Shape from Silhouettes
Class 13

Some of the figures and slides are adapted from S. Sinha, J.S. Franco, J. Matusik's presentations, and referenced papers.

ETH

Outline

- Silhouettes
  - basic concepts
  - extract silhouettes
  - fundamentals about using silhouettes
  - reconstruct shapes from silhouettes
  - use uncertain silhouettes

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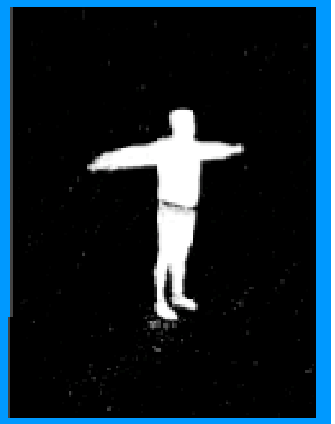

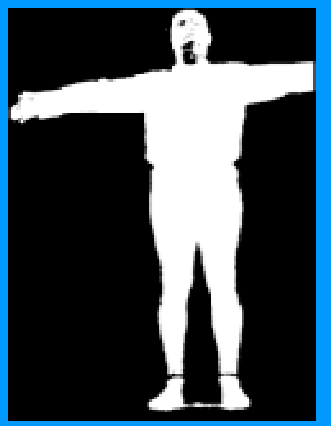

Silhouettes of objects of interest

- Silhouettes are the regions where objects of interest project in images
- Silhouettes can generally be obtained using low level information (fast)
- They give information about the global shape of scene objects

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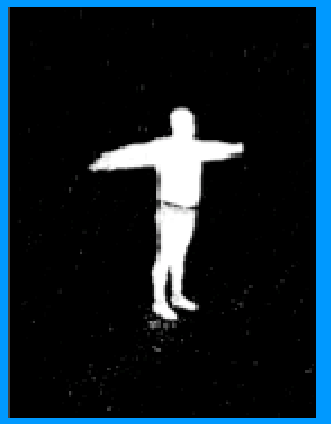

How to extract silhouettes?

- Sometimes done manually (for offline applications, ground truth and verifications)
- Region based-extraction (automatic)
  - silhouette extraction is a 2-region image segmentation problem, w/ specific solutions:
    - chroma keying (blue, green background)
    - background subtraction (pre-observed static or dynamic background)

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How to extract silhouettes?

- Contour-based extraction
- focus on silhouette *outline* instead of region itself
  - snakes, active contours: fitting of a curve to high gradients in image, local optimization

Yilmaz&Shah ACCV04

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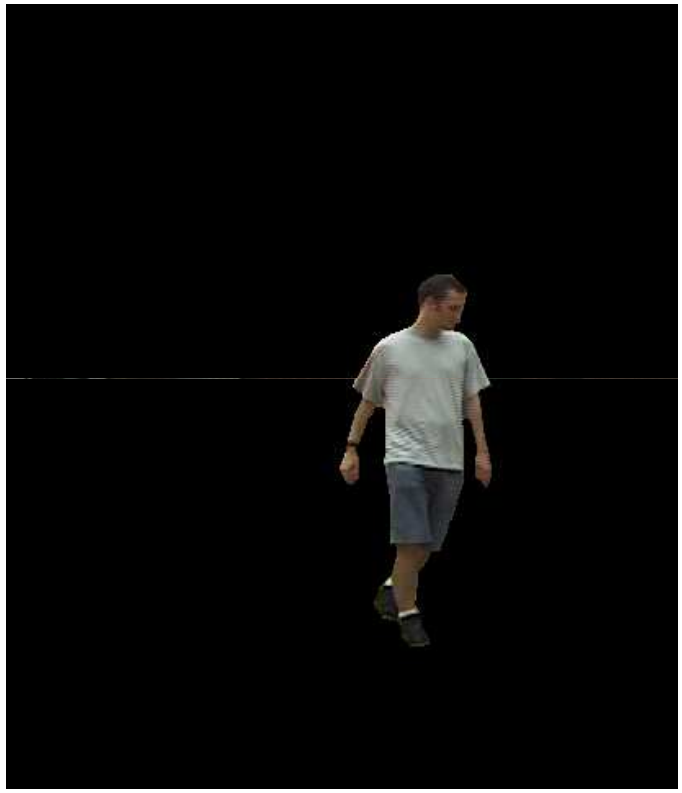
How to extract silhouettes? (cont.)

- Background subtraction
  - Simple thresholding
  - Train an appearance model for each pixel, from a set of background images
    - RGB 3D-Gaussian model
    - HSV model
    - GMM model
    - Non-parametric model (histogram/kernel density function)
  - Apply the pixel color to the model, then classify it to be foreground/background



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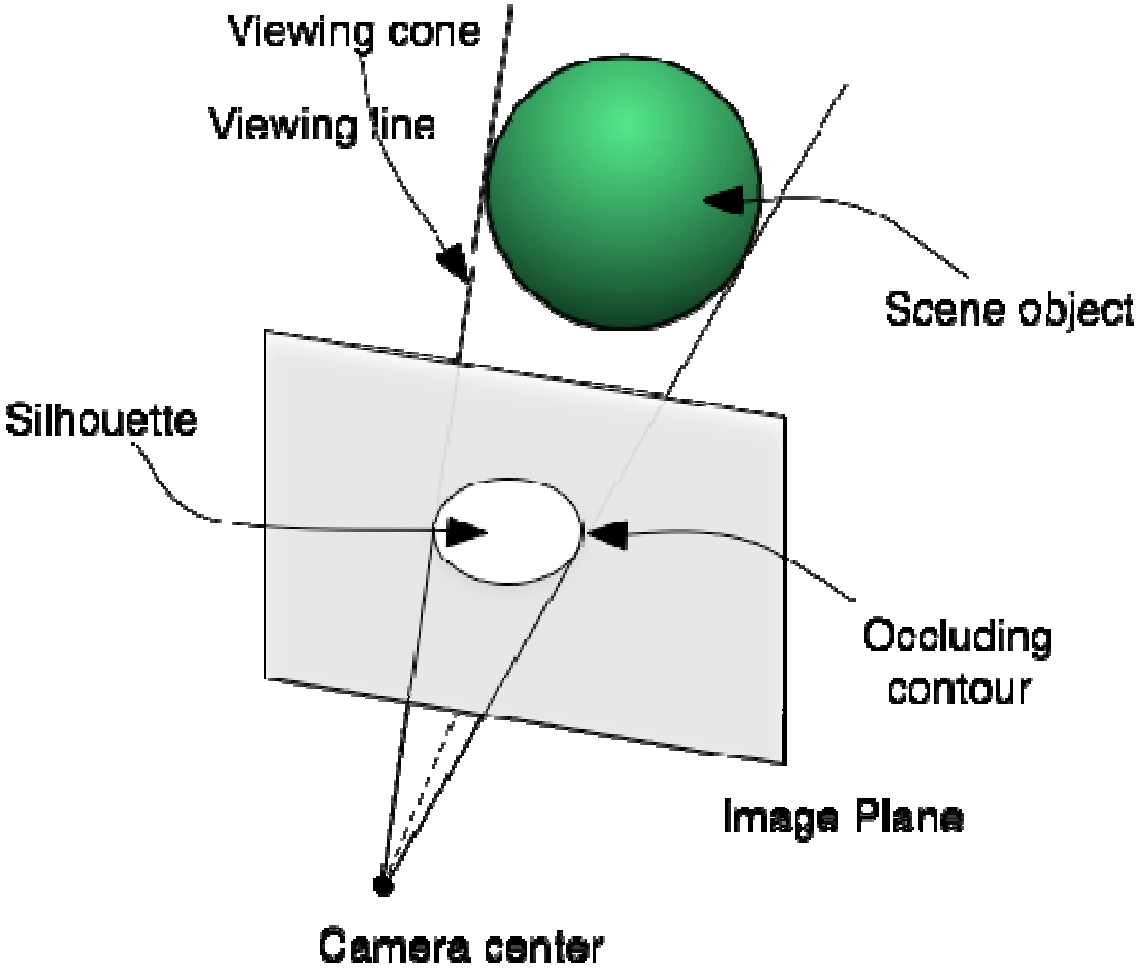
One-view silhouette geometry



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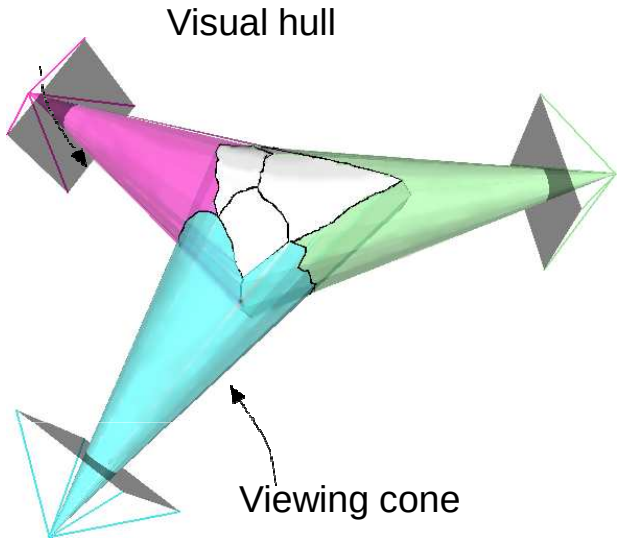
Multi-view silhouette geometry: the Visual Hull



- **Maximal volume consistent with silhouettes**
  [Laurentini94] [Baumgart74]
- Can be seen as the intersection of viewing cones

- Properties:
  - Containment property: contains real scene objects
  - Converges towards the shape of scene objects minus concavities as N increases
  - Projective structure: simple management of visibility problems

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Why use a Visual Hull?

- Good shape representation
- Can be computed efficiently
- No photo-consistency required
- As bootstrap of many fancy refinement …

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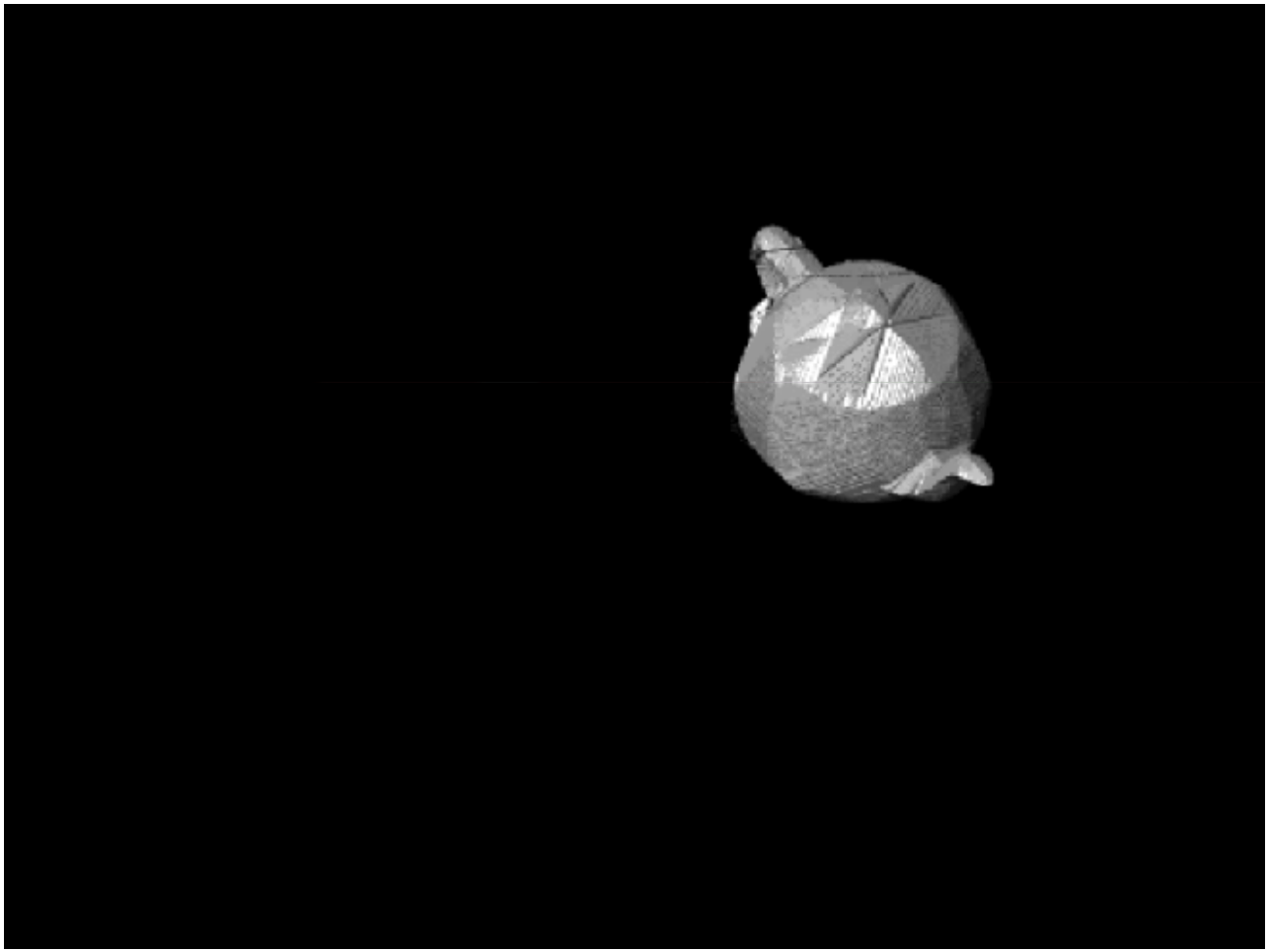
Visual Hull: A 3D Example



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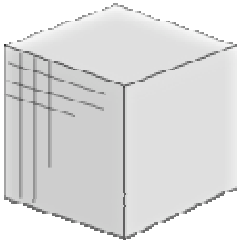
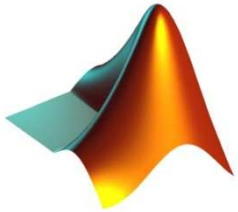
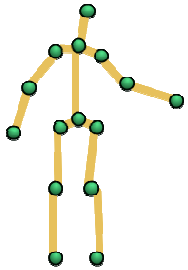
What representation for scene objects?



