Time-Warped Foveated Rendering for Virtual Reality Headsets

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Motivation

Virtual Reality allows:

- Immersive experience
- Exploration of virtual worlds

VR Headsets have become consumer products

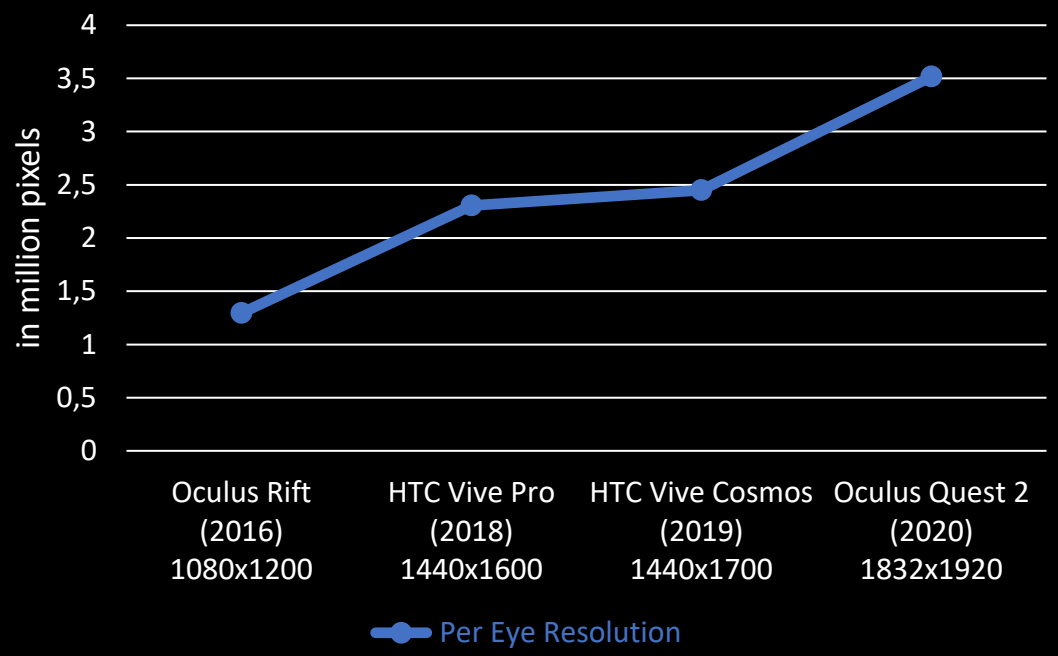
Source: No Man's Sky, Hello Games

Motivation

Rendering for VR is expensive

- High framerate requirements (>70 Hz)
- Over the last years, HMD resolutions increased drastically

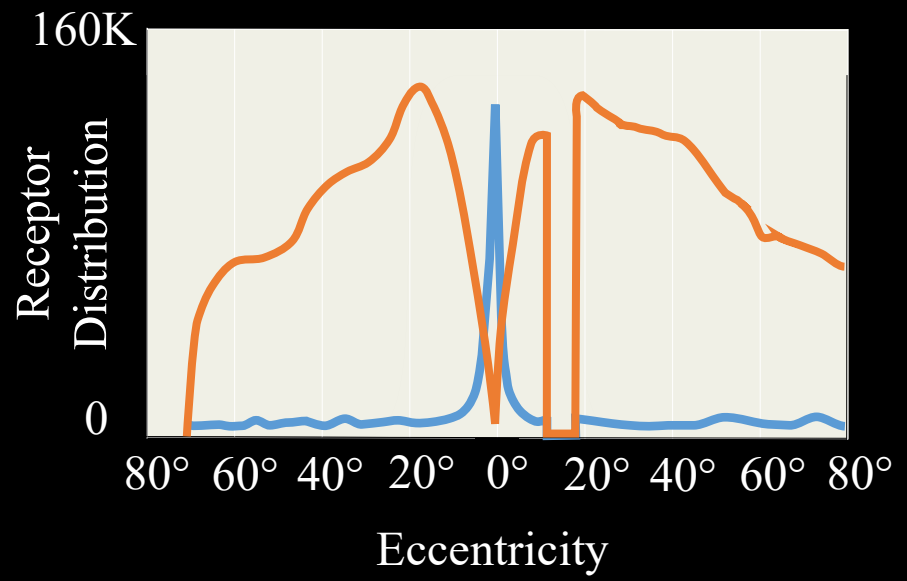
A solution is to exploit weaknesses in the human visual system



Properties of the Human Visual System (simplified)

Cones: High spatial resolution

Rods: High temporal resolution, less spatial resolution



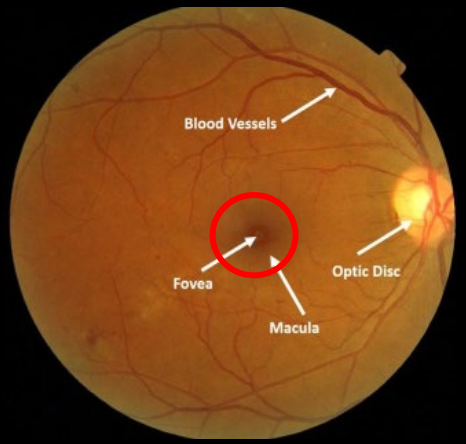
Graphs adapted from Weier et al. 17 and Goldstein 16

Properties of the Human Visual System (simplified)

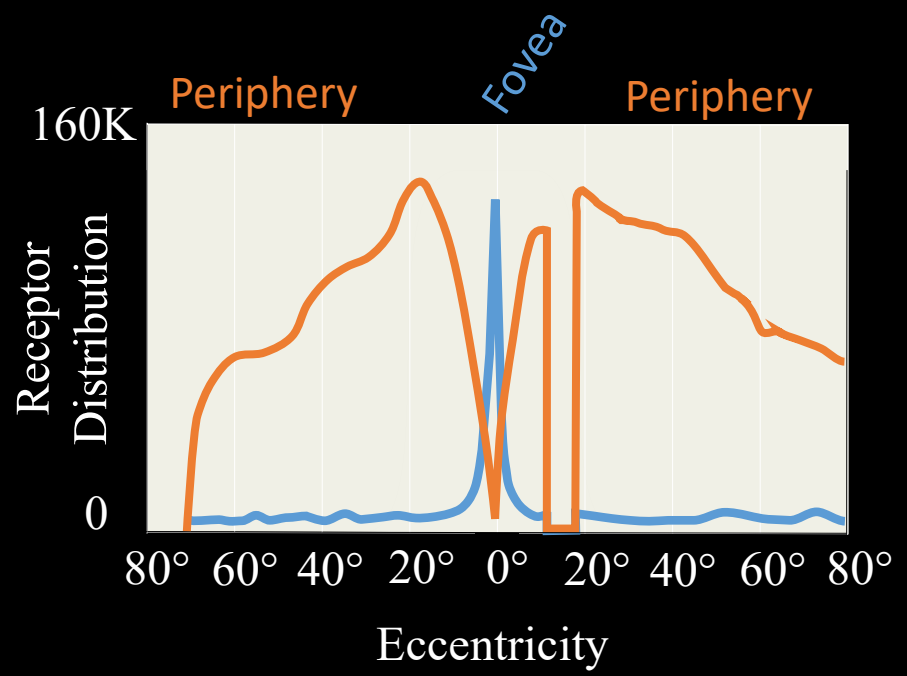
For us, this differentiates the Visual System into two parts:

- Foveal region (or Fovea), from 0° to ~7° eccentricity

- Peripheral region



Source: Al-Bander et al. 17

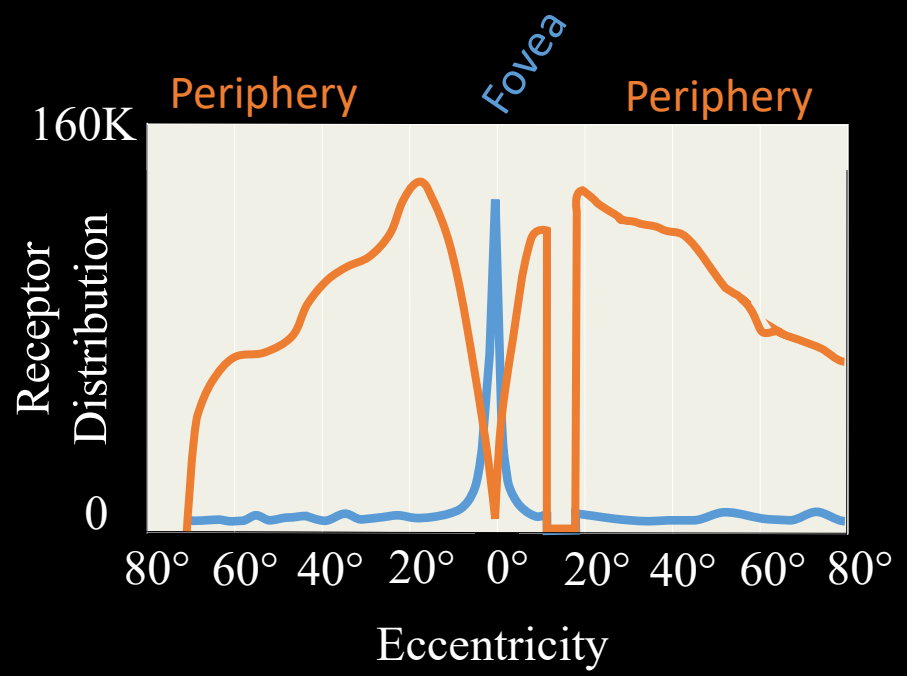


Graphs adapted from Weier et al. 17 and Goldstein 16

Foveated Rendering

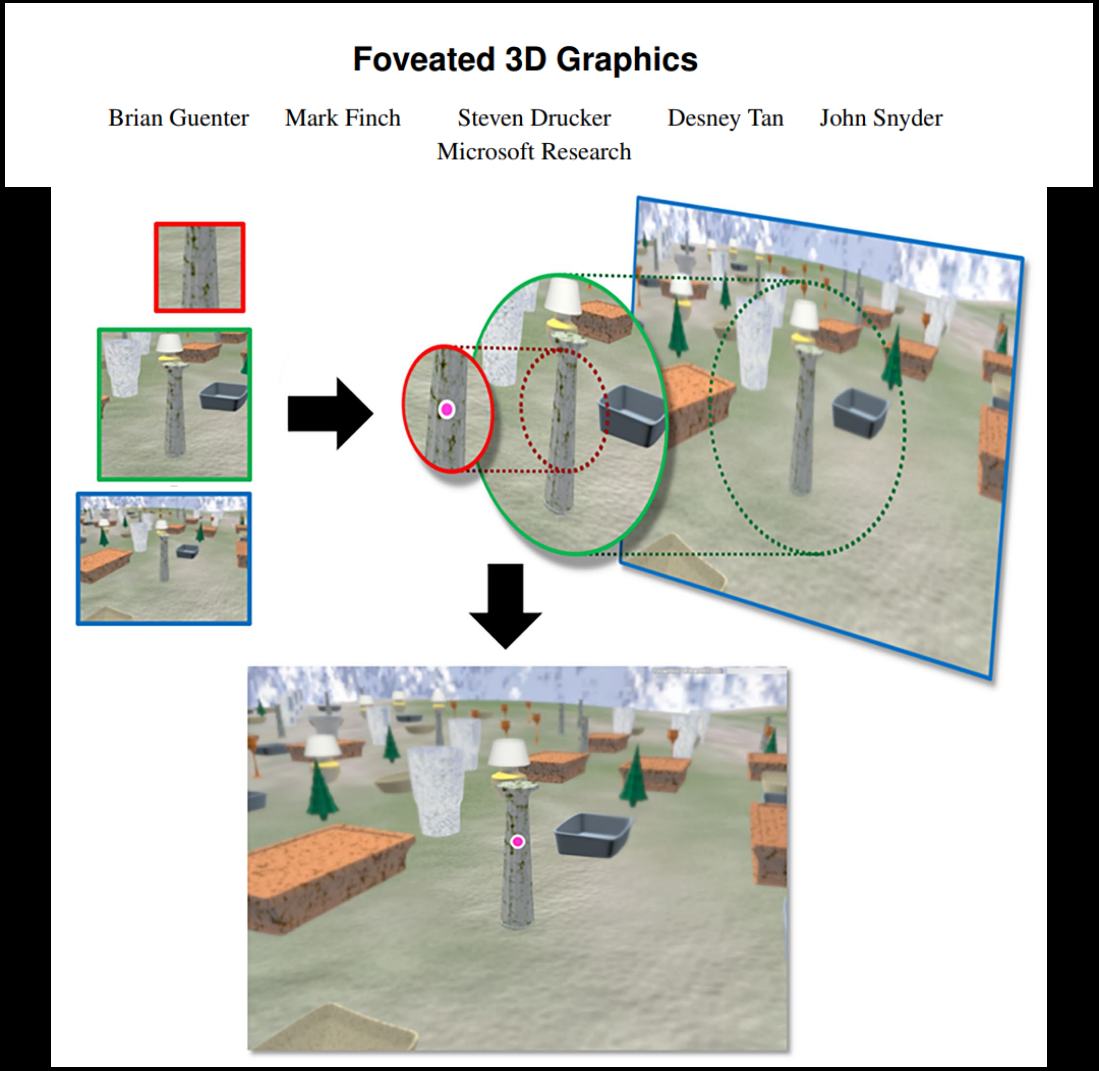
Sensory non-uniformity can be exploited for faster rendering

Requirement: Knowledge of the user's gaze,
usually via real-time ***Eye-Tracking***



Graphs adapted from Weier et al. 17 and Goldstein 16

Foveated Rendering: Related Work



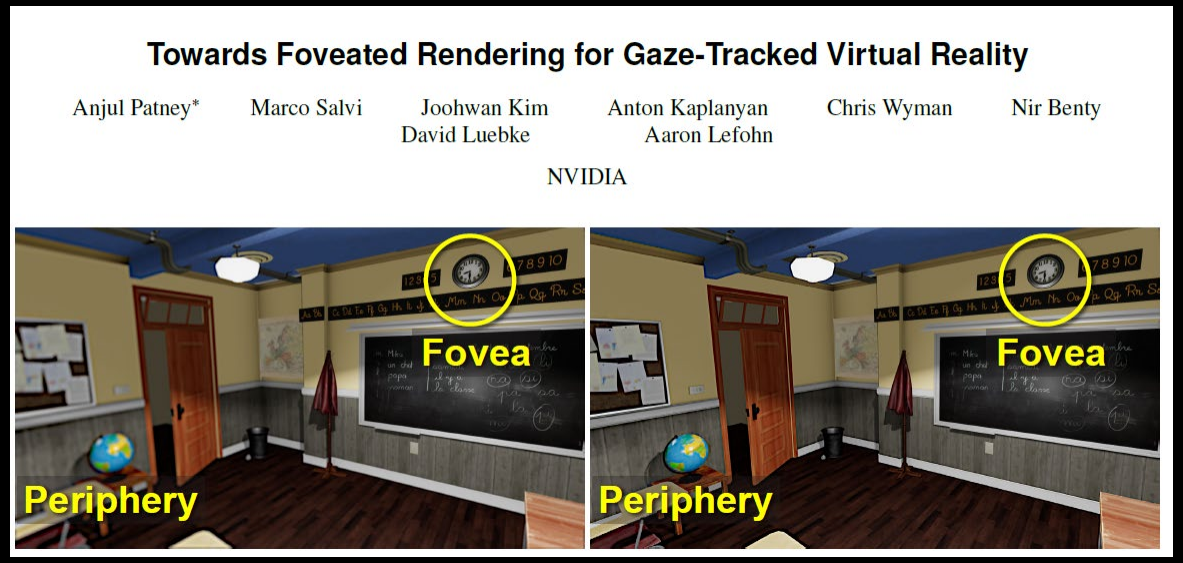
Source: Guenter et al. 2012

Different resolutions approach:

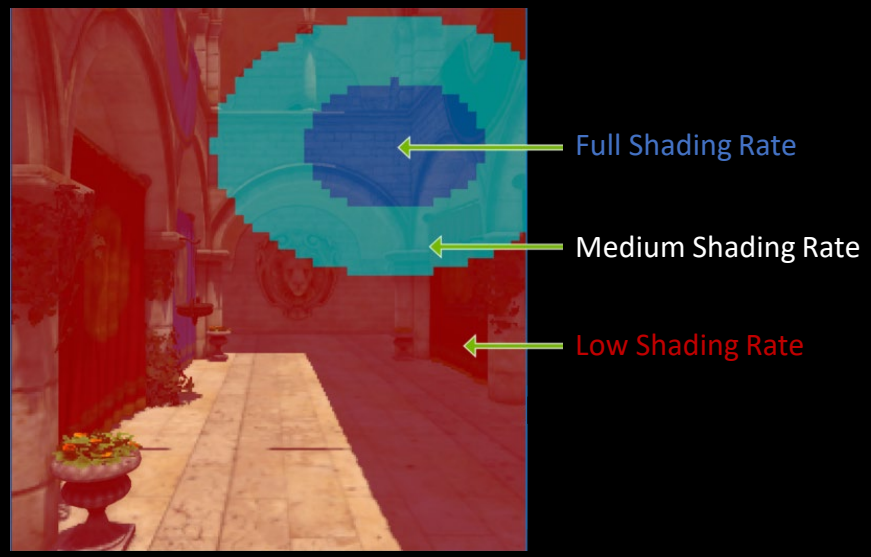
- Full resolution in the fovea
- Progressively lower resolutions for peripheral regions

Strong Anti-aliasing necessary

Foveated Rendering: Related Work



Source: Patney et al. 2016



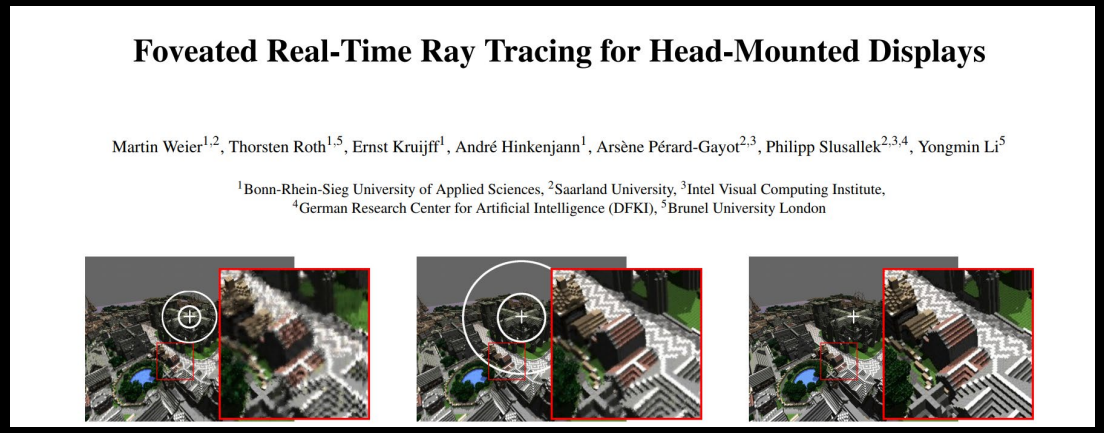
Source: Swaroop Bhonde, Nvidia 2019

Different shading rates approach:

- Shading resolution in the fovea is highest
- Progressively lower rates towards the periphery

No acceleration beyond shading cost

Foveated Rendering: Related Work



Image

Rays per frame

Warped ray-tracing approach:

- Full Samples in the fovea
- Sparsely sample the periphery
- Reuse previous frames for hole-filling and resample

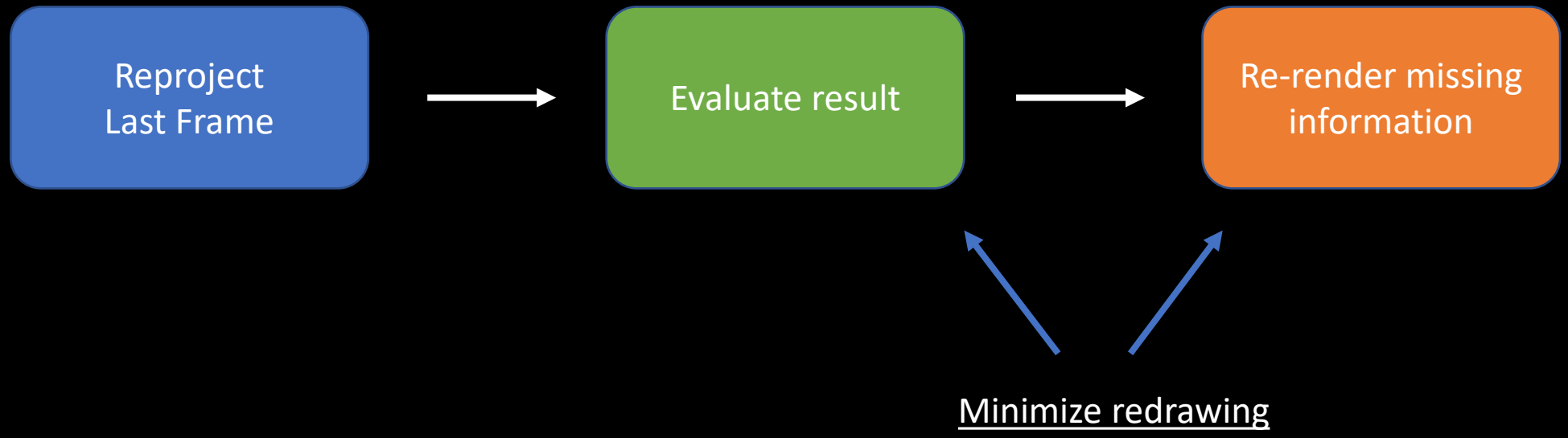
Source: Weier et al. 2016

Time-Warped Foveated Rendering

- Reuse as much samples as possible
- Redraw only what is necessary
- Evaluating cleverly necessary

Time-Warped Foveated Rendering

Outline:

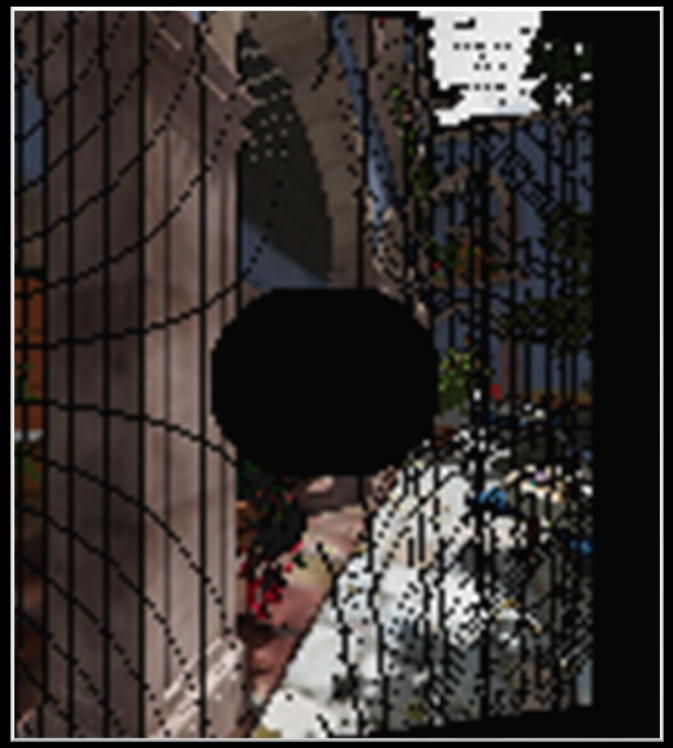


Time-Warped Foveated Rendering

Reproject
Last Frame

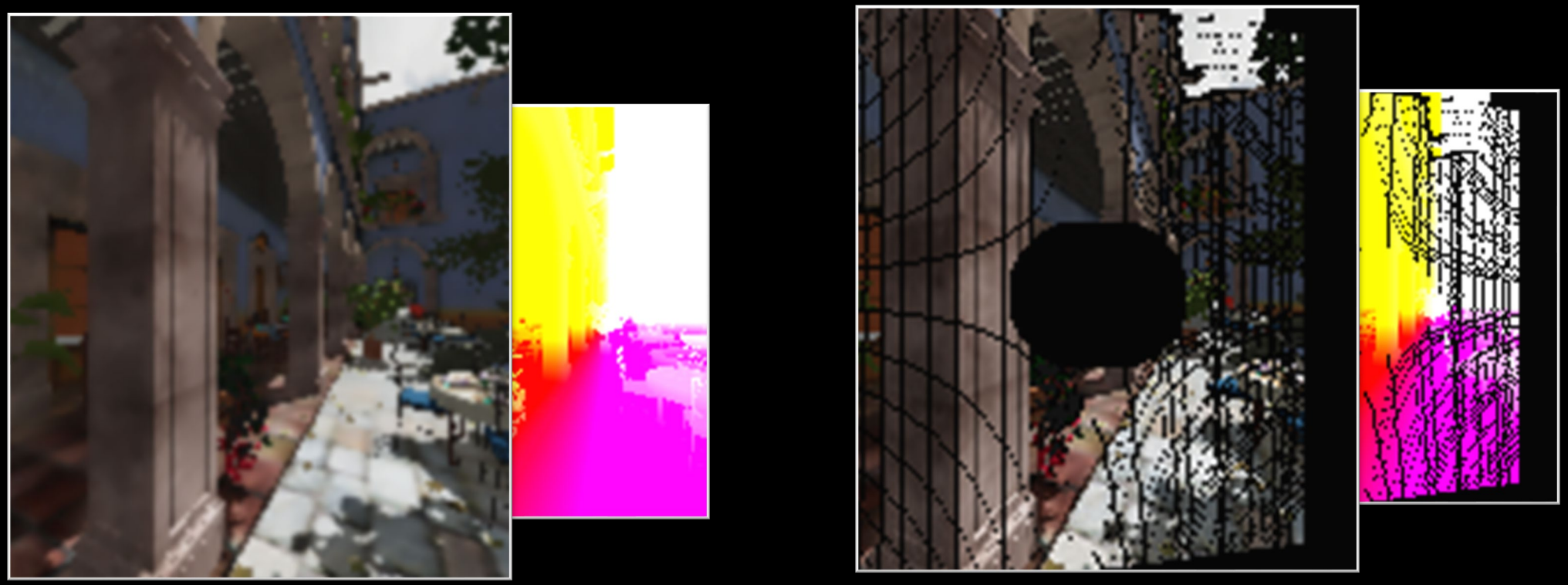
Time-Warped Foveated Rendering

Reproject
Last Frame

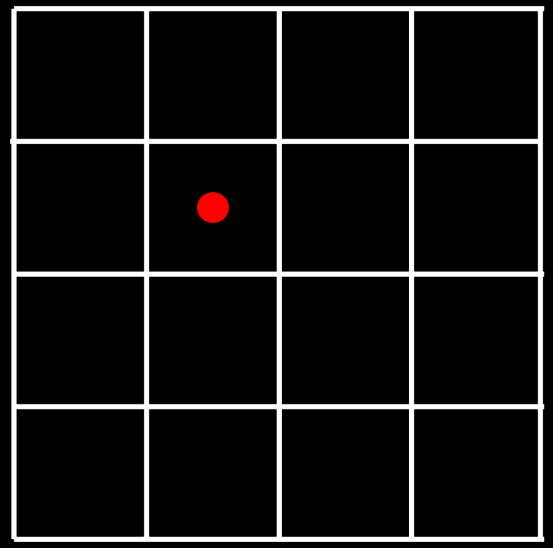


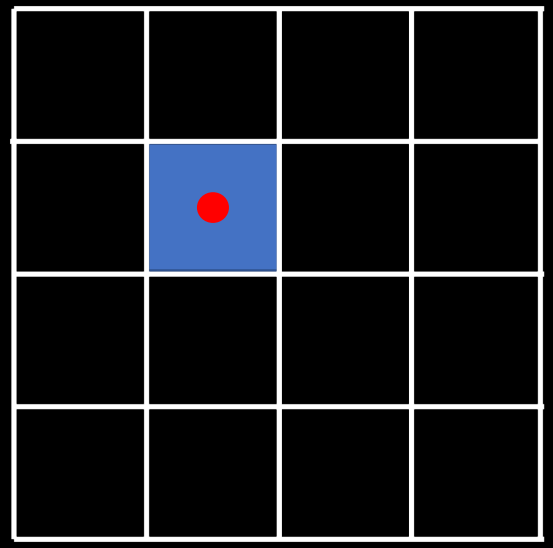
Forward warping

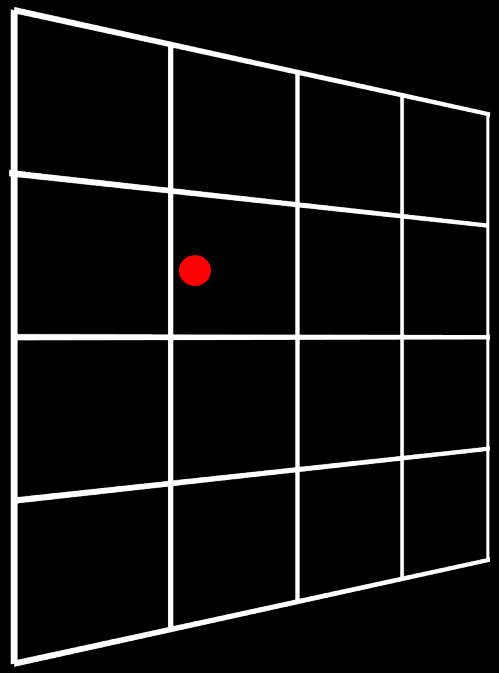
Time-Warped Foveated Rendering

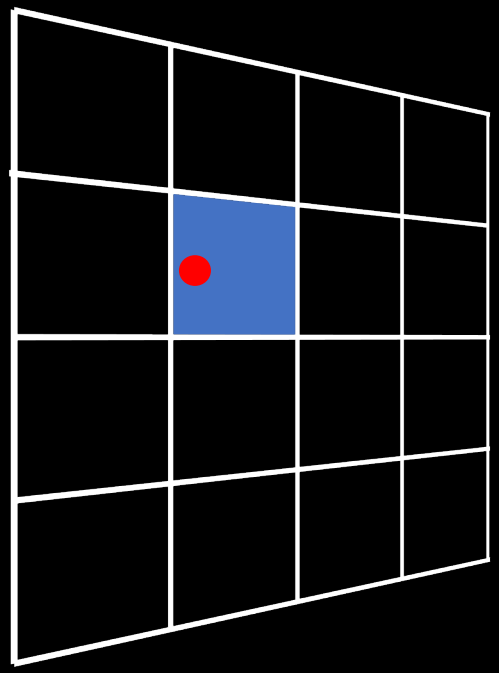


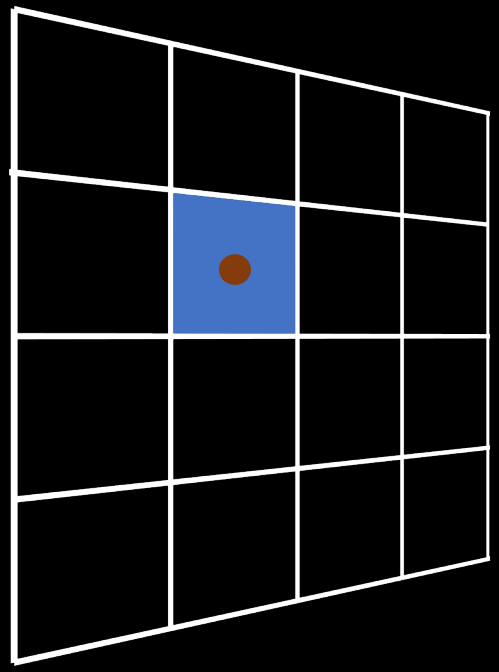
Forward warping, using world position buffer

