Lecture 27:

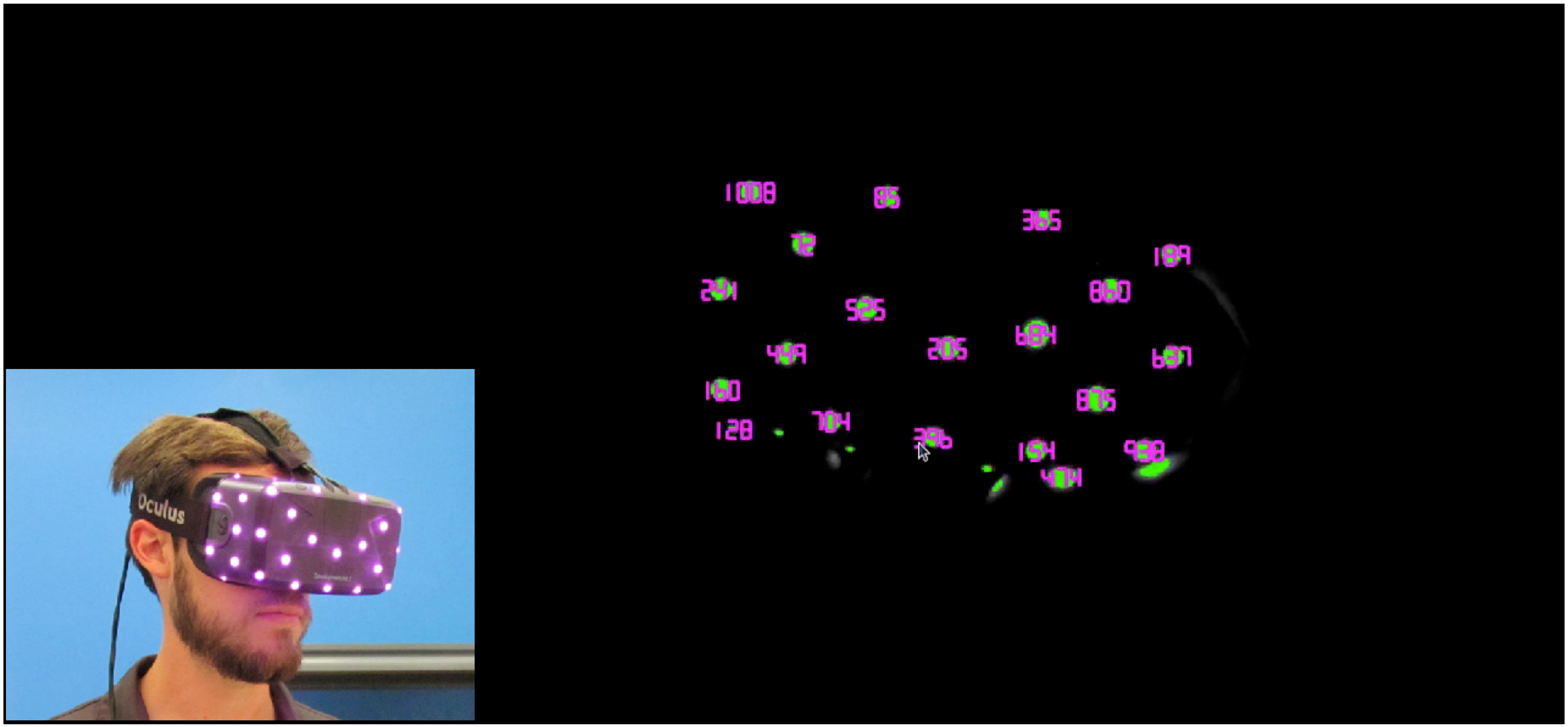
Intro to Virtual Reality (Cont)

Computer Graphics and Imaging
UC Berkeley CS184/284A

Display Requirements Derive From Human Perception

Example #4: Motion Parallax from Eye Motion

Recall: Oculus Rift Uses Active Marker Motion Capture



Credit: Oliver Kreylos, https://www.youtube.com/watch?v=O7Dt9Im34OI

- Motion capture: unknown shape, multiple cameras
- VR head tracking: known shape, single camera

6 DOF Head Pose Estimation

Head pose: 6 degrees of freedom (unknowns)

- 3D position and 3D rotation of headset (e.g. can represent as 4x4 matrix)

Inputs:

- Fixed: relative 3D position of markers on headset (e.g. can represent each marker offset as 4x4 matrix)
- Fixed: camera viewpoint (ignoring distortion, also a 4x4 projective mapping of 3D scene to 2D image)
- Each frame: 2D position of each headset marker in image

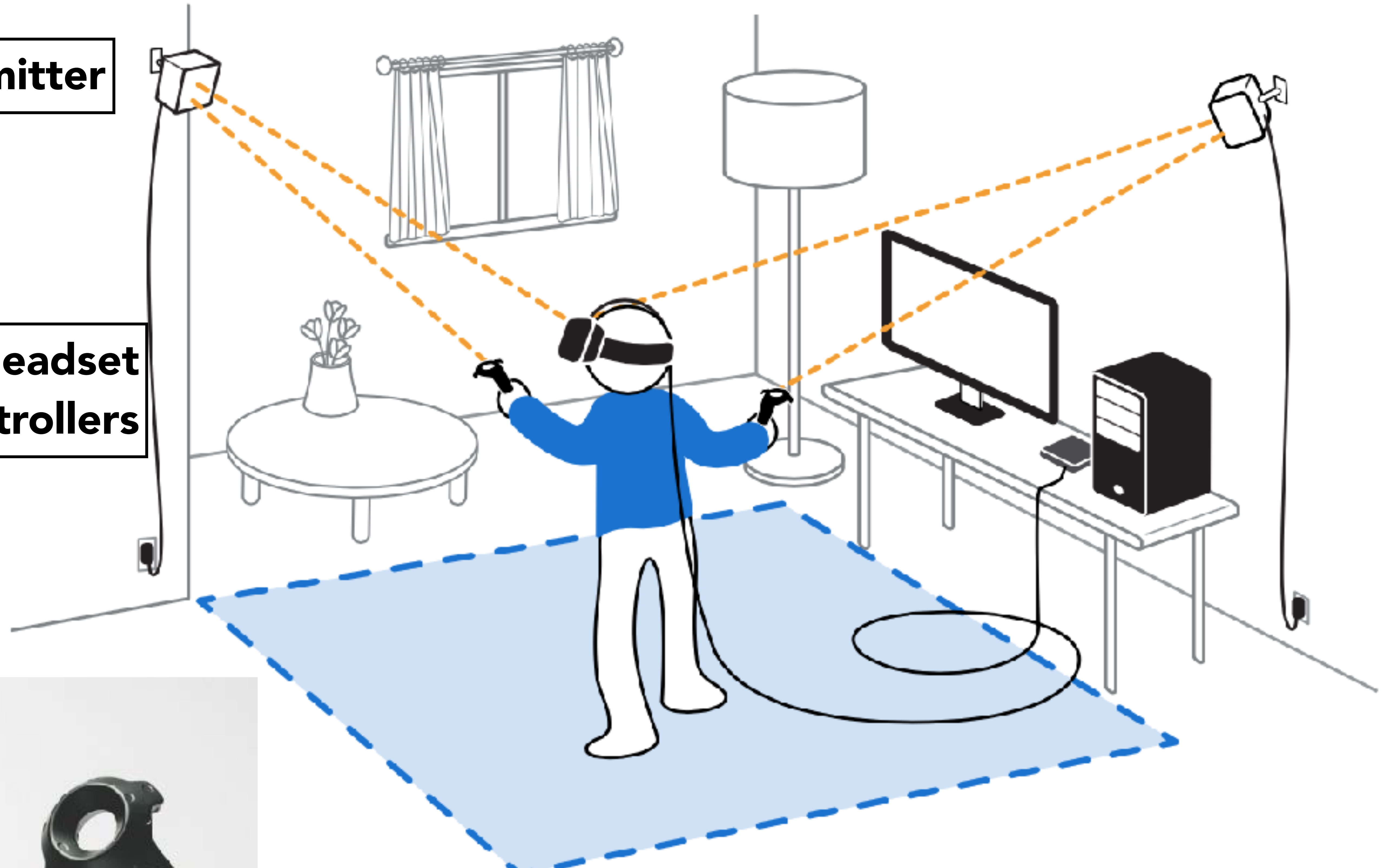
Pose calculation:

- Write down equations mapping each marker to image pixel location as a function of 6 degrees of freedom
- Solve for 6 degrees of freedom (e.g. least squares)

HTC Vive Tracking System ("Lighthouse")

Structured light transmitter

Photodiode arrays on headset
and hand-held controllers



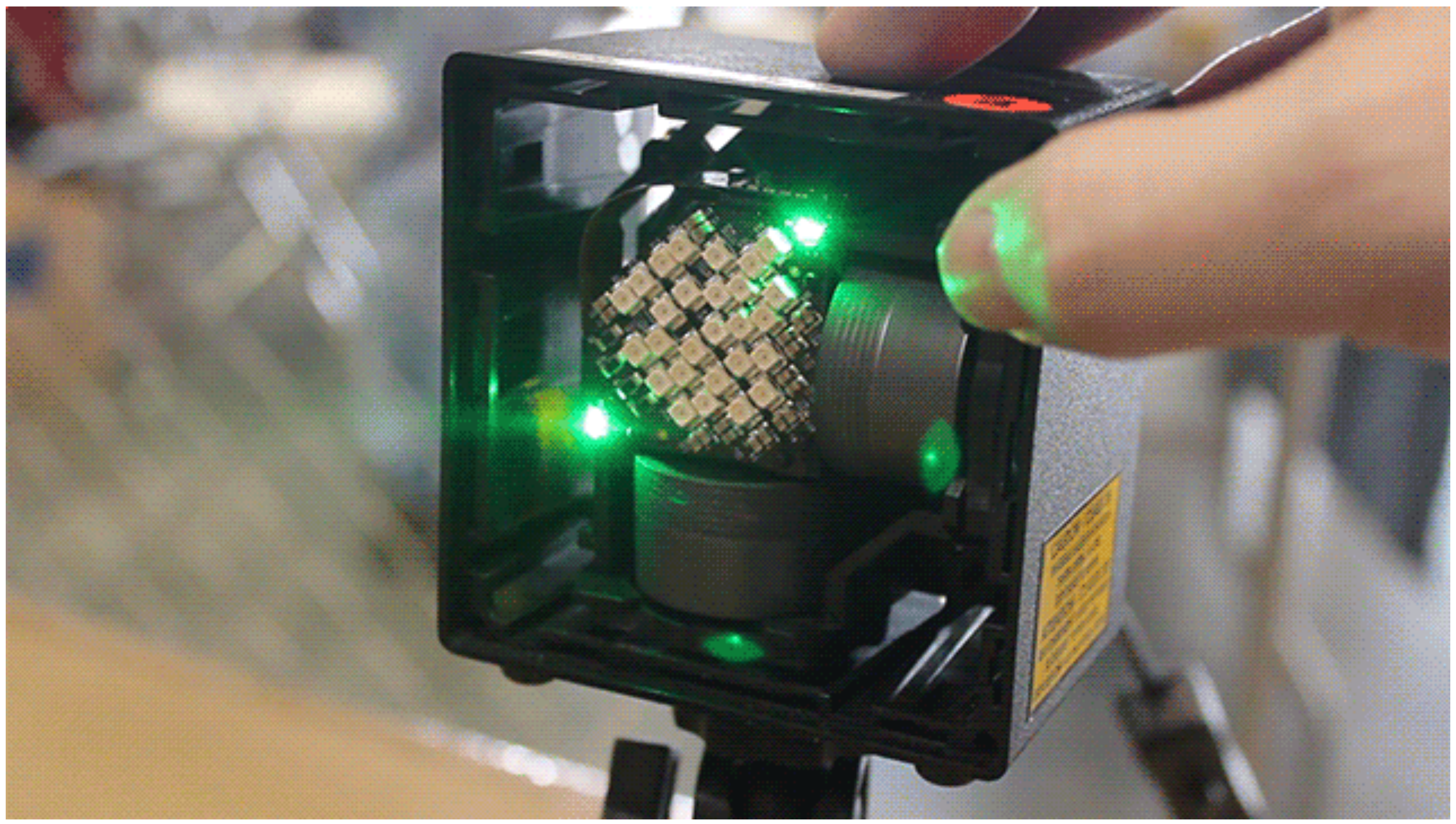
Vive Headset & Controllers Have Array of IR Photodiodes