Voxel grid
Volumetric approaches



Surface
Surface approaches



A priori knowledge
ex: articulated model

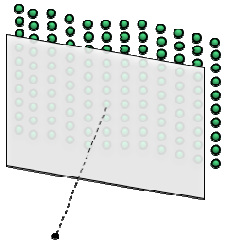
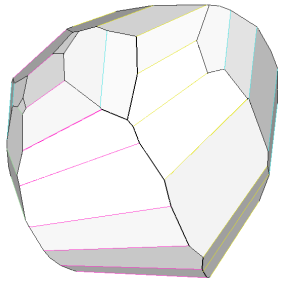


Image-based approaches



Polyhedron mesh

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General idea and assumptions

- 2 main families of approaches for VH:
  - focus on visual hull as volume: locate portions of space that don't project in silhouettes (carving)
    - use 2D silhouette *regions* in images
  - focus on visual hull as surface: locate the boundary surface of the visual hull
    - use 2D silhouette *contours* in images
- General assumptions:
  - very good silhouettes are extracted
  - views are calibrated
    - parameters and positions are known

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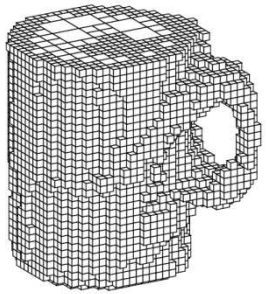
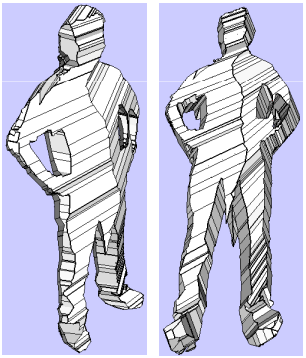
Algorithms

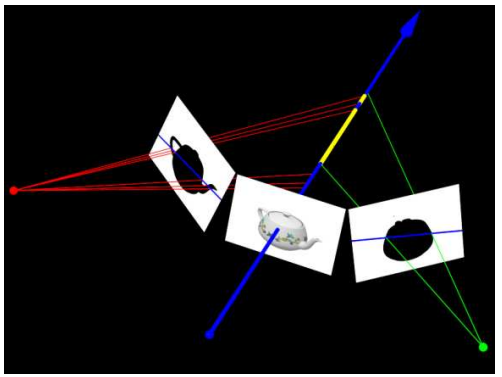
- Standard voxel based method



- Exact polyhedral methods

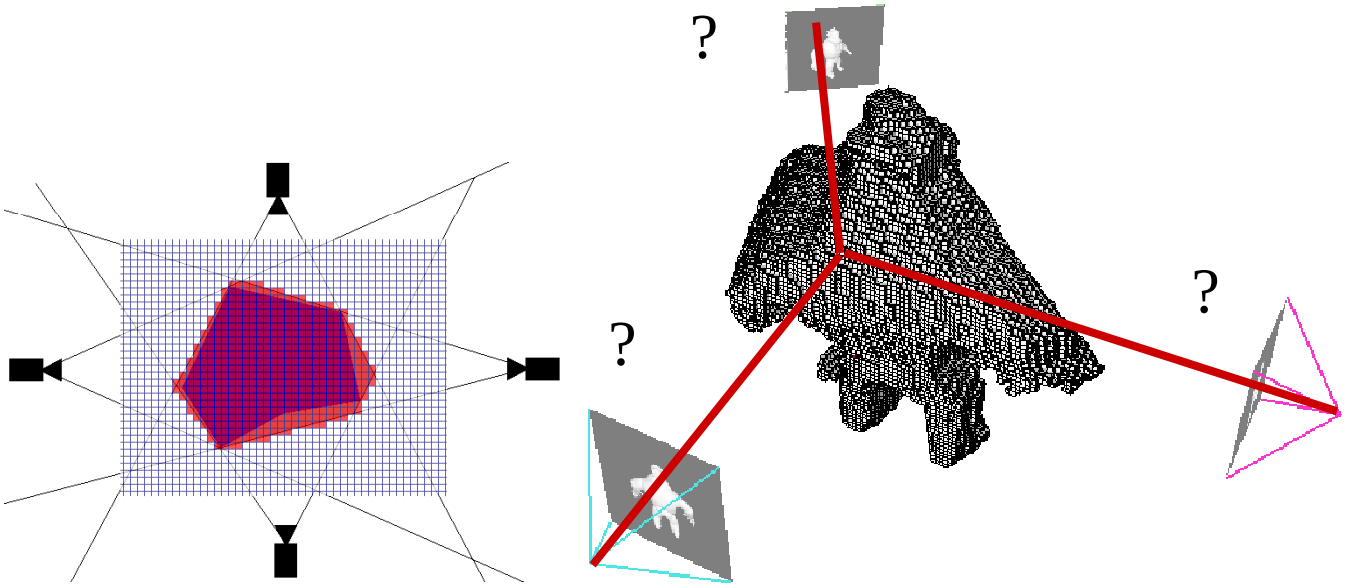


- Image-based visual hulls



Visual hull as voxel grid

- Identify *3D region* using voxel carving
  - does a given voxel project inside all silhouettes?



- pros: simplicity
- cons: bad precision/computation time tradeoff

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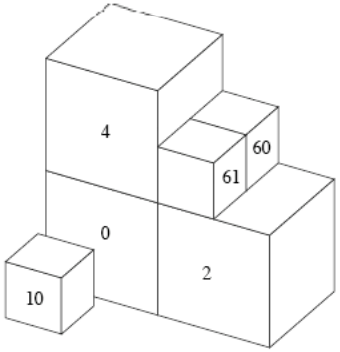
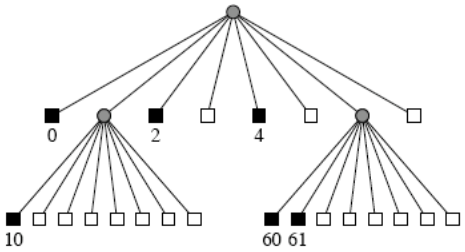
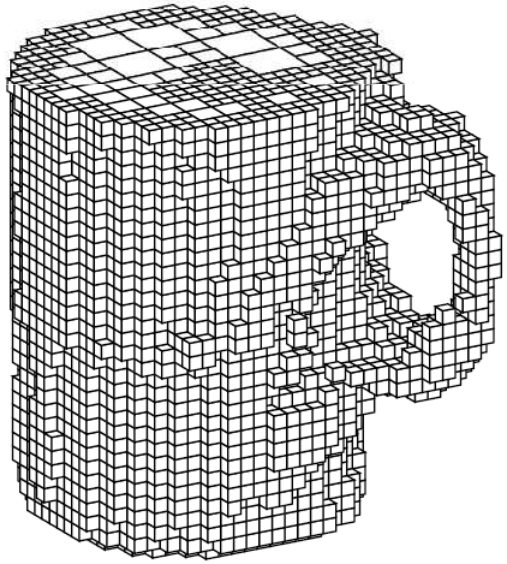
Classical voxel grid improvement: octrees

- Same principle, but refinement through space subdivision







[Szeliski TR 90']

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Voxel grid based algorithm

- First the object space is split up into a 3D grid of voxels.
- Each voxel is intersected with each silhouette volume.
- Only voxels that lie inside all silhouette volumes remain part of the final shape.

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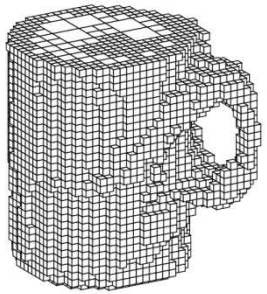
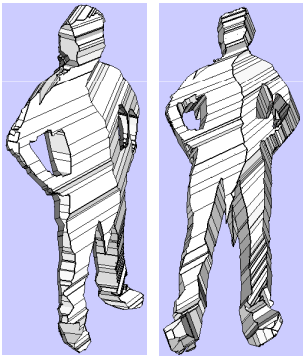
Algorithms

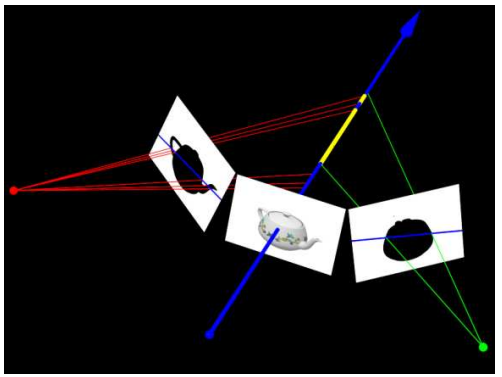
- Standard voxel based method



- Exact polyhedral methods



- Image-based visual hulls



Exact Polyhedral Methods

- First, silhouette images are converted to polygons. (convex or non-convex, with holes allowed)
- Each edge is back projected to form a 3d polygon.
- Then each polygon is projected onto each image, and intersected with each silhouette in 2D.
- The resulting polygons are assembled to form the polyhedral visual hull

W. Matusik, *An Efficient Visual Hull Computation Algorithm*

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Visual Hull as surface

- Additional assumptions:
  - good silhouettes
  - either of the following is true
    - full calibration *with consistent orientation information* is known
    - cameras are weakly calibrated and the oriented epipolar geometry of the cameras is known
  - this is necessary to recover the correct outward surface normals

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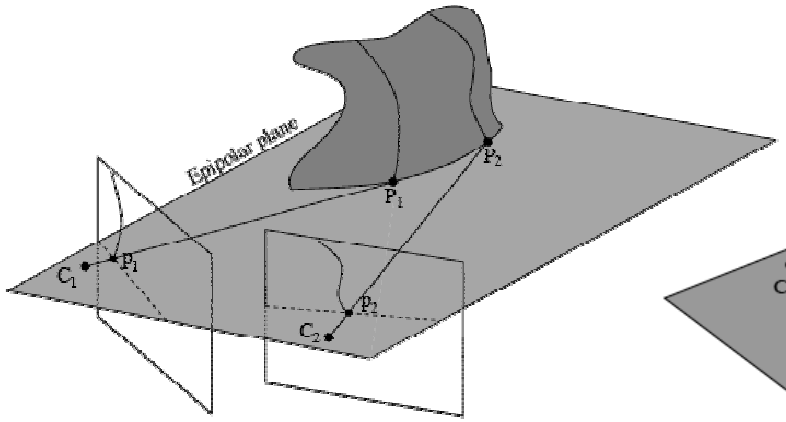
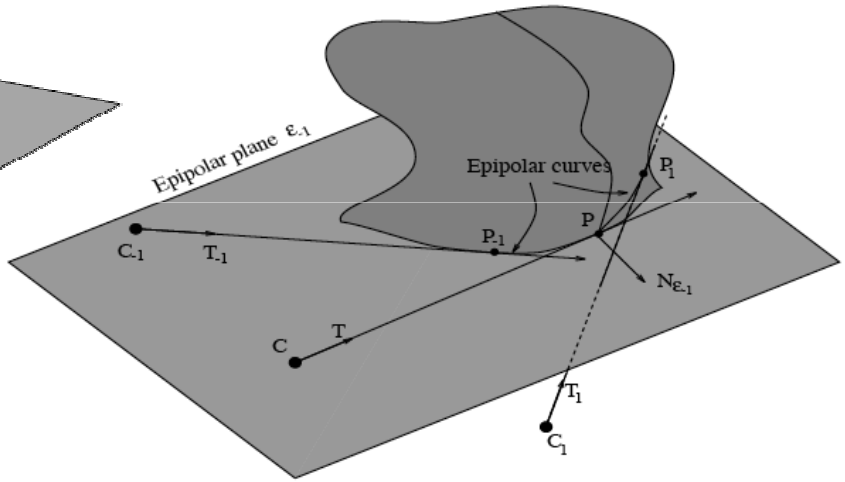
Visual Hull as smooth surface

- "shape-from-contours"



Boyer IJCV 95



- can compute tangent and normals to smooth surfaces quite accurately from epipolar correspondances between adjacently observed occluding contours (turntable sequences)

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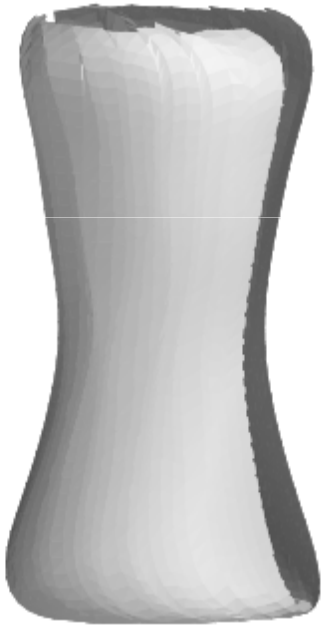
Visual hull as smooth surface

- results: problems with topology



Boyer IJCV 95

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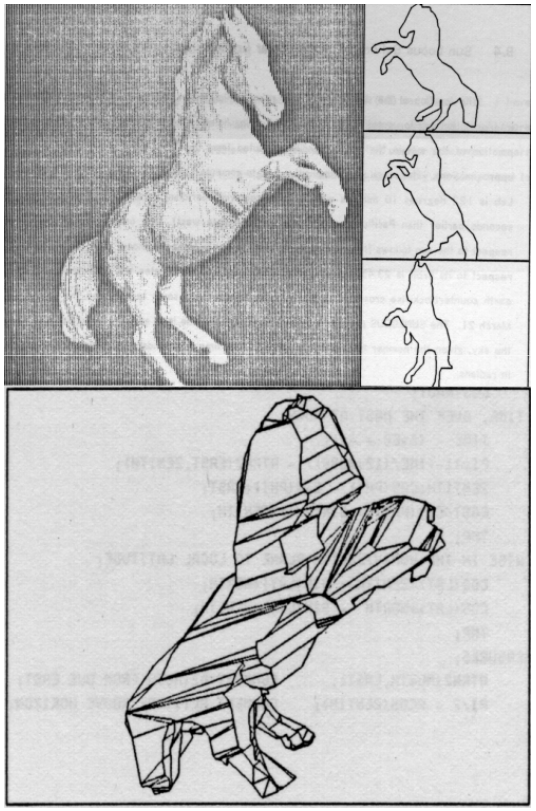
Visual Hull as Polyhedron