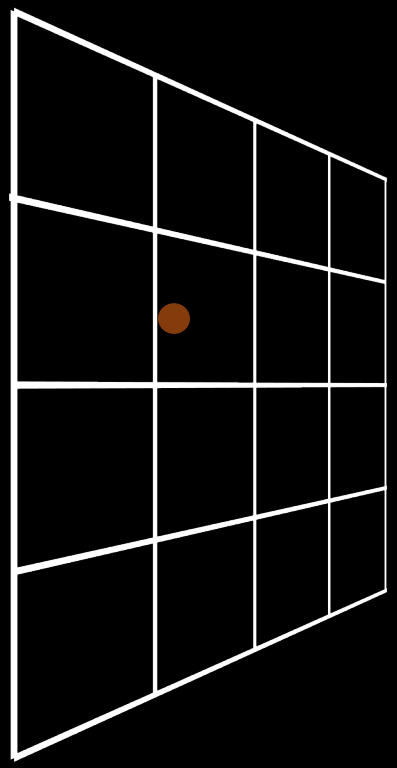


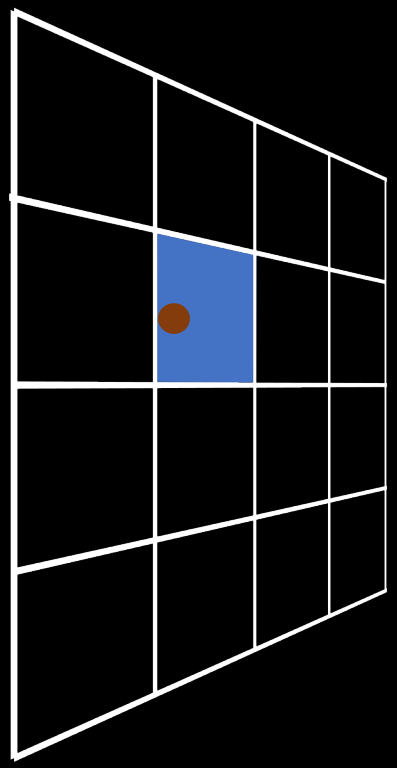


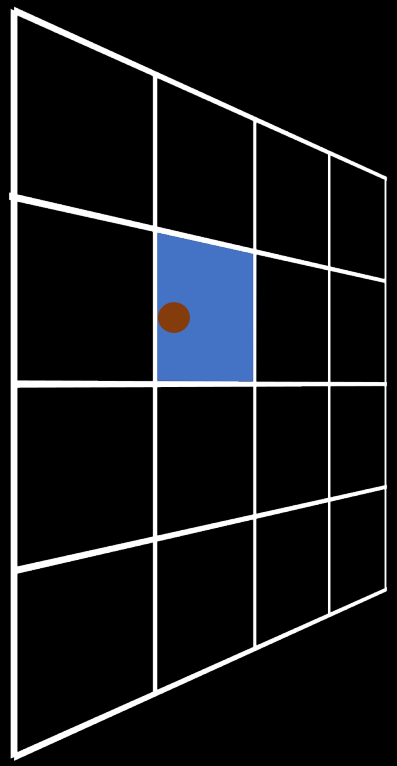


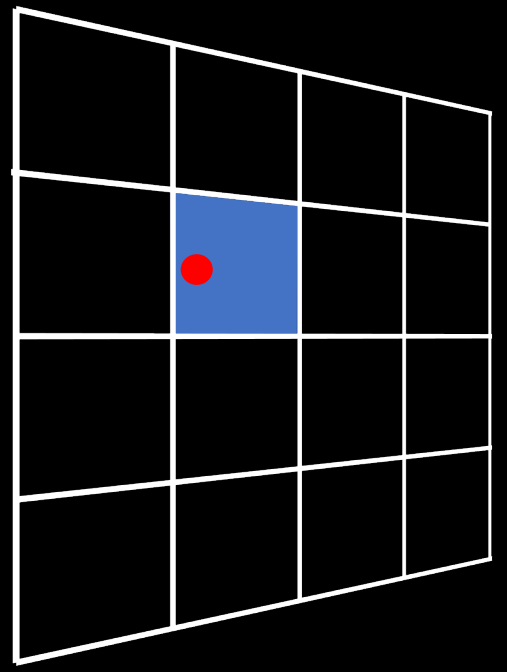


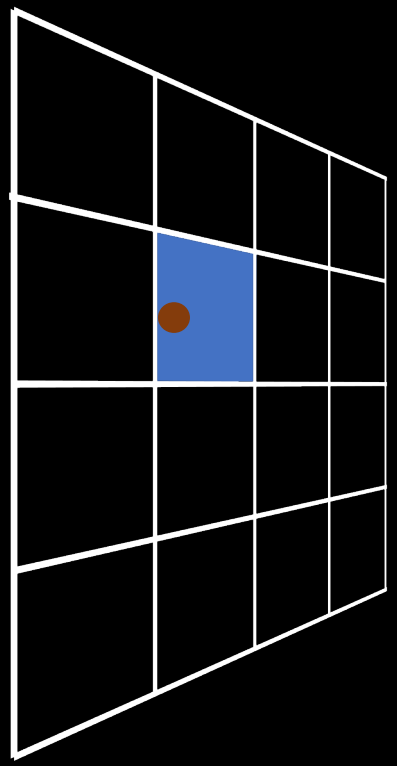


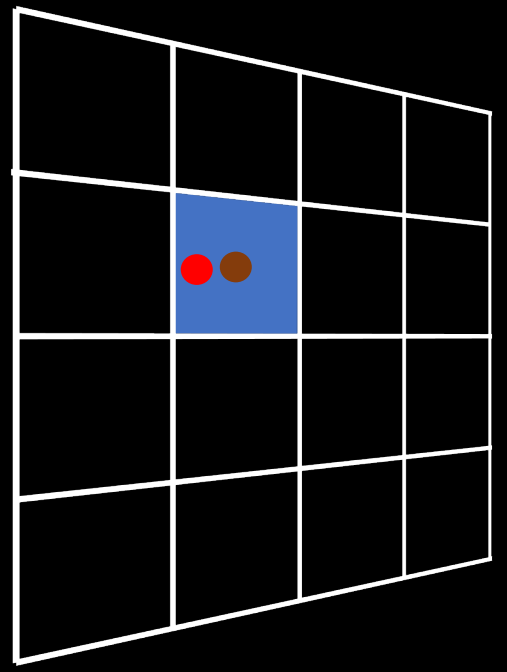


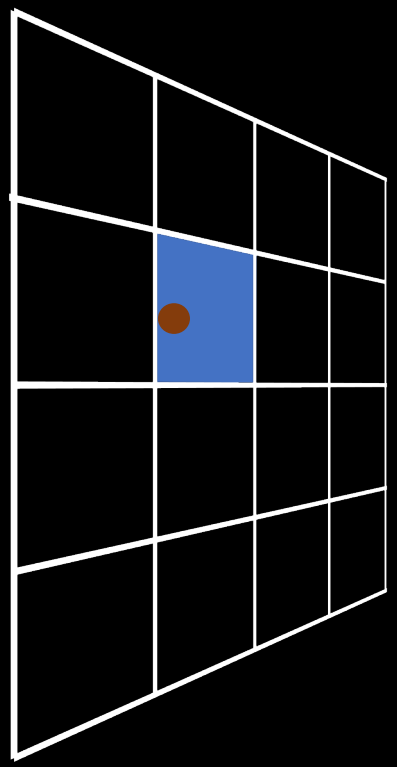


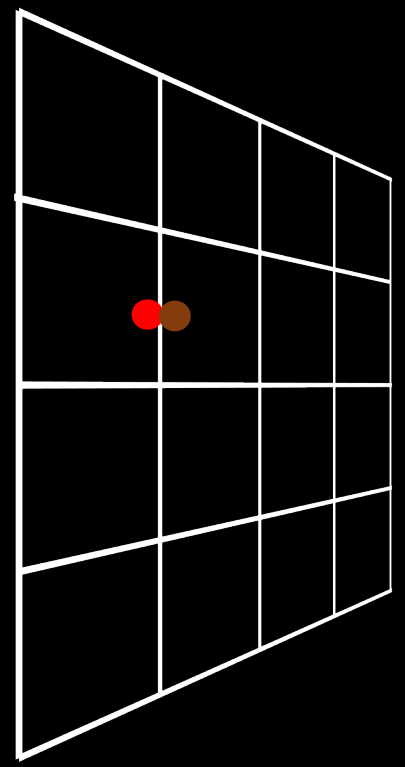


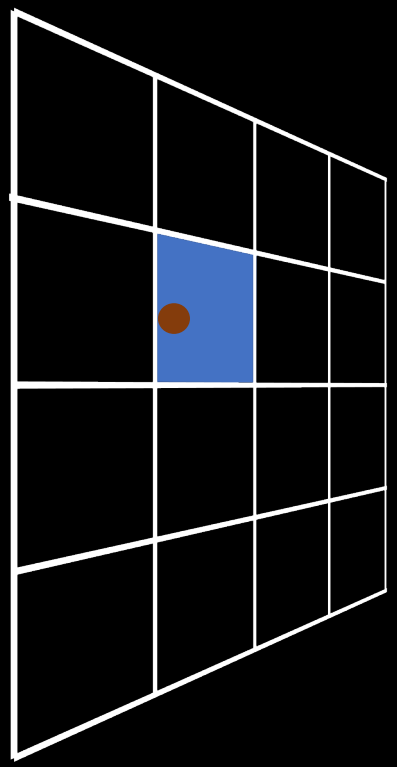


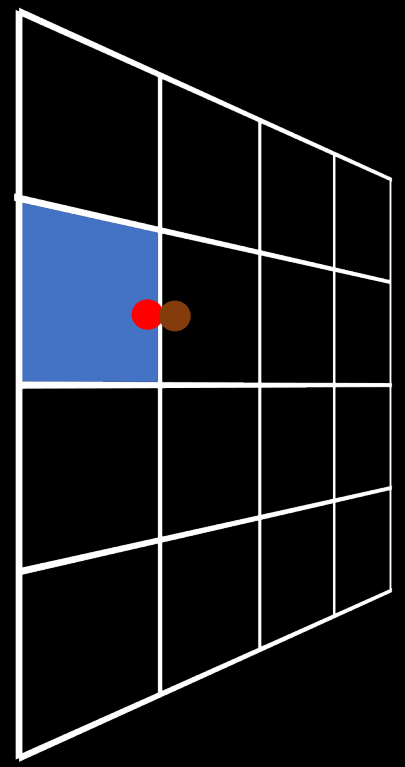




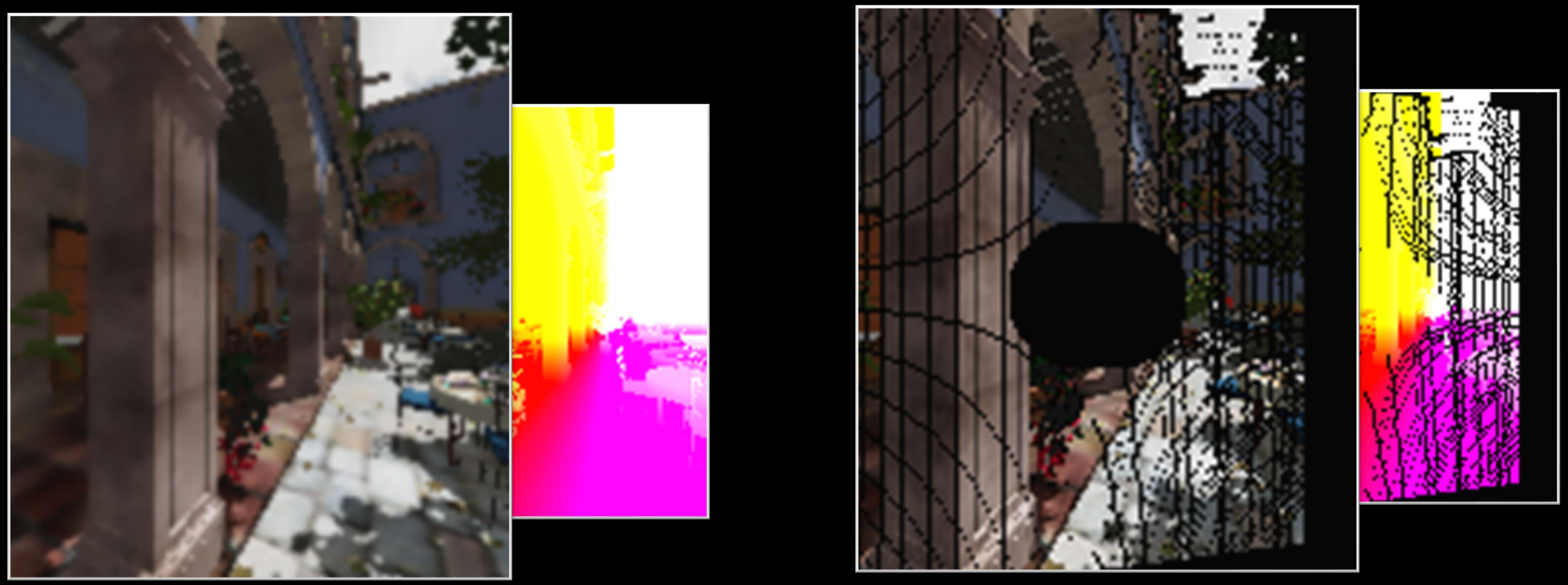








Time-Warped Foveated Rendering



Forward warping, using world position buffer

Time-Warped Foveated Rendering

Evaluate result

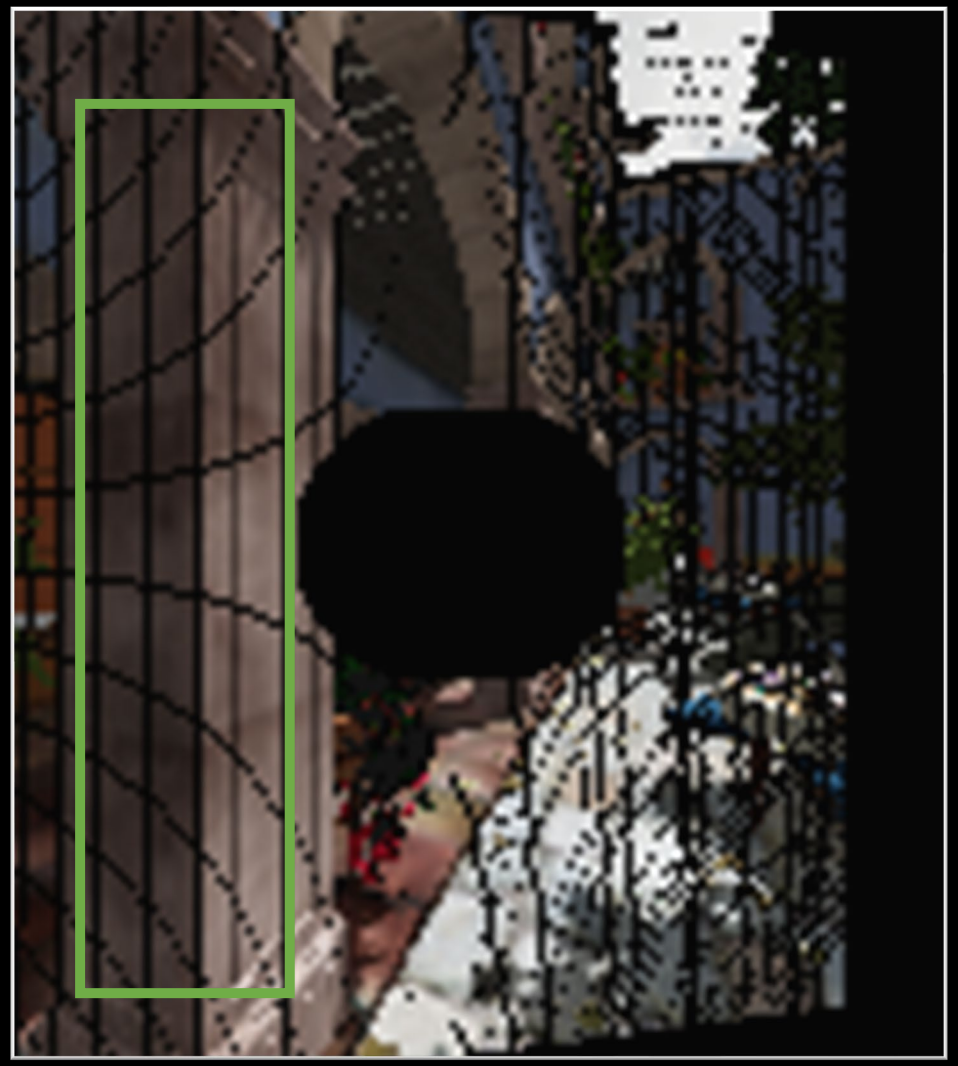
Time-Warped Foveated Rendering

Evaluate result