IR photodiode

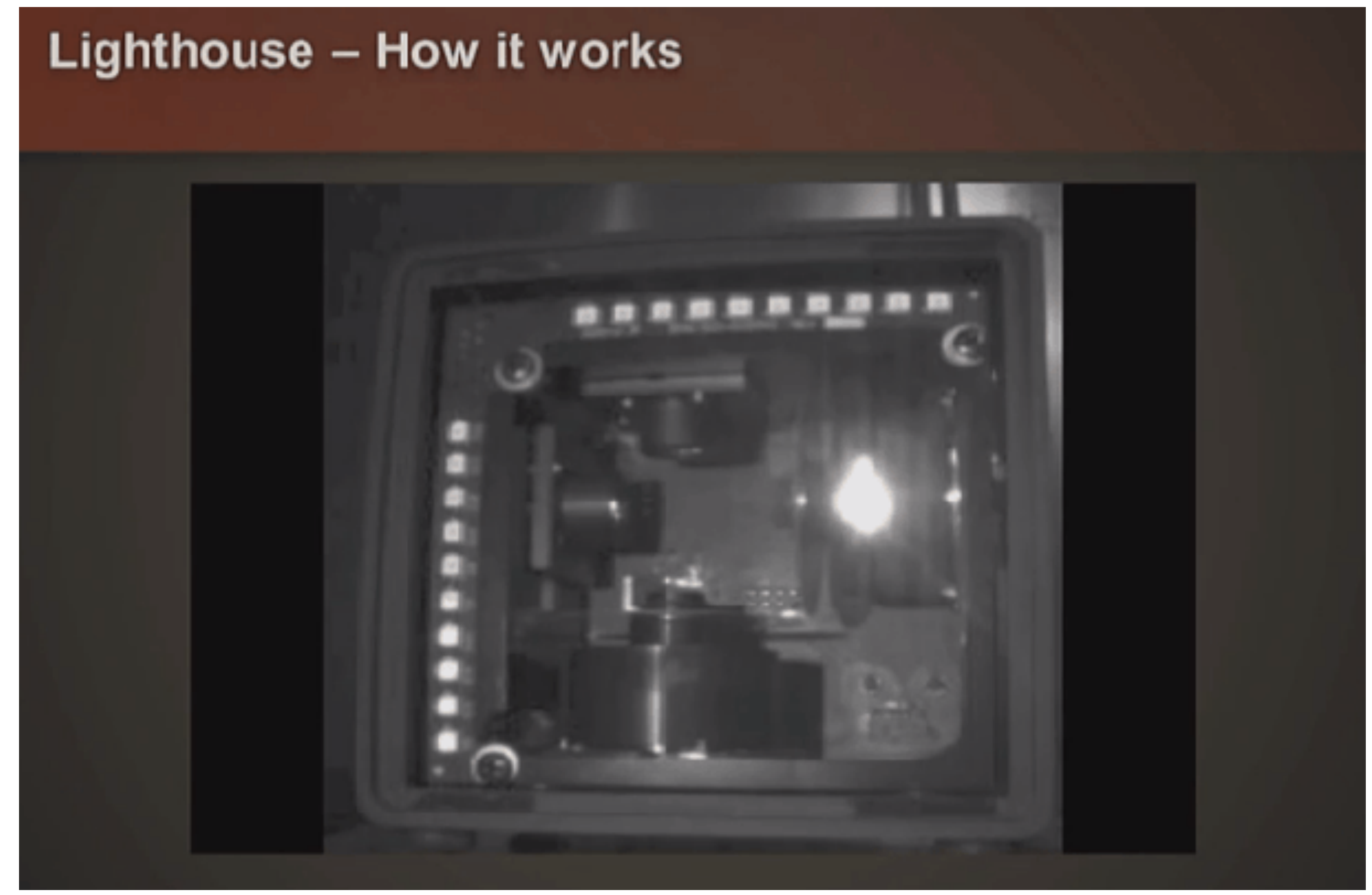
Image credit: uploadvr.com

(Prototype) Headset and controller are covered with IR photodiodes

HTC Vive Structured Light Emitter ("Lighthouse")



Light emitter contains array of LEDs (white) and two spinning wheels with lasers



Sequence of LED flash and laser sweeps provide structured lighting throughout room

Credit: Gizmodo: http://gizmodo.com/this-is-how-valve-s-amazing-lighthouse-tracking-technol-1705356768

HTC Vive Tracking System

For each frame, lighthouse does the following:

- LED pulse, followed by horizontal laser sweep
- LED pulse, followed by vertical laser sweep

Each photodiode on headset measures time offset between pulse and laser arrival

- Determines the x and y offset in the lighthouse's field of view
- In effect, obtain an image containing the 2D location of each photodiode in the world
  - (Can think of the lighthouse as a virtual "camera")

HTC Vive Tracking System ("Lighthouse")

Credit: rvdm88 / youtube. https://www.youtube.com/watch?v=J54dotTt7k0

Tracking Summary

Looked at three tracking methods

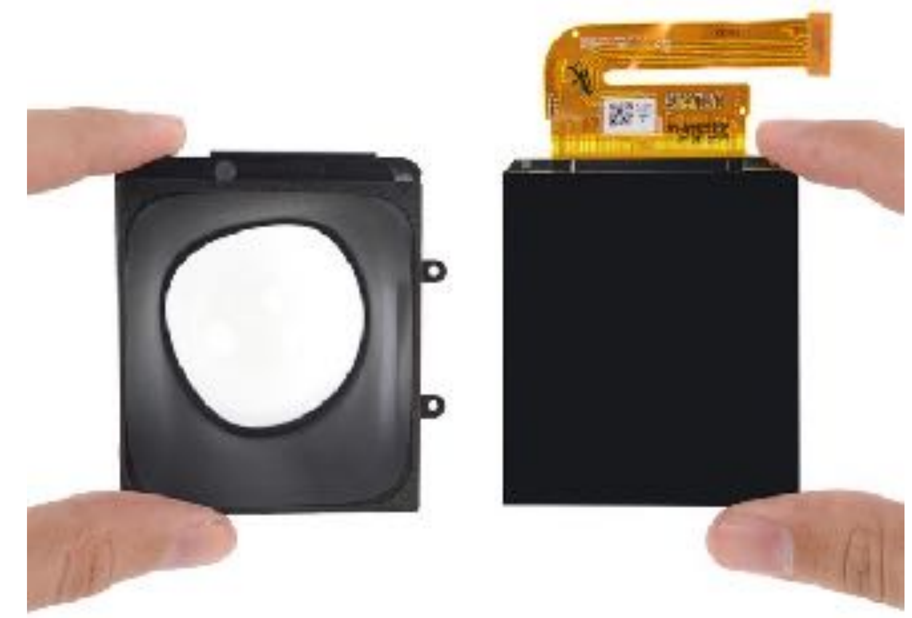
- Camera on headset + computer vision + gyro
- External camera + marker array on headset
- External structured light + sensor array on headset

3D tracking + depth sensing an active research area

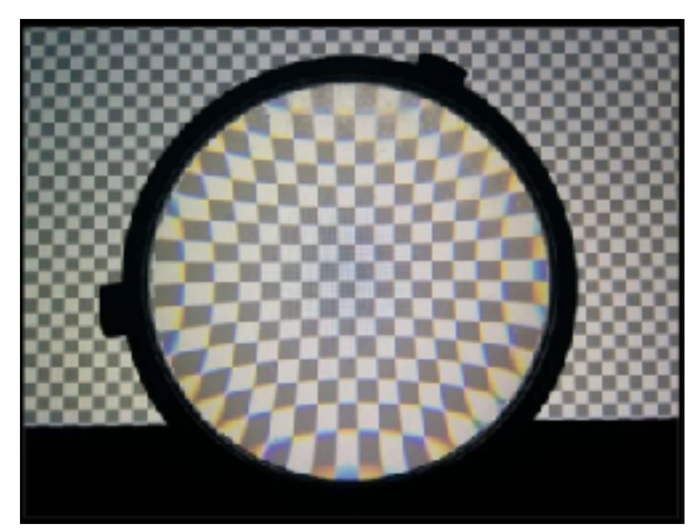
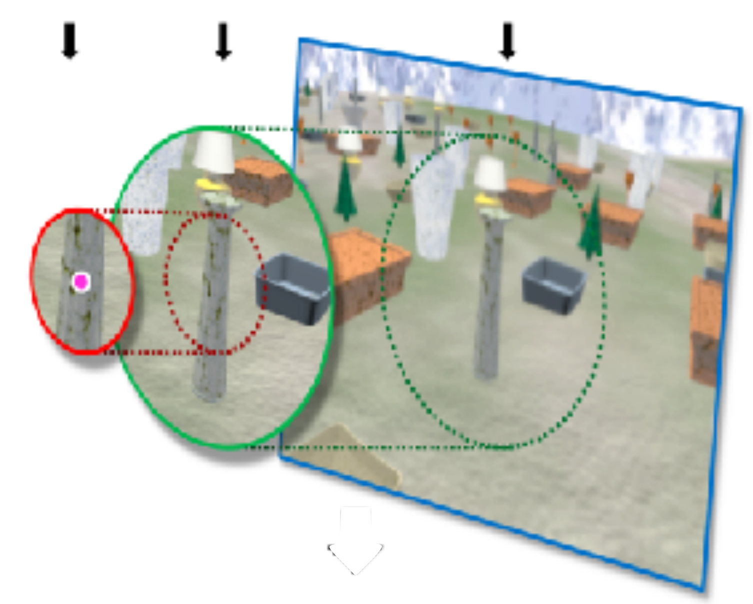
- SLAM, PTAM, DTAM…
- Microsoft Hololens, Magic Leap, Google Tango, Intel Realsense, …