- assumes *polygonal* occluding contours $O(n^2p^2)$
- Baumgart (1974!): tests all possible intersections between primitives

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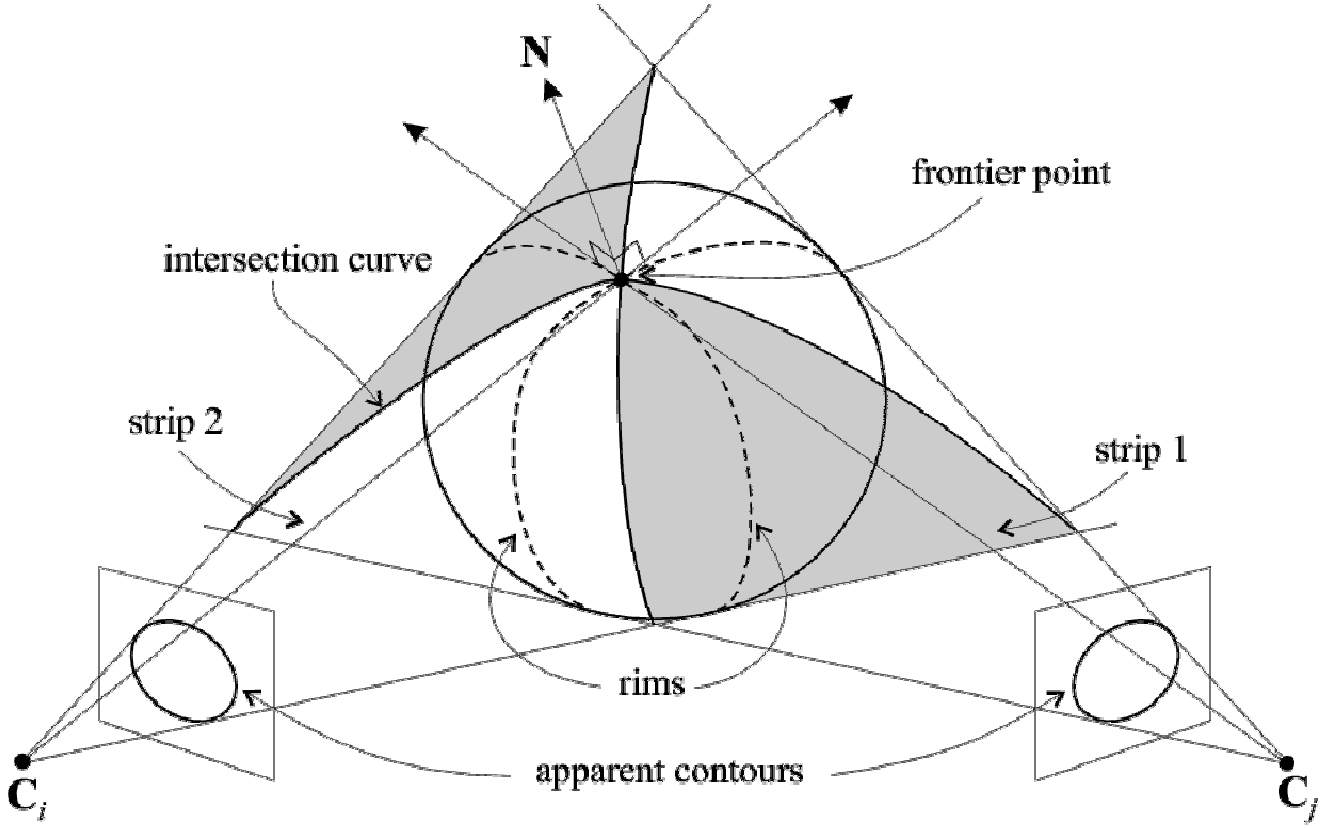
Visual hull as smooth surface

- Lazebnik 01: study of visual hull topology from smooth contours.
  Problems: numerical instability to compute frontier points



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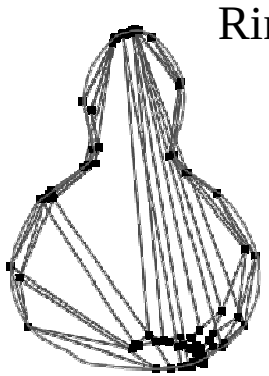
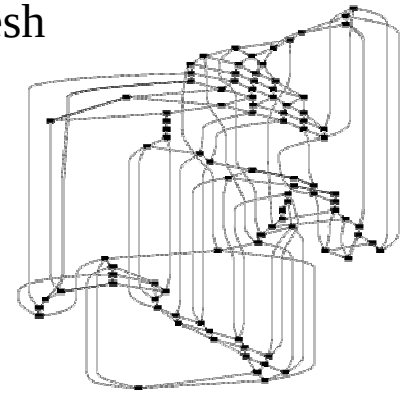
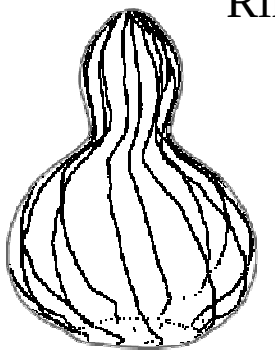
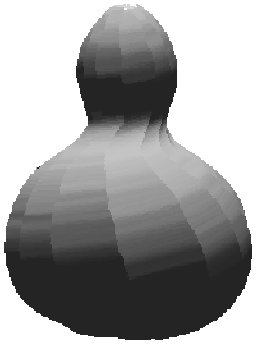


Rim mesh

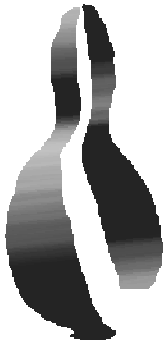




Rims

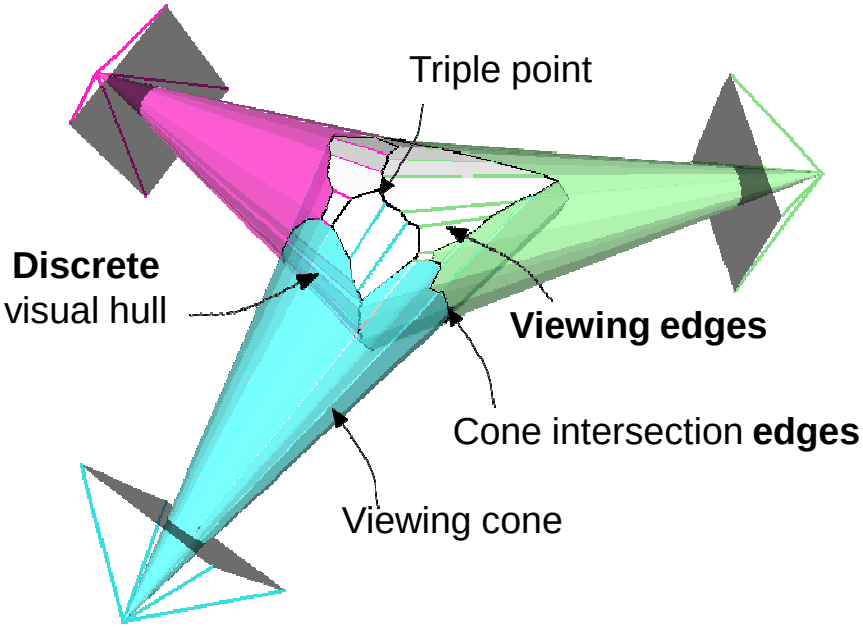


Visual hull



Strips

Exact Polyhedral Visual Hulls



[Franco & Boyer, *BMVC*, 2003]

- Analysis of discrete visual hull structure leads to topologically correct surface reconstruction algorithm

- The contour discretization imposes the geometry of viewing cones, and the geometry of the surface
  - viewing edges
  - cone intersection edges

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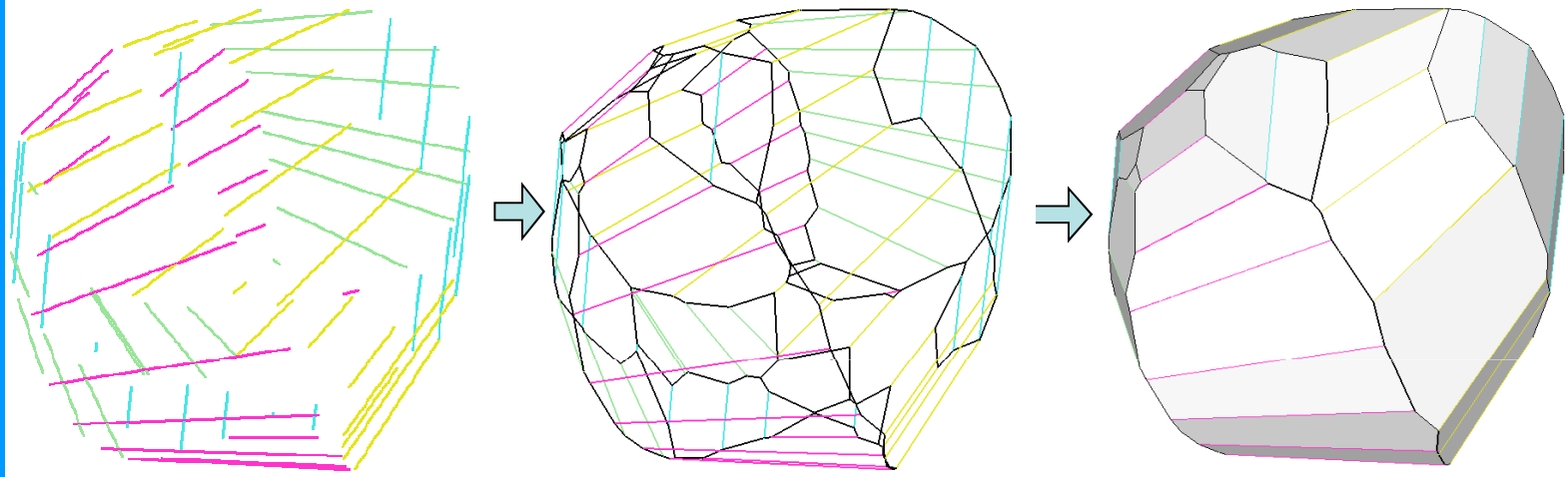
EPVH Algorithm



3 steps:

1. Compute viewing edges
2. Cone intersection edges and triple points
3. Faces.

$$O(n^2 \log p)$$

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Computational complexity

- Intersection of many volumes can be slow
- Simple polyhedron-polyhedron intersection algorithms are inefficient

- To improve performance, most methods:
  - Quantize volumes

  and/or
  - Perform Intersection computations in 2D not 3D

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Image based visual hulls

- This algorithm will only produce renderings of a visual hull from any view.
- Every pixel in the desired output image is back-projected to form a 3D ray.
- Each of those rays is intersected with each of the input silhouettes.
- Then a pixel in the output image is inside the new rendering of the visual hull if its ray has any segments left in it that are intersecting the visual hull. The depth of these pixels is known from the depth of the nearest entry point on the ray

[W. Matusik, *Image Based Visual Hulls*]

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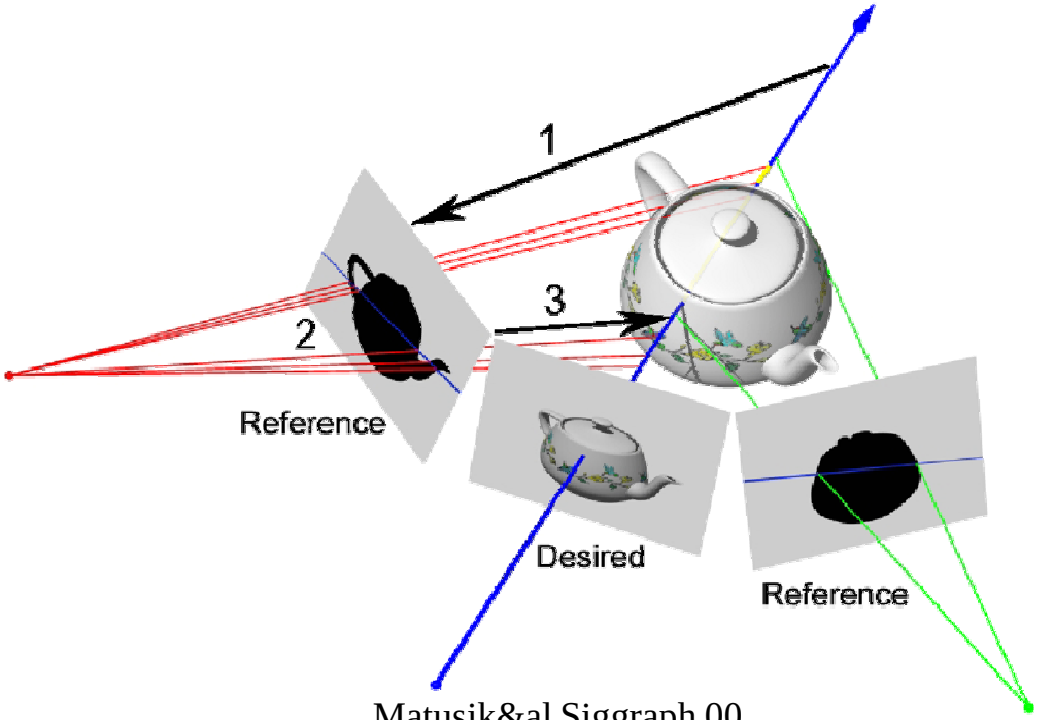
Visual Hull as view dependent image-based representation

- pros: can be useful for many tasks based on pixel rendering
- cons: view-dependent representation



