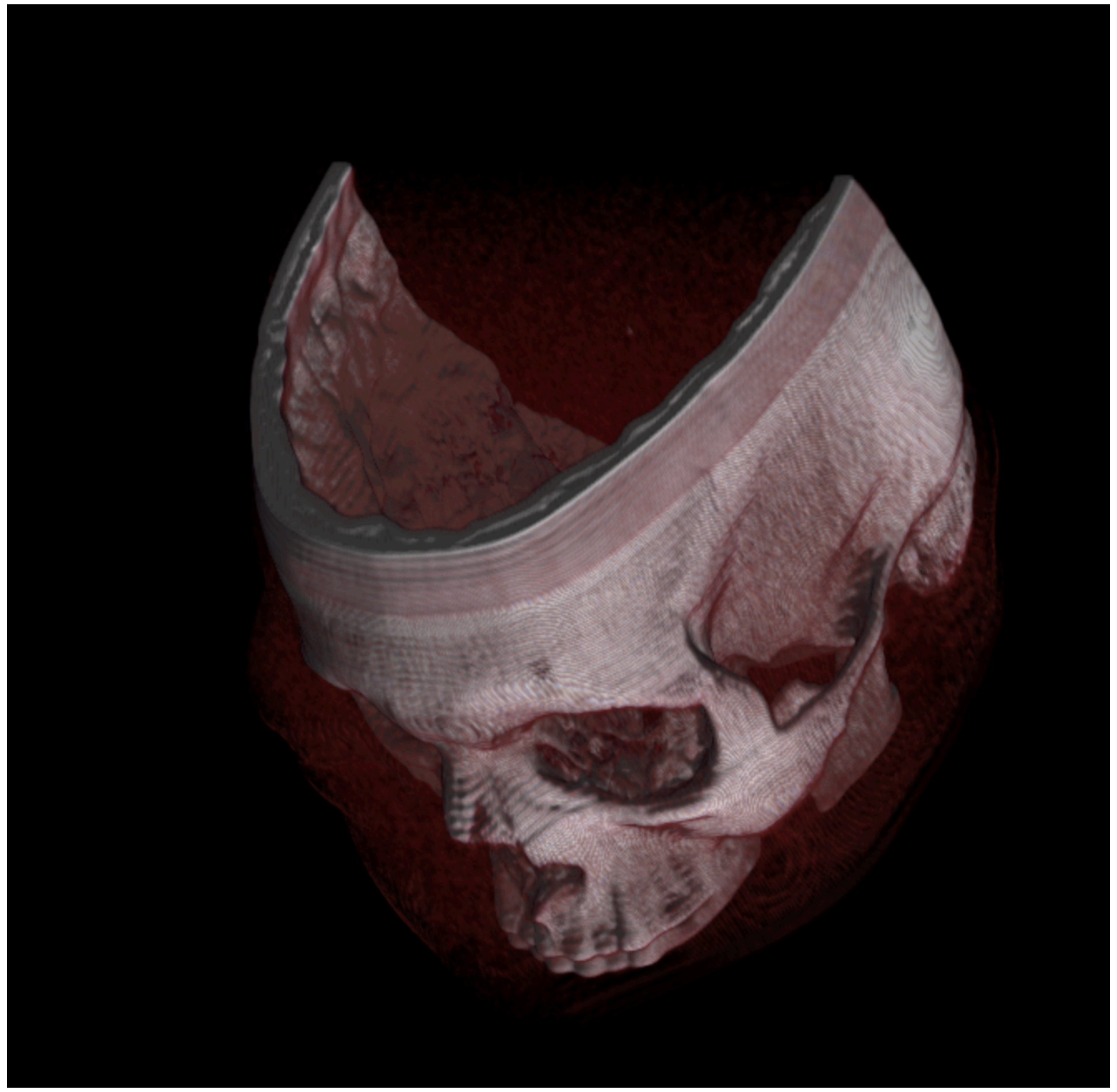


Visual Computing: Interactive Computer Graphics and Vision

Rendering Techniques: Volume Data



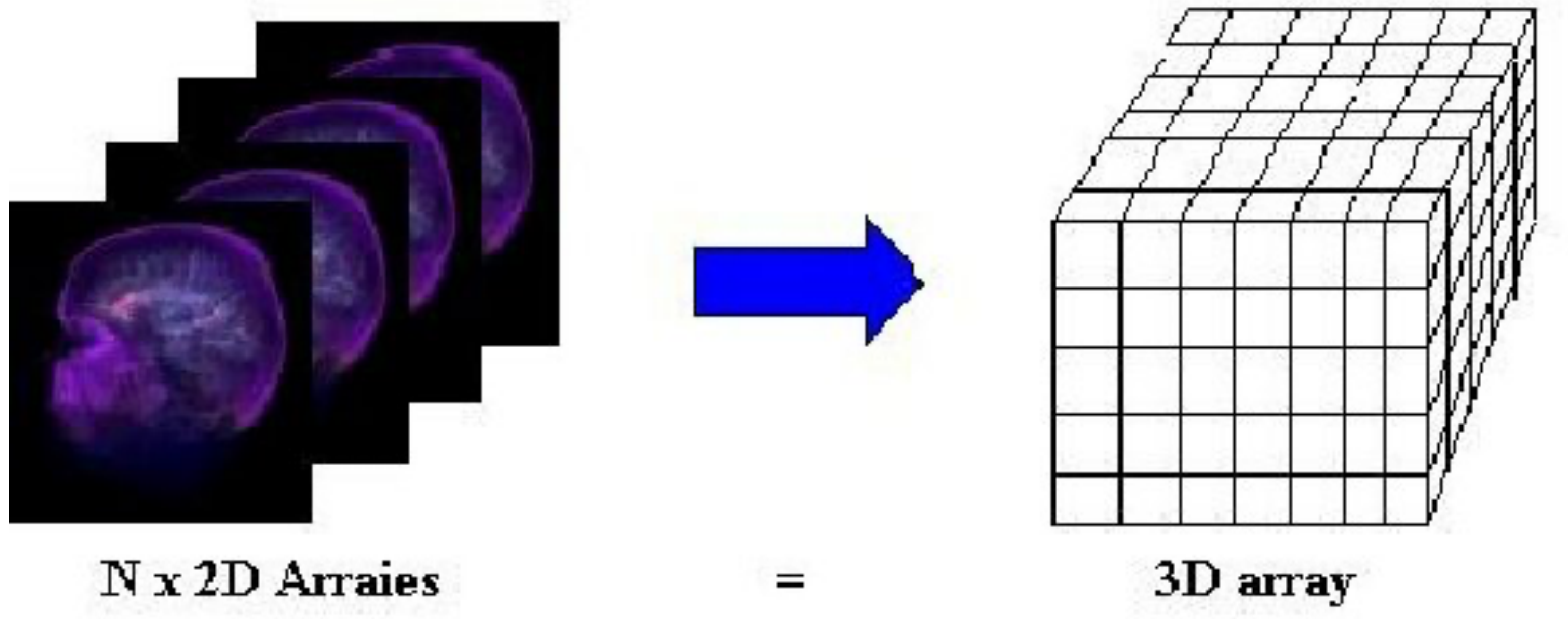
The crocodile mummy provided by the Phoebe A. Hearst Museum of Anthropology, UC Berkeley. CT data was acquired by Dr. Rebecca Fahrig, Department of Radiology, Stanford University, using a Siemens SOMATOM Definition, Siemens Healthcare. The image was rendered by High Definition Volume Rendering® engine (Fovia, Inc).



Sjschen at English Wikipedia.

Volume Data

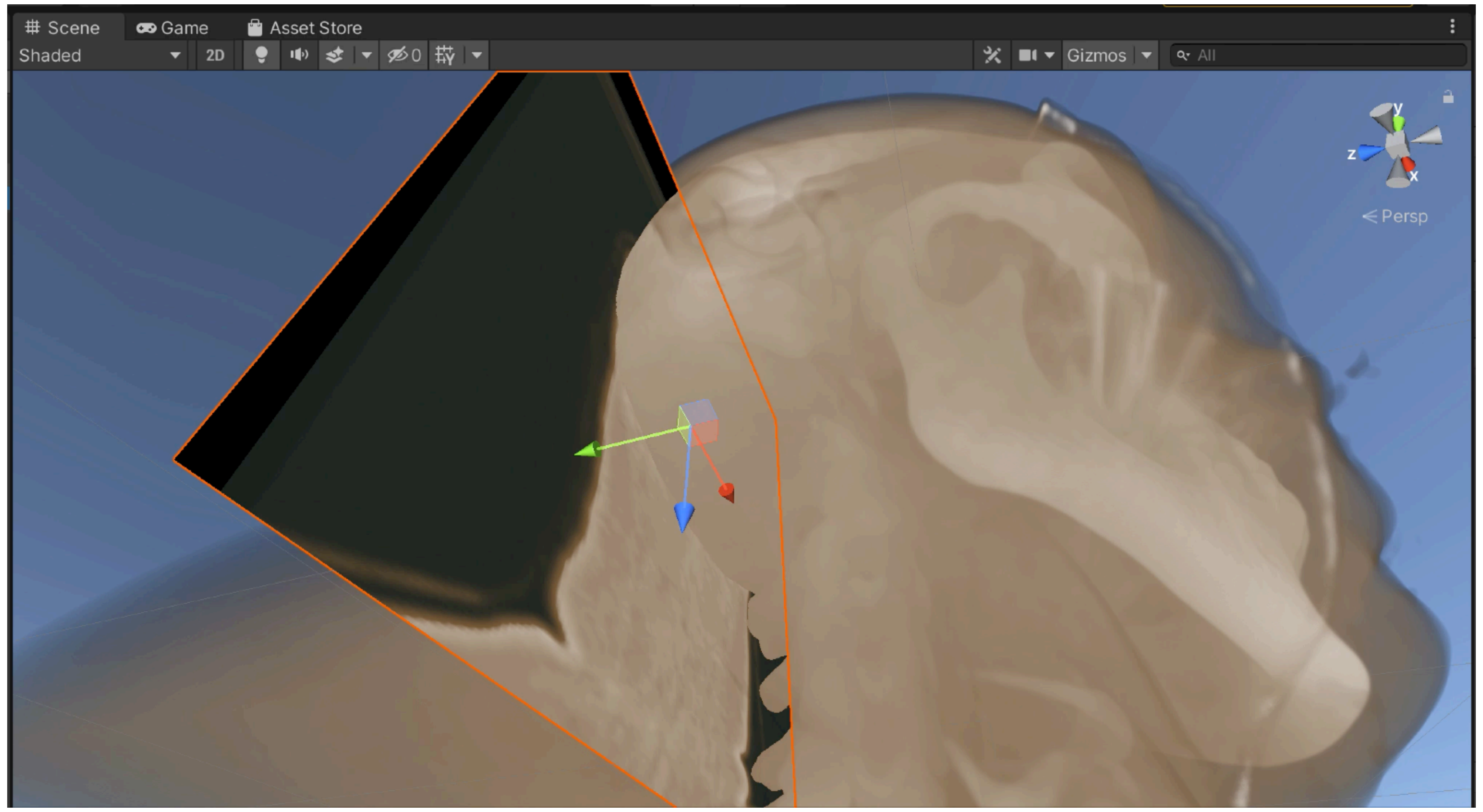
- Volume data from
  - Simulations (e.g. fluid dynamics)
  - Geosciences
  - Medical Imaging (CT and MRI Data)
  - Material Science
- Input can be:
  - Image sequence
  - 3D array
  - Single color channel vs color