Time-Warped Foveated Rendering

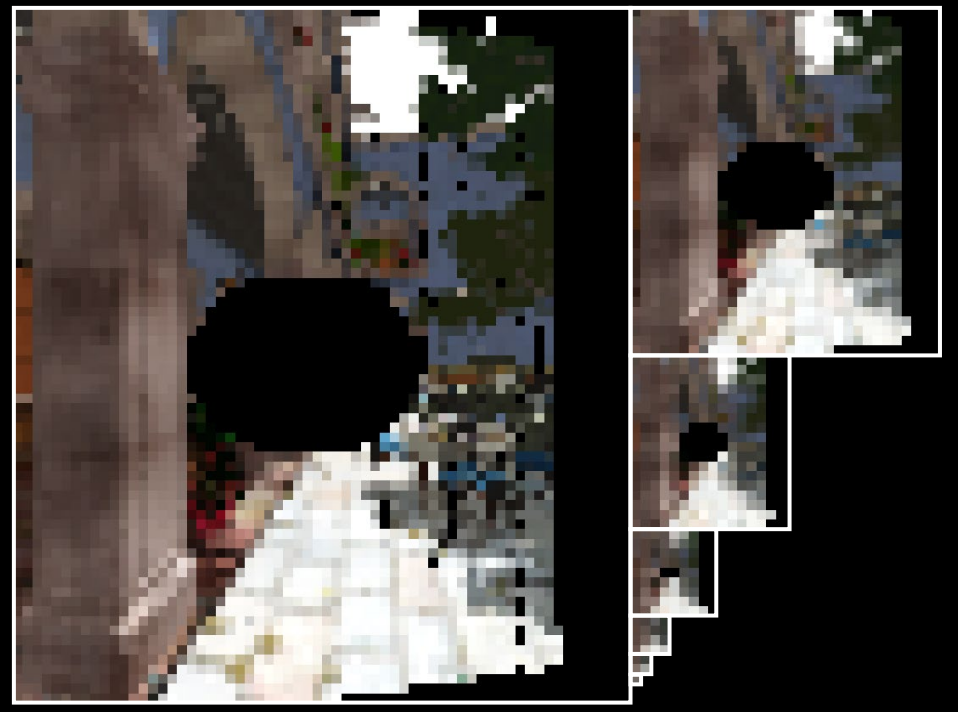
LGDV

Evaluate result



Time-Warped Foveated Rendering

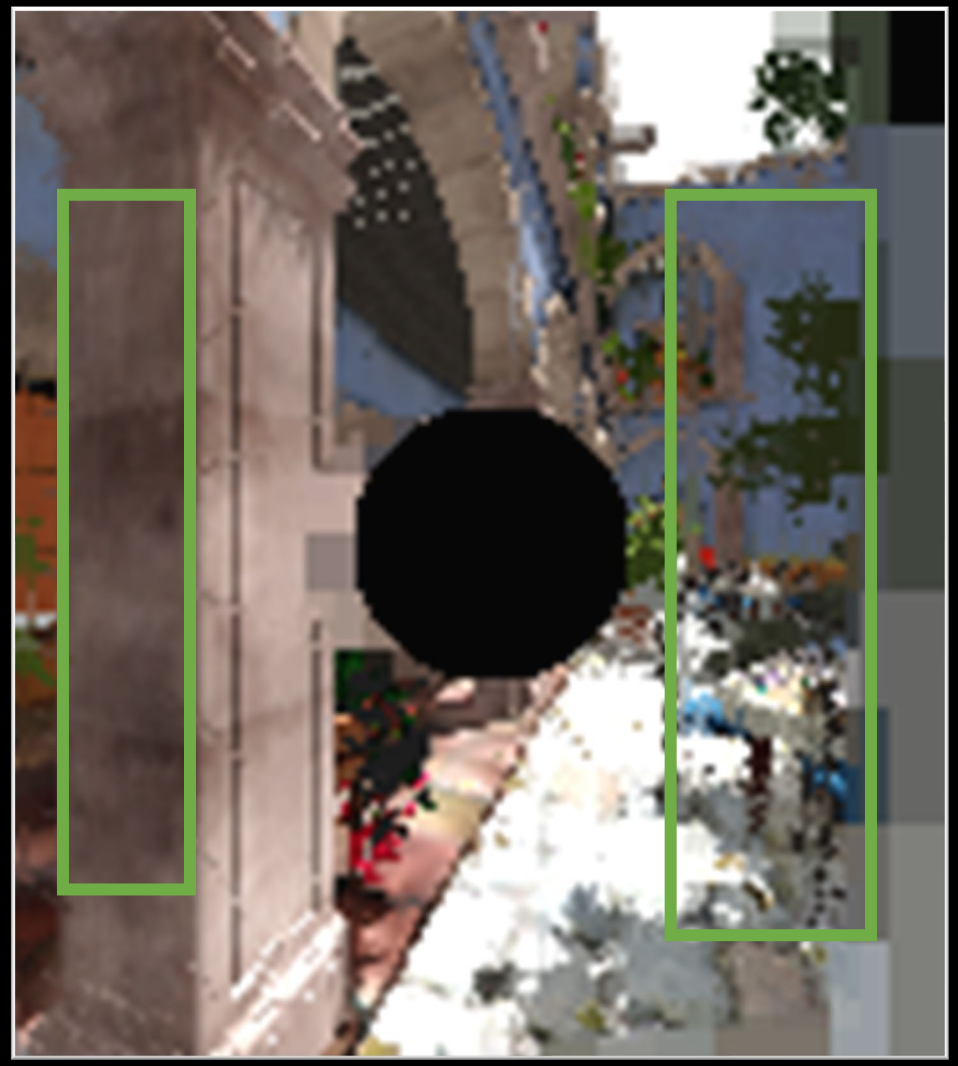
Reprojection



Hole-fill Mipmap

Time-Warped Foveated Rendering

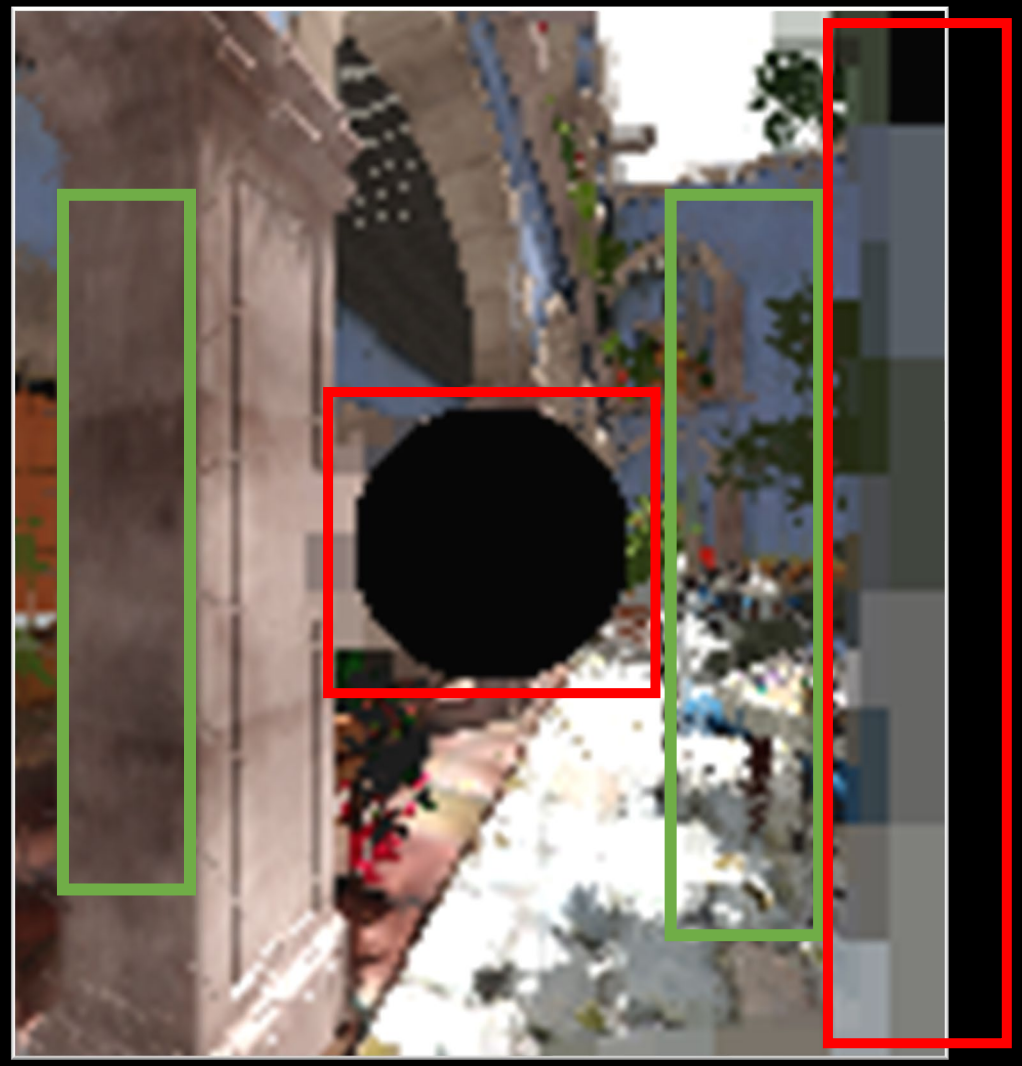
Time-Warped Foveated Rendering



Hole-filled image

Reprojection only

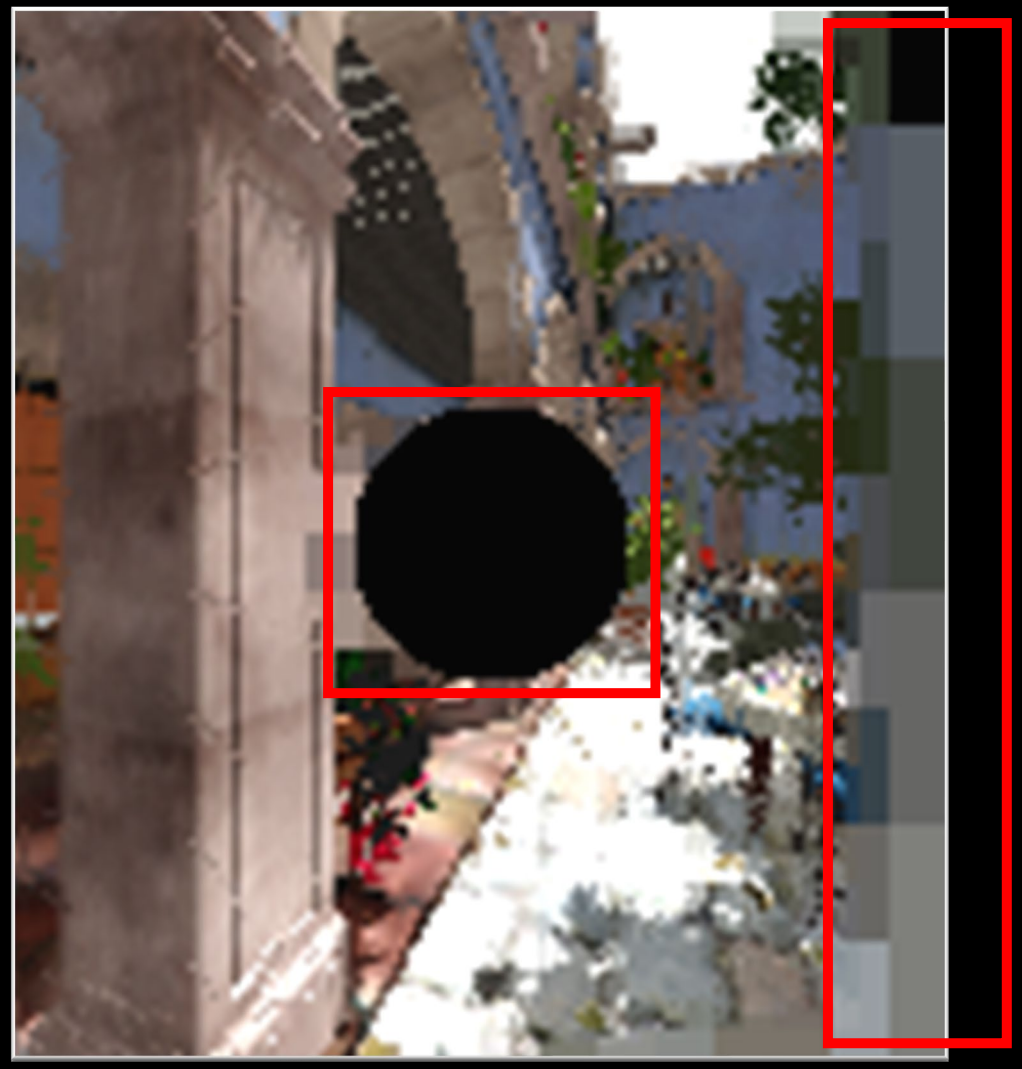
Time-Warped Foveated Rendering



Hole-filled image

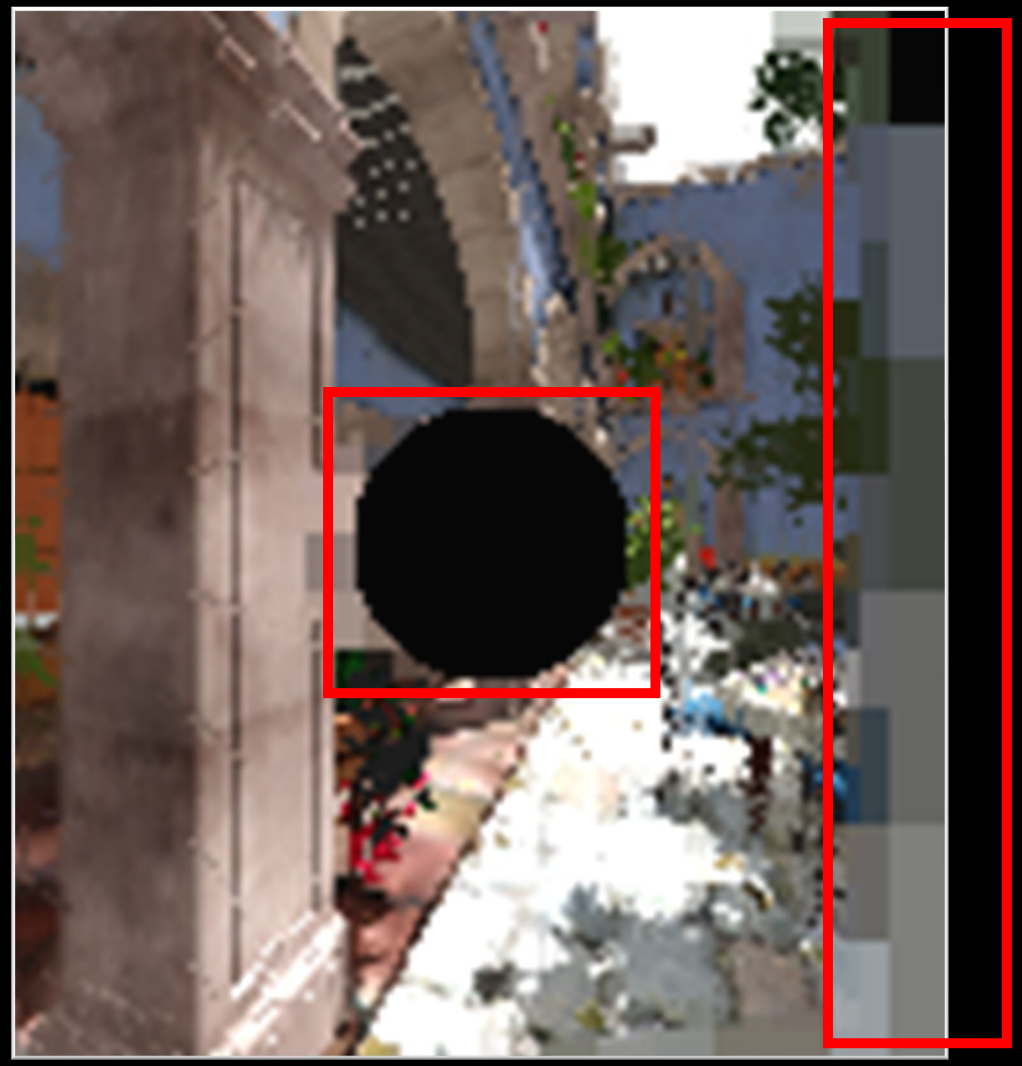
Reprojection only

Time-Warped Foveated Rendering

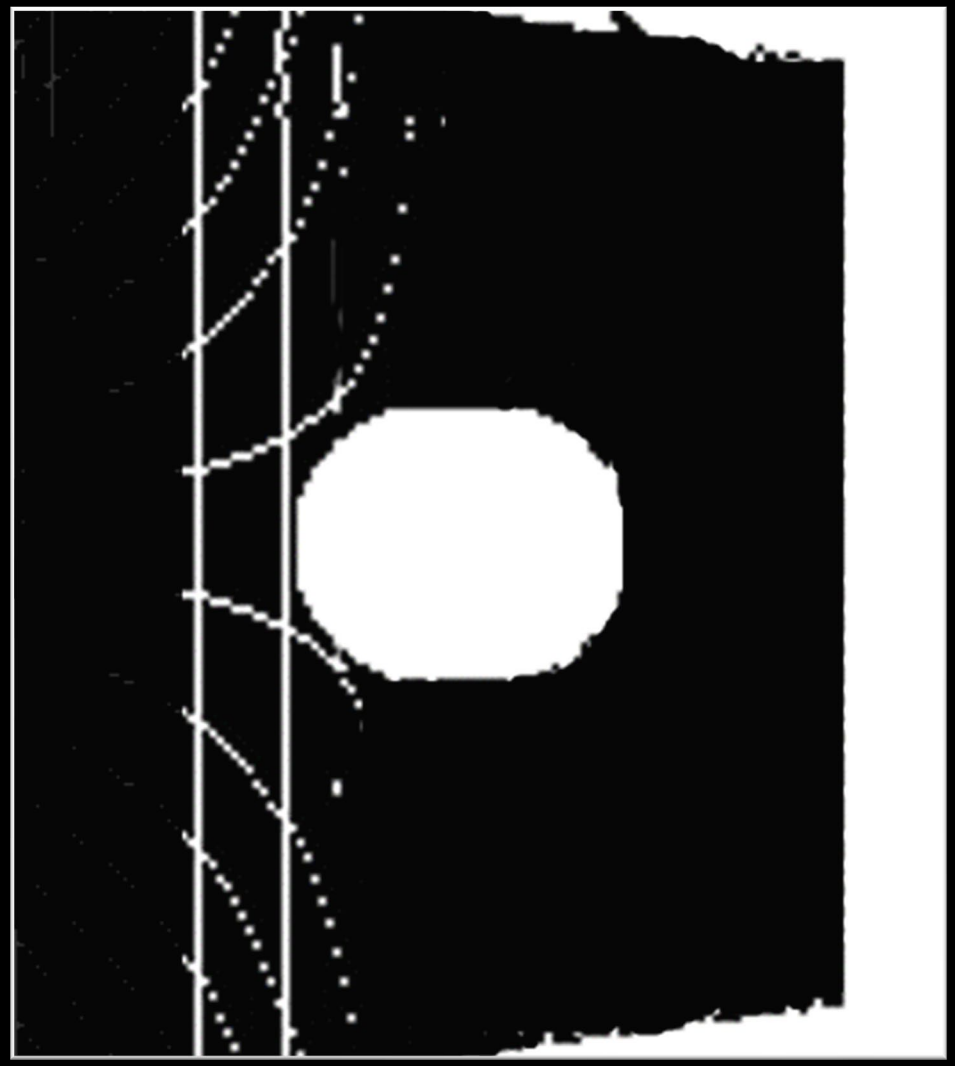


Hole-filled image

Time-Warped Foveated Rendering

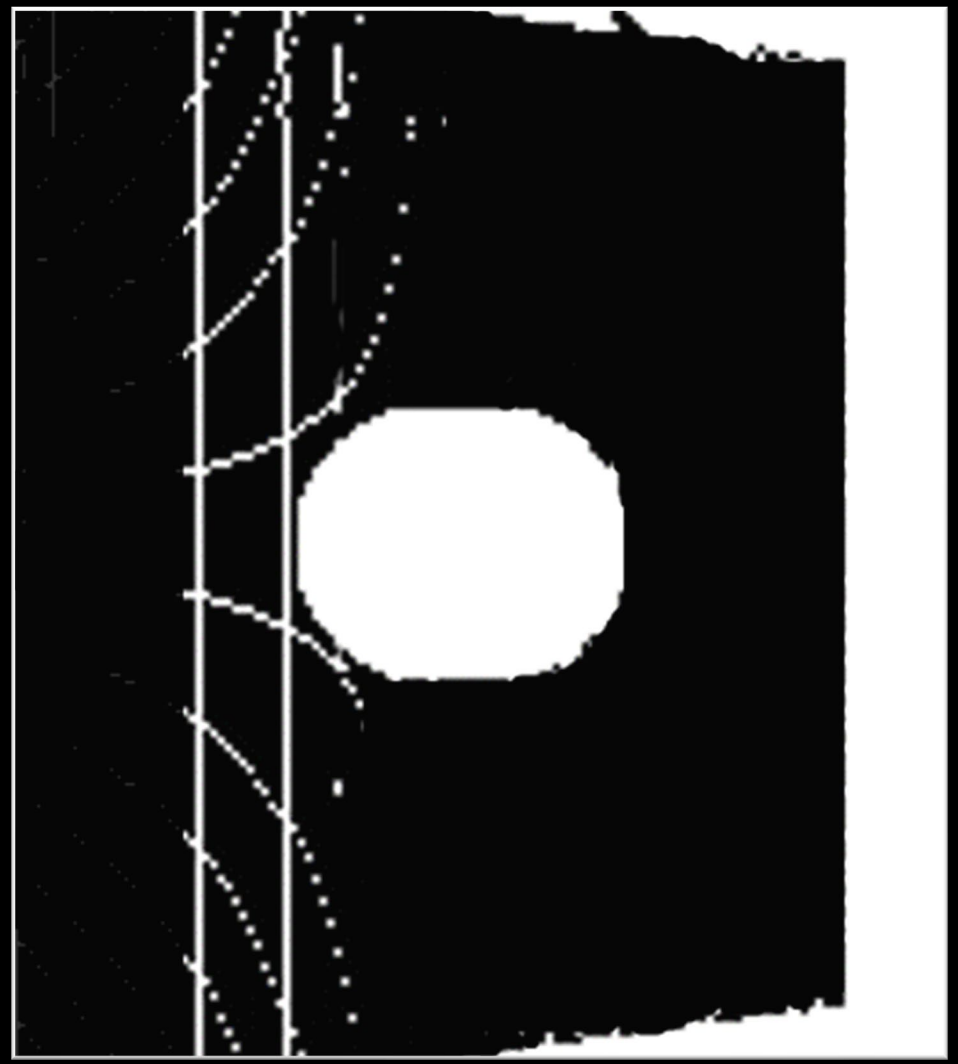


Hole-filled image