Matusik&al Siggraph 00

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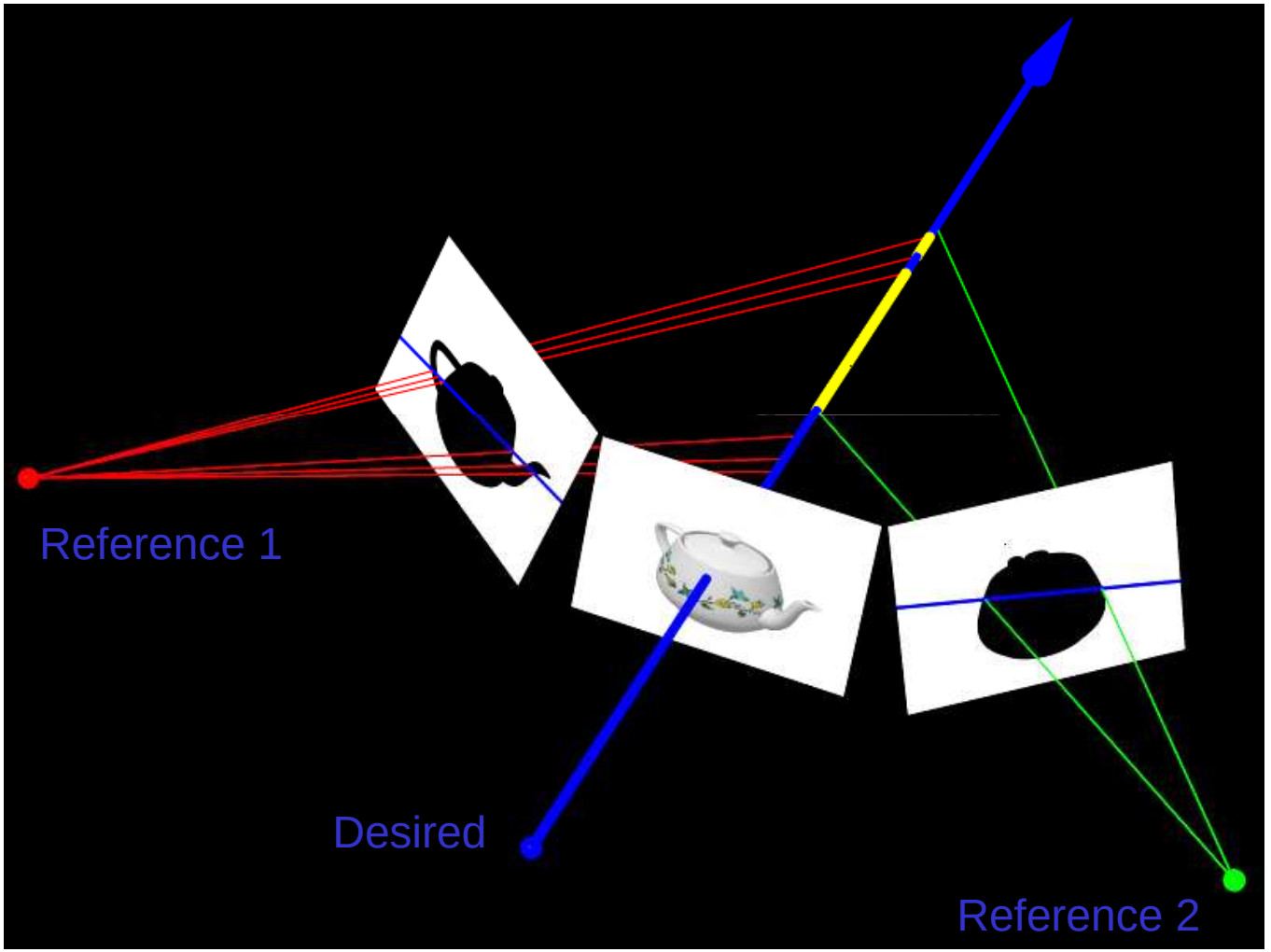
Image-Based Computation



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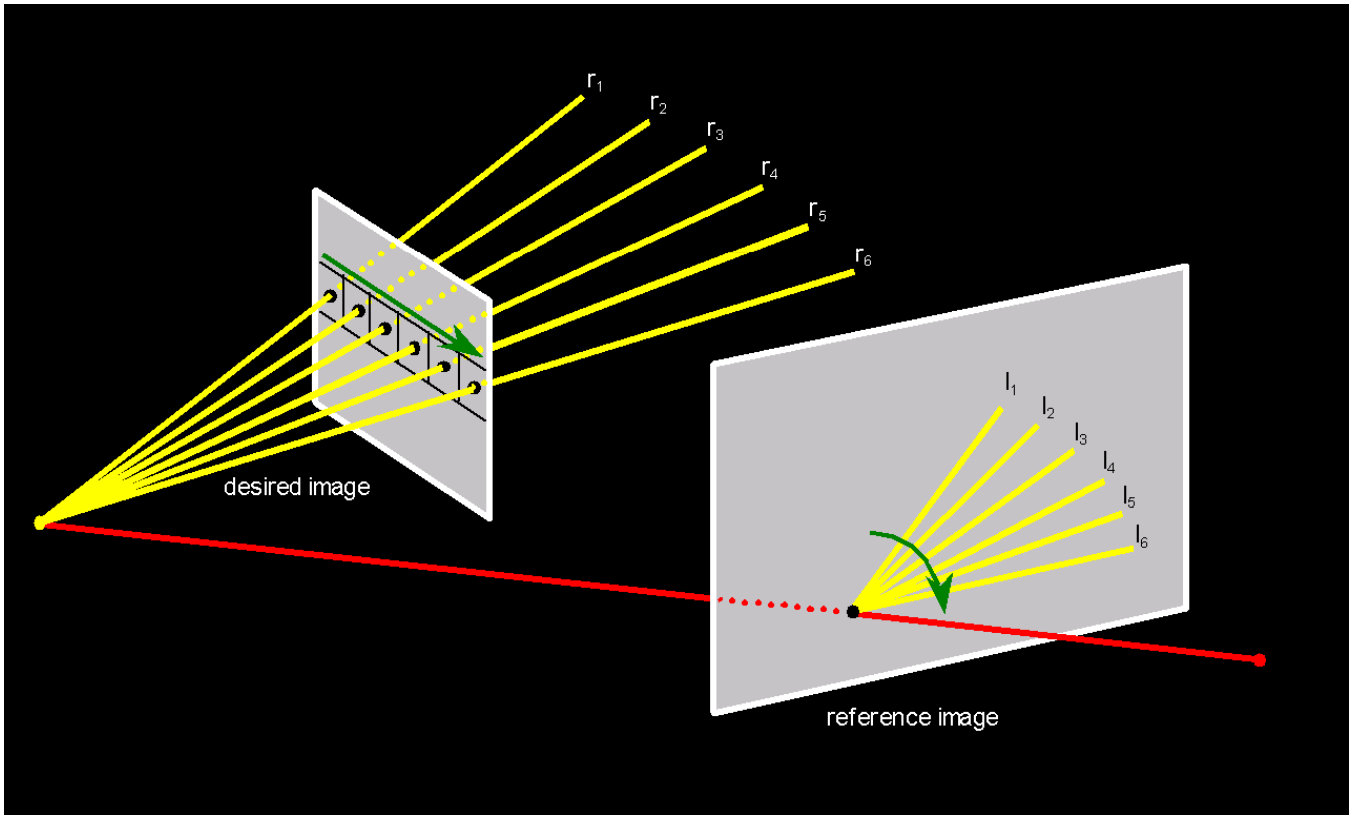
Observation

- Incremental computation along scanlines



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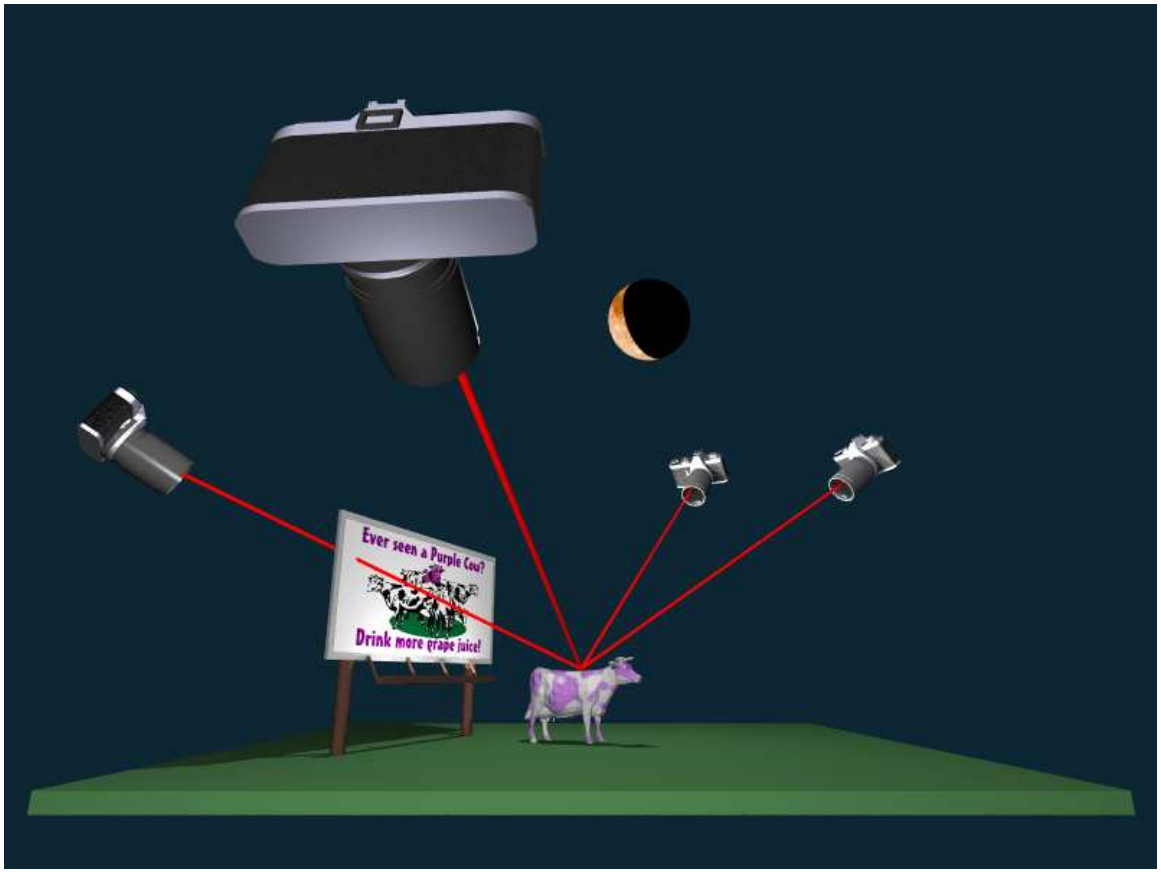
Shading Algorithm

- A view-dependent strategy



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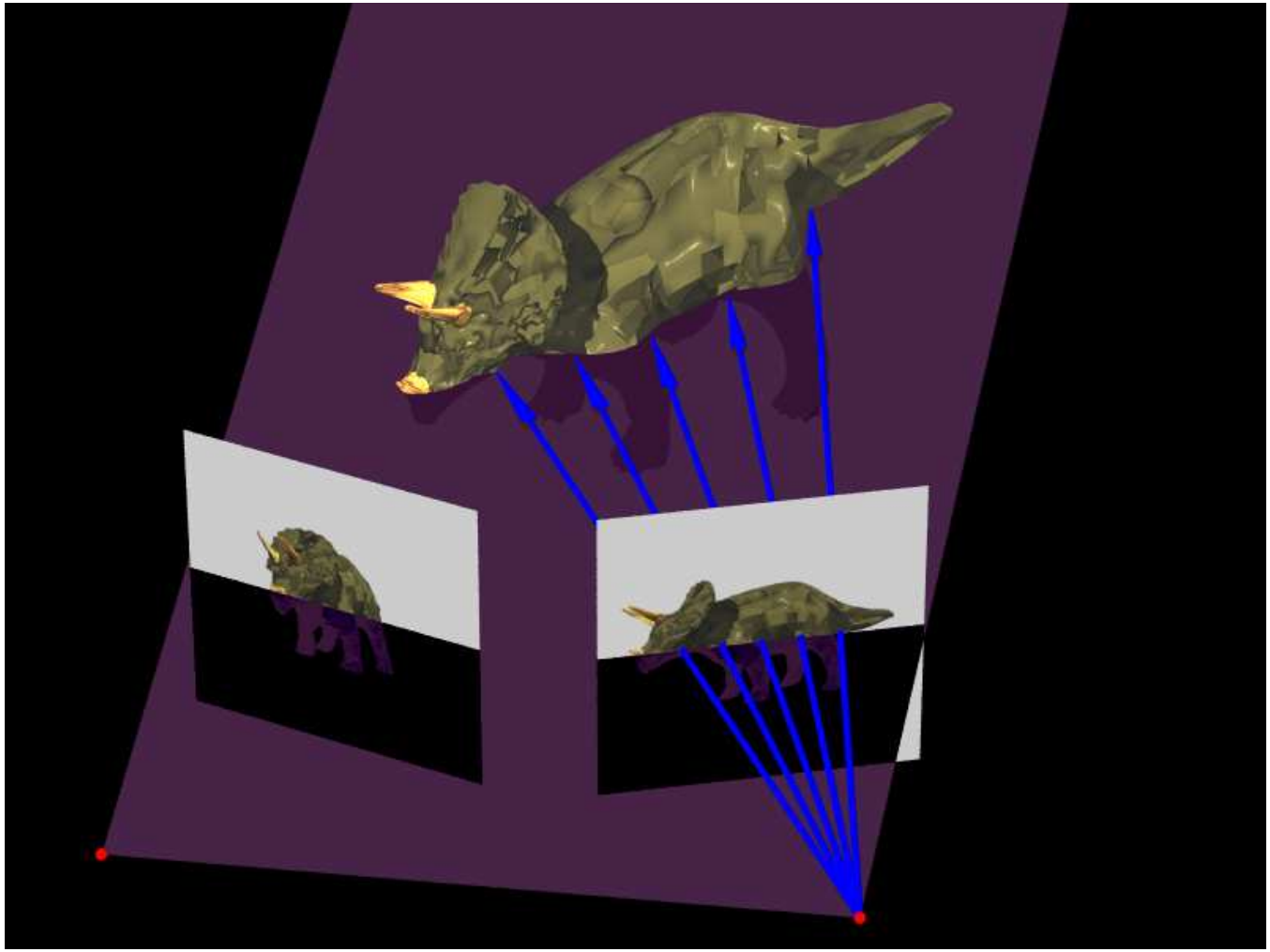
Visibility Algorithm