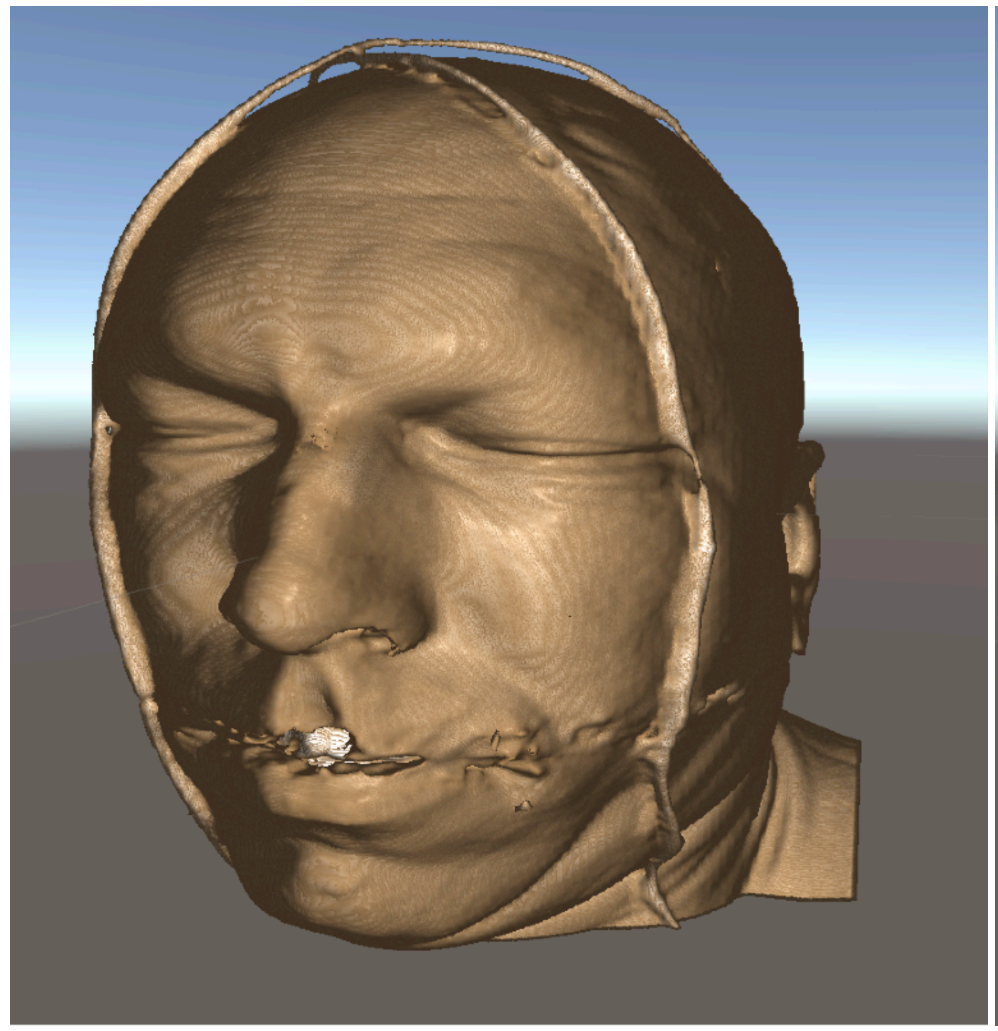


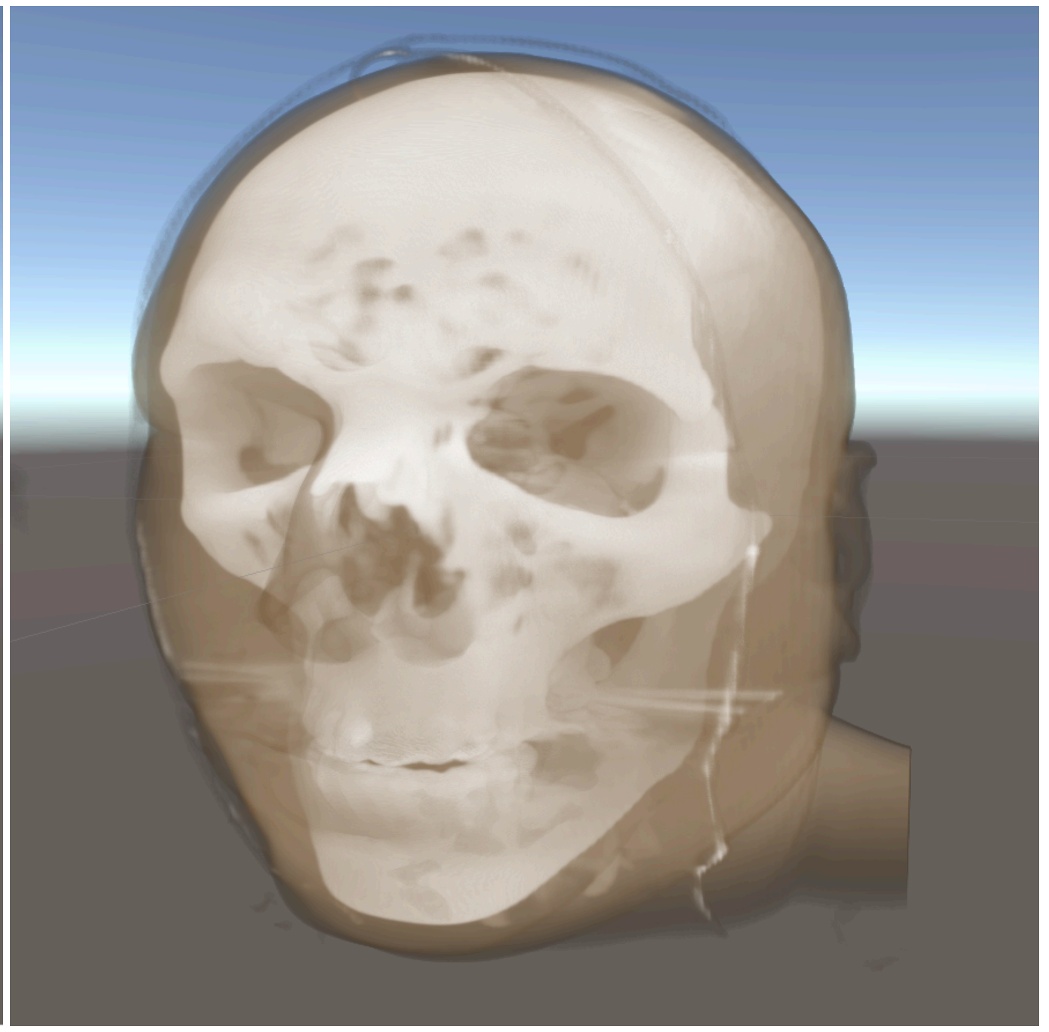
[Zhou and Toennis State of The Art for Volume Rendering]

Volume Rendering Techniques

- Slicing: showing single slices cutting through the data
- Indirect Volume Rendering: Using isosurfaces based on user specifications
- Direct Volume Rendering: directly rendering the volume data for instance by using raytracing techniques