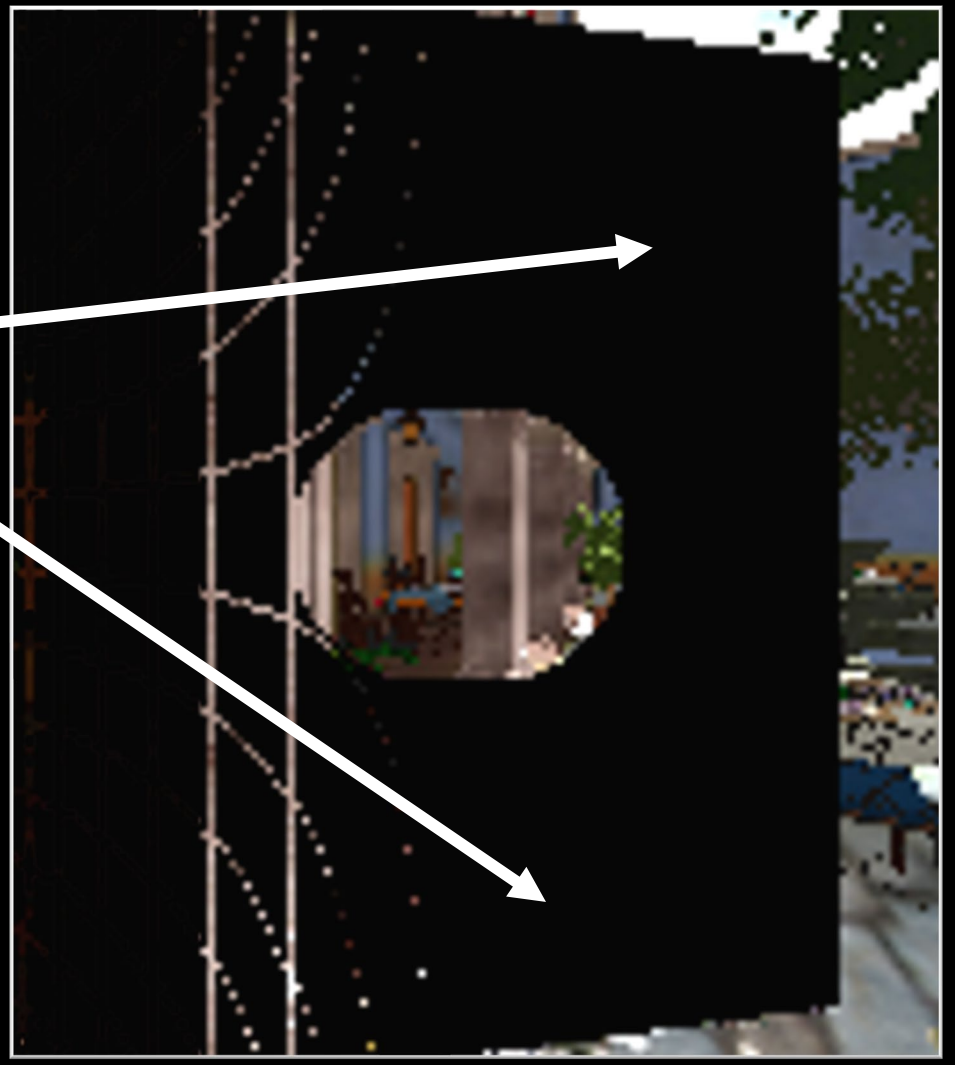
Redraw Map

Time-Warped Foveated Rendering



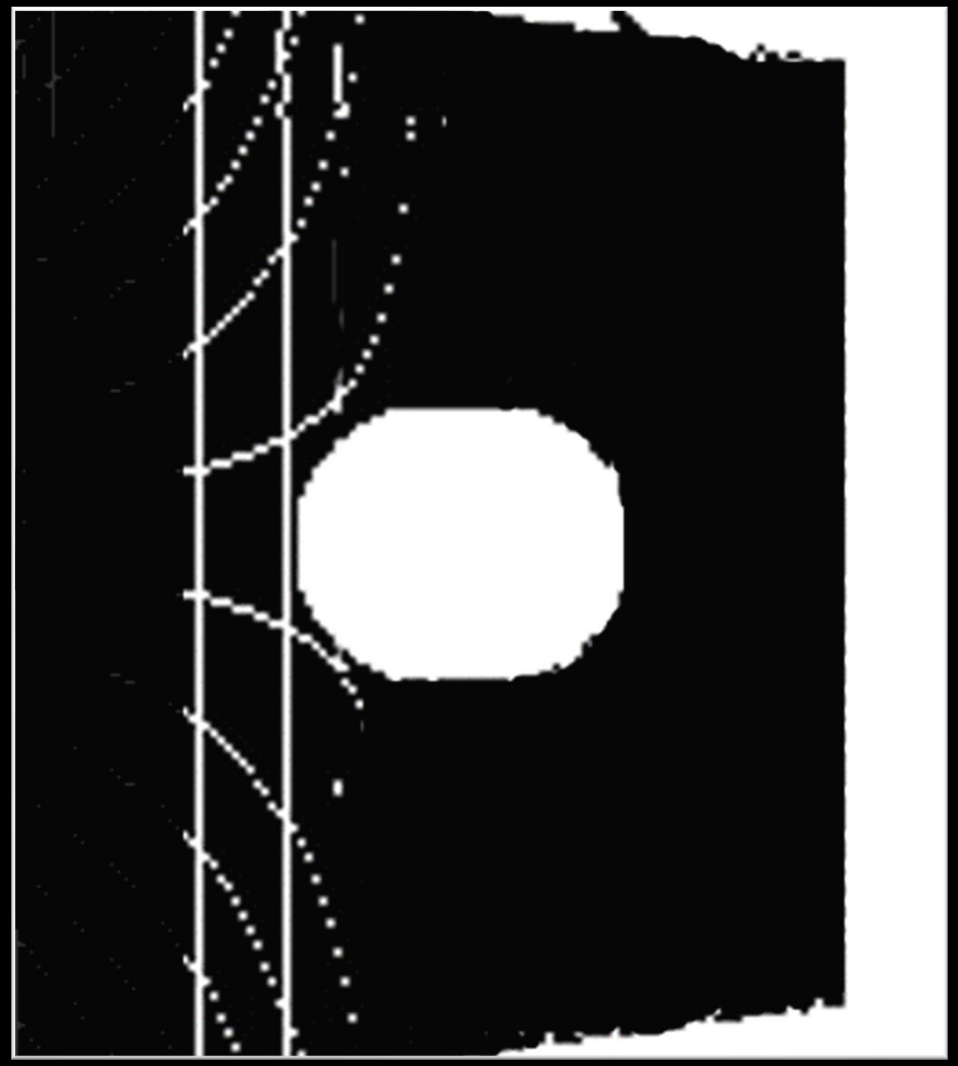
Redraw Map

Hierarchical culling of objects



Rendered freshly

Time-Warped Foveated Rendering

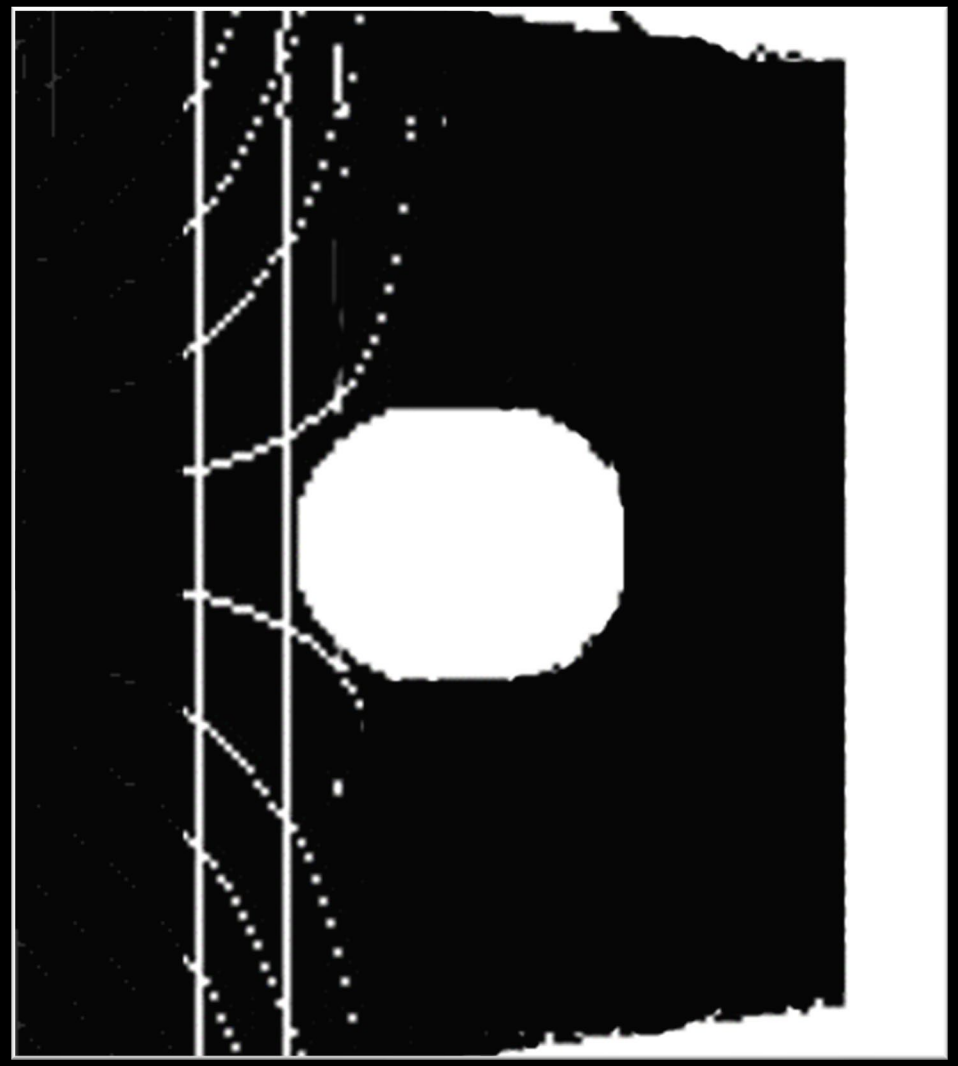


Redraw Map

Hierarchical culling of objects

Rendered freshly

Time-Warped Foveated Rendering



Redraw Map

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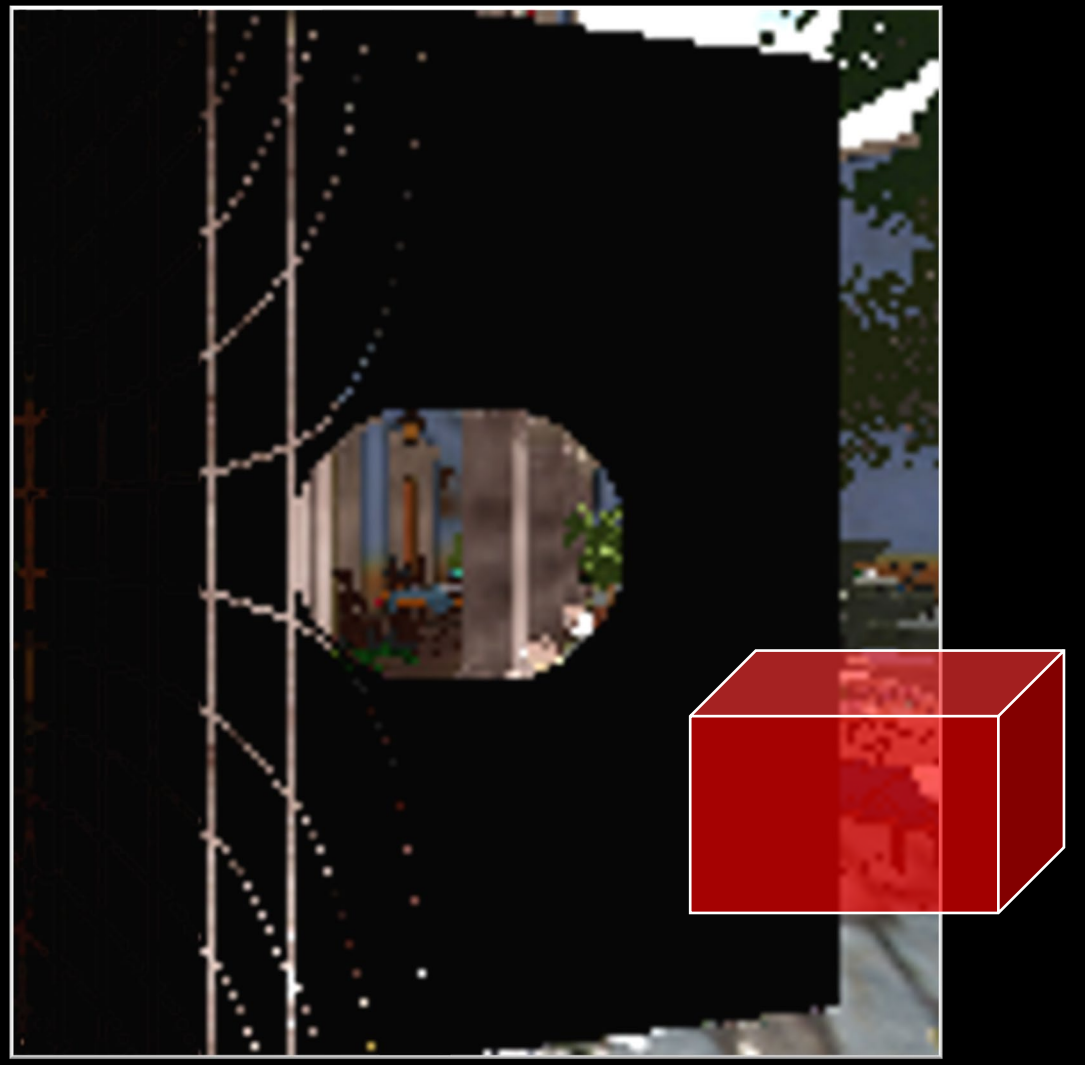
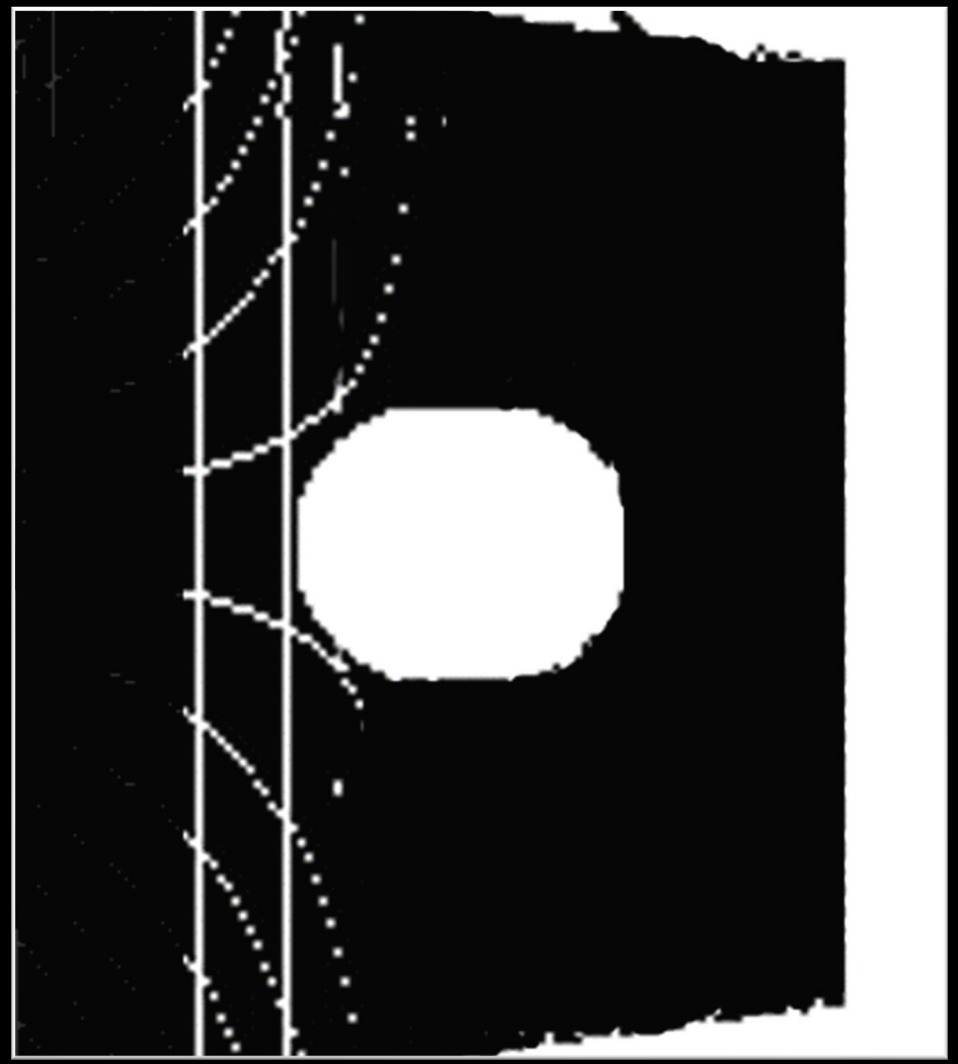


Rendered freshly

Time-Warped Foveated Rendering



Redraw Map

Hierarchical culling of objects

Rendered freshly

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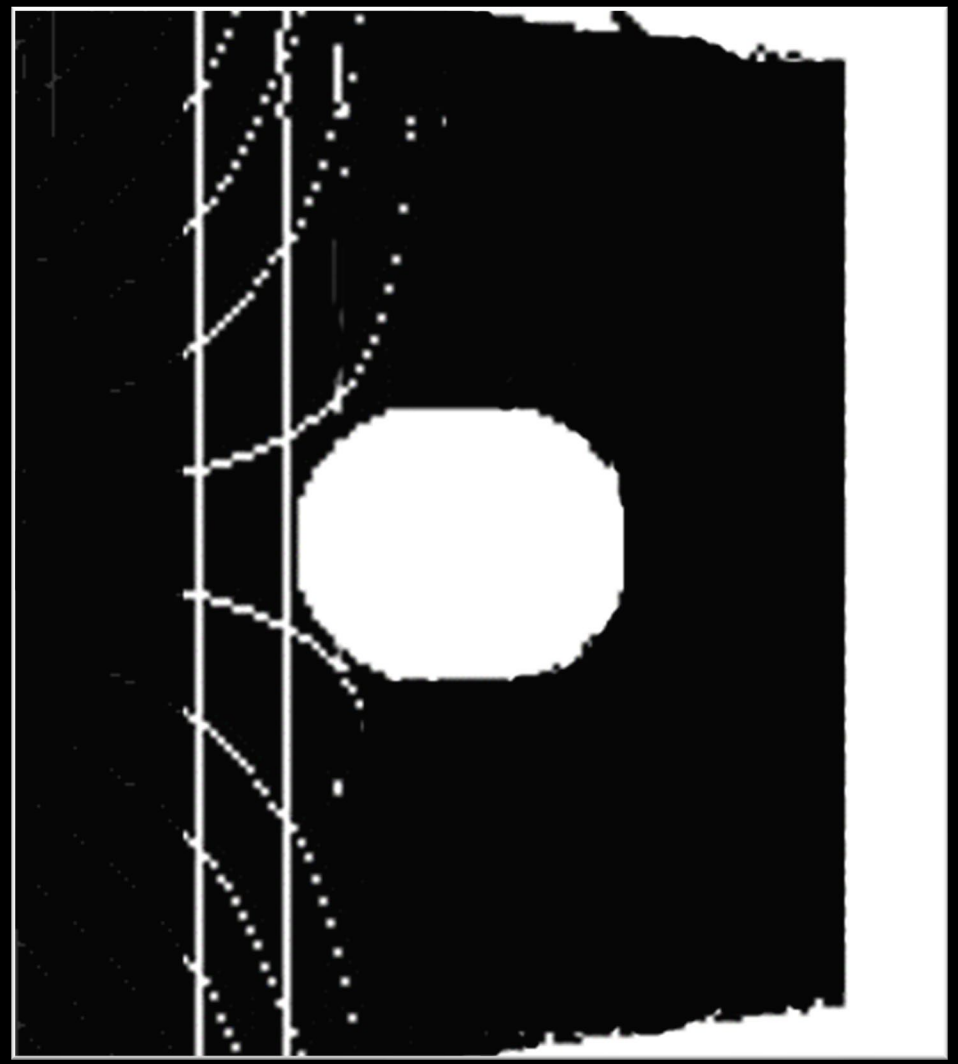