Overview of VR Topics

- VR Displays


- VR Rendering

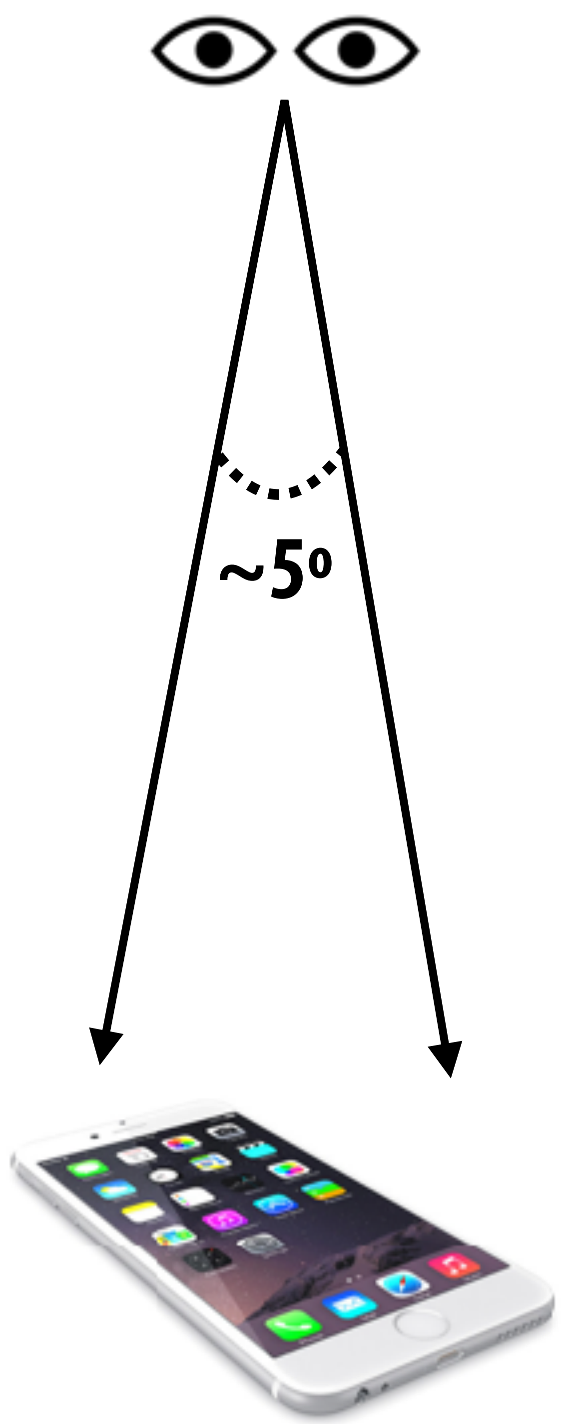



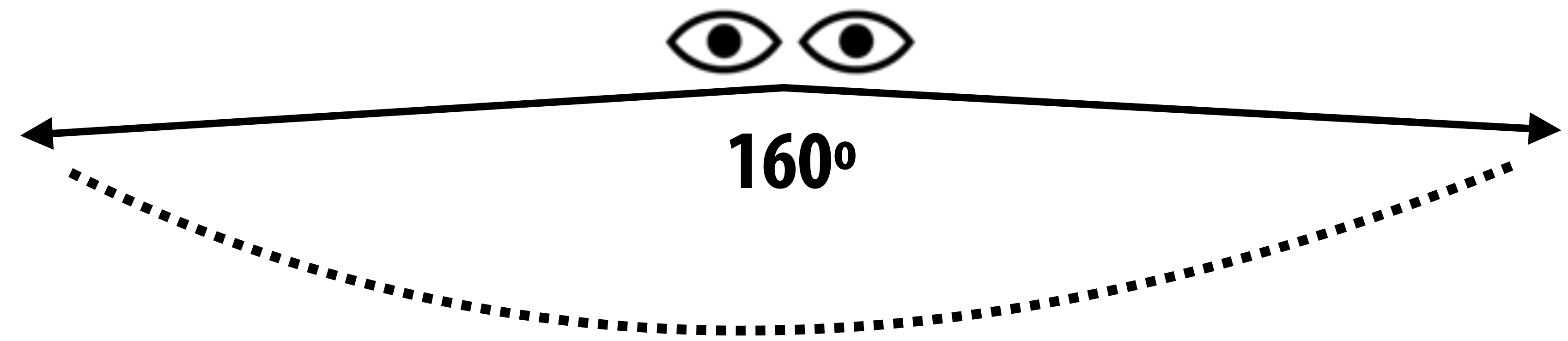
- VR Imaging



Rendering Latency in VR

Resolution Requirements in VR Are Very High





Human: ~160° view of field per eye (~200° overall)
(Note: does not account for eye's ability to rotate in socket)

Future "retina" VR display:
57 ppd covering 200°
= 11K x 11K display per eye
= 220 MPixel

iPhone 6: 4.7 in "retina" display:
1.3 MPixel
326 ppi → 57 ppd

Eyes designed by SuperAtic LABS from the thenounproject.com

Latency Requirements in VR Are Challenging

The goal of a VR graphics system is to achieve “presence”, tricking the brain into thinking what it is seeing is real

Achieving presence requires an exceptionally low-latency system

- What you see must change when you move your head!
- End-to-end latency: time from moving your head to the time new photons hit your eyes
    - Measure user’s head movement
    - Update scene/camera position
    - Render new image
    - Transfer image to headset, then transfer to display in headset
    - Actually emit light from display (photons hit user’s eyes)
- Latency goal of VR: 10-25 ms
    - Requires exceptionally low-latency head tracking
    - Requires exceptionally low-latency rendering and display

Thought Experiment: Effect of Latency

Consider 1,000 x 1,000 display spanning 100° field of view

- 10 pixels per degree

Assume:

- You move your head 90° in 1 second (only modest speed)
- End-to-end latency of system is a slow 50 ms (1/20 sec)

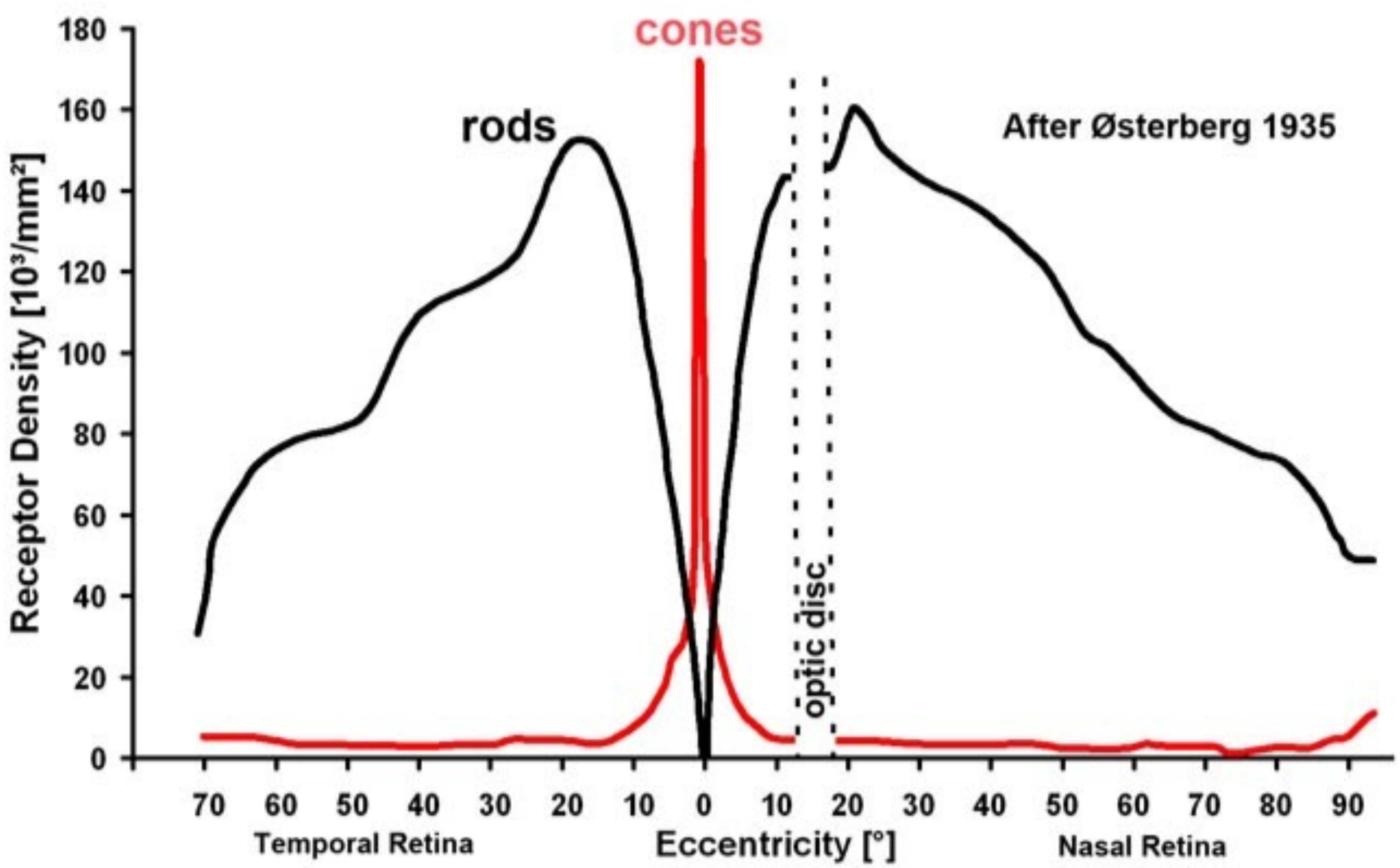
Result:

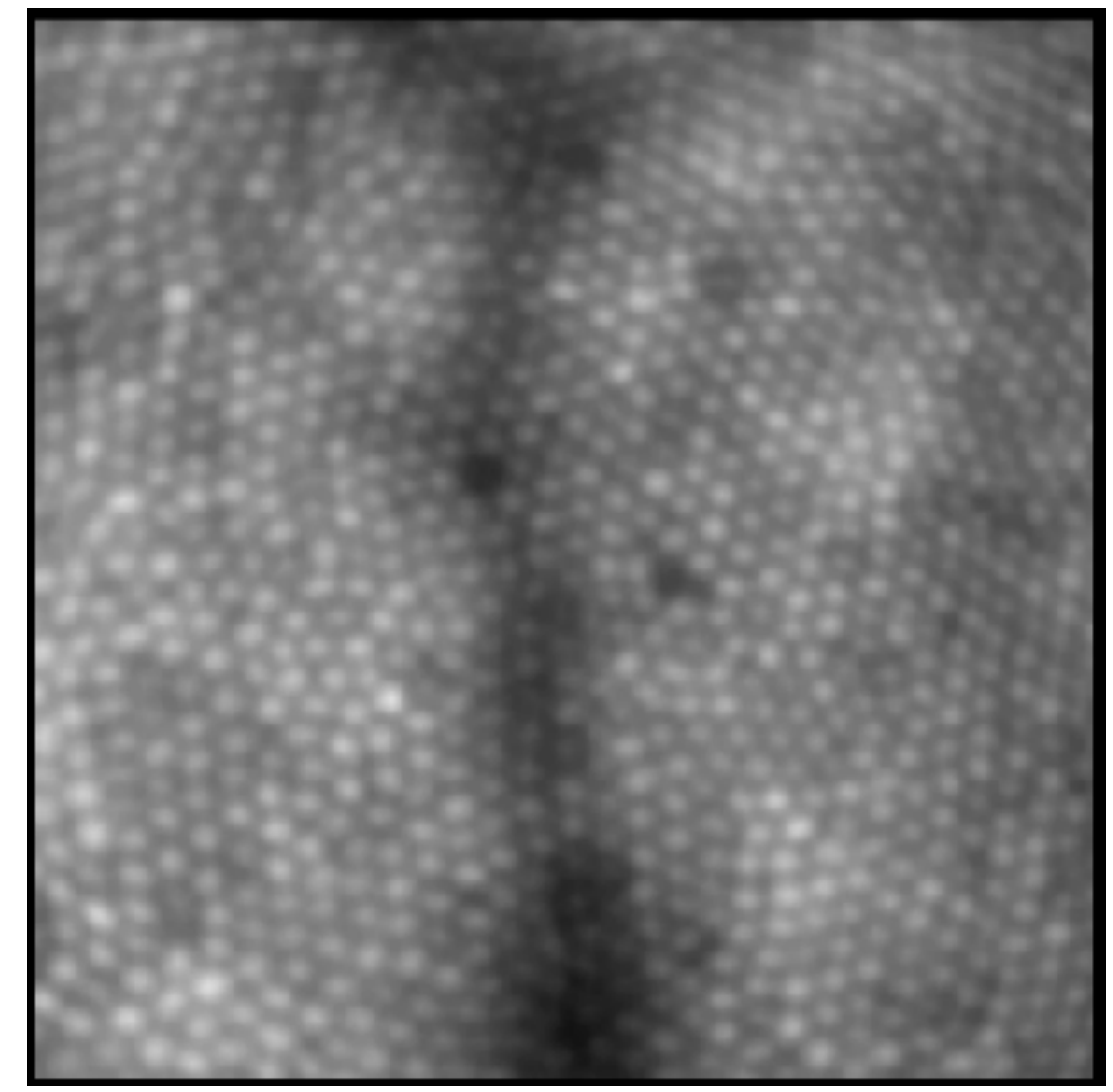
- Displayed pixels are off by 4.5° ~ 45 pixels from where they would be in an ideal system with 0 latency

Example credit: Michael Abrash

Challenge:
Low Latency and High Resolution
Require High Rendering Speed

Recall: Retinal Resolution Falls Away from Fovea



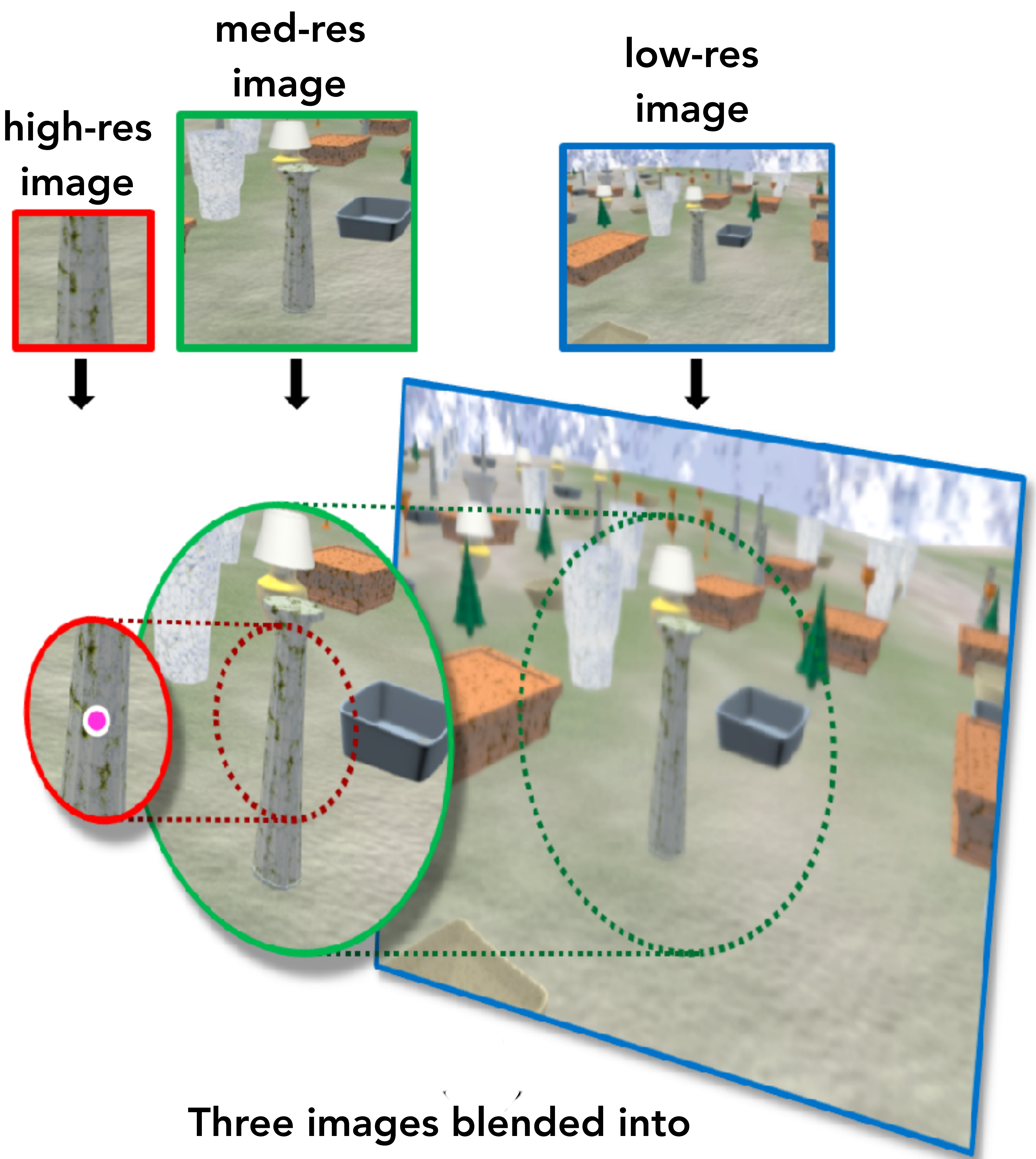


[Roorda 1999]

- Highest density of cones in fovea (and no rods there)
- "Blind spot" at the optic disc, where optic nerve exits eye

Foveated Rendering

Idea: track user's gaze, render with increasingly lower resolution farther away from gaze point

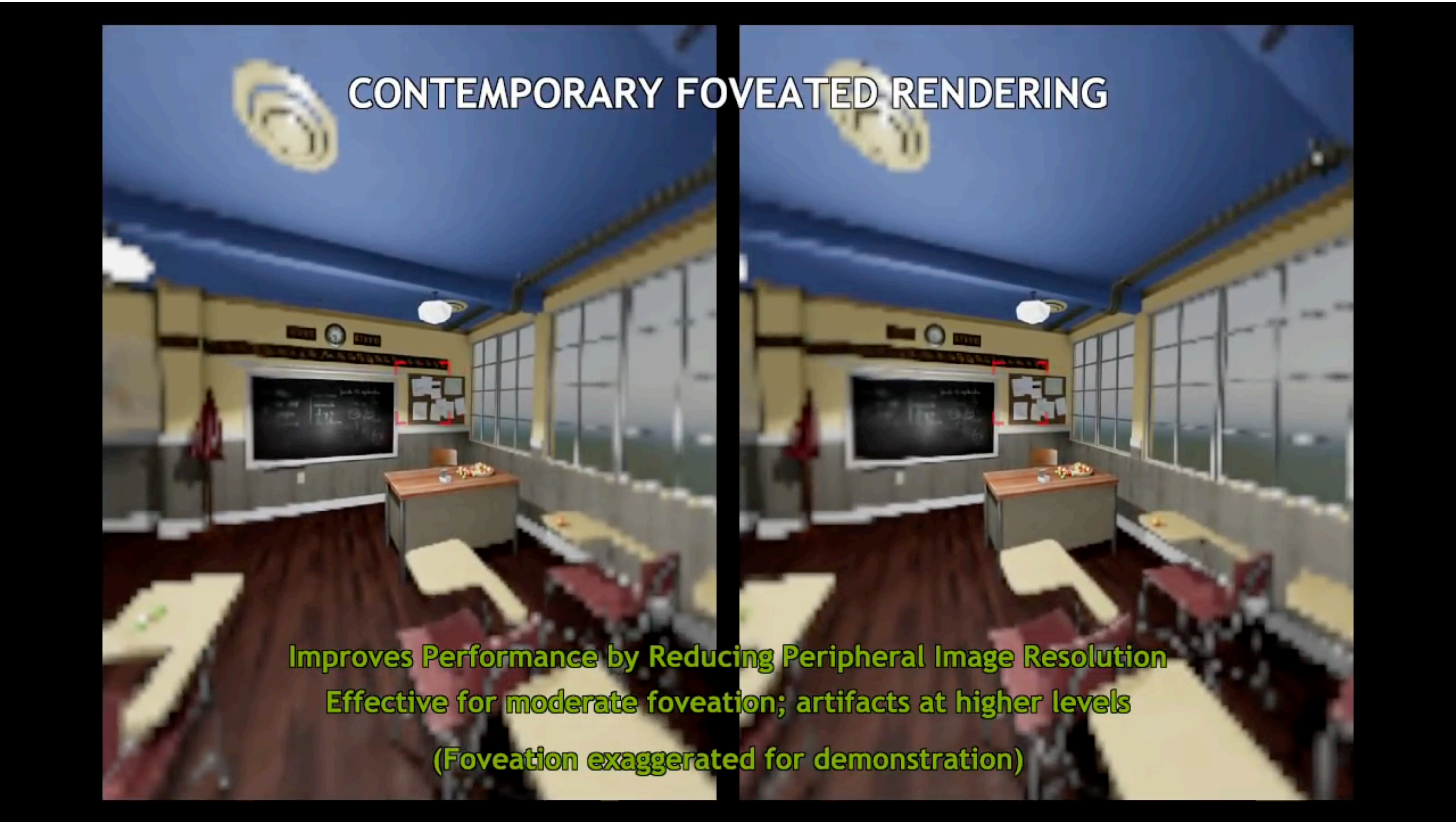


Three images blended into one for display

Foveated Rendering - Perceptual Effects

Patney et al., Towards Foveated Rendering for Gaze-Tracked Virtual Reality
SIGGRAPH Asisa 2016.