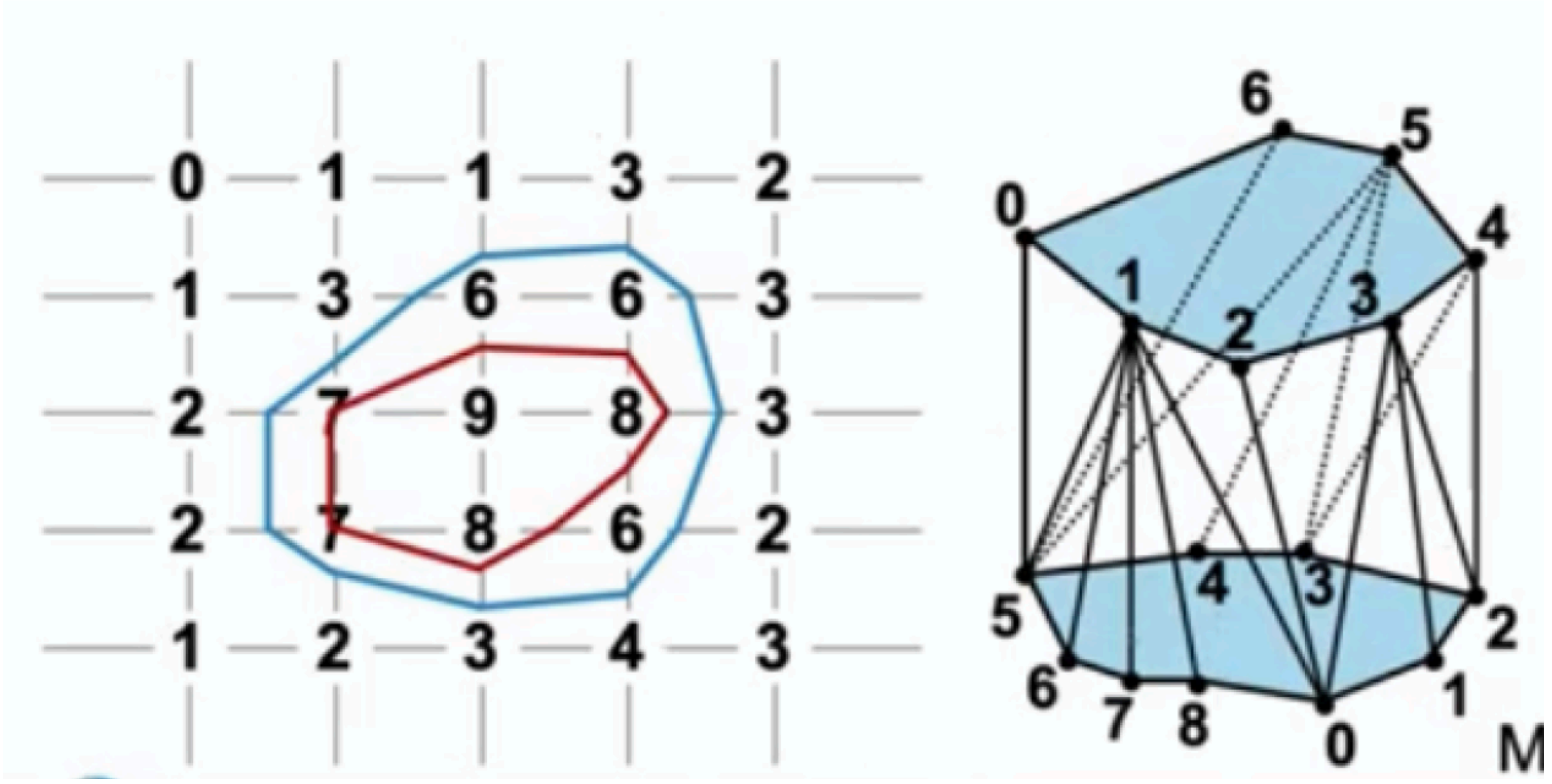






Indirect Volume Rendering

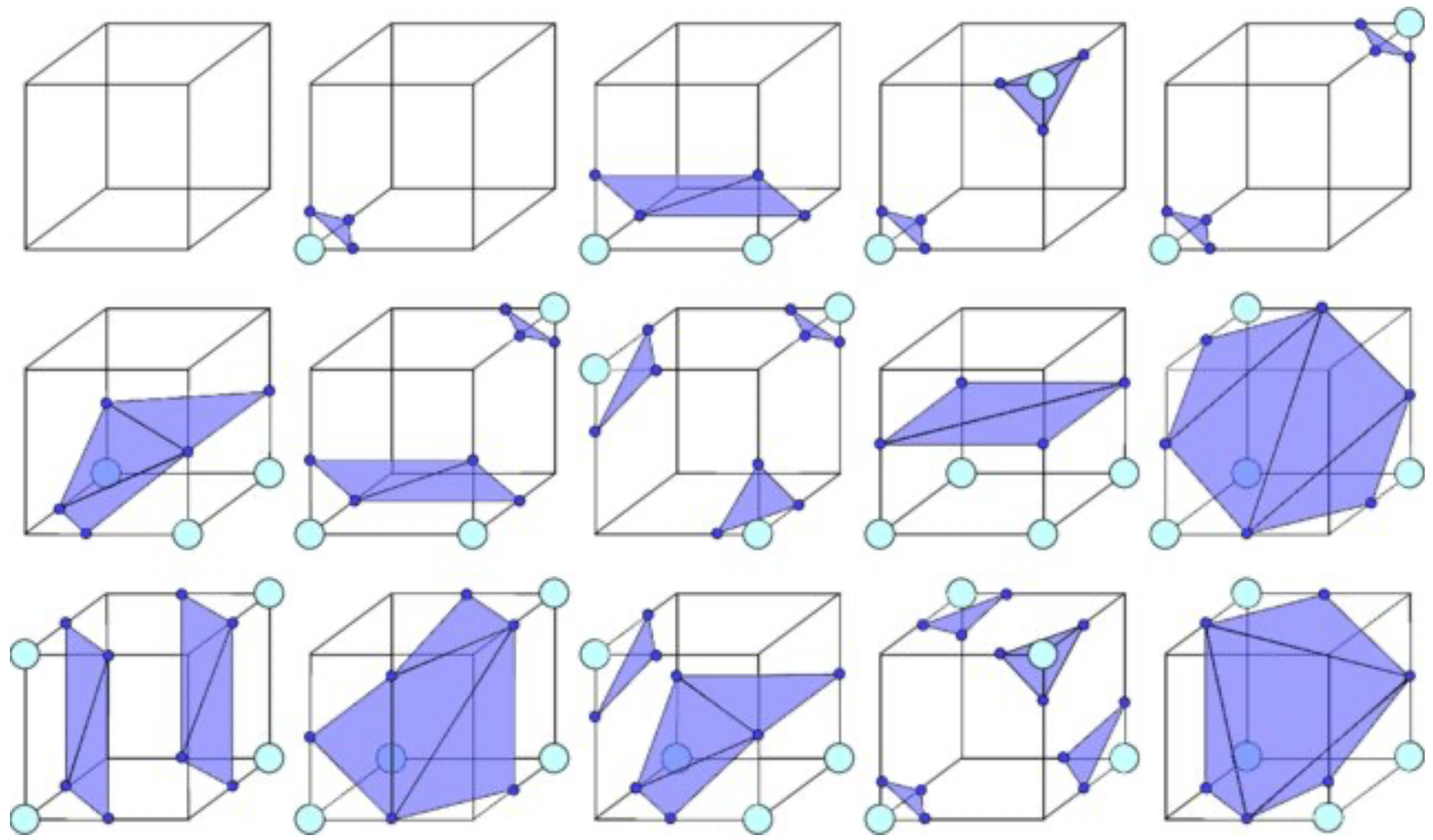
- Using contour lines (similar to contour lines in 2D)
- Extended to 3D, for each slice in the volume data extract contour lines
- Connect vertices of contours in adjacent slices
- Challenges: Topological changes, interface to select contour thresholds



Preim 2020

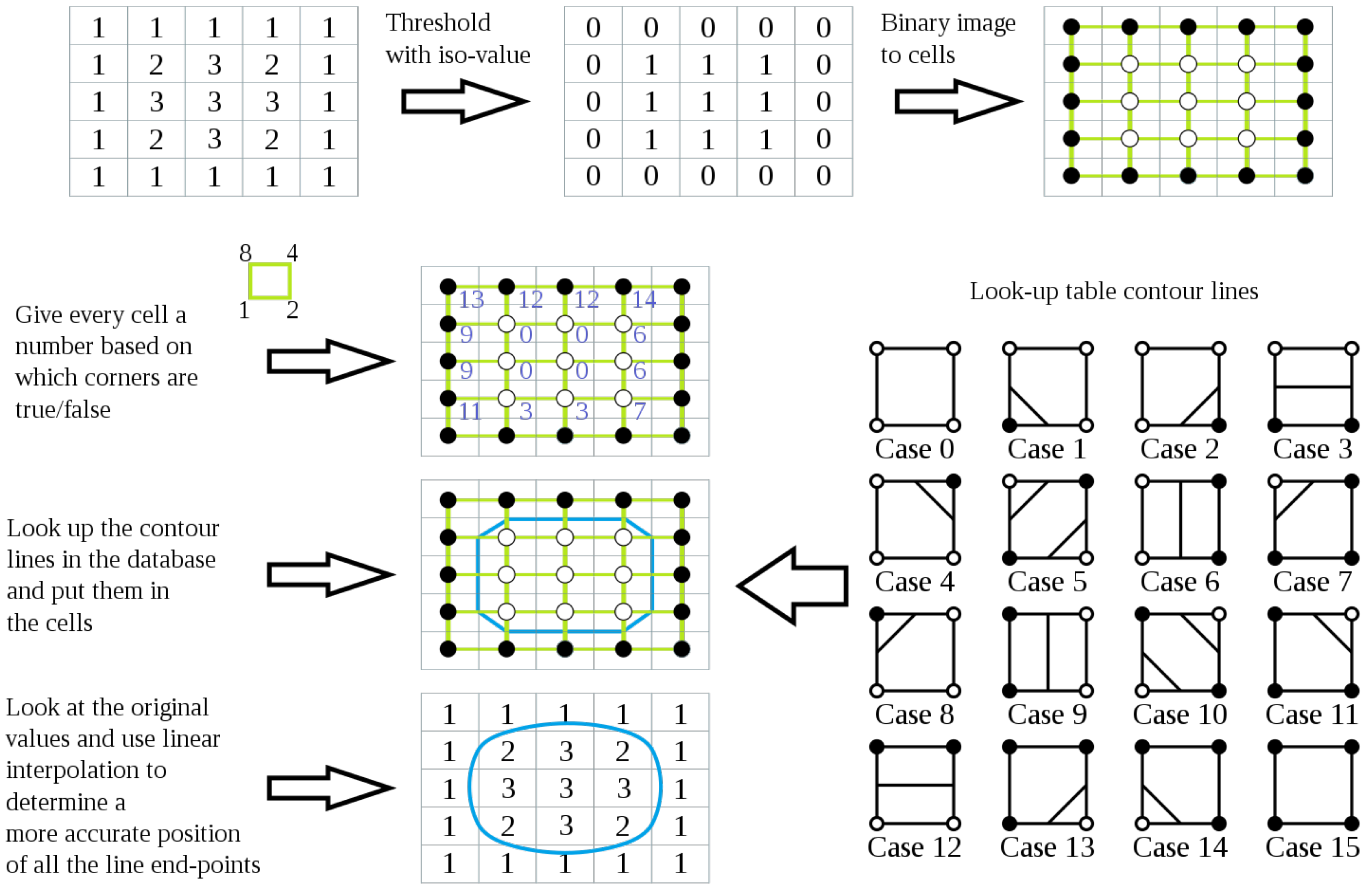
Indirect Volume Rendering: Marching Cubes

- Idea:
  - Considering single cells and extracting isolines and isosurfaces
  - Limited number of possible configurations
  - Construction of case table



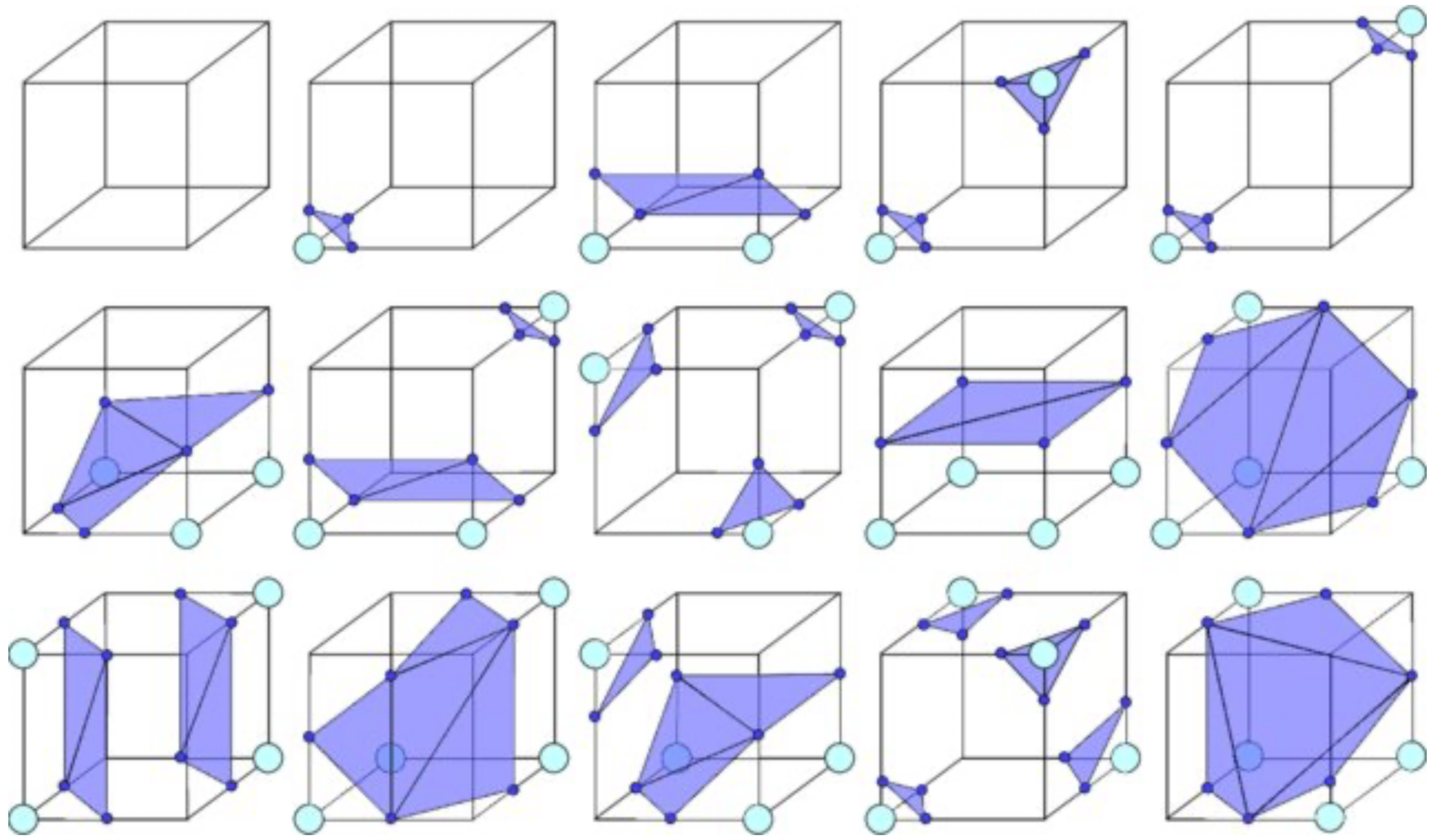
Zellmann, Interactive High Performance Volume Rendering