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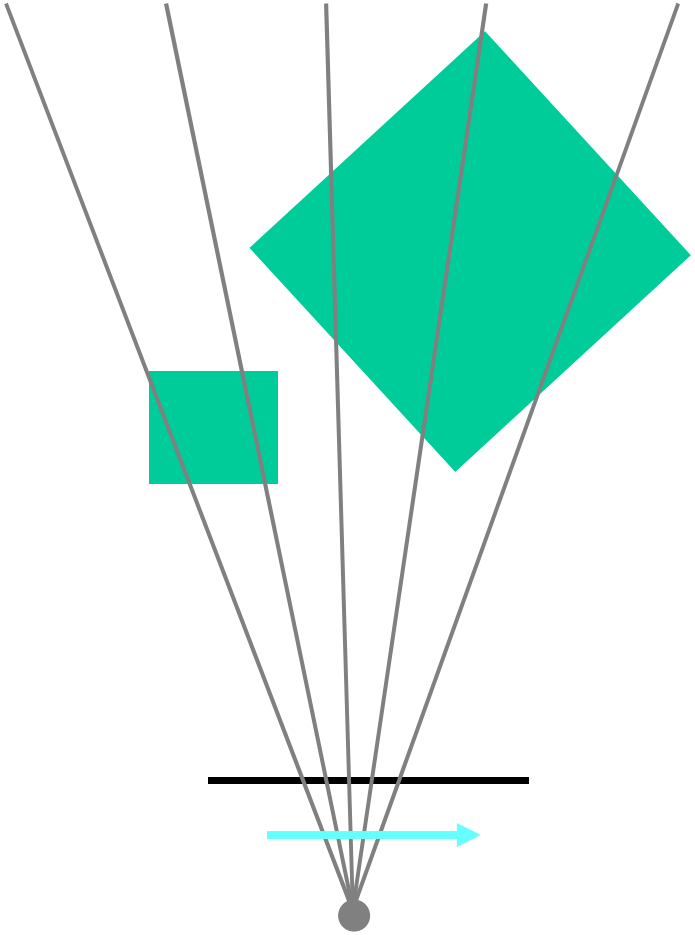
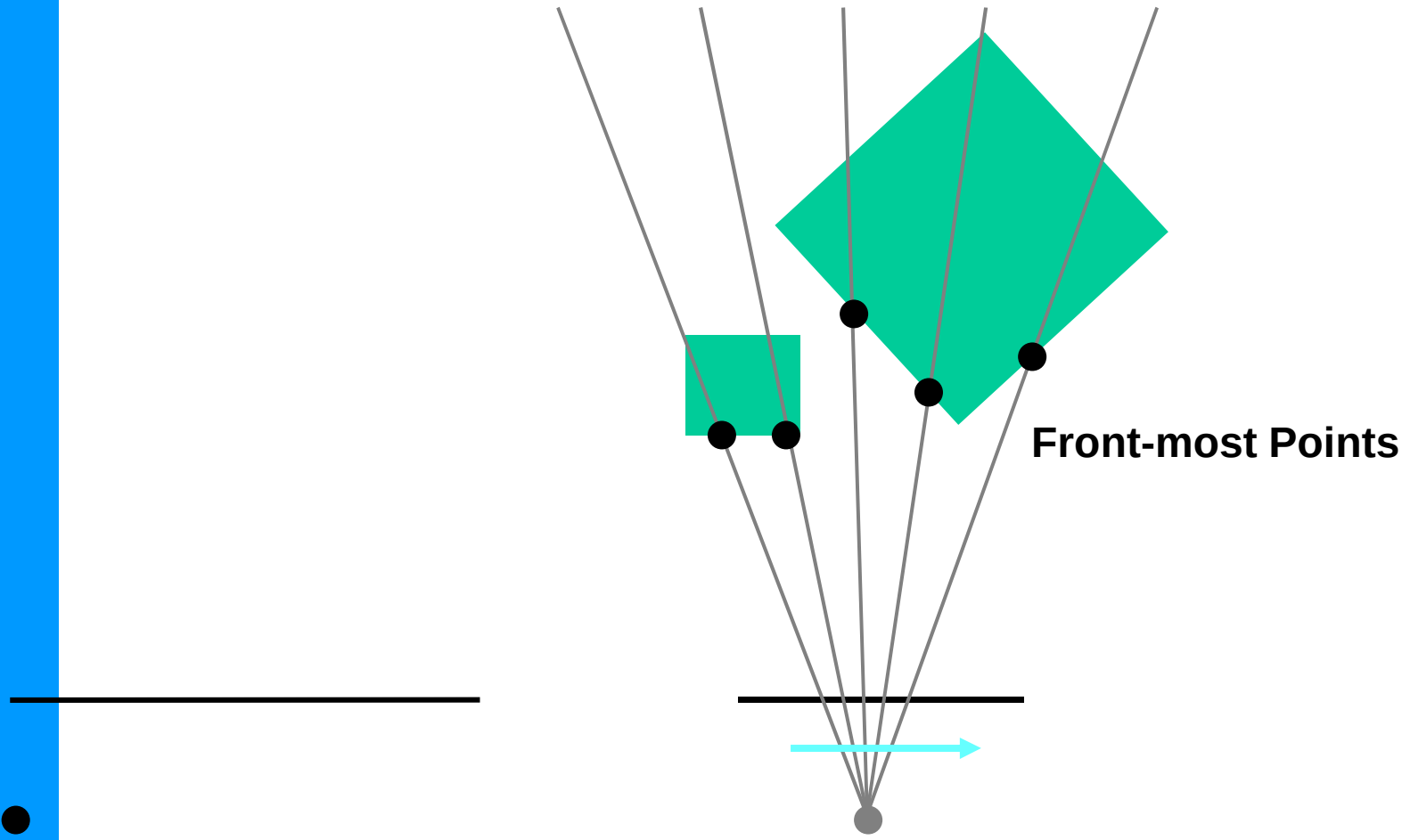
Visibility in 2D



Reference view

Desired view

Visibility in 2D



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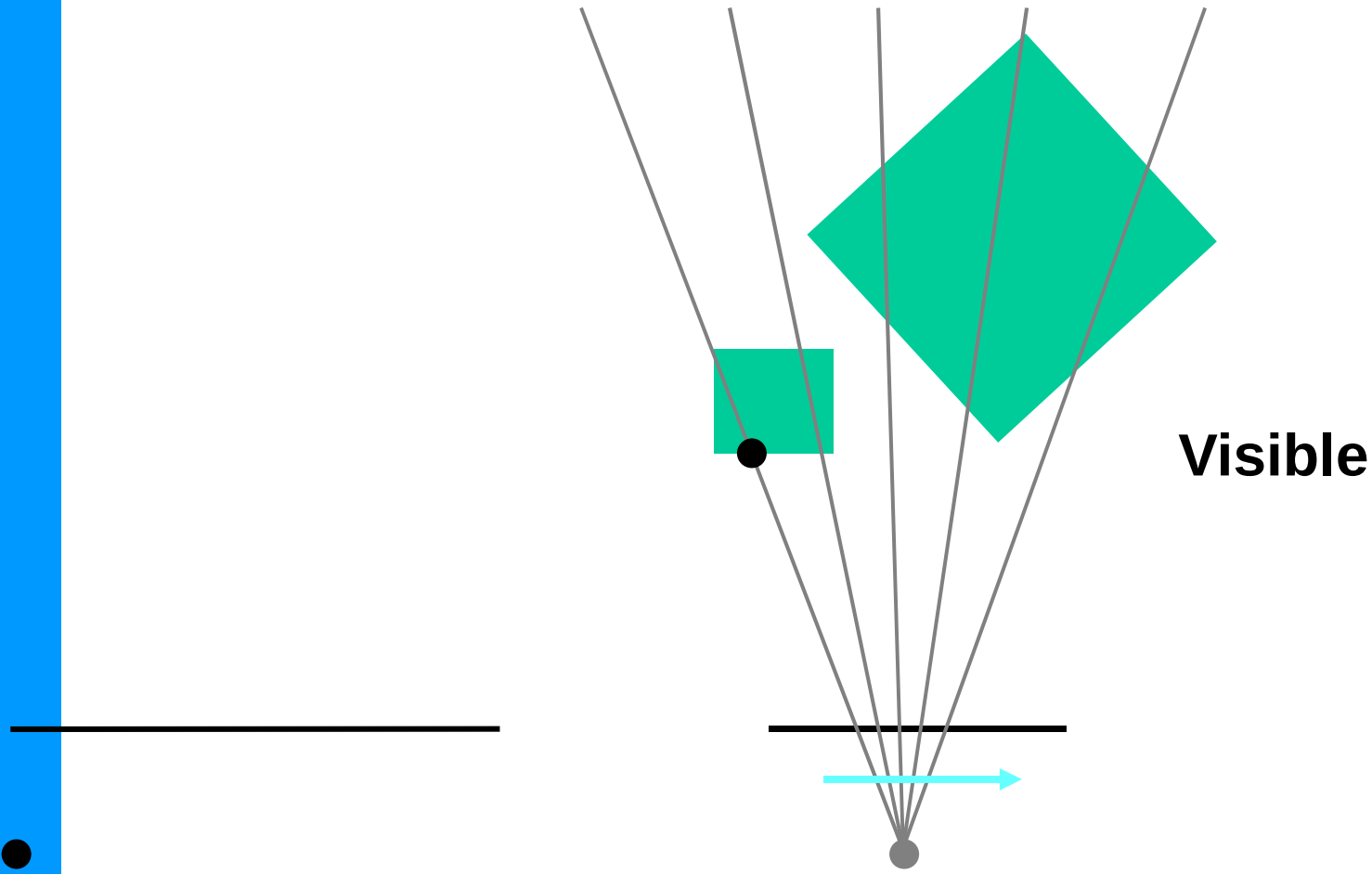
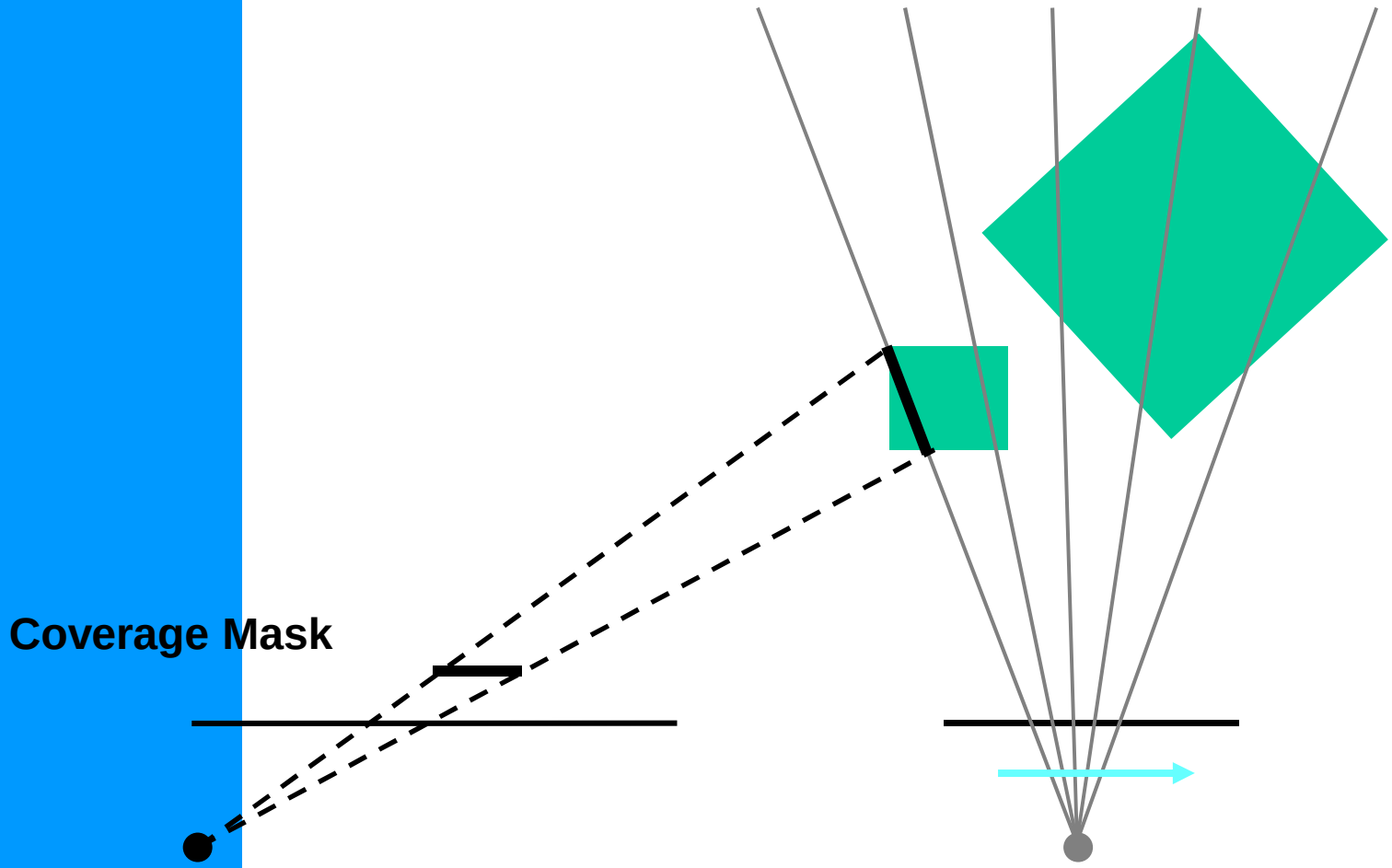
Visibility in 2D