Foveated Rendering - Perceptual Effects

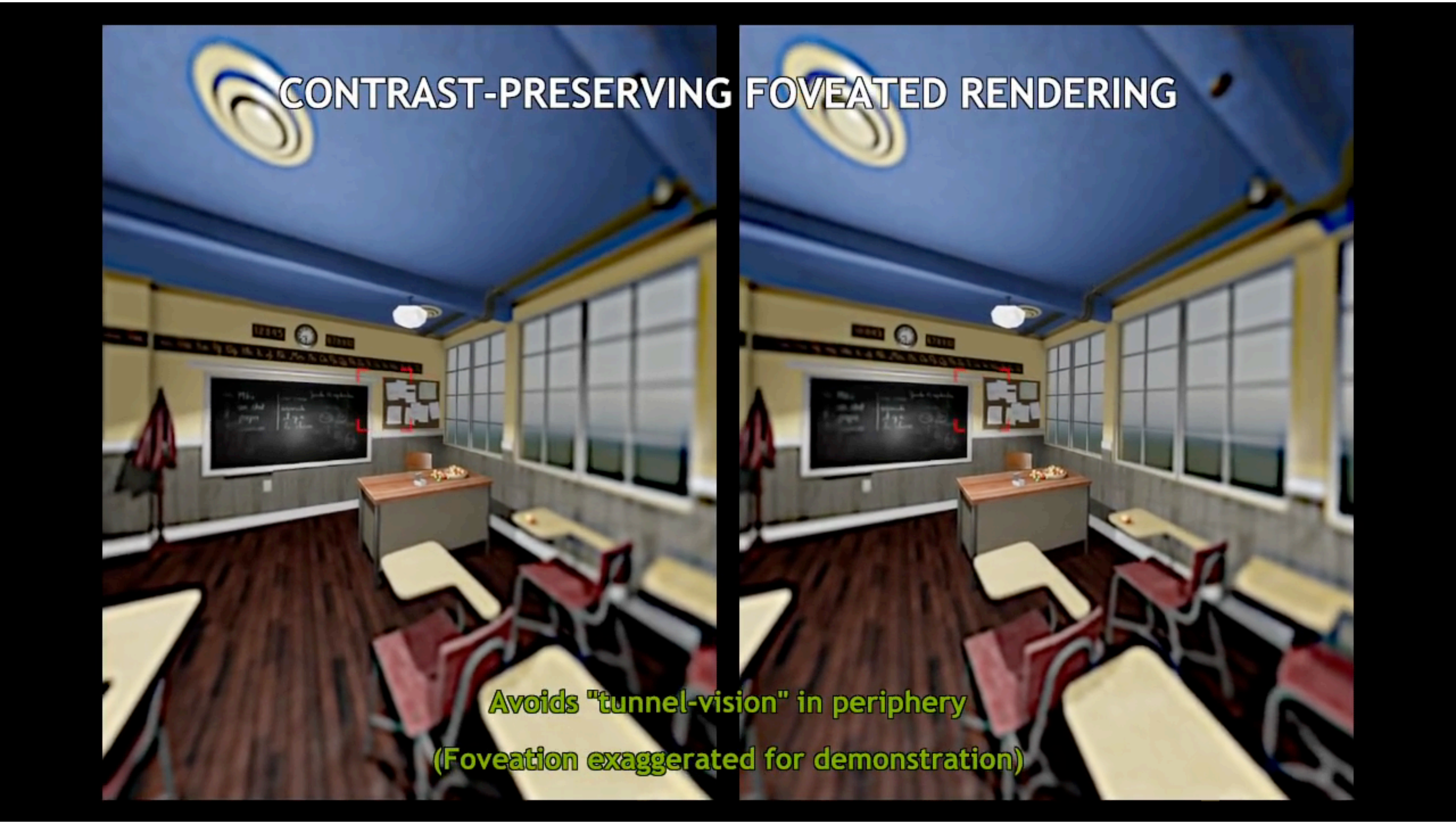


Patney et al., Towards Foveated Rendering for Gaze-Tracked Virtual Reality
SIGGRAPH Asisa 2016.

Foveated Rendering - Perceptual Effects

Patney et al., Towards Foveated Rendering for Gaze-Tracked Virtual Reality
SIGGRAPH Asisa 2016.

Foveated Rendering - Perceptual Effects



Patney et al., Towards Foveated Rendering for Gaze-Tracked Virtual Reality
SIGGRAPH Asisa 2016.

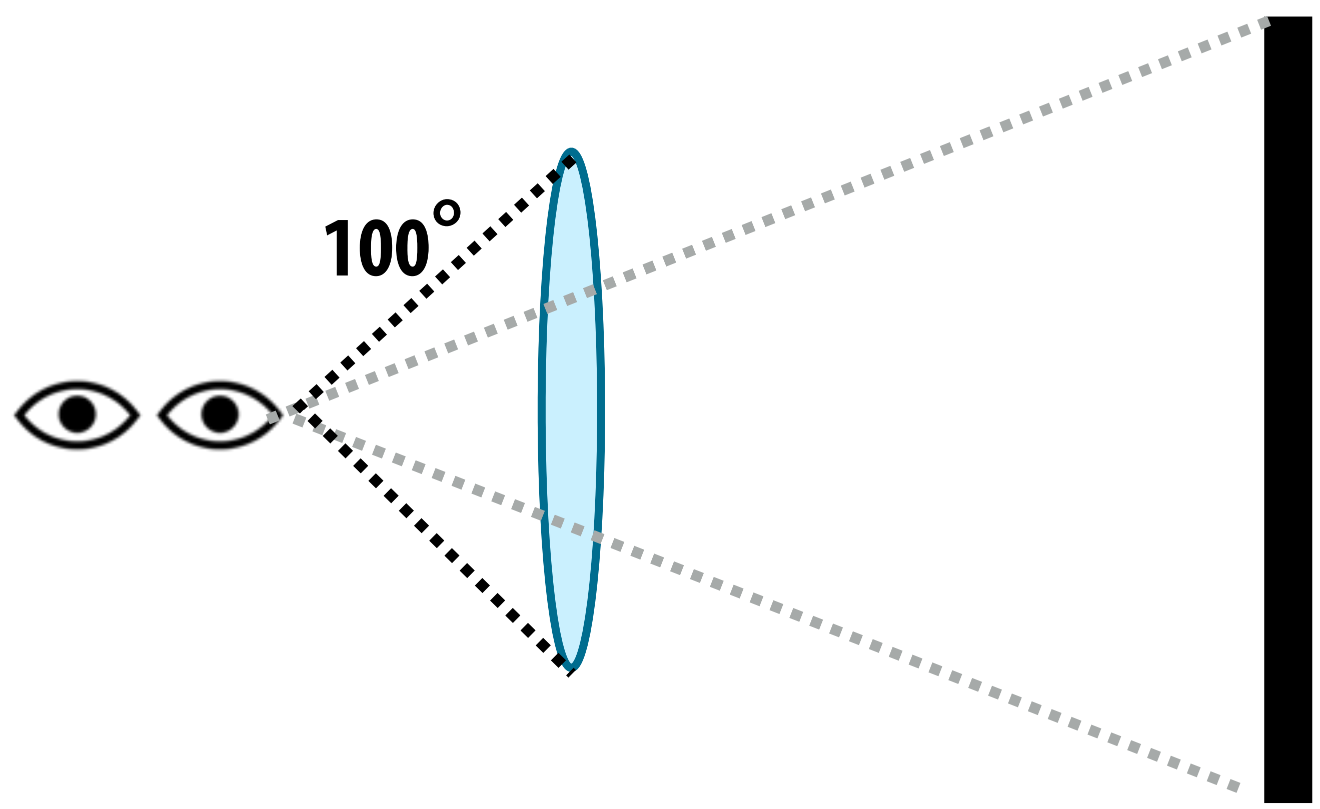
Foveated Rendering

Perceptual considerations:

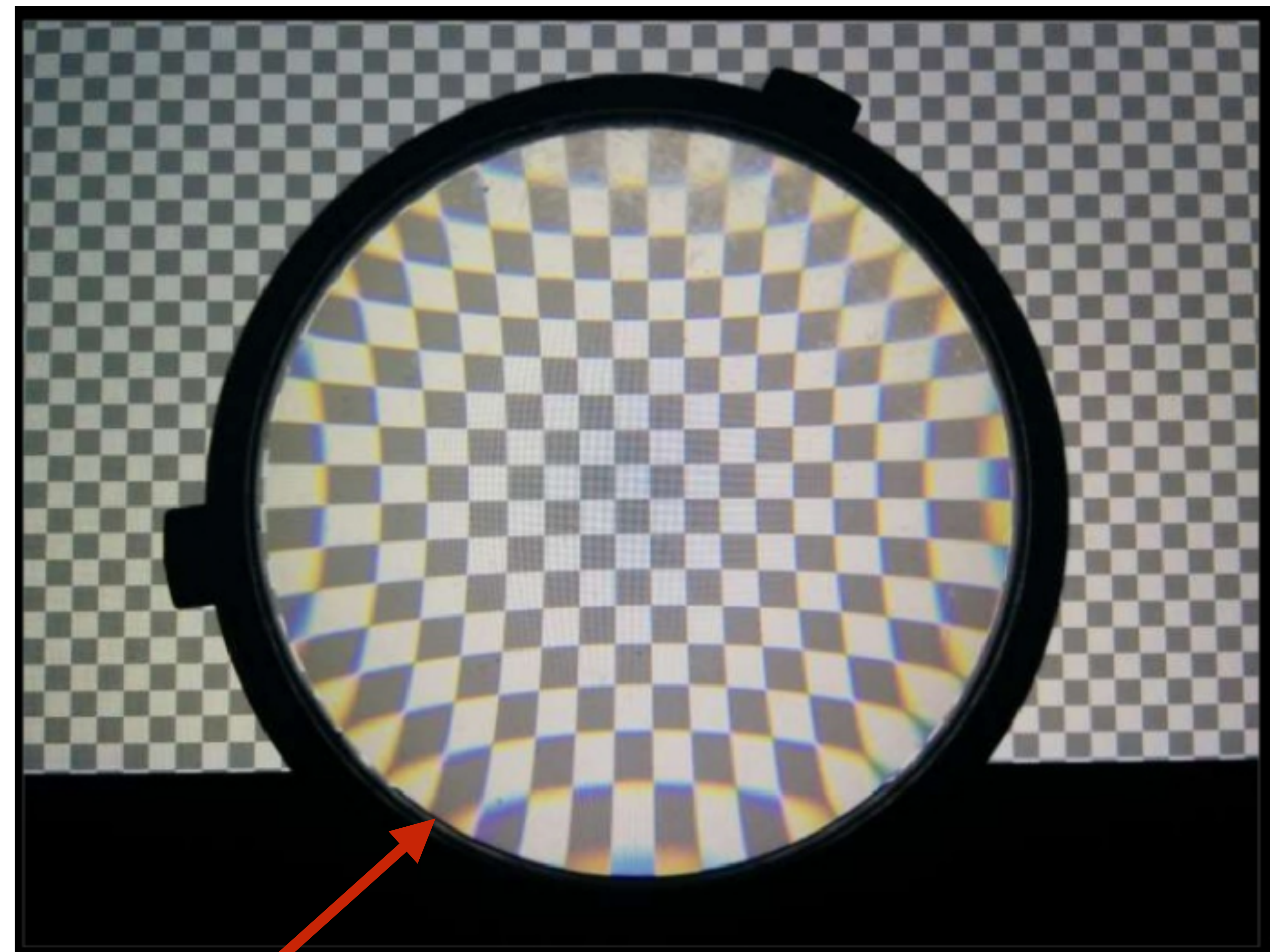
- If we render low resolution in periphery, have to be careful of aliasing / flickering
- If we render with a smooth image blur in the periphery, users experience a “tunnel vision” effect
- Research indicates that we should boost the contrast of low-frequency content in the periphery