Recap: Marching Squares



Marching Cubes

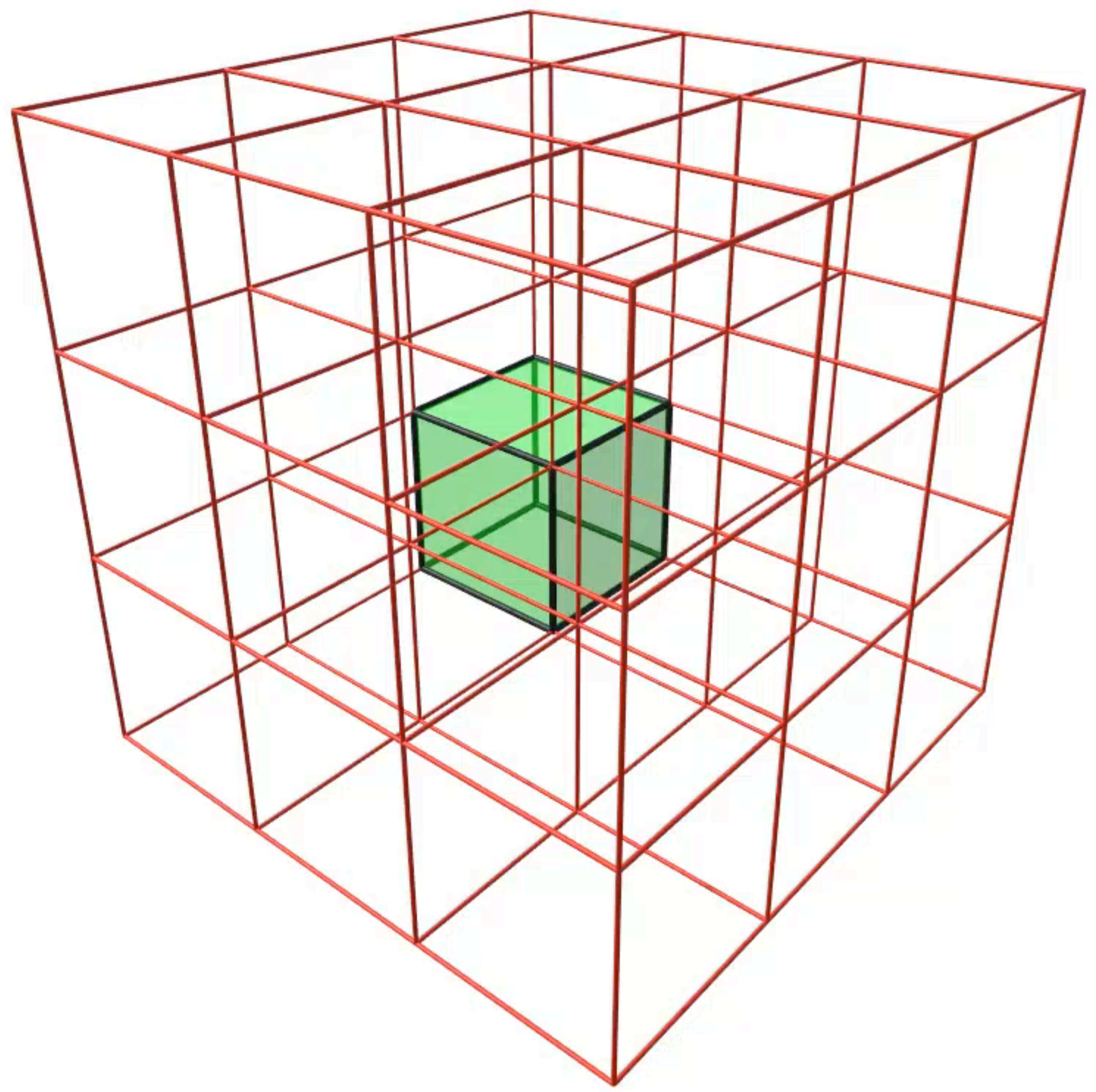
```
For each cell {
   For each vertex{
      ComputeState(above or below is-value)
   }
   Compute index for the cell
   Compute intersections using linear interpolation
   Connect intersections and create triangles
   Compute normals
}
```



Zellmann, Interactive High Performance Volume Rendering

Marching Cubes

Marching cubes

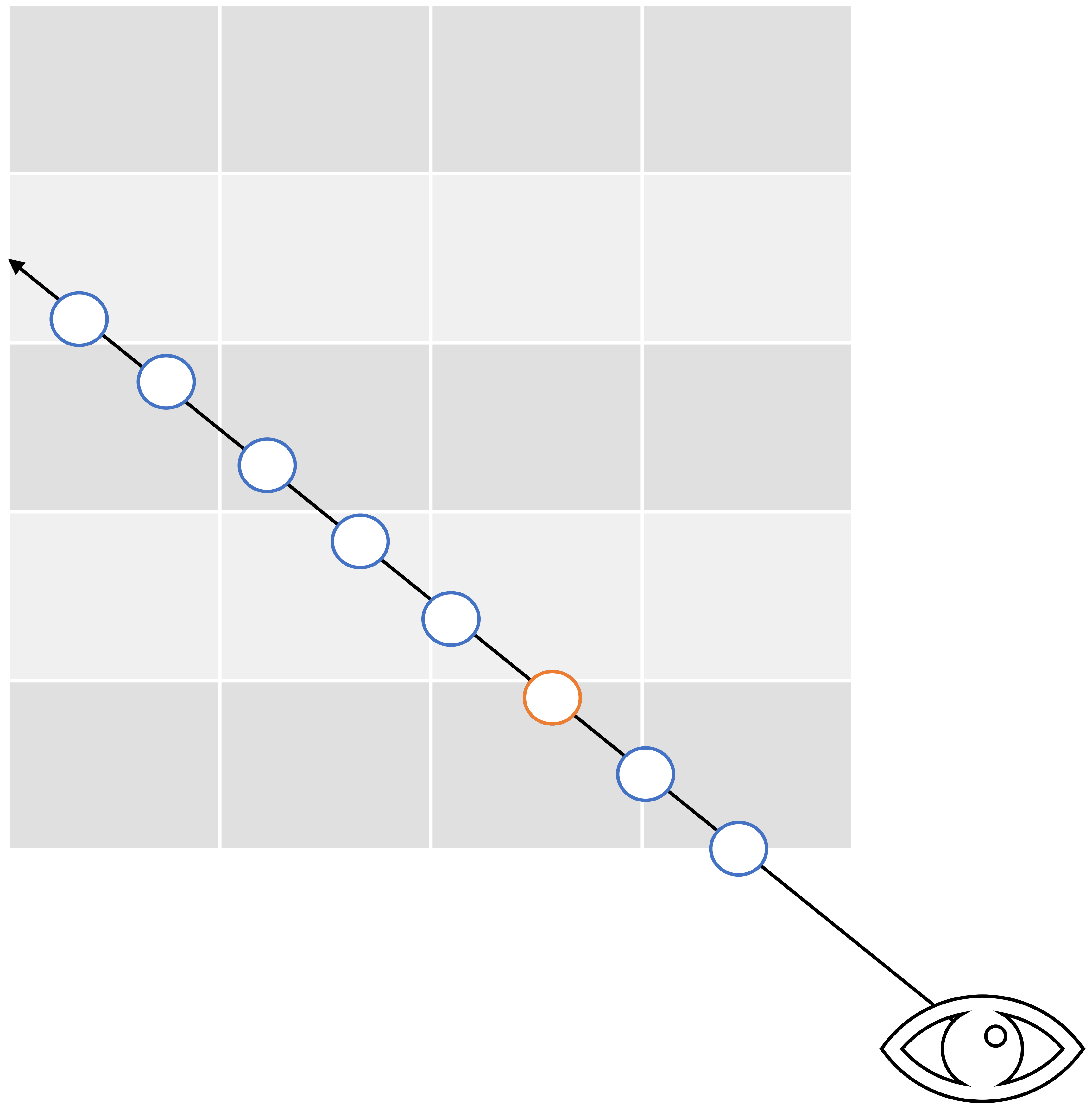


Direct Volume Rendering

- Image-based
  - Raytracing: for each pixel trace ray into volume data
  - Grey or color values computed by the data from each voxel
  - Uses weighting from transparency values
- Object-based approaches
  - Uses each voxel to compute color in output image
- Texture-based, uses texture mapping on GPU

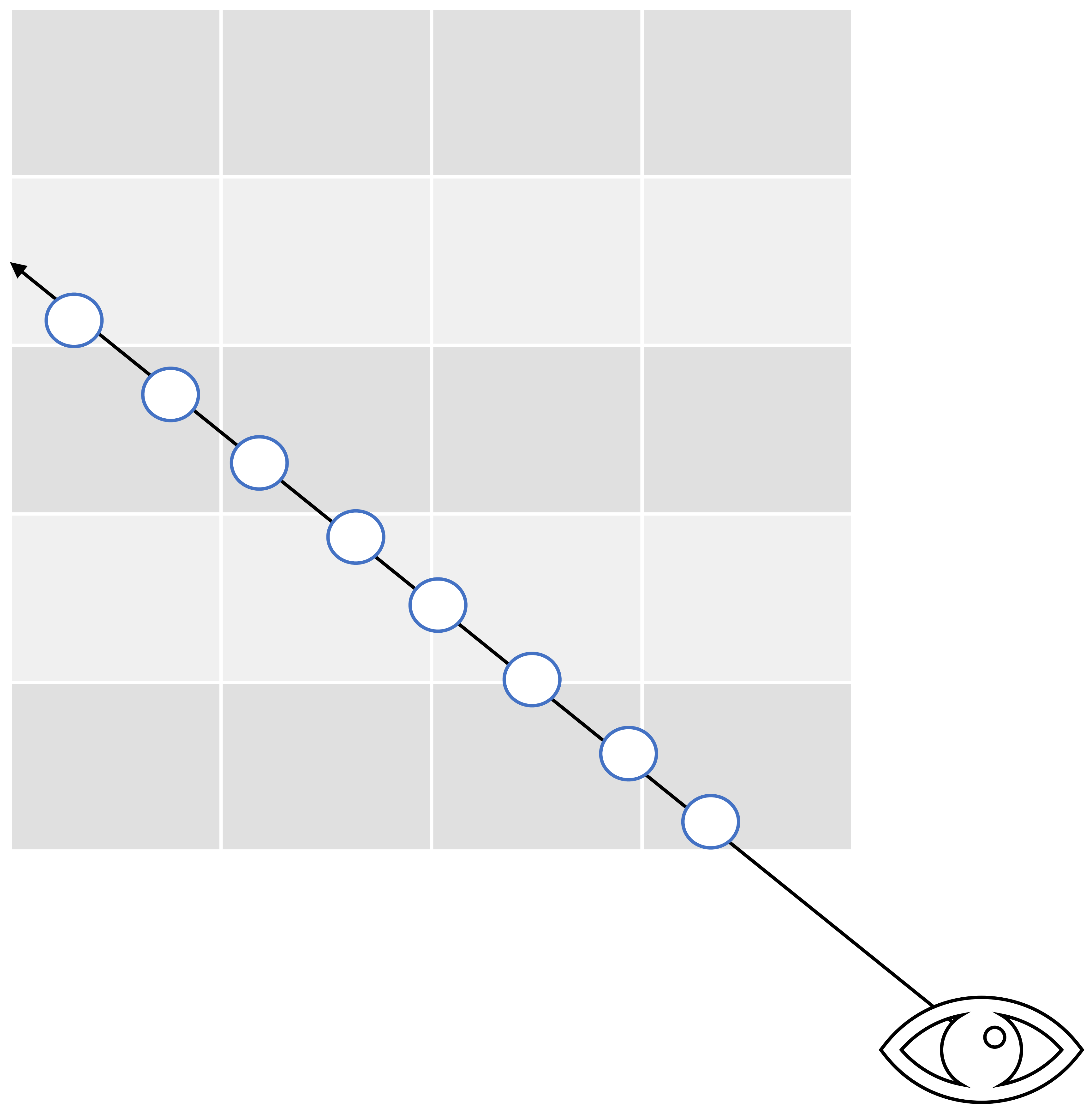
Image-Based

- Raytracing
  - Cast ray into scene and take first hit
- Raymarching
  - Cast ray and sample along the ray (divide ray into N sample points and combine the result)
  - Simple approach is to use the highest value in along the ray (Maximum Intensity Projection)