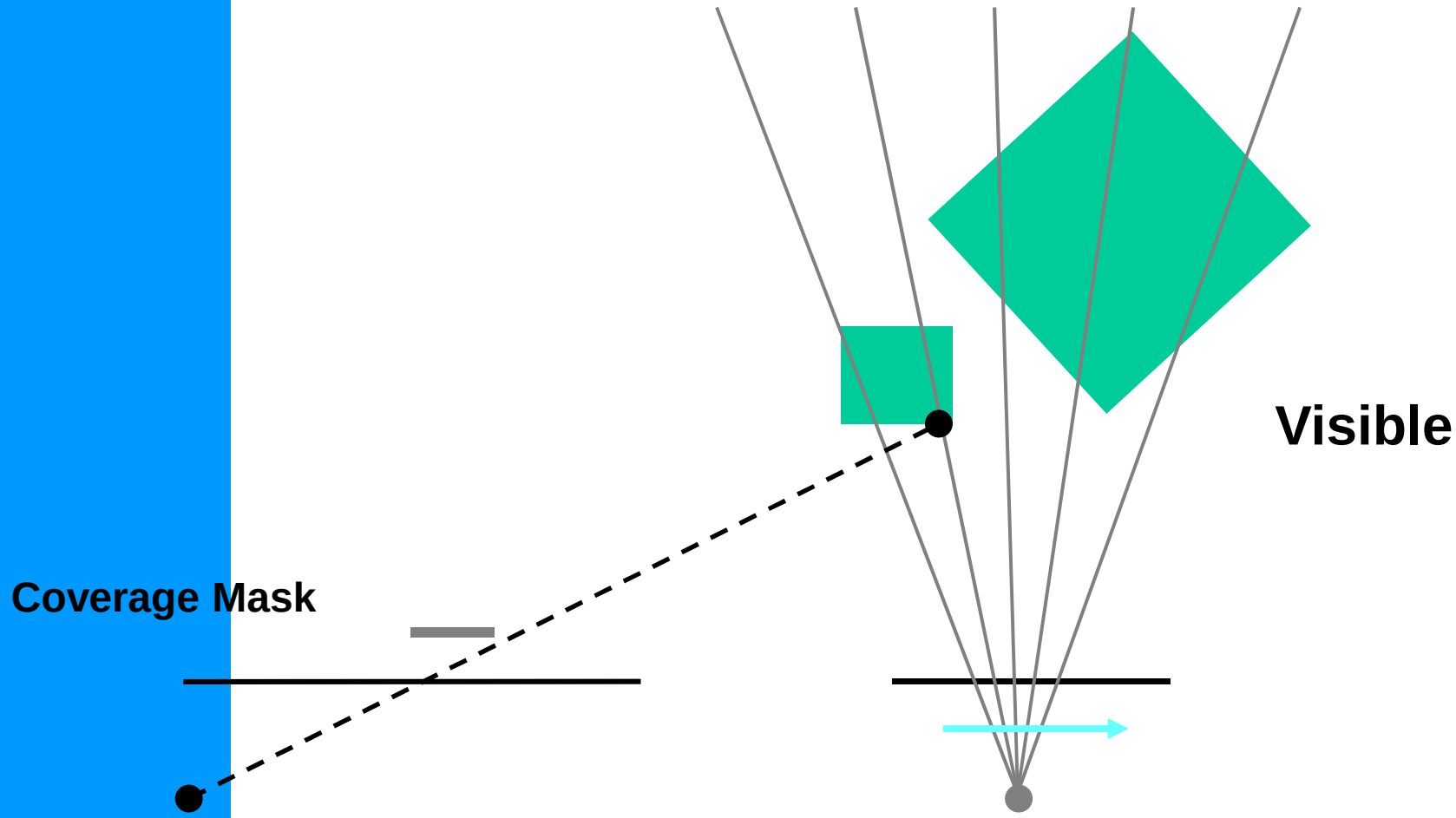
ETH

Visibility in 2D



ETH

Visibility in 2D



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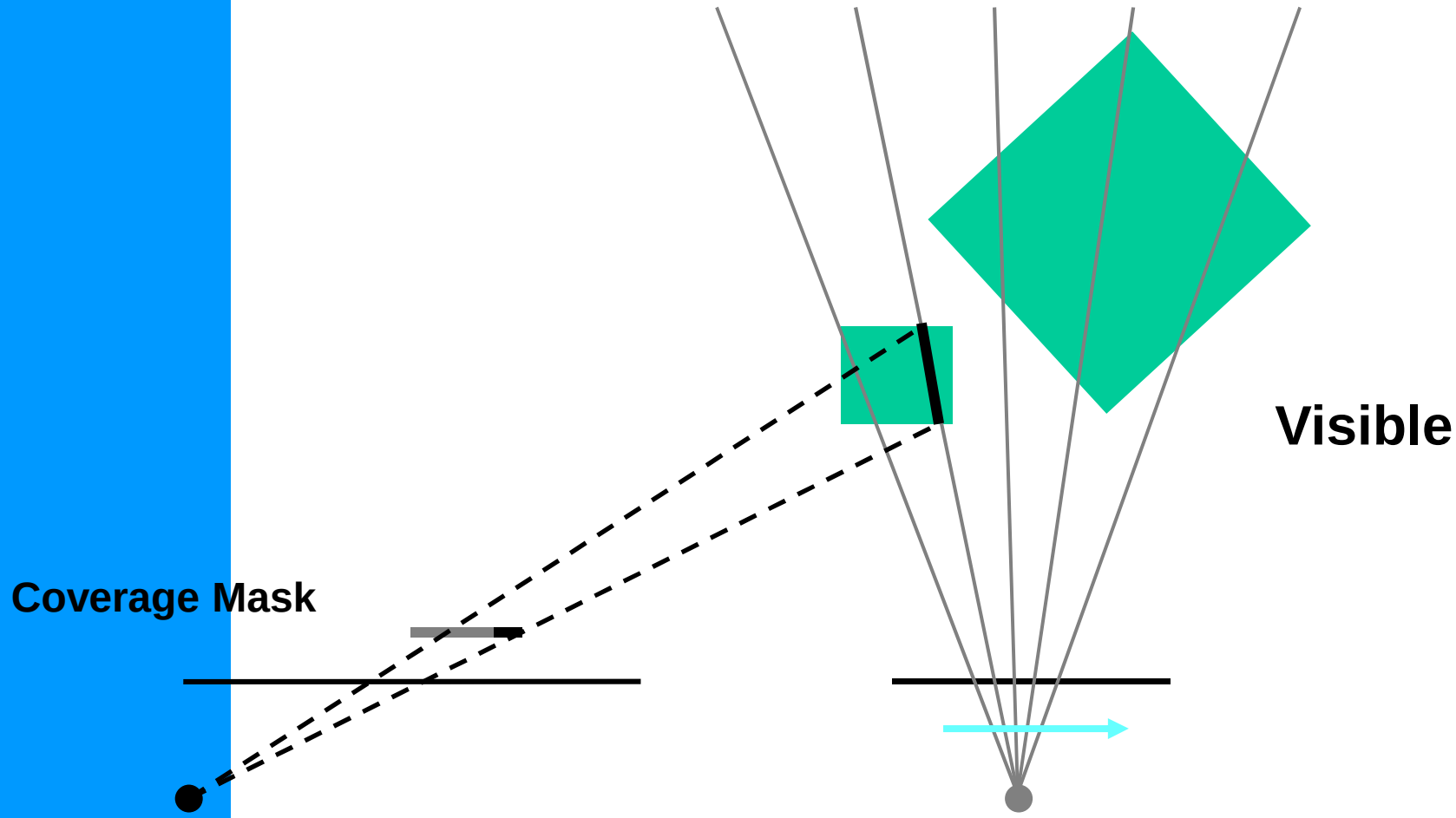
Visibility in 2D



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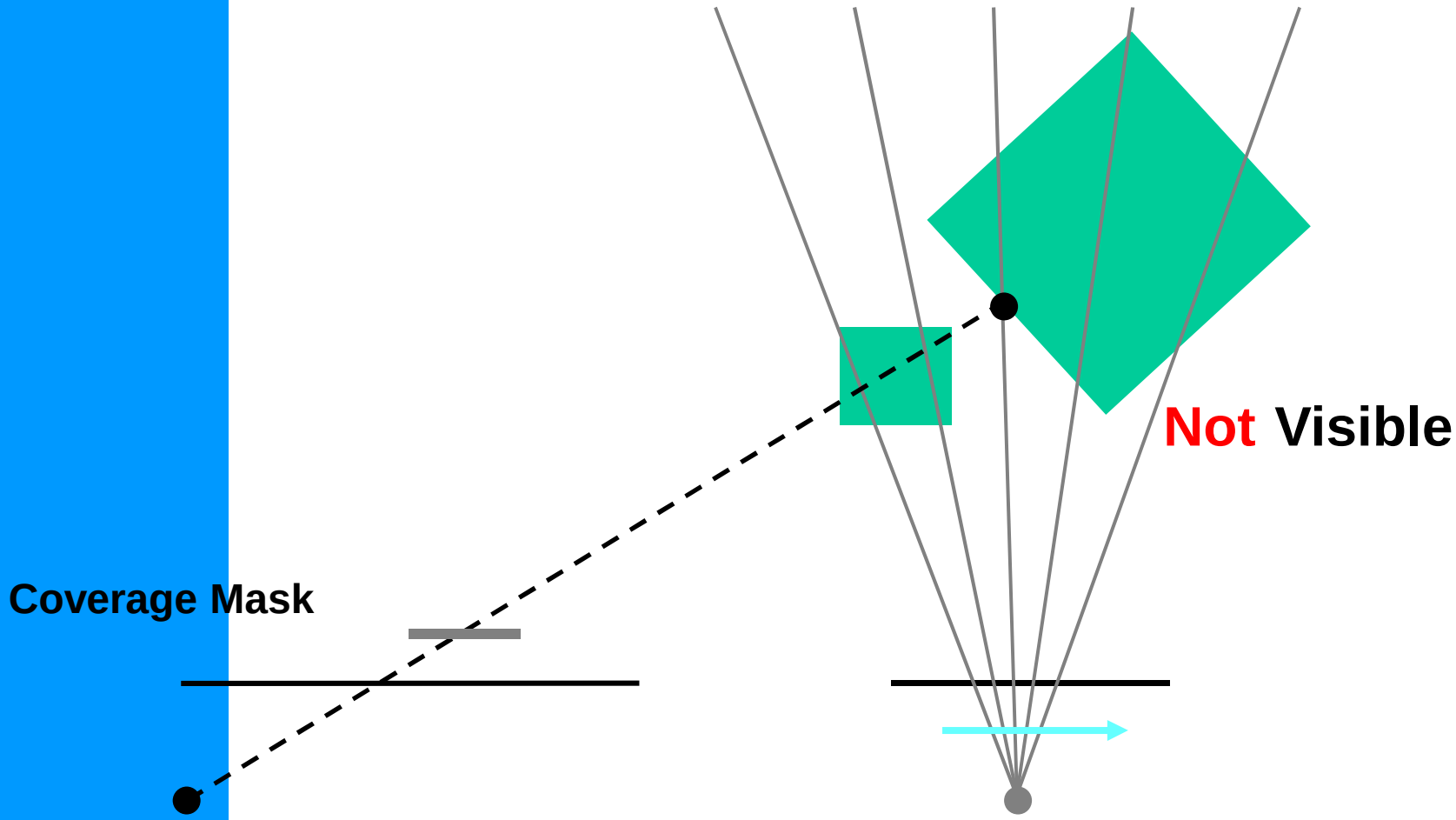
Visibility in 2D



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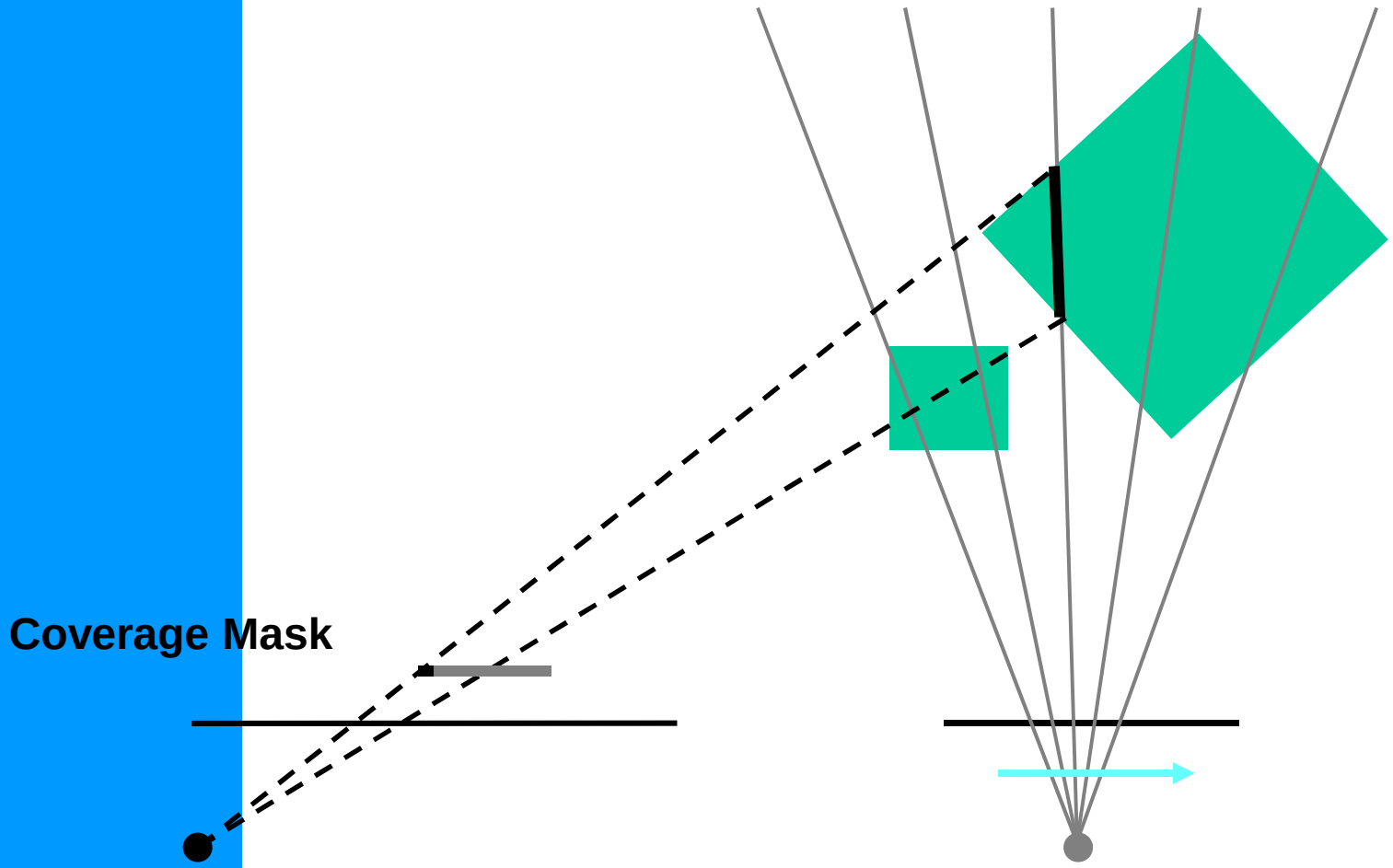
Visibility in 2D