Challenge: Distortion in VR Rendering

Requirement: Wide Field of View



View of checkerboard through Oculus Rift (DK2) lens

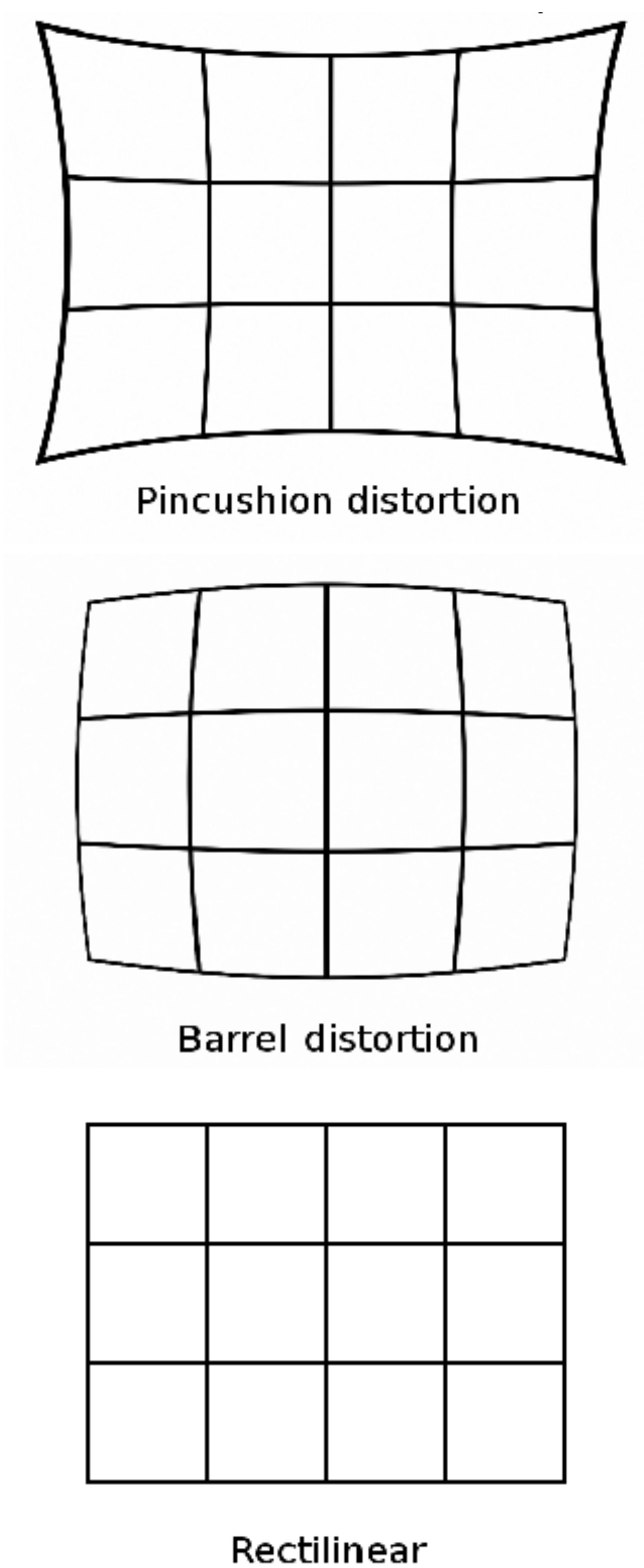


Lens introduces distortion

- Pincushion distortion
- Chromatic aberration (different wavelengths of light refract by different amount)

Icon credit: Eyes designed by SuperAtic LABS from the thenounproject.com
Image credit: Cass Everitt

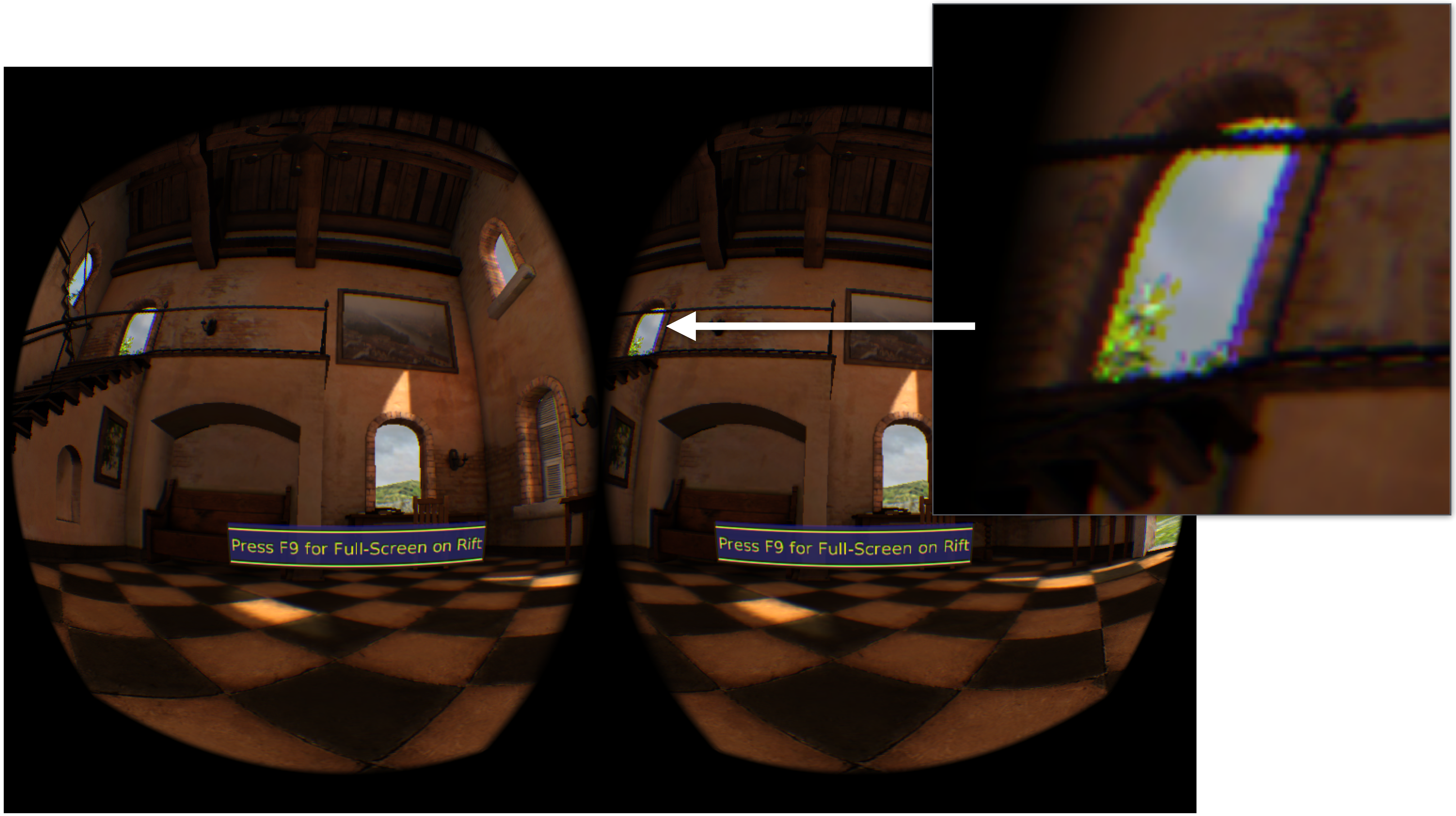
Recall Software Correction of Lens Distortion in Photography



m43photo.blogspot.com

Credit: The Photoshop Creative Team
http://blog.photoshopcreative.co.uk

Software Compensation of Lens Distortion in VR Rendering



Step 1: Render scene using traditional graphics pipeline at full resolution for each eye

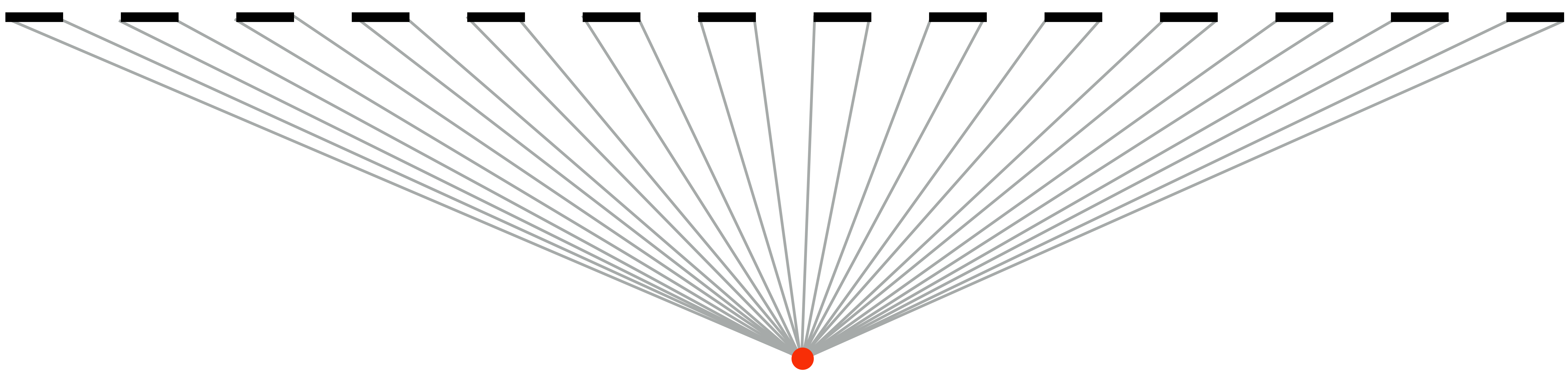
Step 2: Warp images in manner that scene appears correct after physical lens distortion