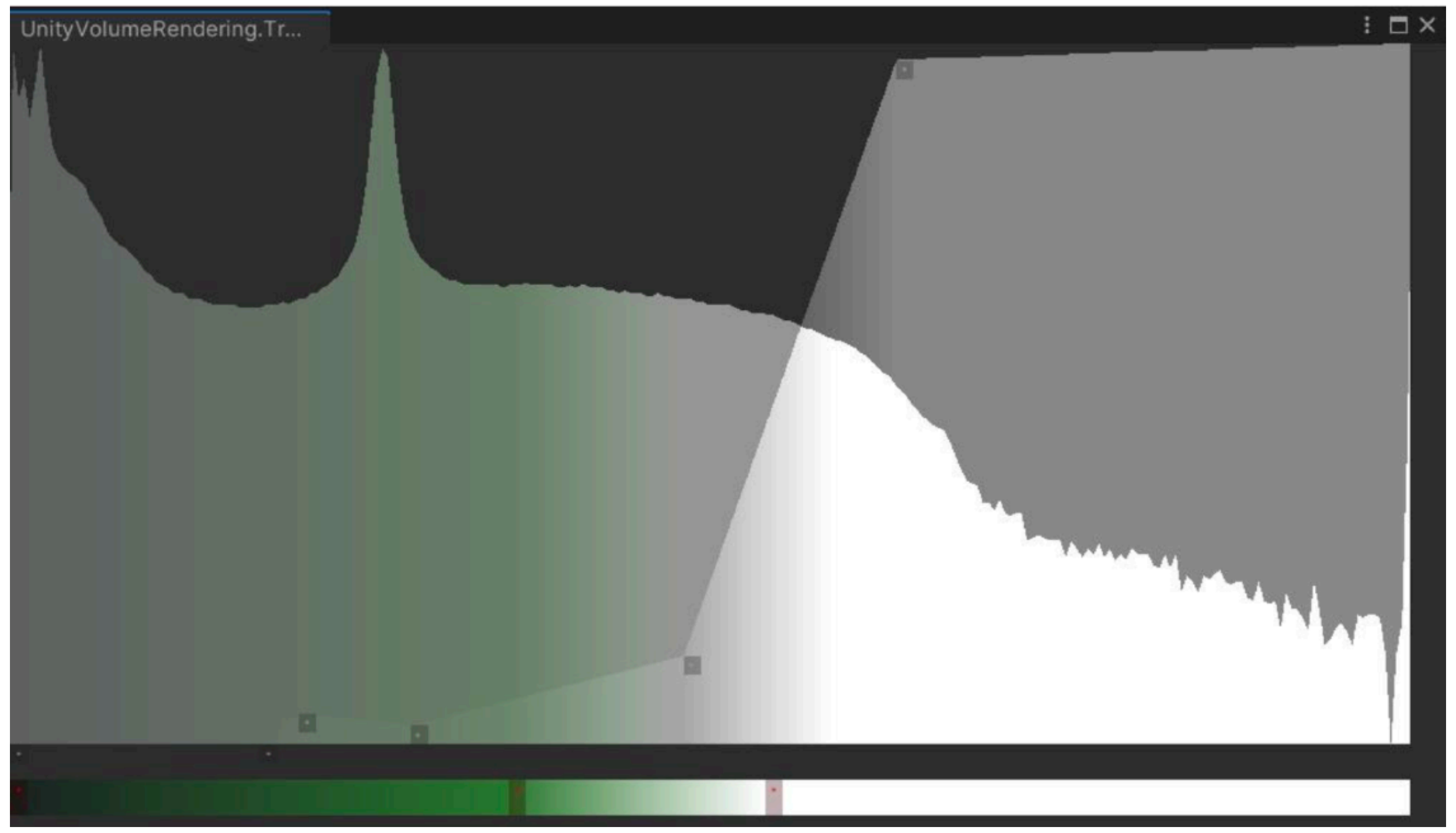
Direct Volume Rendering

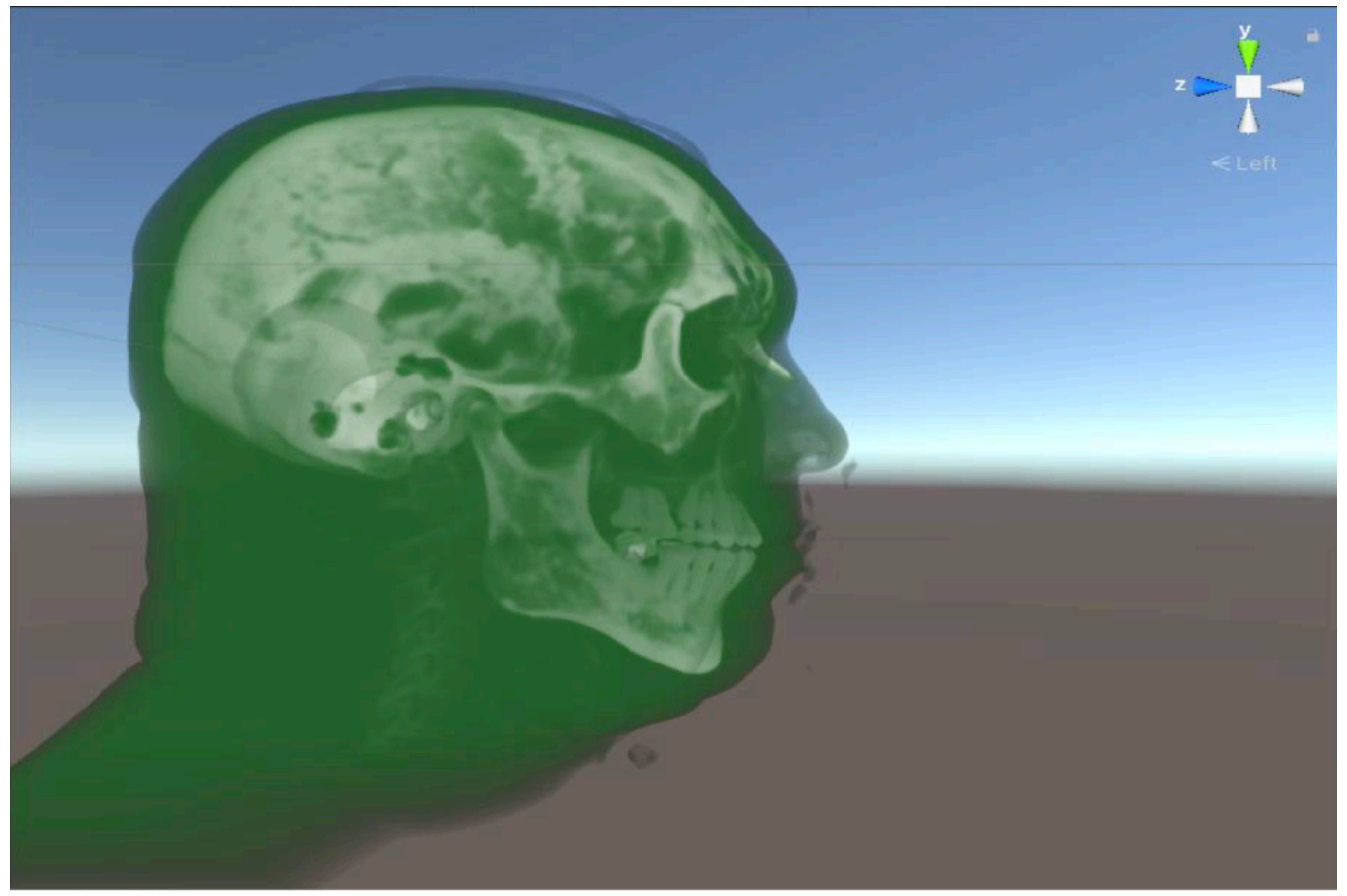
- Compositing Approach
  - Combine current voxel color with the accumulated color value from the previous steps
  - Linearly interpolate the RGB values using alpha
  - Compute new alpha by using previously computed alpha (weighted)



Transfer Functions

- Define visual result (which color, which transparency)
- Basic idea:
  - Voxels of different elements have different density levels
  - e.g bones have high density, skin has low density
- 1D transfer functions:
  - Map range of values to color and opacity
  - Often implemented as 1D texture lookup tables (x-axis = density, RGBA defines color and opacity)





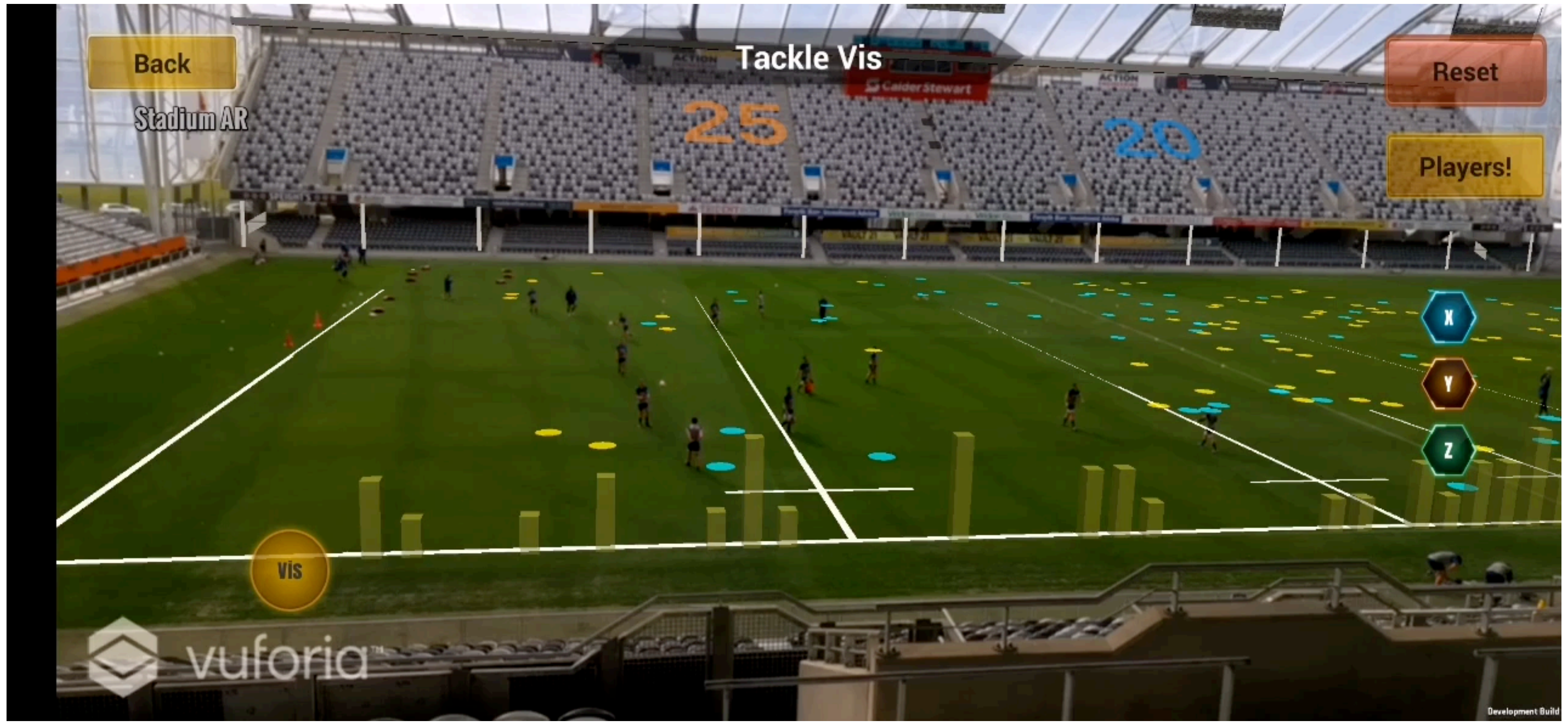
Matias Lavik: https://matiaslavik.wordpress.com/about/

Display: Visualisation in AR

Situated vs Non-Situated Visualisation in AR

Situated Visualisation

- Situated visualisation as a “visualisation that is related to and displayed in its environment.” (White and Feiner)
- Three key characteristics that a situated visualisation should have:
  - (1) The data in the visualisation is related to the physical context
  - (2) Visualisation is based on the relevance of the data to the physical context
  - (3) the display and the presentation of the visualisation lie in the physical context



W.H. Lo, S. Zollmann and H. Regenbrecht
Stats on-site — Sports spectator experience through situated visualizations

Situated Visualisation

Textual labels for architectural sights

Image: Raphael Grasset

Pollution levels on the street

Image: Sean White and Steve Feiner

Non-Situated Visualisation

Inspecting an AR visualisation of a three-dimensional mathematical model is not a situated visualisation, because no semantically significant real-world object is referred to.