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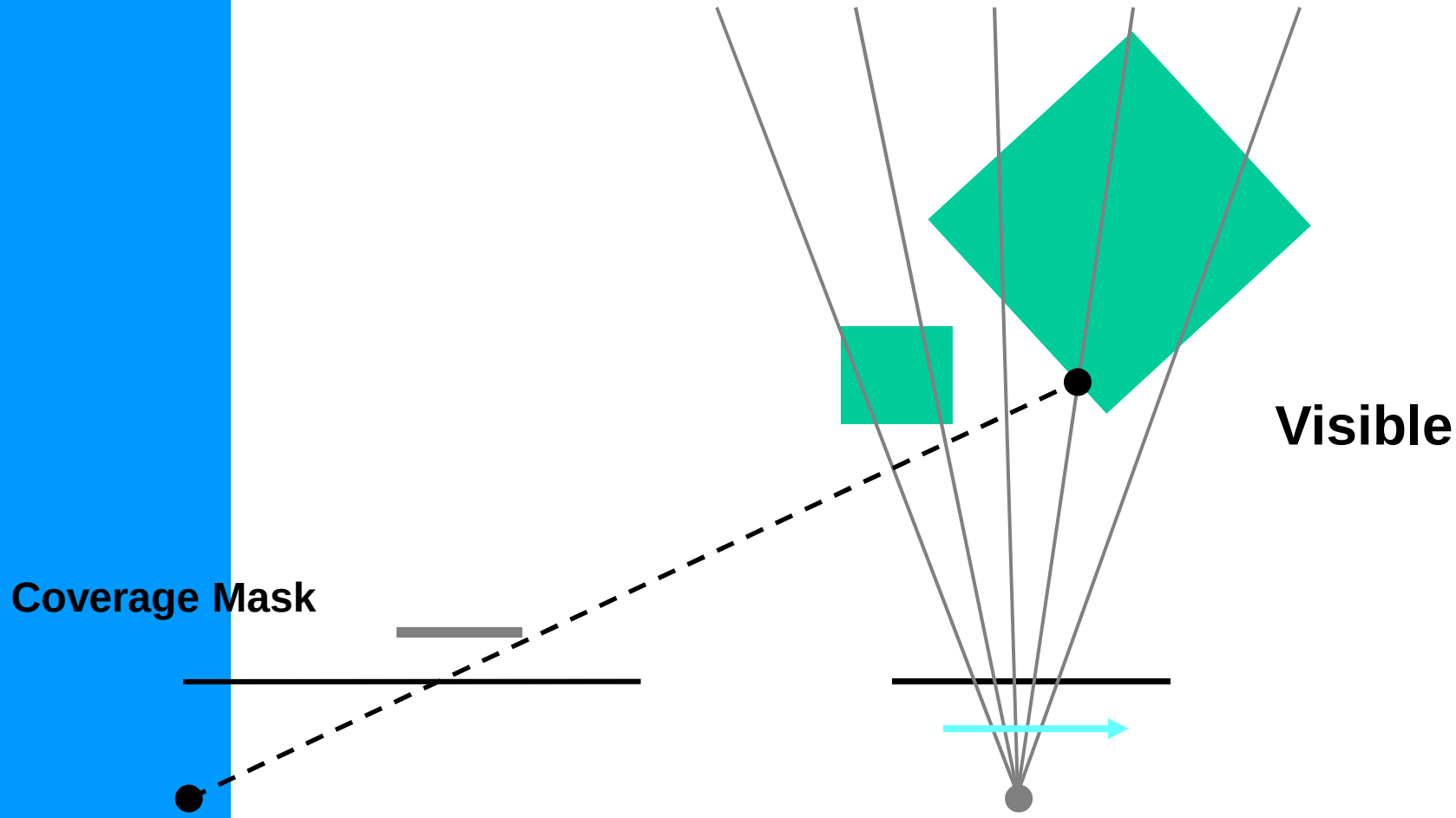
Visibility in 2D



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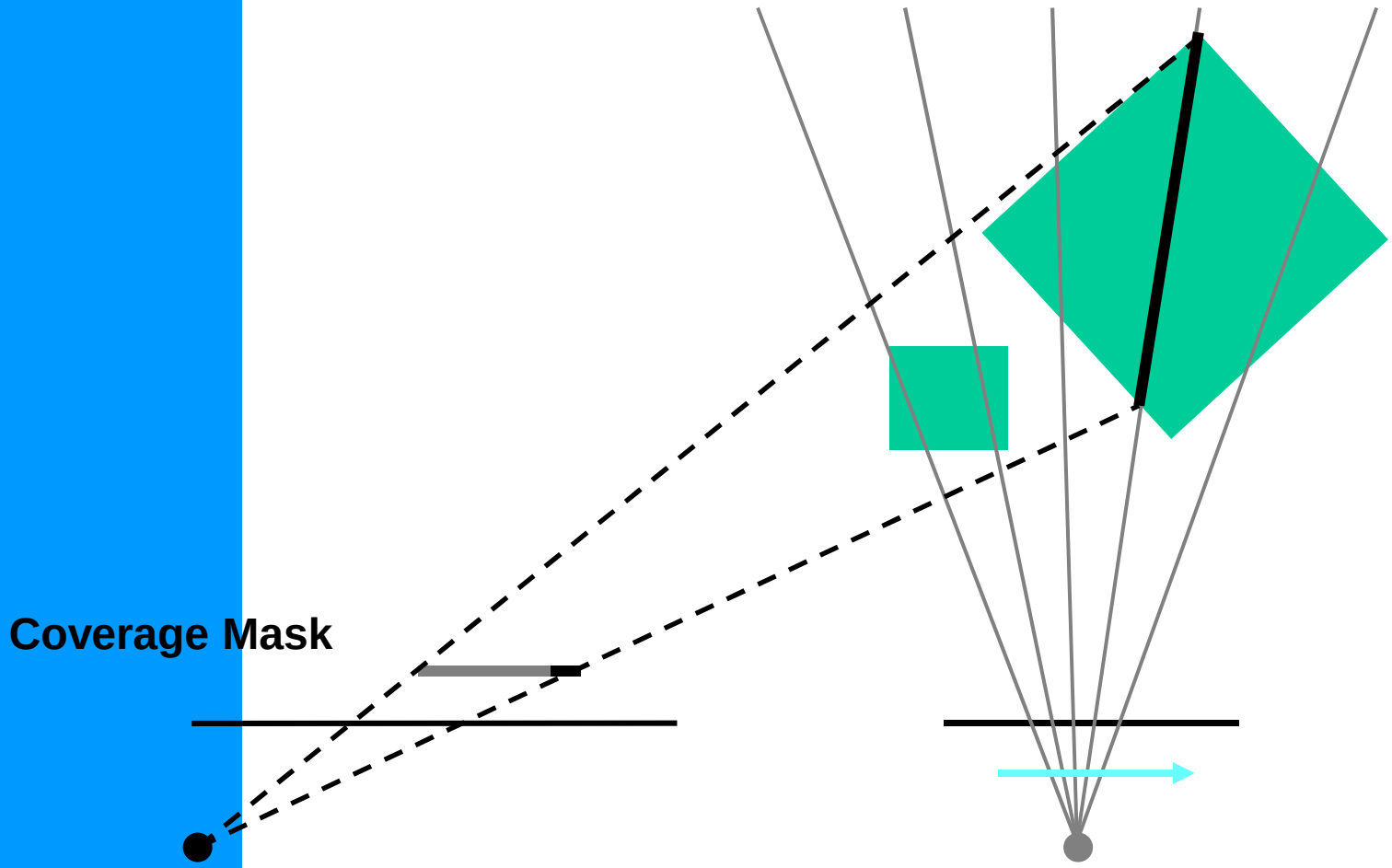
Visibility in 2D



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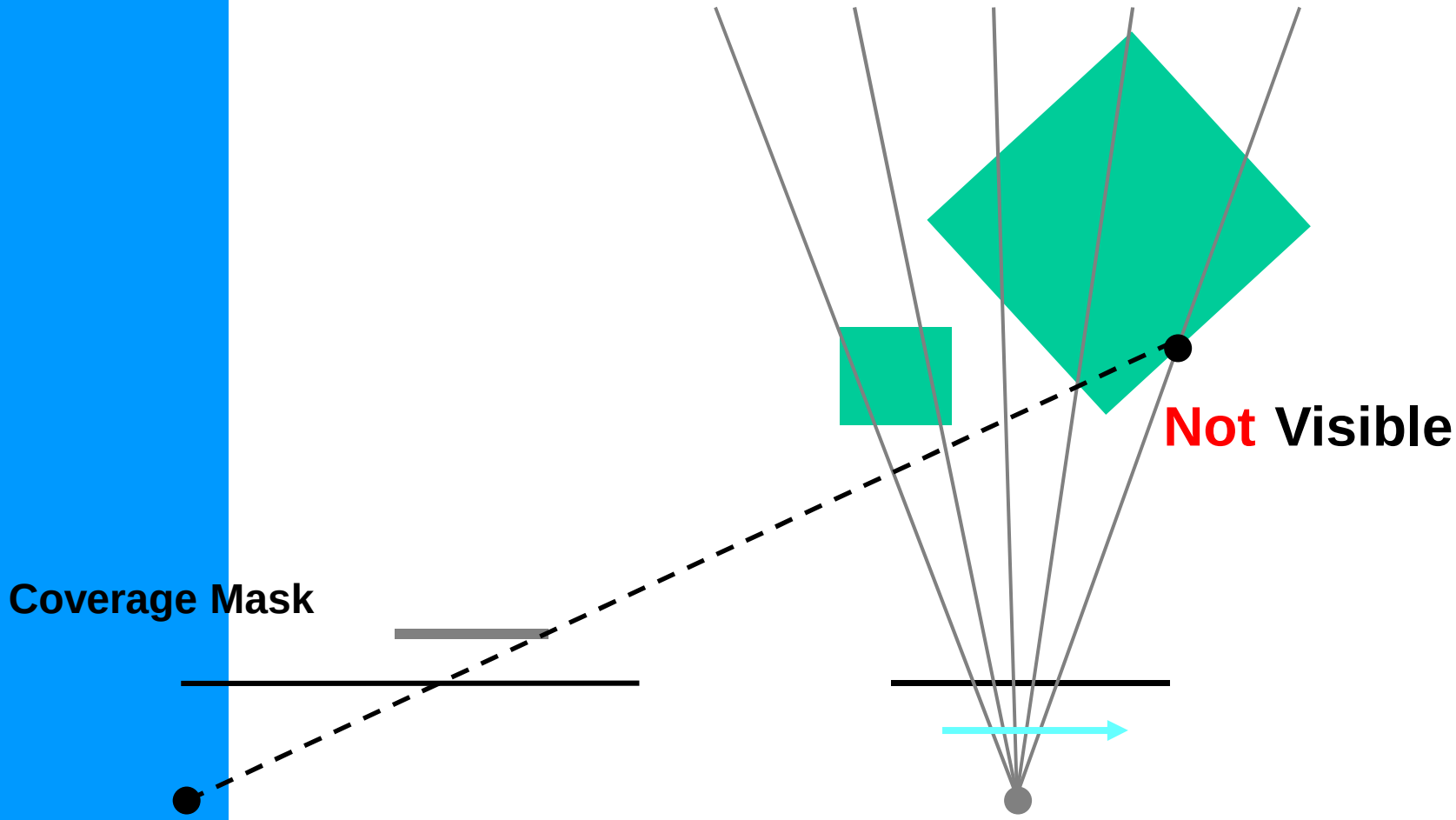
Visibility in 2D



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IBVH Results

- Approximately constant computation per pixel per camera
- Parallelizes
- Consistent with input silhouettes