(Can use separate distortions to R, G, B to approximately correct chromatic aberration)

Image credit: Oculus VR developer guide

Related Challenge: Rendering via Planar Projection

Recall: rasterization-based graphics is based on perspective projection to plane
- Distorts image under high FOV, as needed in VR rendering
- Recall: VR rendering spans wide FOV



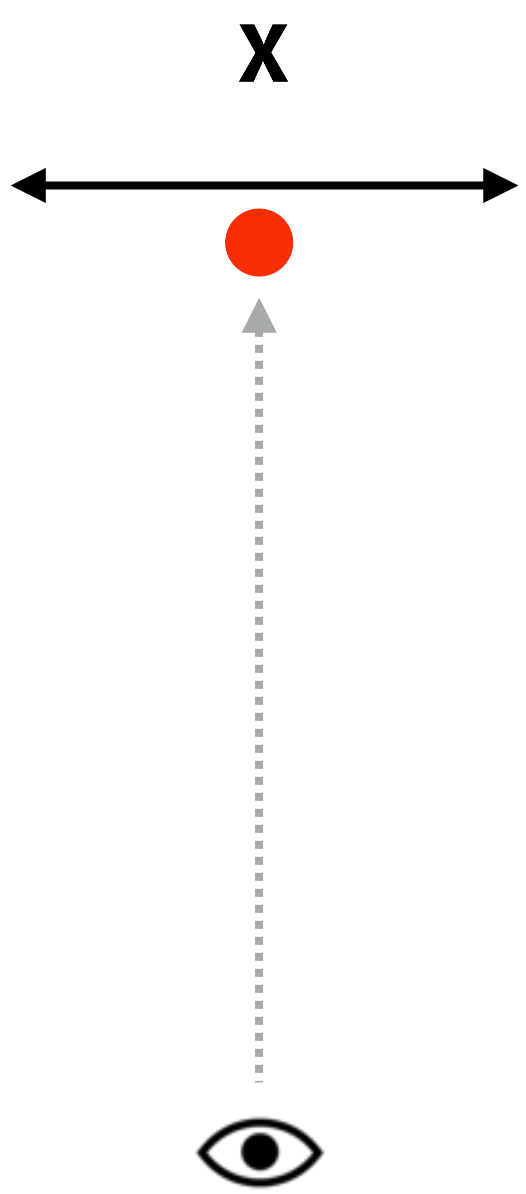
Pixels span larger angle in center of image
(lowest angular resolution in center)

Potential solution space: curved displays, ray casting to achieve uniform angular resolution, rendering with piecewise linear projection plane (different plane per tile of screen)

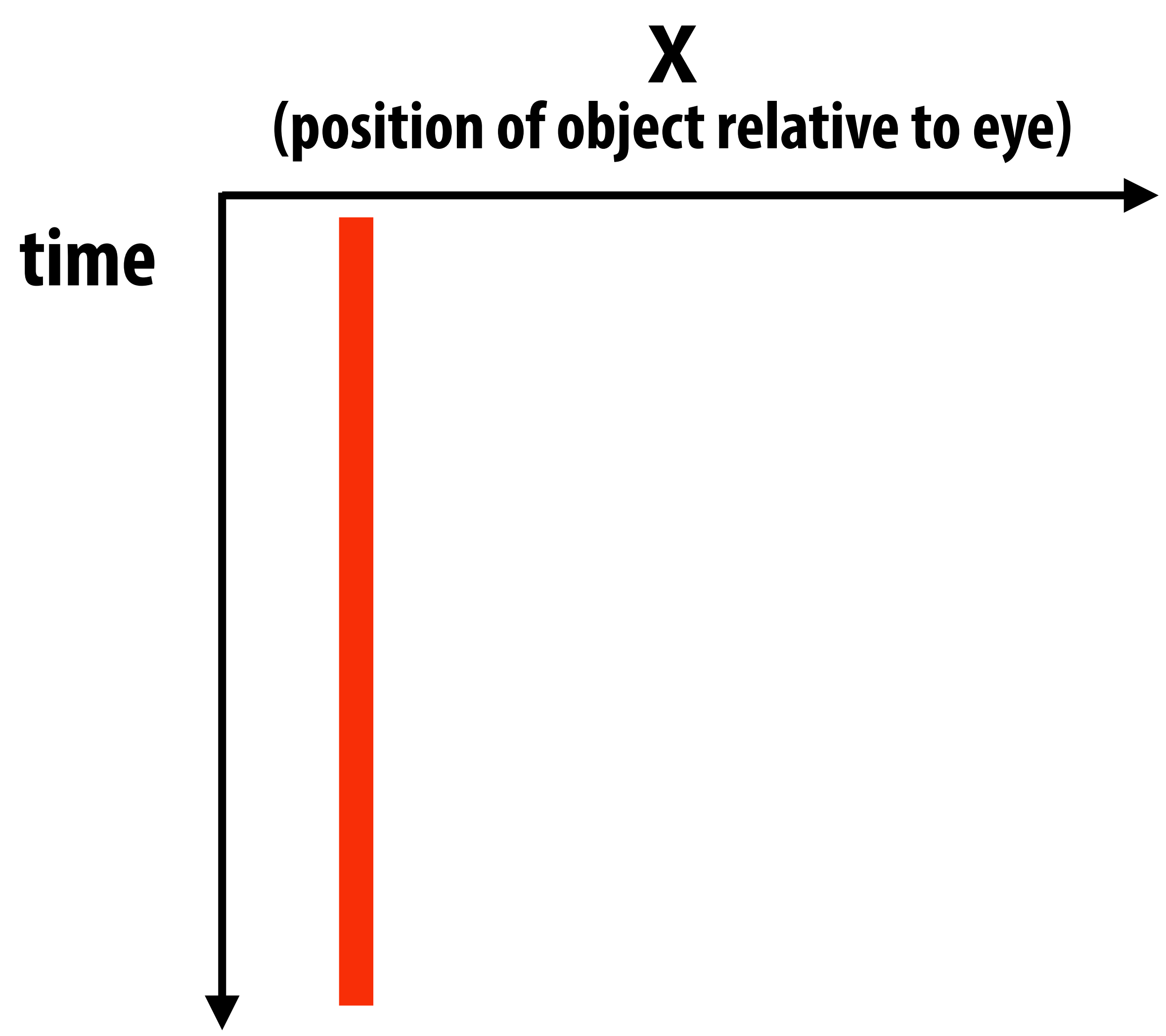
Image credit: Cass Everitt

Challenge: Eye Motion And Finite Rendering Rate

Consider Finite VR Display Refresh Rate

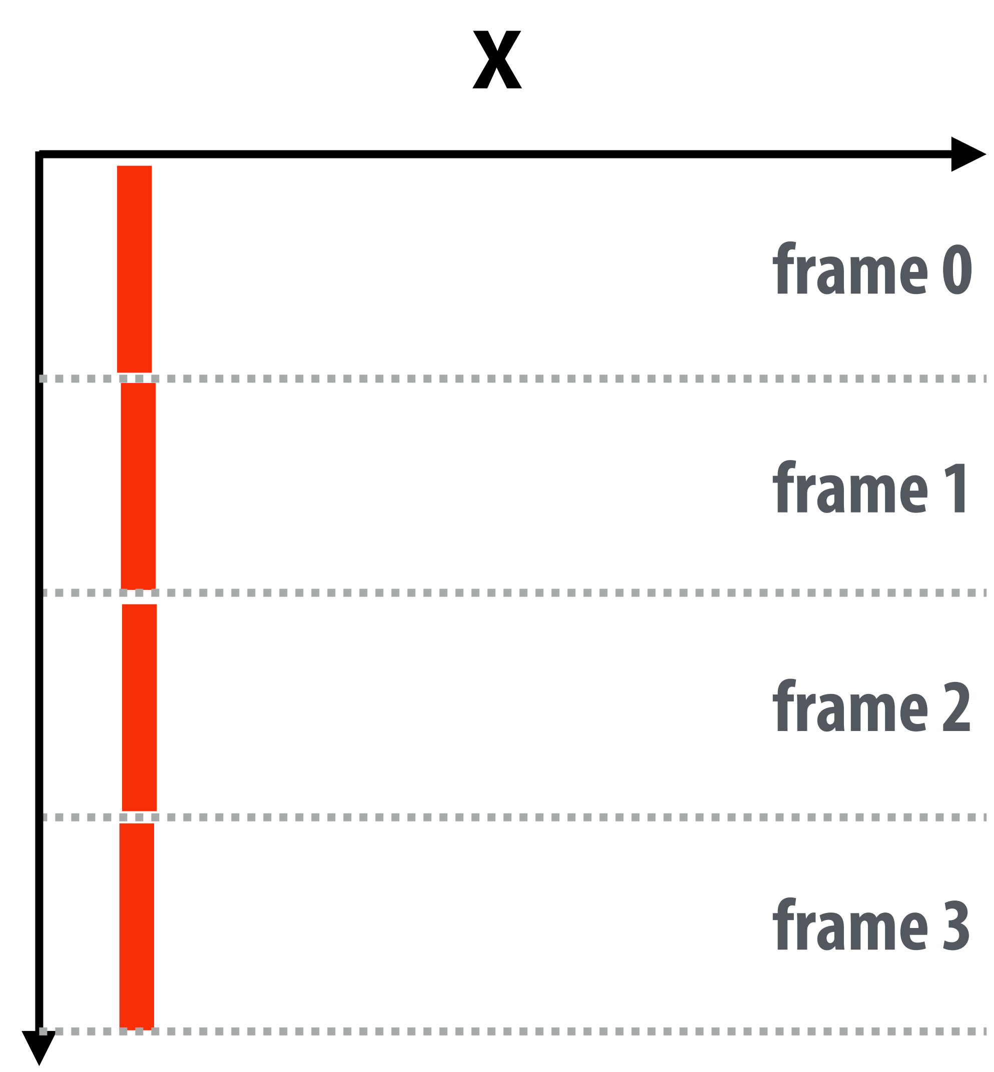


Reality (continuous)