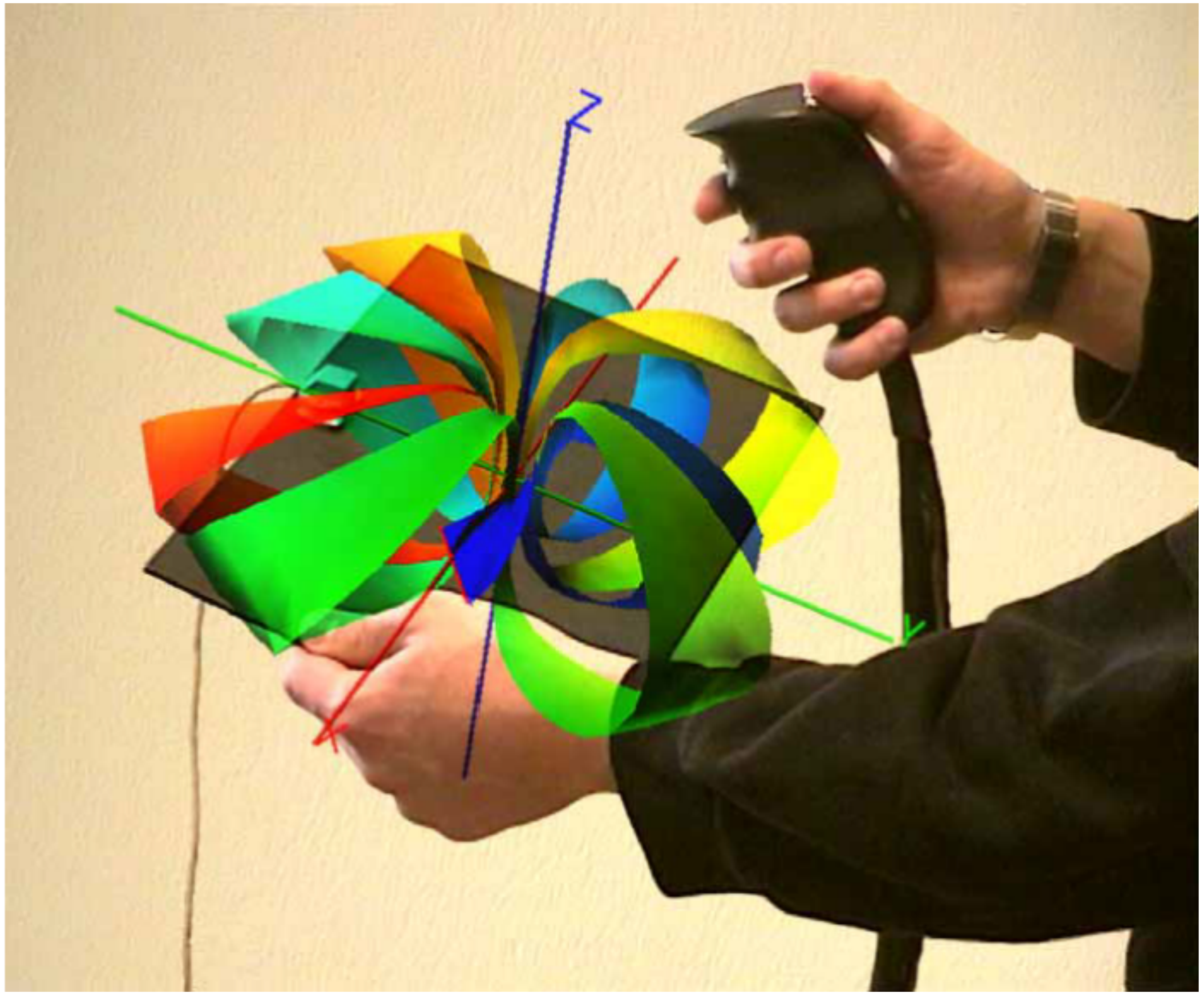
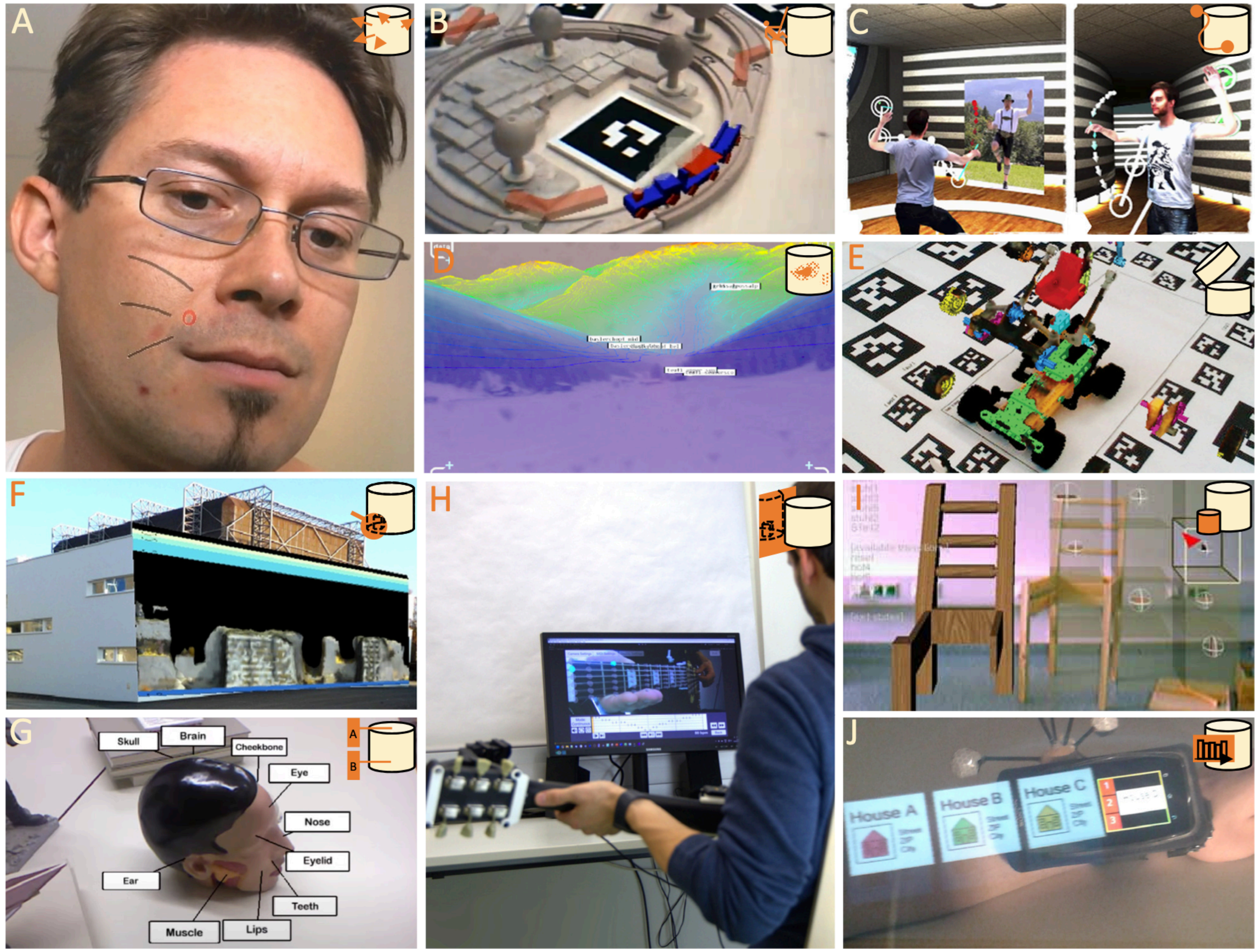


Image: Anton Fuhrmann

Design Patterns for Situated Visualisation

Glyph		Magic Lens	
Ghost		Label	
Trajectory		Mirror	
Decal		Proxy	
Morph		Panel	

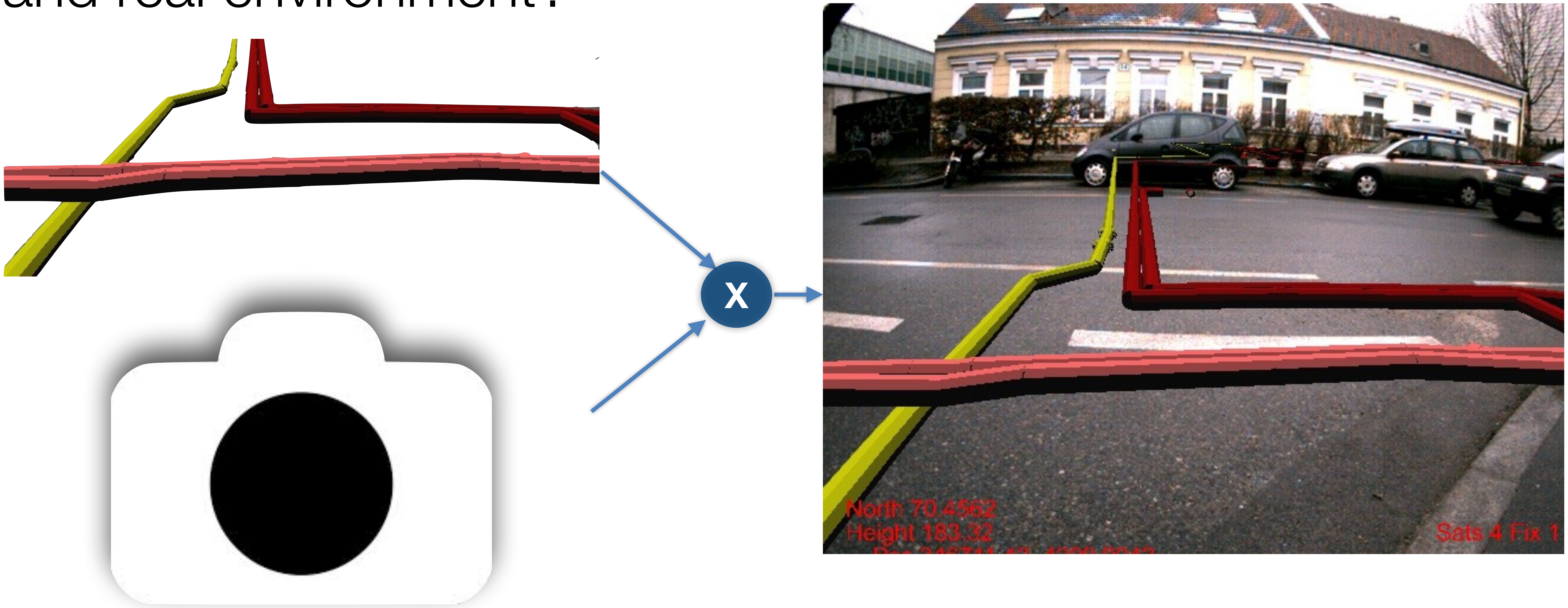


Lee et al. Design Patterns for Situated Visualization in Augmented Reality, 2023

Visual Coherence

Visual Coherence in AR

- How to combine virtual data and real environment?