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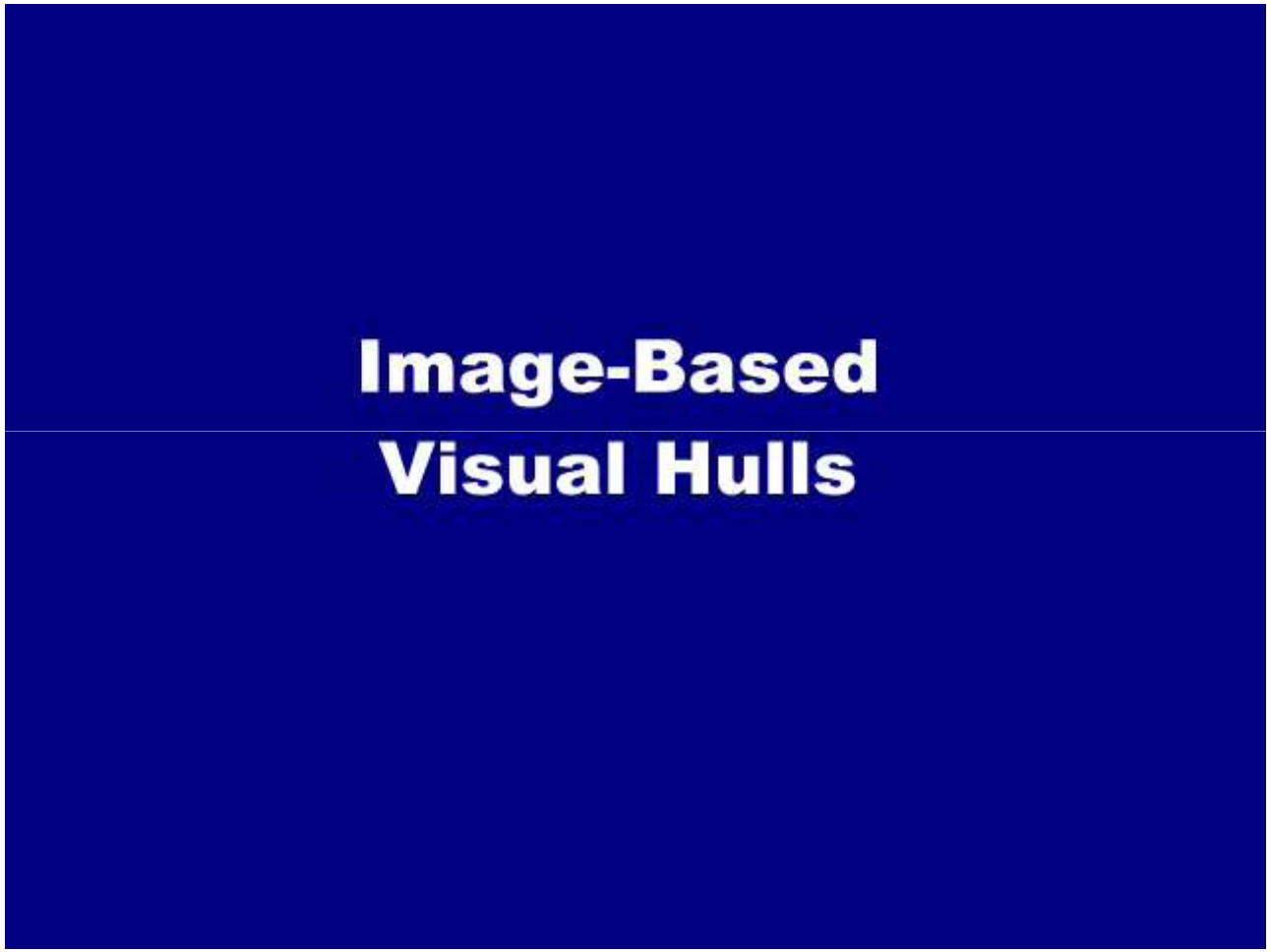
IBVH Results



Movie

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Outline

- Silhouettes
  - basic concepts
  - extract silhouettes
  - fundamentals about using silhouettes
  - reconstruct shapes from silhouettes
  - use uncertain silhouettes

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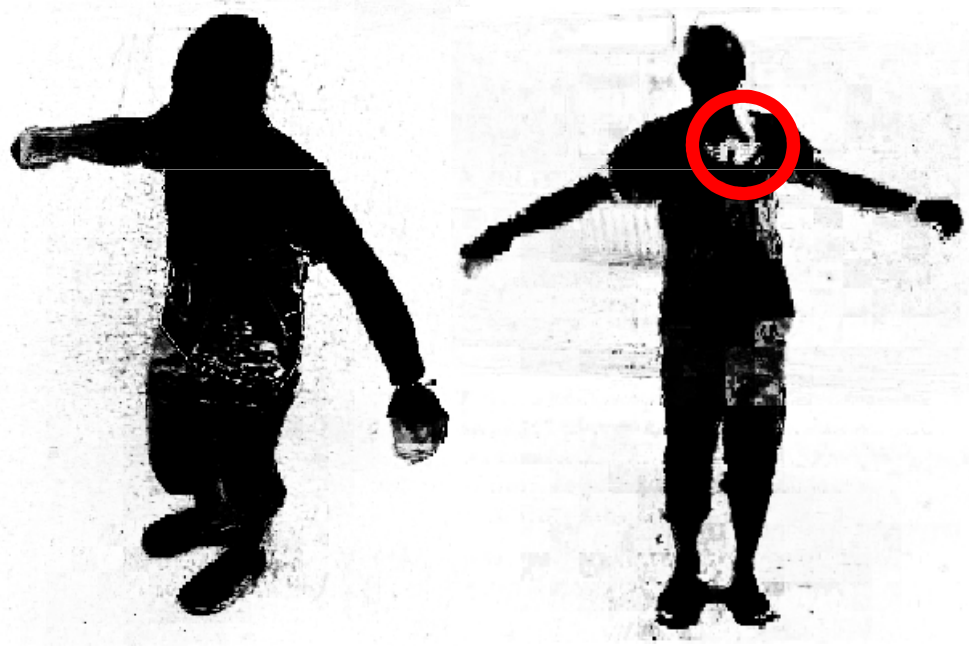
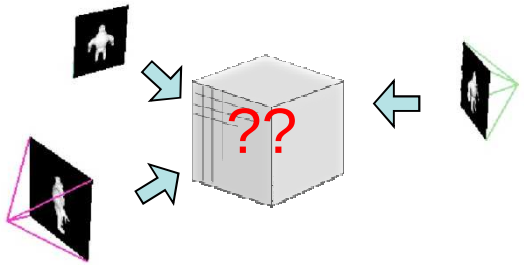
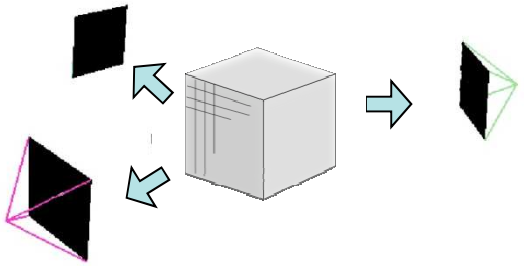
What if my silhouettes are noisy?



What if my silhouettes are noisy?





- Idea: we wish to find the content of the scene from images, as a probability grid
- Modeling the forward problem - explaining image observations given the grid state - is easy. It can be accounted for in a *sensor model*.
- Bayesian inference enables the formulation of our initial inverse problem from the sensor model
- Simplification for tractability: independent analysis and processing of voxels

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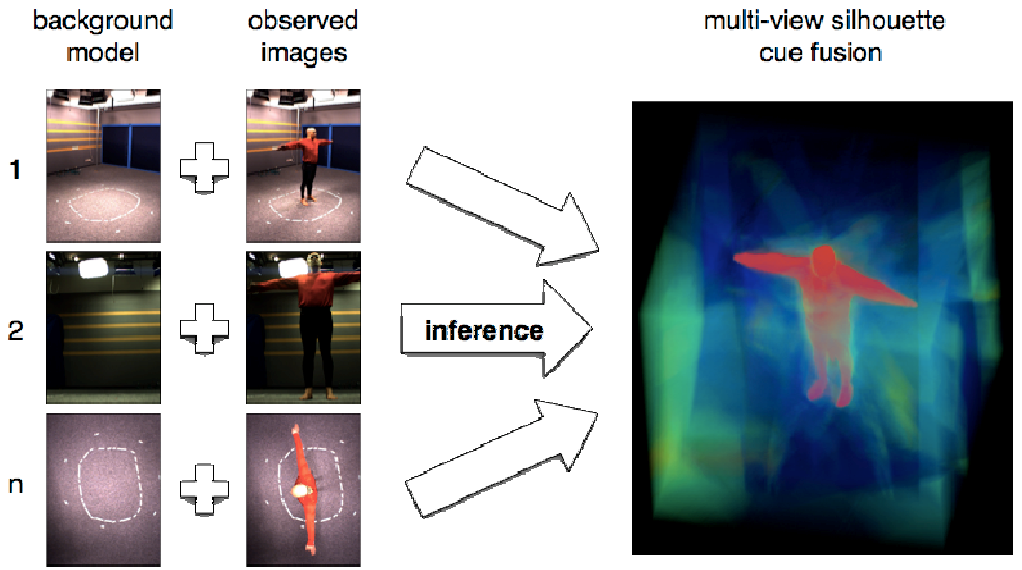
Idea

- Unreliable silhouettes: do not make decision about their location
- Do sensor fusion: use all image information simultaneously



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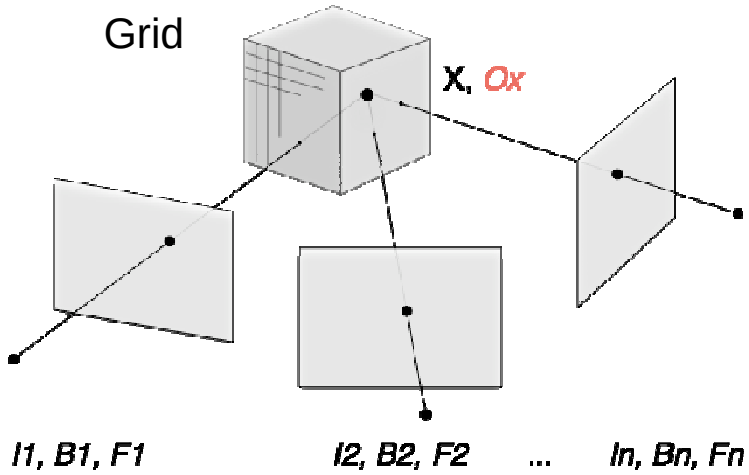
Modeling



Sensor model:

$$P(I \mid O_X) = \sum_F P(I \mid F, B) P(F \mid \mathrm{O}_X)$$

Inference:

$$P(O_X \mid I) = \frac{\prod_{img,pixel} P(I_{img,pixel} \mid \mathrm{O}_X)}{\sum_{O_X} \prod_{img,pixel} P(I_{img,pixel} \mid \mathrm{O}_X)}$$

- I: color information in images
- B: background color model
- F: silhouette detection variable (0 or 1): hidden
- Ox: occupancy at voxel X (0 ou 1)

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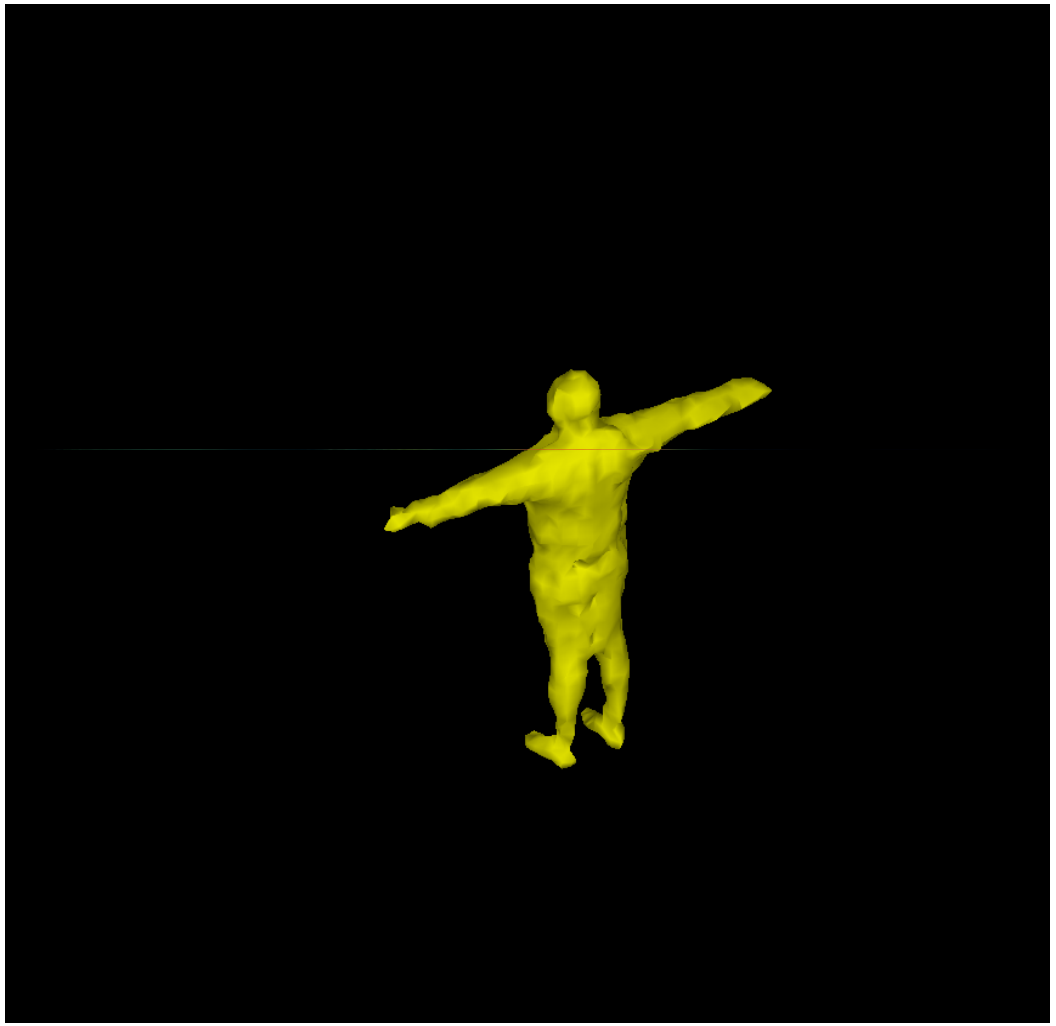
Visualization



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