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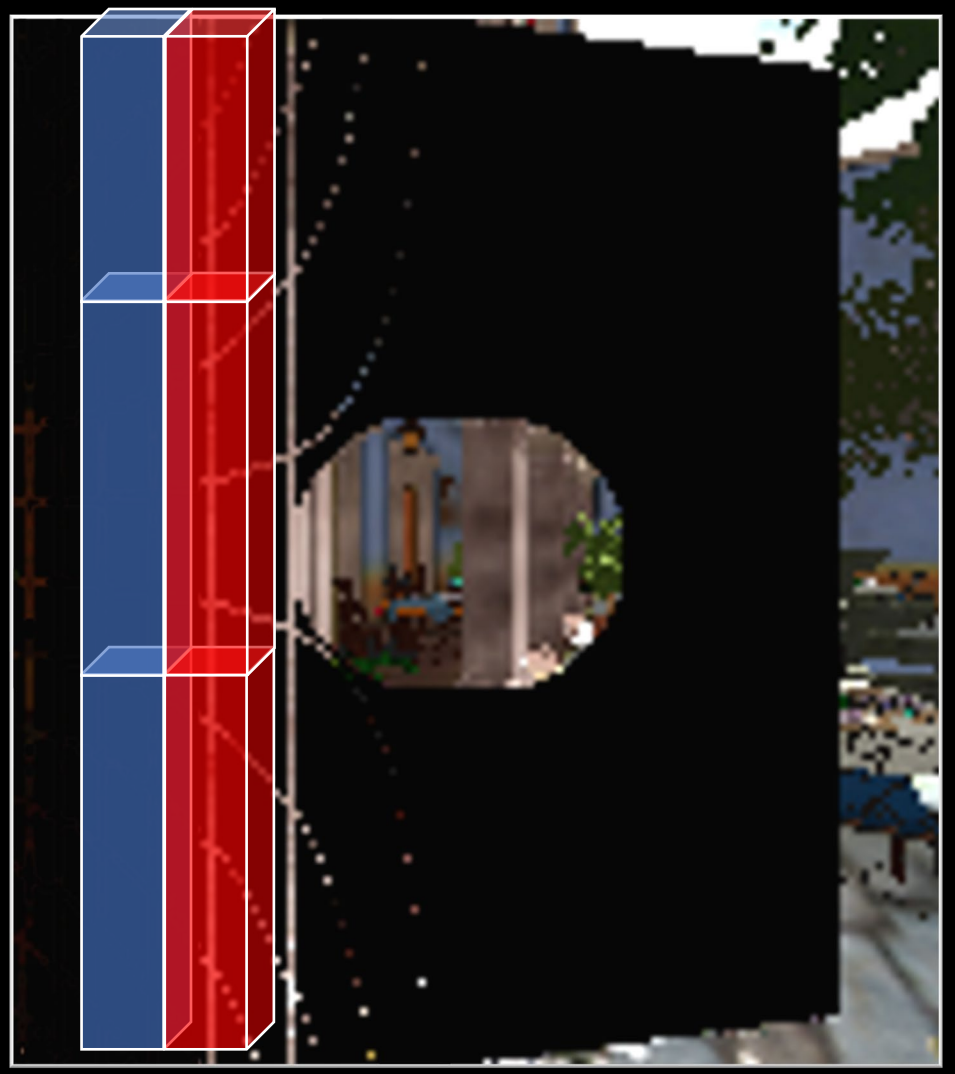


Rendered freshly

Time-Warped Foveated Rendering

Hole-filled

Rendered freshly

Time-Warped Foveated Rendering

Time-Warped Foveated Rendering

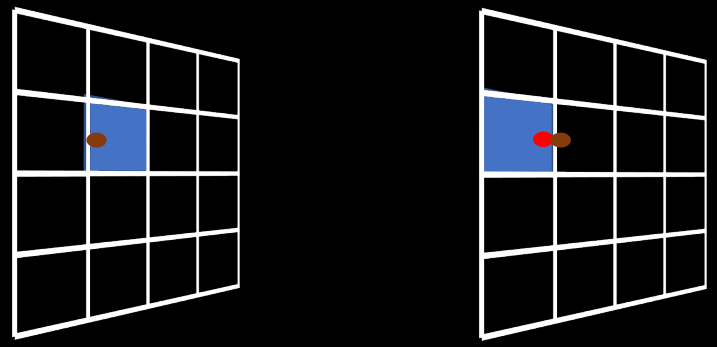
(Almost) Final Image
Used for next frames as input

Motion Smoothing

Redraw is improved by anti-aliasing

Reprojection can use motion smoothing

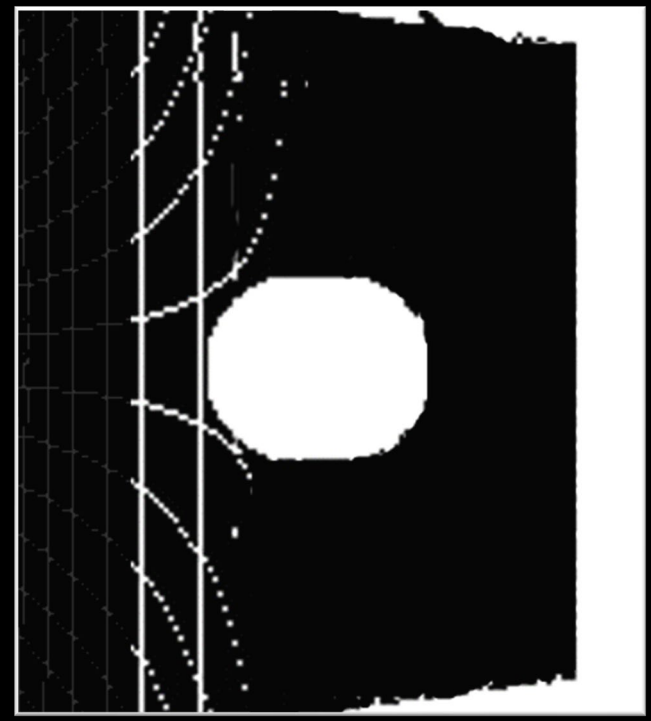
Reuse „inaccurate“ depth based reprojection in TAA pipeline



Confidence

- Formalize redraw decision
- Base on perceptual and reprojection characteristics

Confidence Function



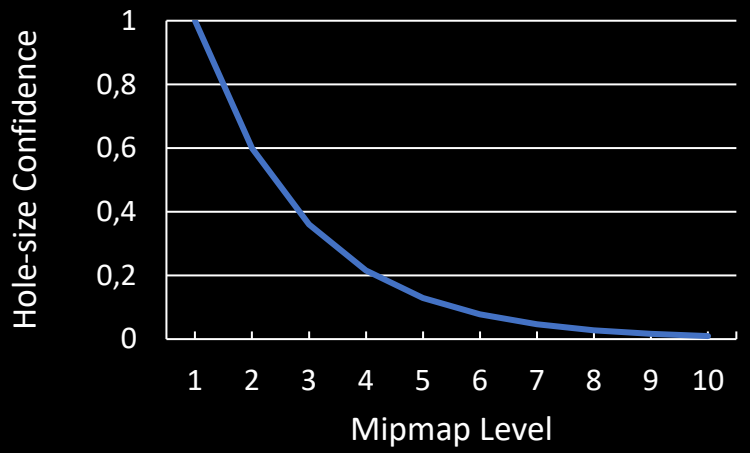
Confidence

Three main factors:

Confidence

Three main factors:

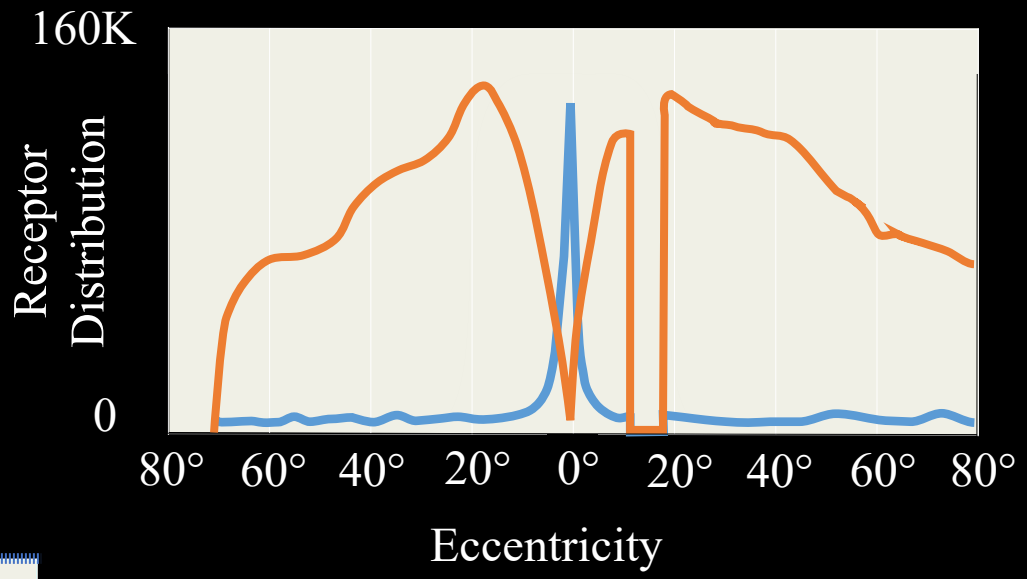
- Size of holes

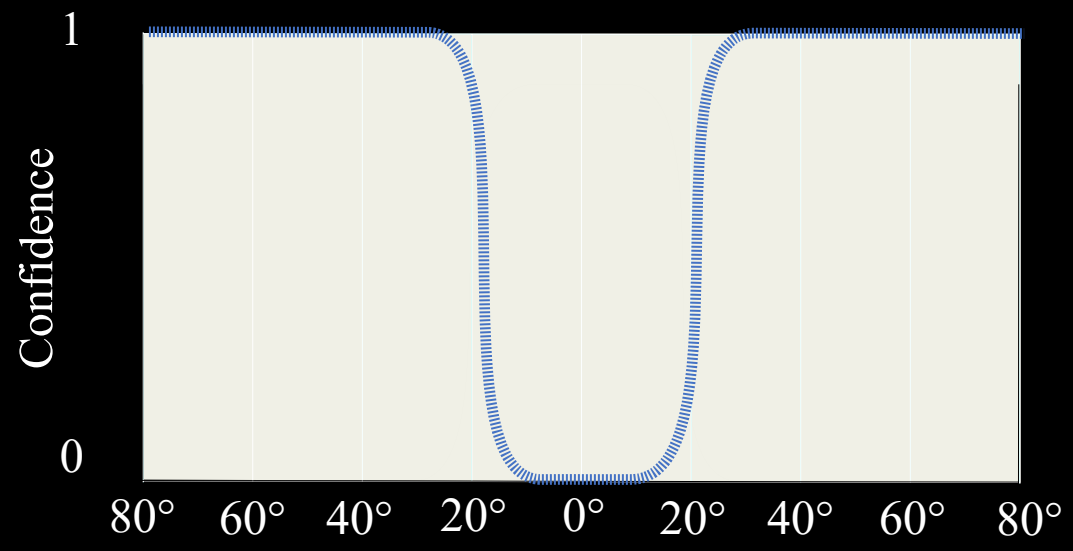


Confidence

Three main factors:

- Size of holes
- Eccentricity





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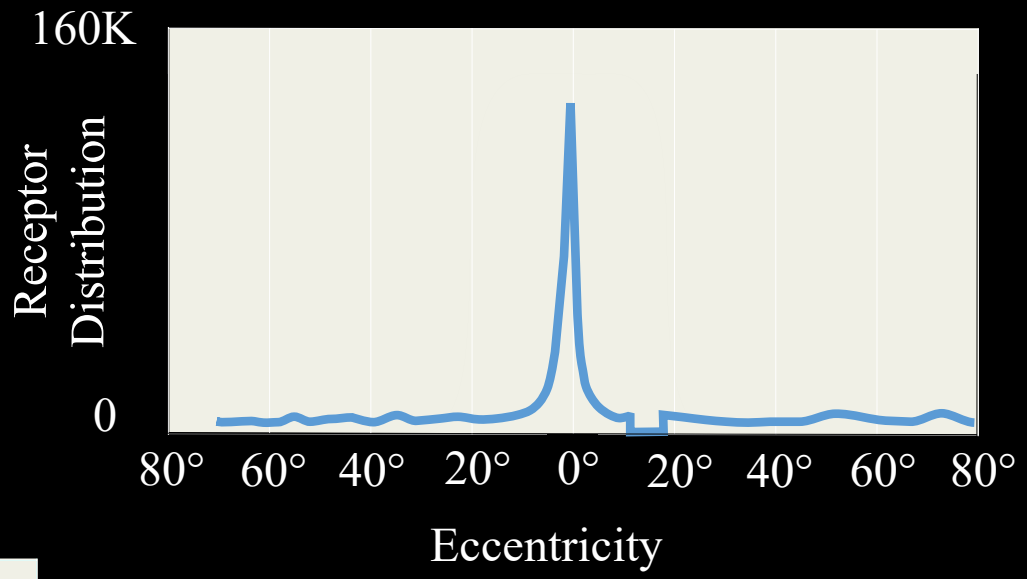
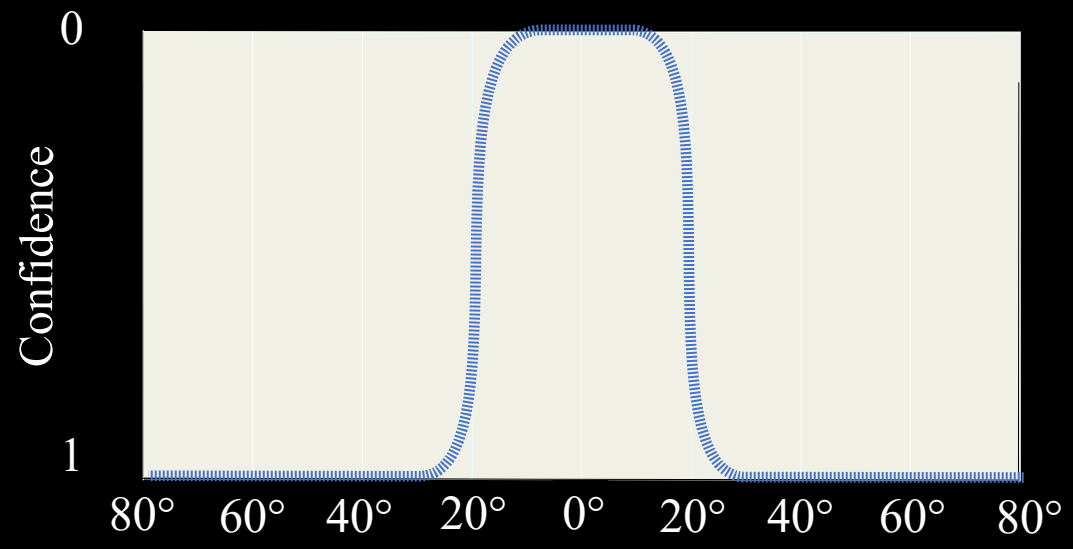
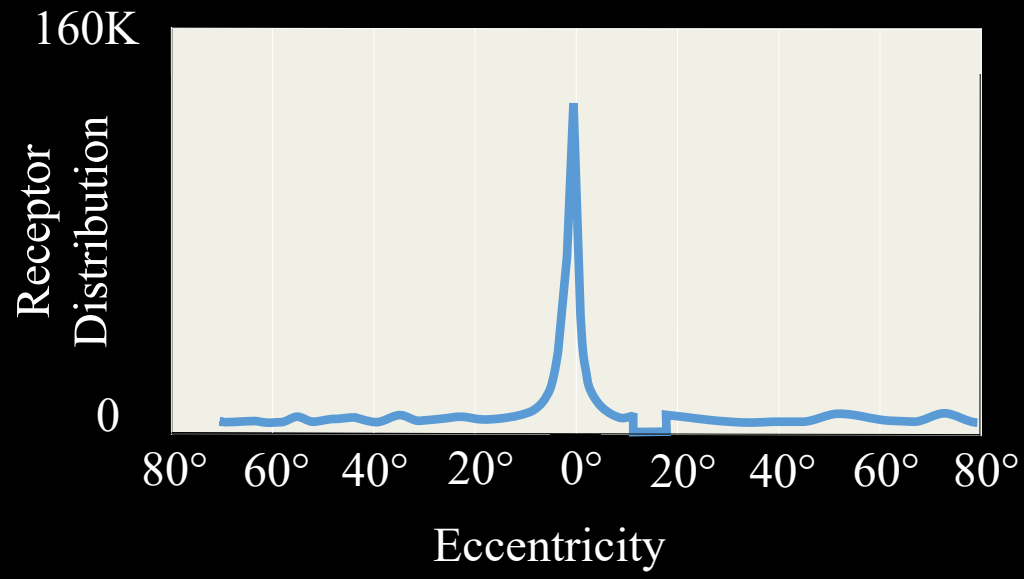


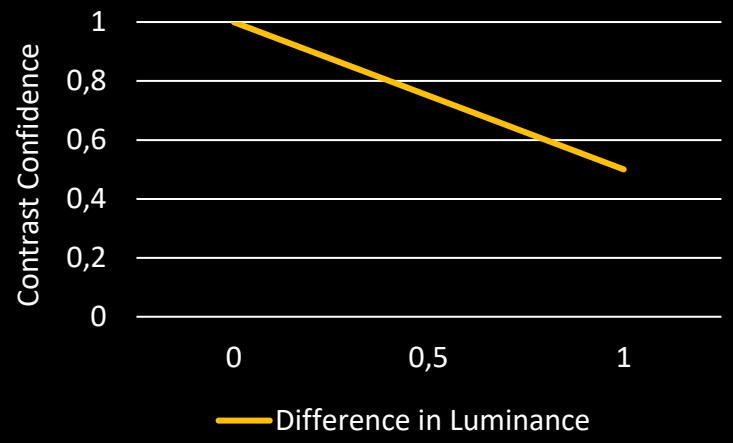


Confidence

Three main factors:

- Size of holes
- Eccentricity
- Contrast





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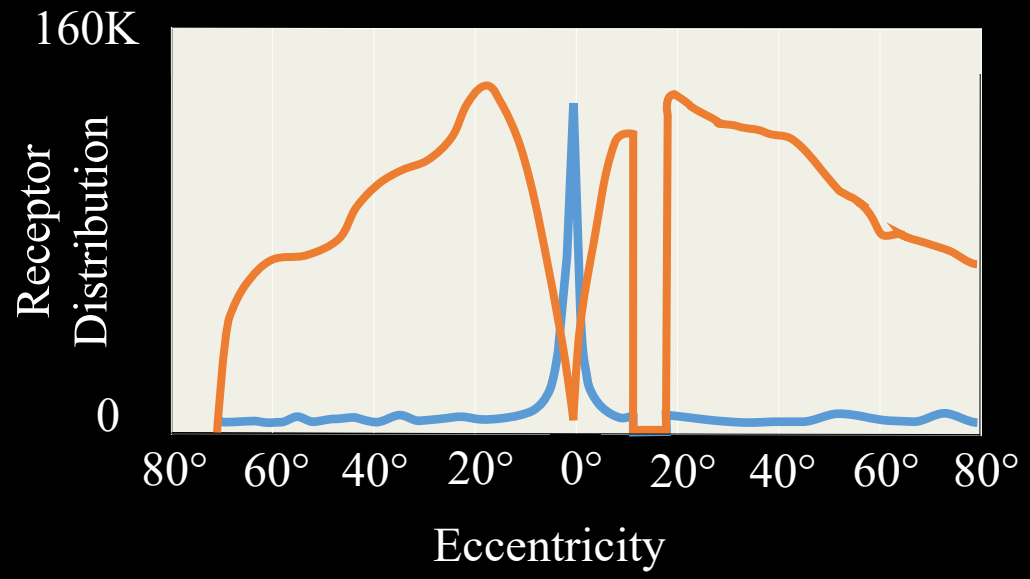
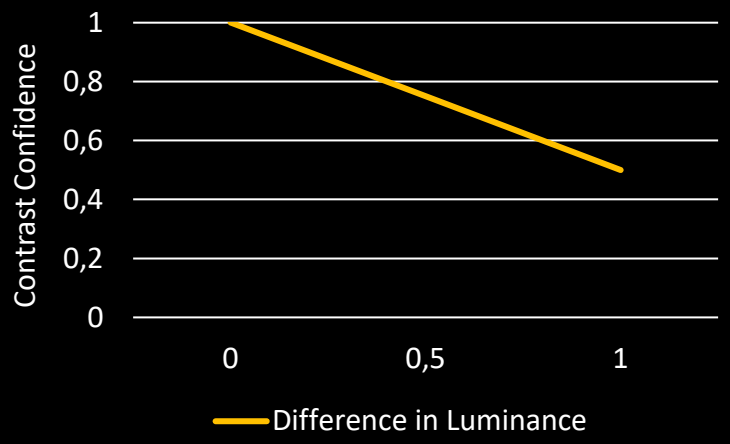
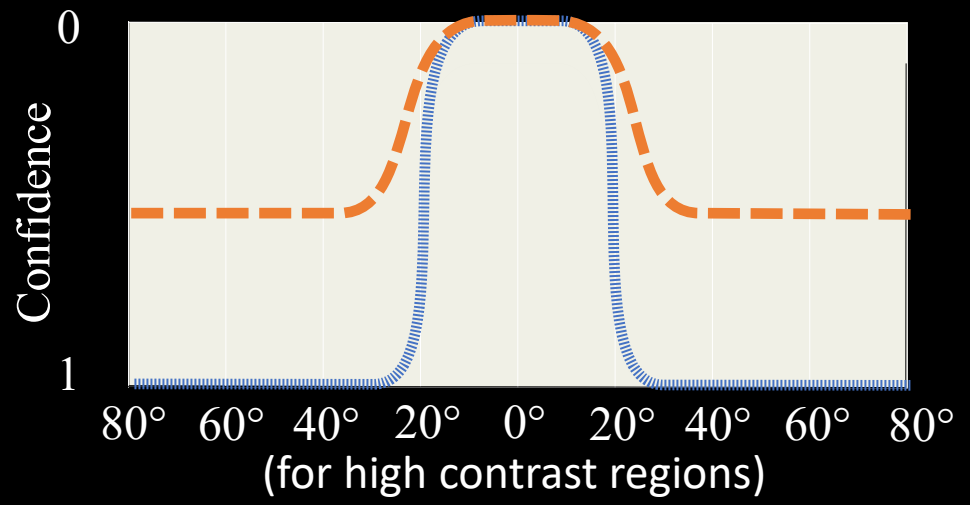
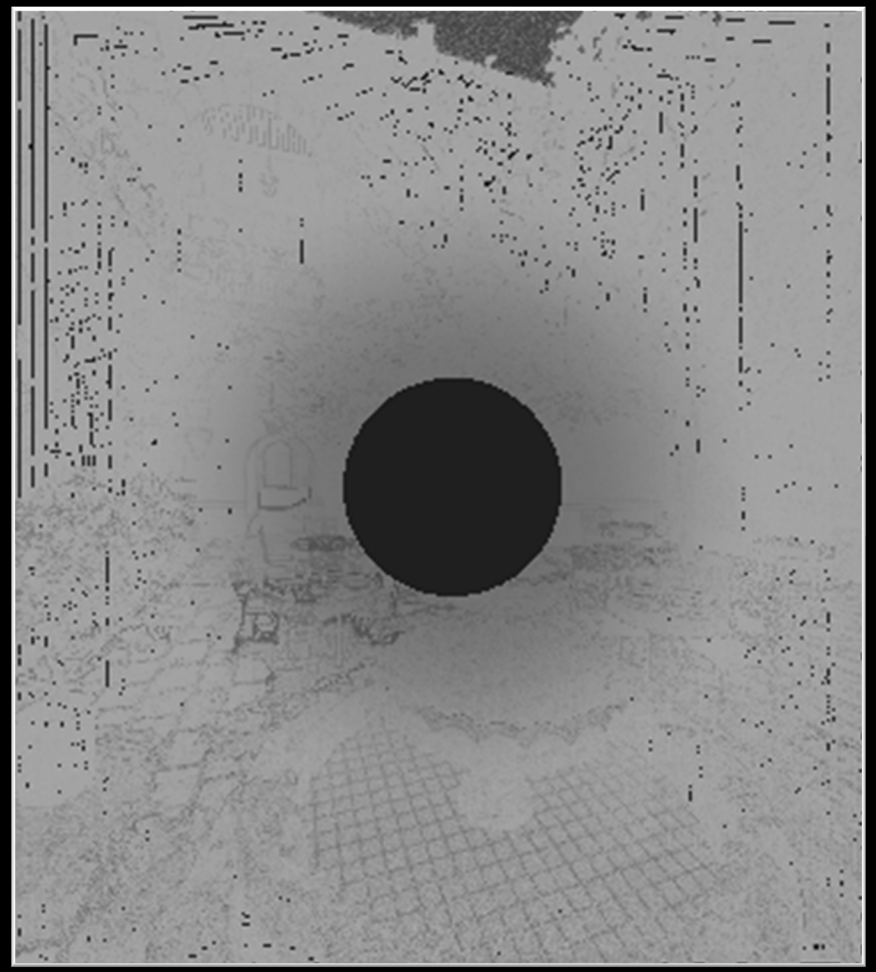
- Eccentricity
- Contrast





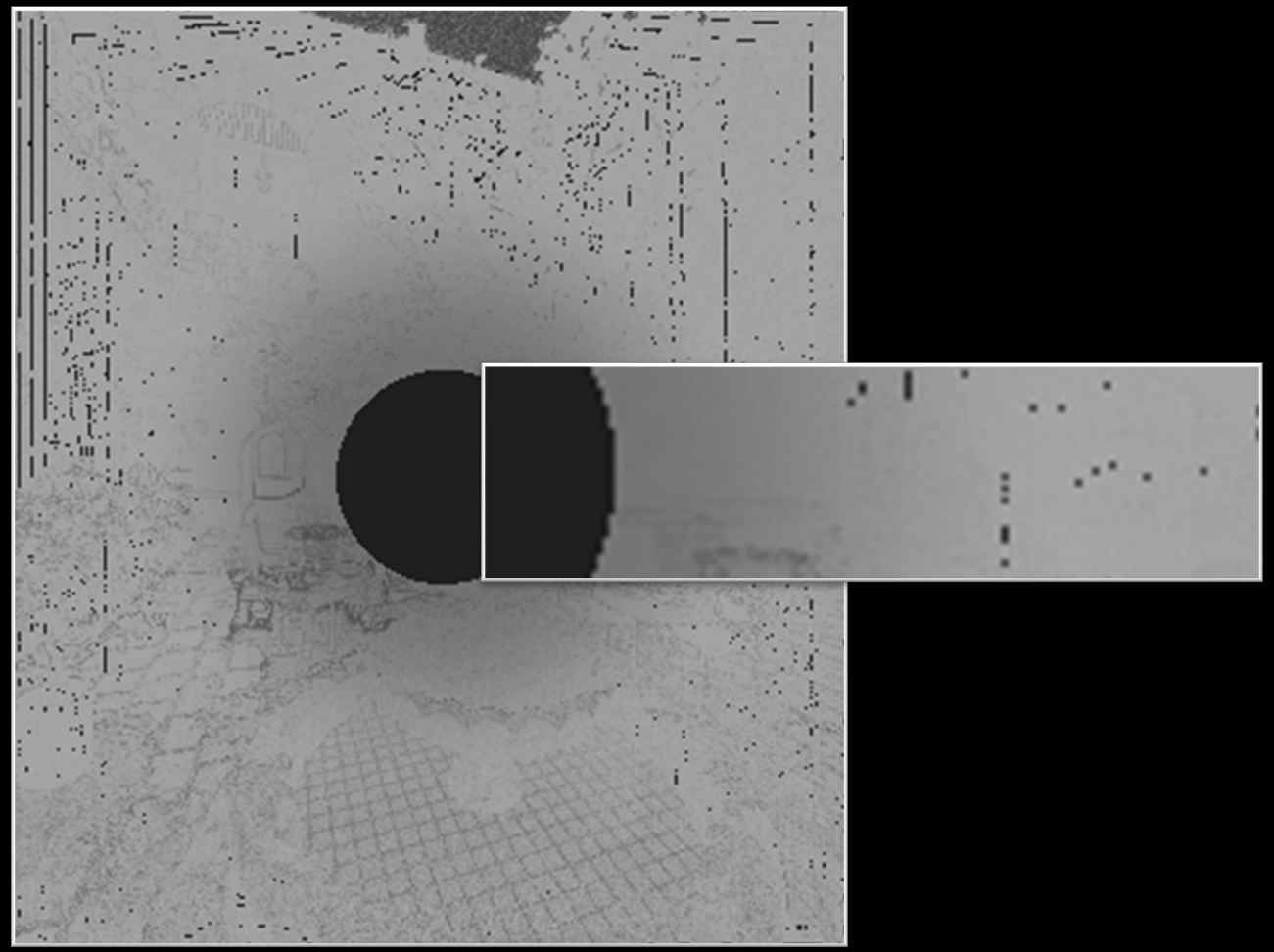


Confidence



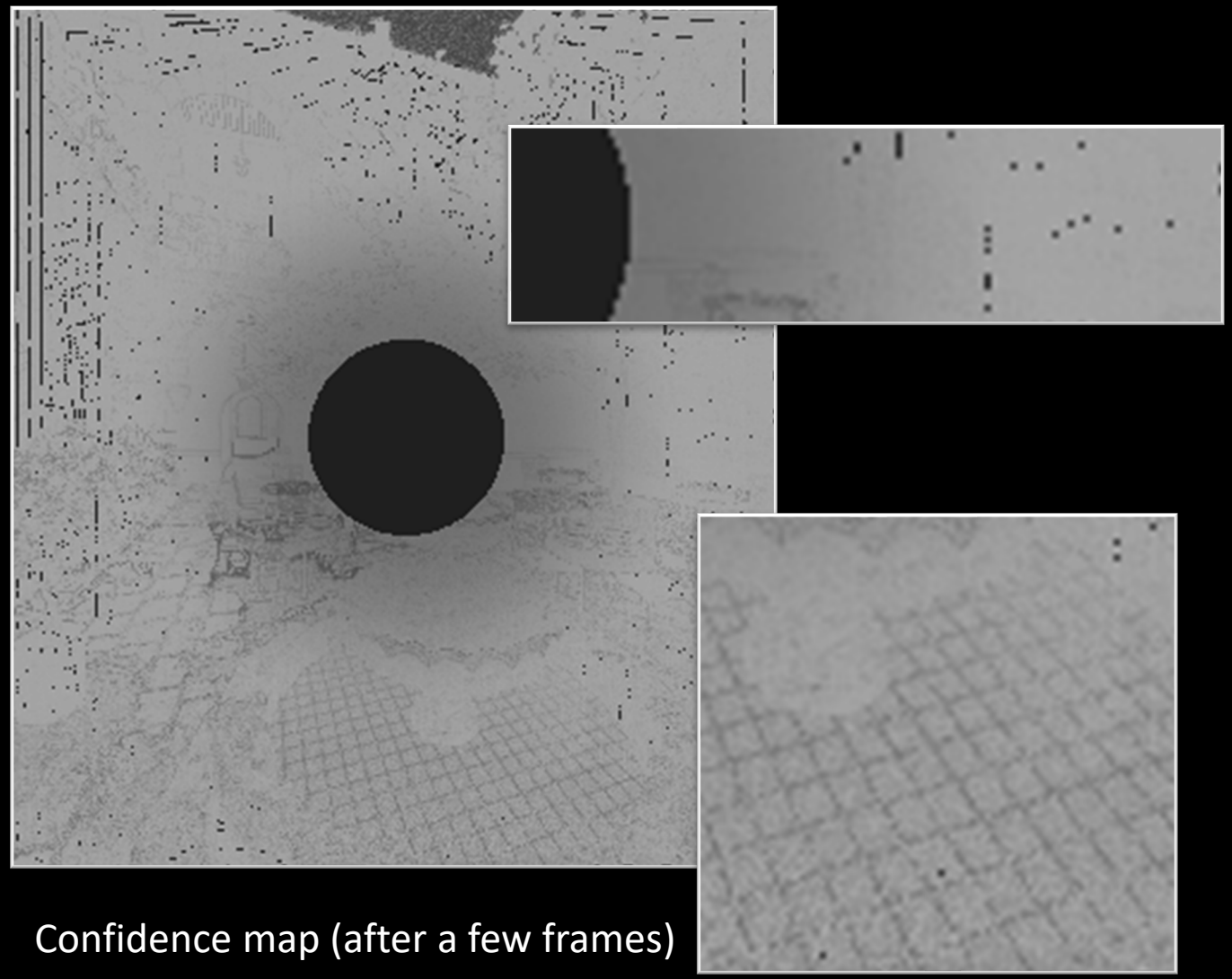
Confidence map (after a few frames)

Confidence



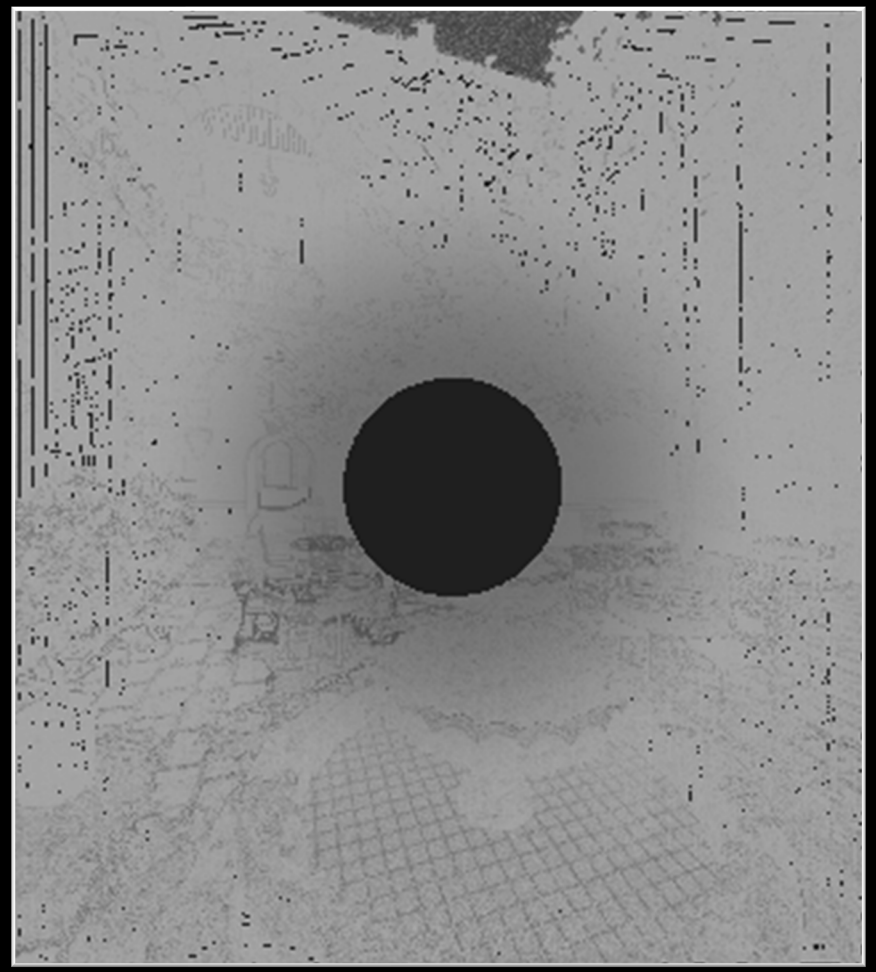
Confidence map (after a few frames)

Confidence



Confidence map (after a few frames)

Confidence



Confidence map (after a few frames)

Redraw decision based on cut-off value ϵ

Calibration user study (21 participants) identified

$\epsilon = 0.2$

Rendered freshly

Composed Image

Evaluation – Validation User Study

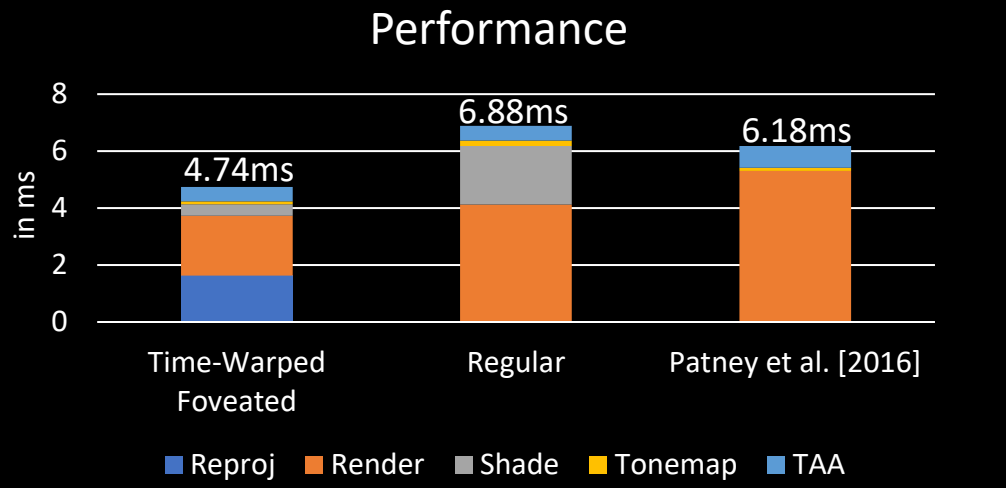




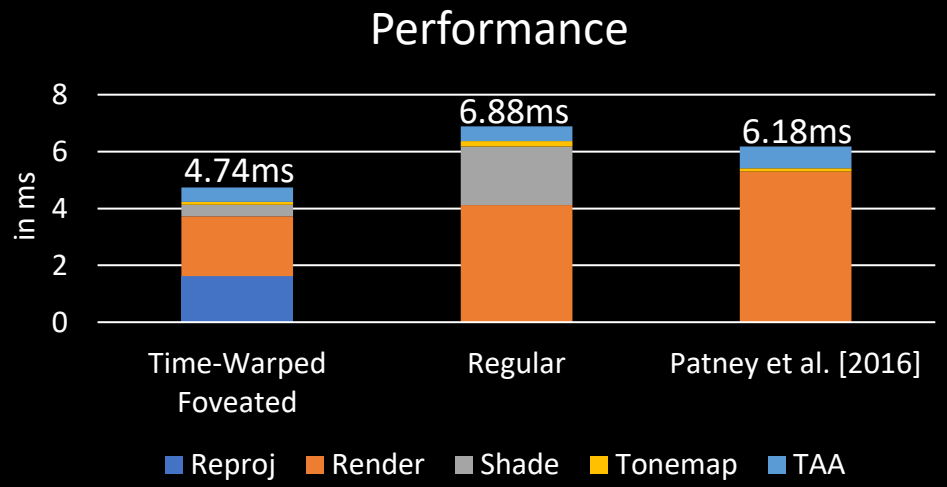

Compare regular to time-warped foveated rendering

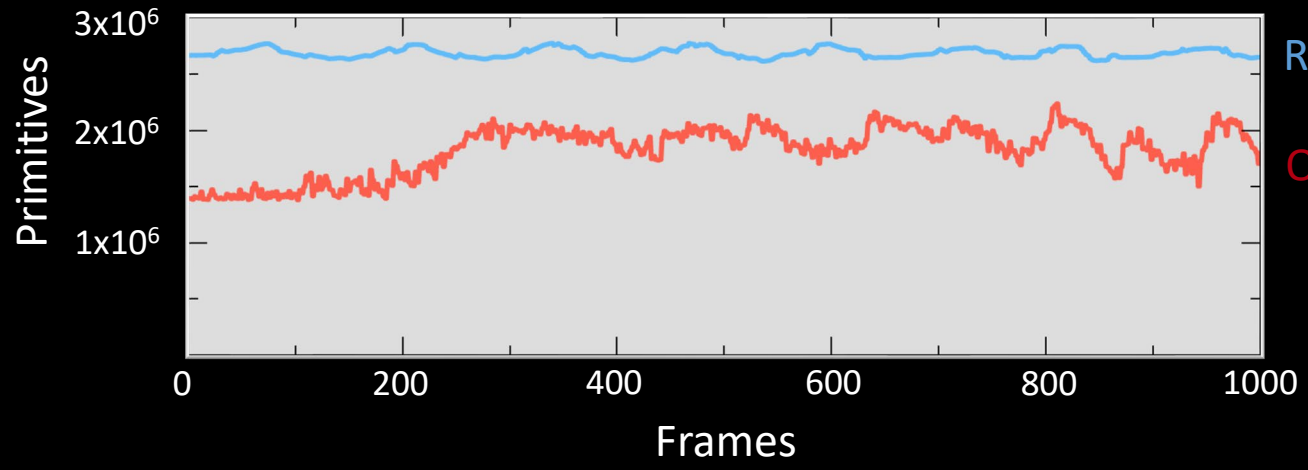
- 22 Participents
- No significant preference for any mode