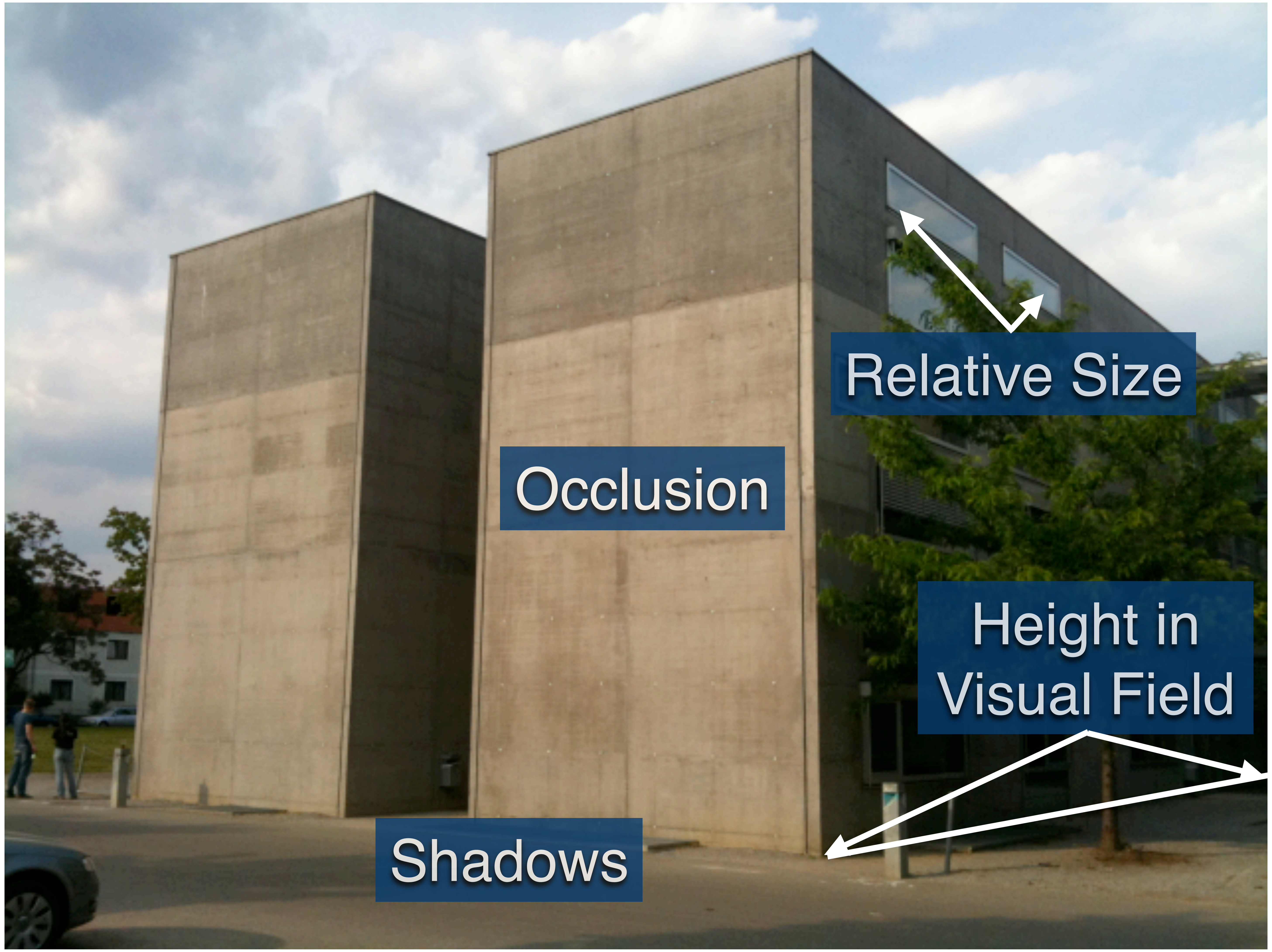


Visual Coherence in AR

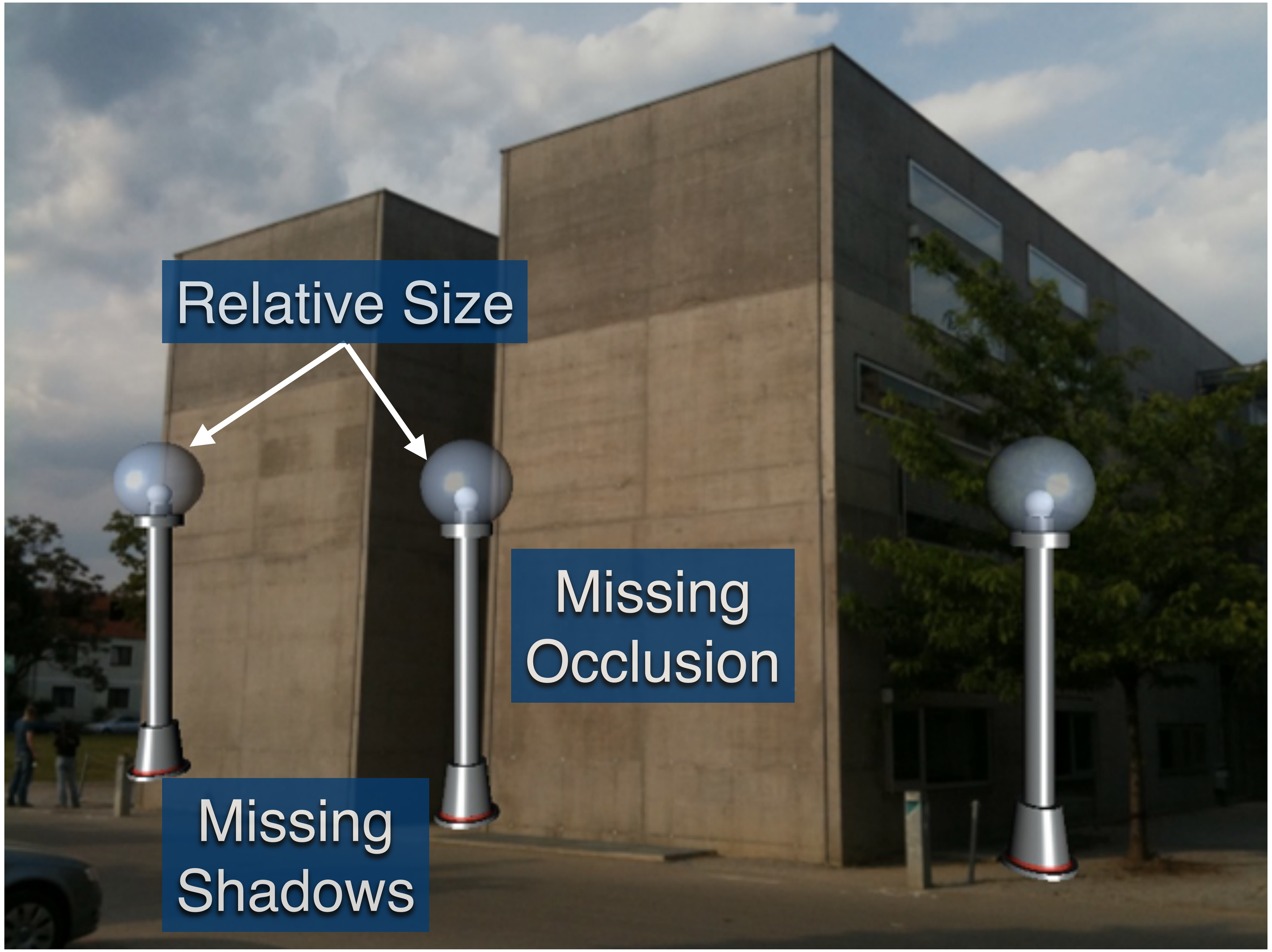
- How to achieve a realistic and coherent integration between virtual content and real environment?

Incoherent Scene Integration

Depth Cues

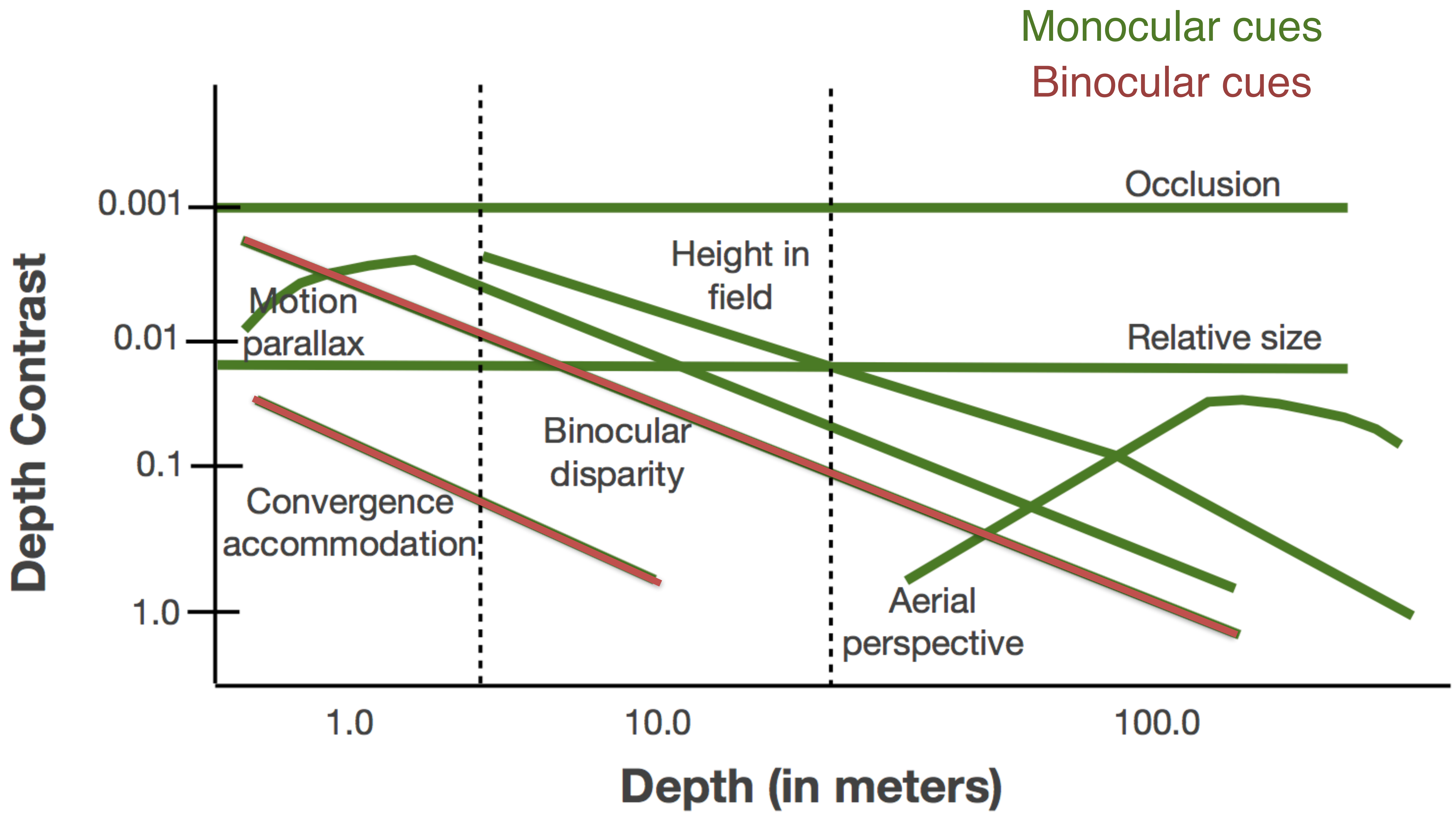


Missing Depth Cues in AR



Depth Cues

- Occlusion
- Binocular Disparity
- Motion Parallax
- Height in Visual Field
- Relative Size
- Relative Density
- Convergence
- Accommodation
- Aerial Perspective



Cutting, 97

Depth Cues

- Occlusion
- Binocular Disparity
- Motion Parallax
- Height in Visual Field
- Relative Size
- Relative Density
- Convergence
- Accommodation
- Aerial Perspective

Depth Cues

Cutting, 97

- Occlusion
- Binocular Disparity
- Motion Parallax
- Height in Visual Field
- Relative Size
- Relative Density
- Convergence
- Accommodation
- Aerial Perspective

Source of Information	Assumptions	Implied Measurement Scale
All	Linearity of light rays, Luminance or textual contrast, Rigidity of objects	-
Occlusion	Opacity of objects, Helmholtz's rule, or good continuation of the occluding object's contour	Ordinal.
Height in the visual field	Opacity of objects and of the ground plane. Gravity, or the bases of objects are on the ground plane. The eye is above the surface of support. The surface of support is roughly planar. (In hilly terrain, use may be restricted to the surface directly beneath the line of sight to the horizon.)	Ordinal, perhaps occasionally better. In [24], Cutting and Vishton state an absolute depth measurement.
Relative size	Similarly shaped objects have similar physical size. Objects are not too close. Plurality of objects in sight. (Not familiarity with the objects, which denotes "familiar size").	Unanchored ratio possible, but probably ordinal.
Relative density	Similarly shaped objects or textures have uniform spatial distribution. Plurality of objects or textures in the field of view.	Probably ordinal at best.
Aerial perspective	The medium is not completely transparent. The density of the medium is roughly uniform.	Probably ordinal.
Binocular disparities	The distance between eyes. The current state of vergence. Unambiguous correspondences.	Absolute, but perhaps only ordinal
Accommodation	Complex spatial frequency distribution.	Ordinal at best.
Convergence	The distance between eyes. The current state.	Ordinal.
Motion perspective	A rigid environment. A spatial anchor of zero motion (horizon or fixed object).	Absolute, unanchored ratio. Perhaps only ordinal.