Evaluation - Performance

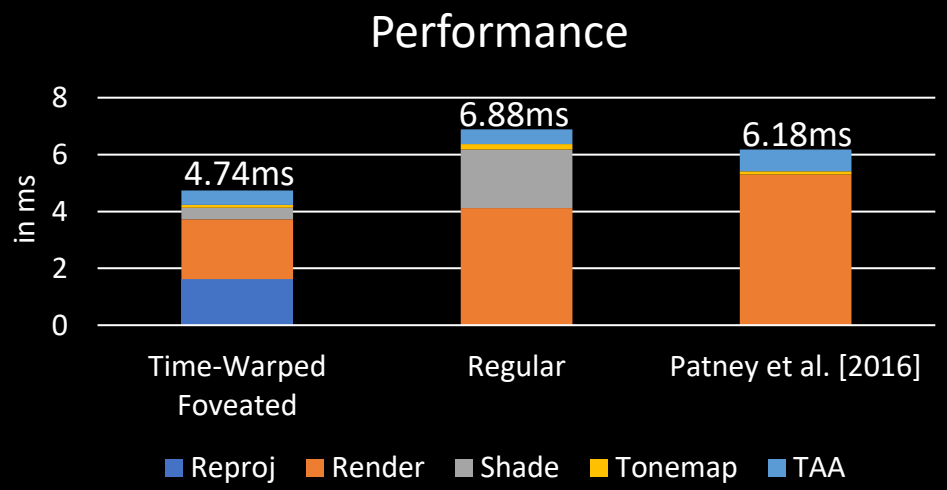


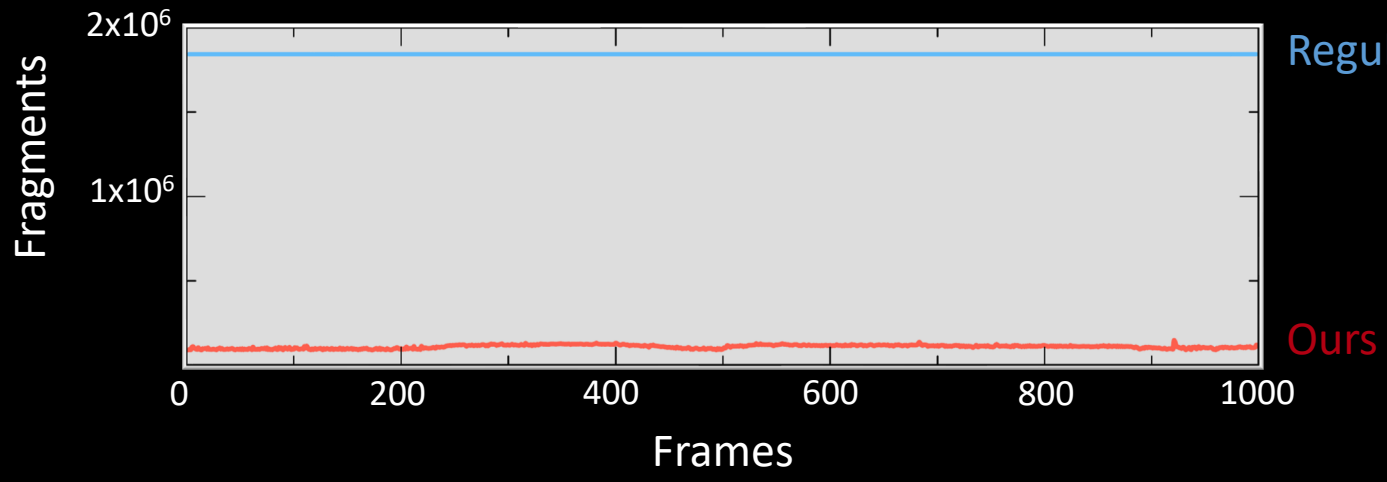
Evaluation - Performance





Evaluation - Performance

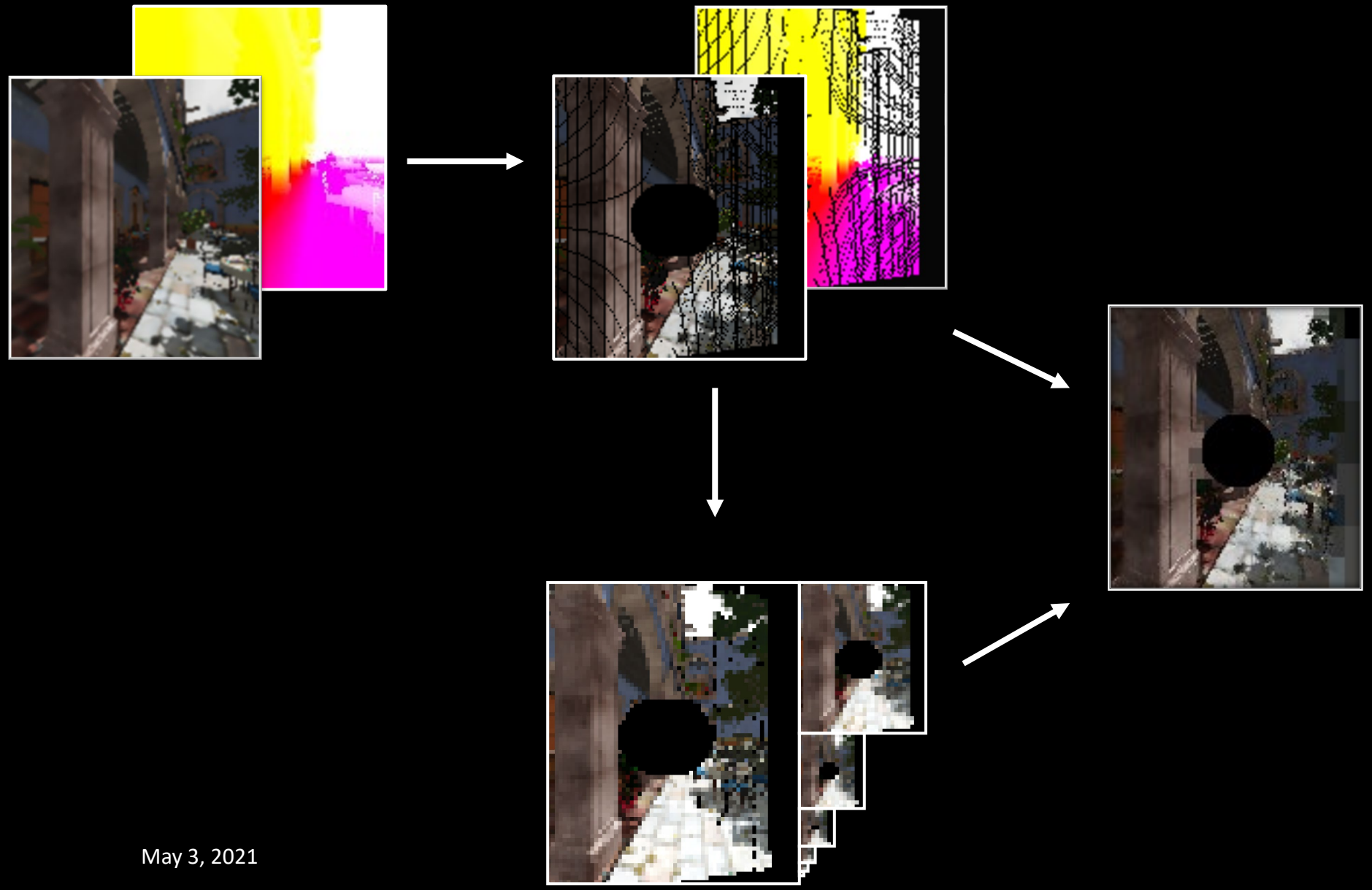




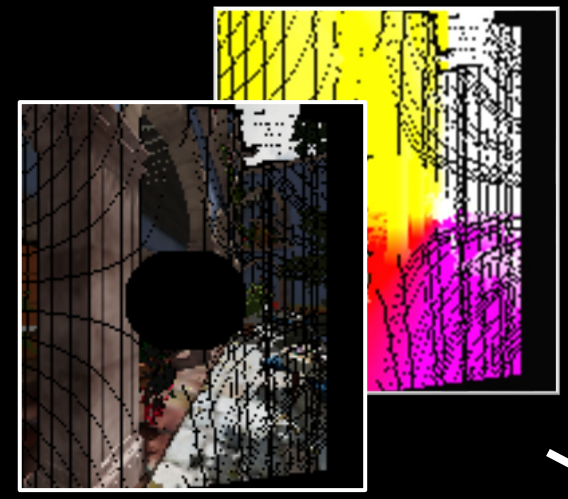
Limitations and future work

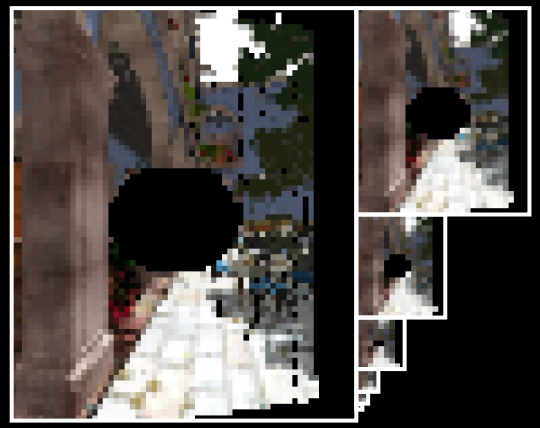
- No support for moving lights
- No acceleration for transparency
- Difficulties with view-dependent post-processing (e.g. reflections)

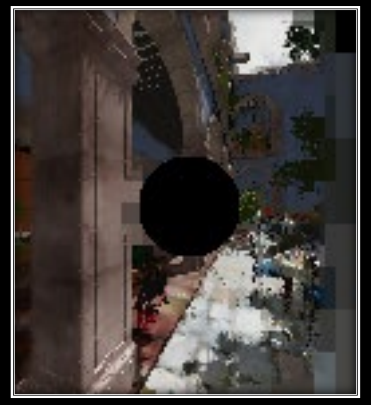
Recap



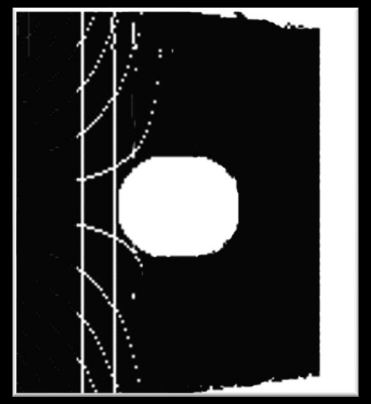
Recap



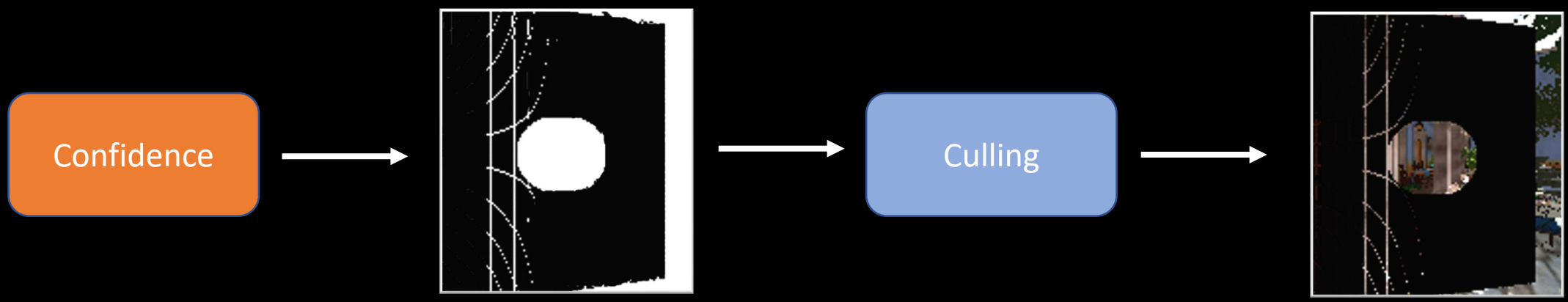




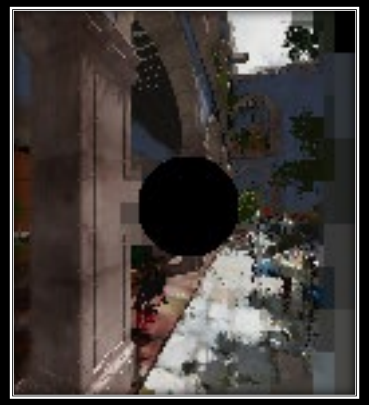
Confidence



Recap



Recap



TAA
&
Motion Smoothing

next frame

Questions?

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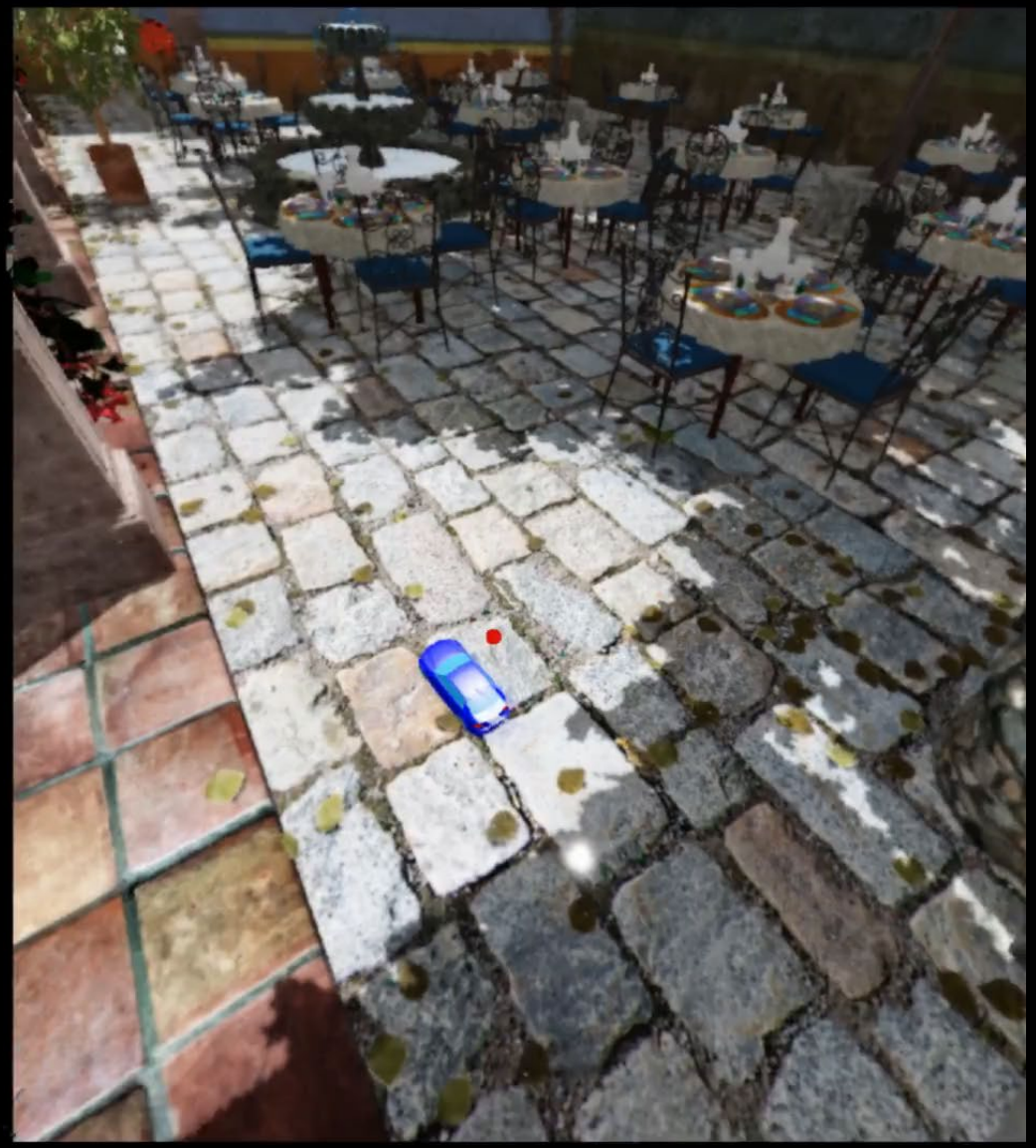
Twitter: @_linus_franke

Additional Slides

Dynamic Objects



Dynamic Objects

Errors if dynamic confidence falloff is too low:


Restaurant