Incoherent Scene Integration

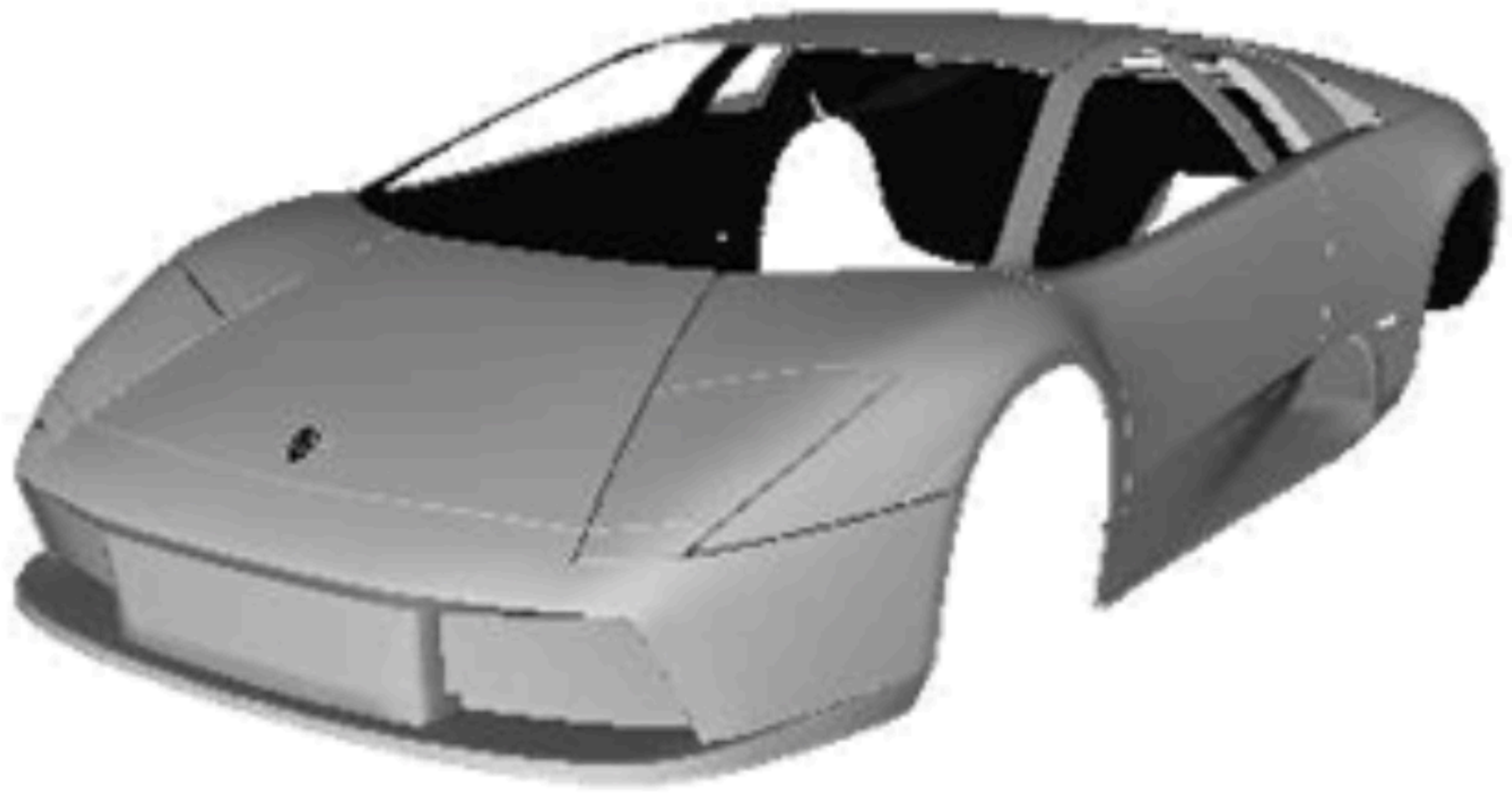
Addressing Occlusions

Zollmann et al. 2012, Dense depth maps from sparse models and image coherence for augmented reality, VRST 2012

Occlusion Management: Using a Phantom Geometry

- Render registered virtual representations of real objects
- Step-by-step:

1. Draw Video
2. Use virtual representations of real scene (Phantoms) to test what is in front and what is occluded
3. Draw virtual objects



Kalkofen et al: Phantom Rendering

Occlusion Management: Using a Phantom Geometry

- Render registered virtual representations of real objects
- Step-by-step:

  1. Draw Video

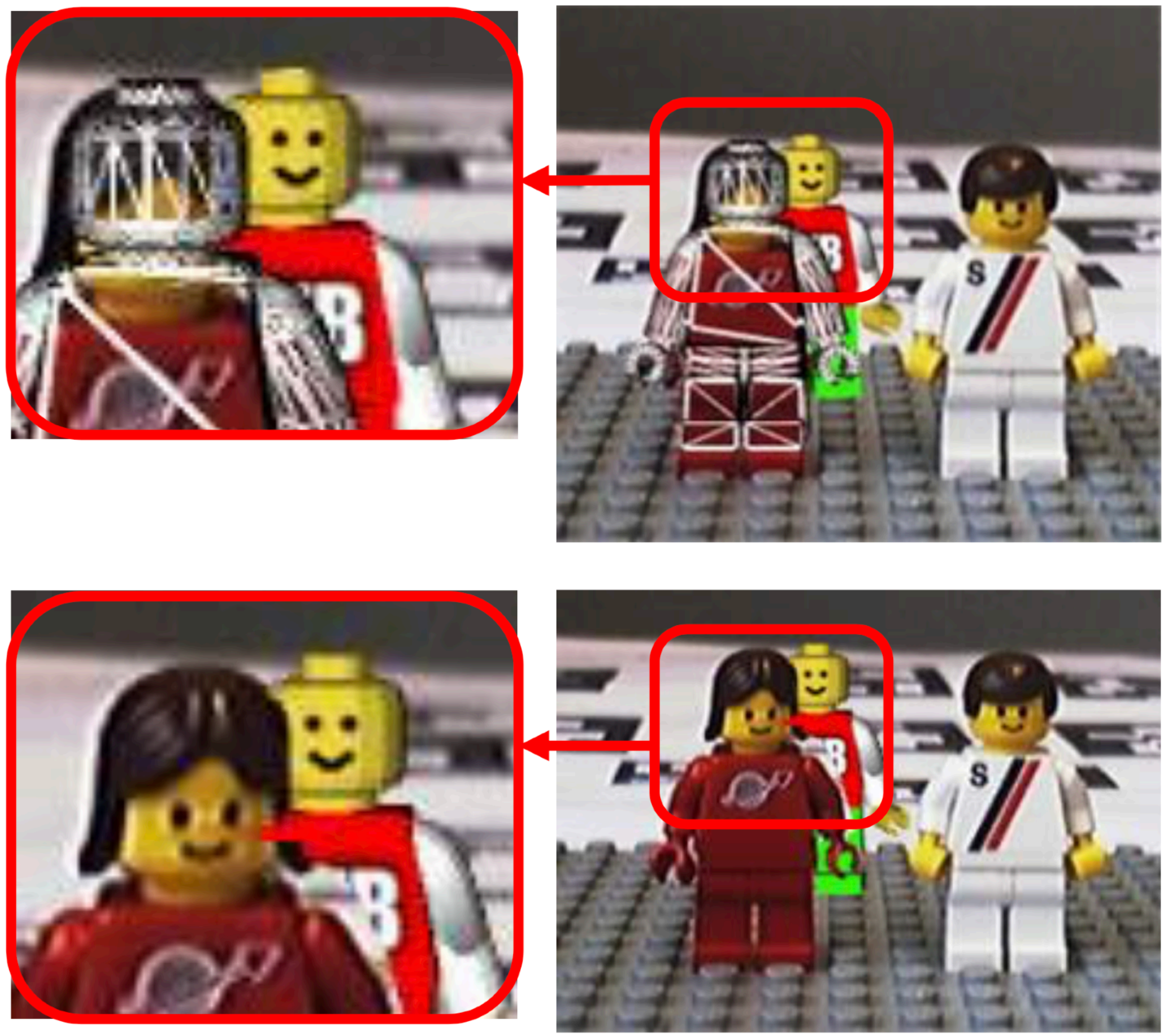
  2. Use virtual representations of real scene (Phantoms) to test what is in front and what is occluded

  3. Draw virtual objects

Fiala: Dark Matter Method for Correct Augmented Reality Occlusion Relationships

Occlusion Management: Challenges with Phantom Geometry

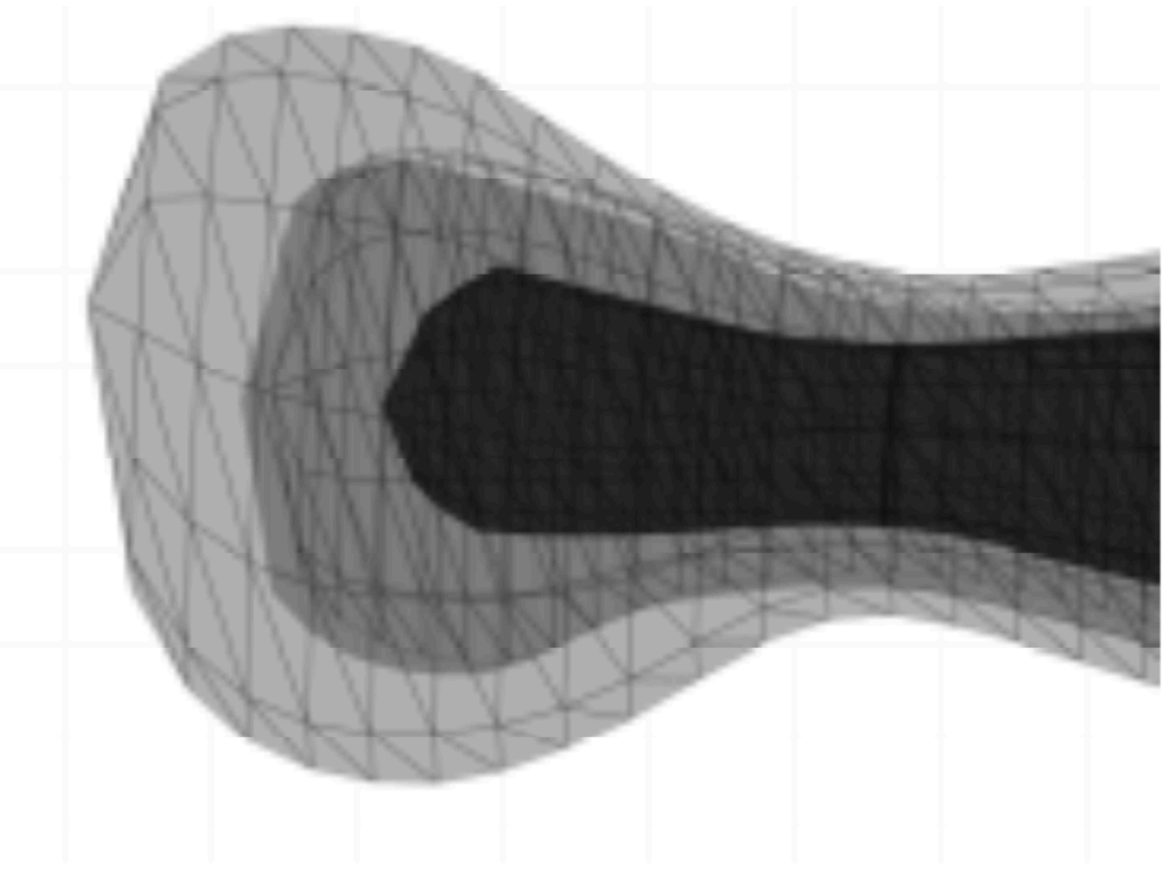
- Problems
  - Need accurate model
  - Need accurate tracking data
  - Need accurate registration



Kalkofen et al.

Occlusion Management: Probabilistic Occlusion Handling

- Soft transition between occluding and hidden objects
- Compensate for tracking and registration error
- By reducing the occluder's transparency depending on the probability of occlusion



Fuhrman et al.: Occlusion in Collaborative Augmented Environments

The end!