- Red object fixed;
- Eye gaze fixed

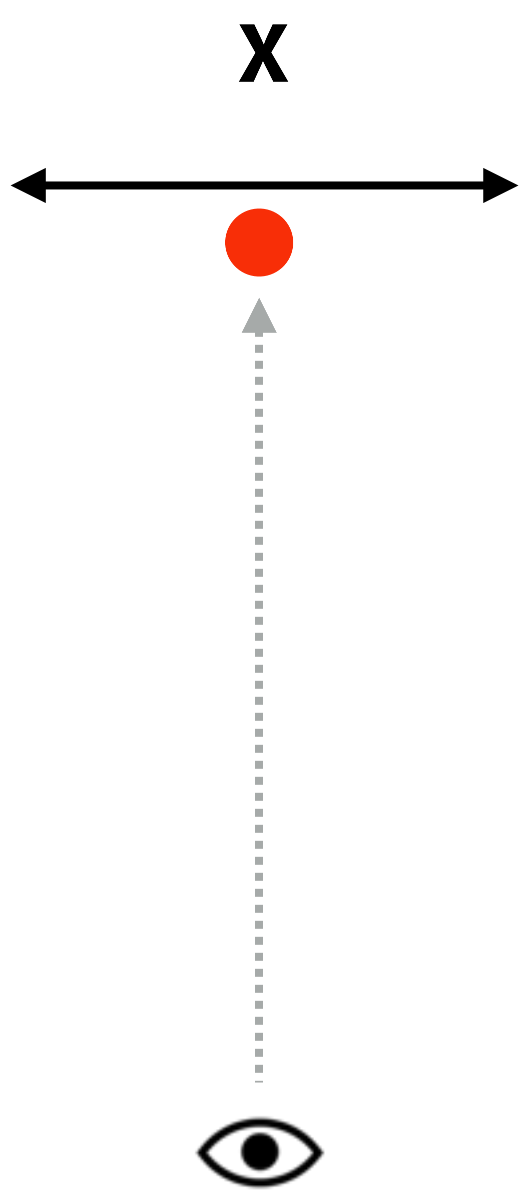
VR (discrete display refresh)



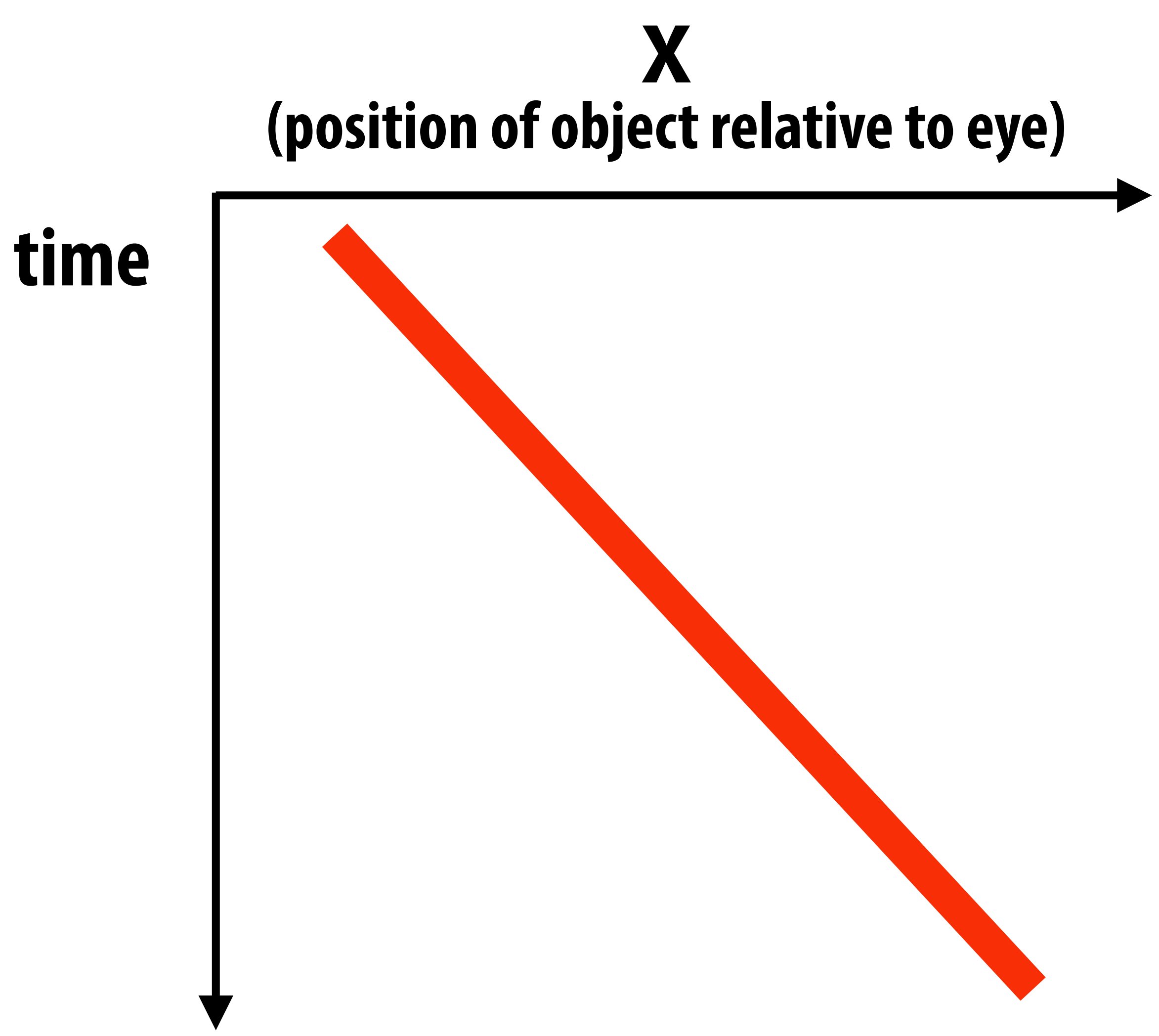
- Light from display
  (light updates every frame)

Spacetime diagrams adopted from presentations by Michael Abrash
Eyes designed by SuperAtic LABS from the thenounproject.com

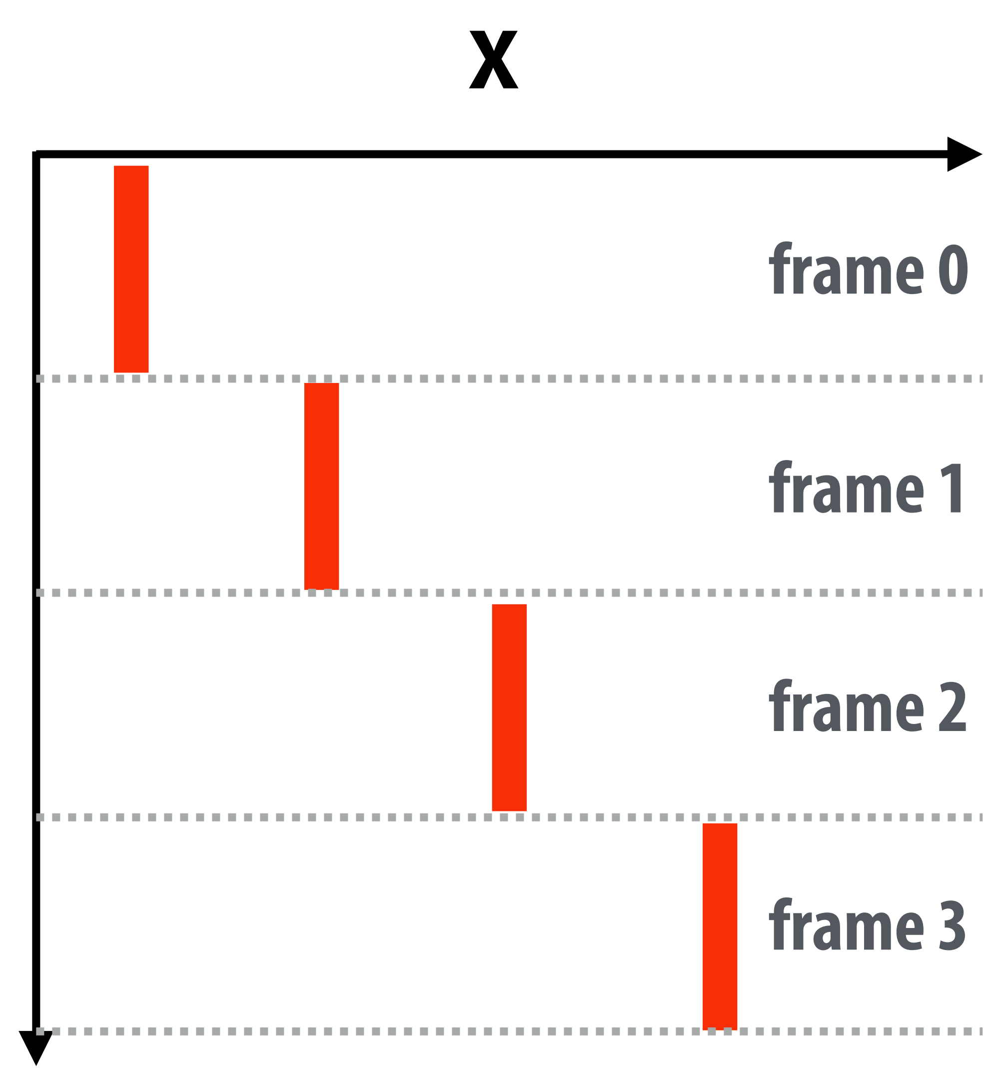
Case 2: Object Moving Relative to Eye



Reality (continuous)



VR (discrete display refresh)

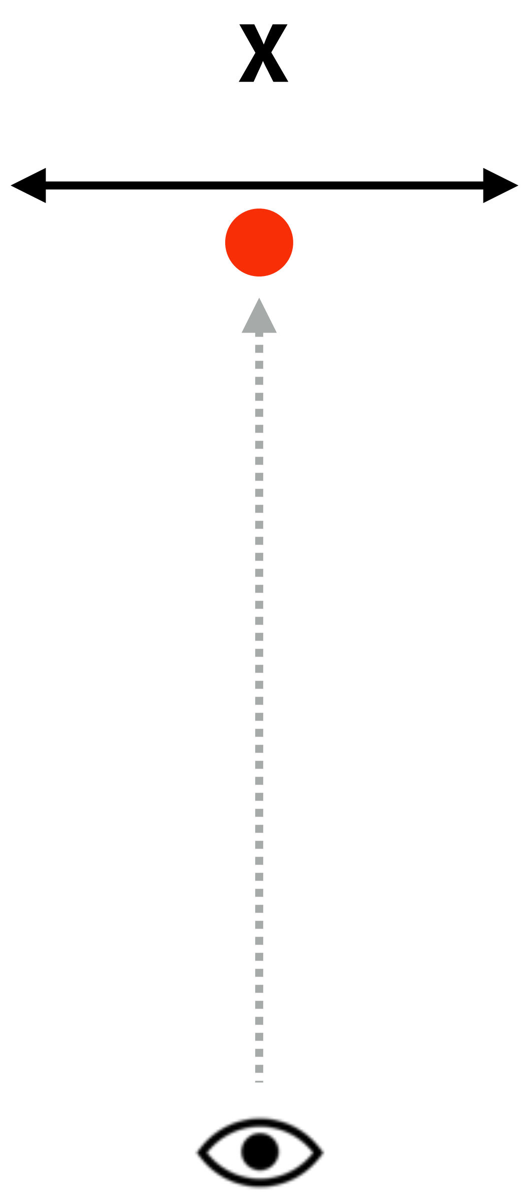


- Red object moving left to right;
- Eye gaze fixed

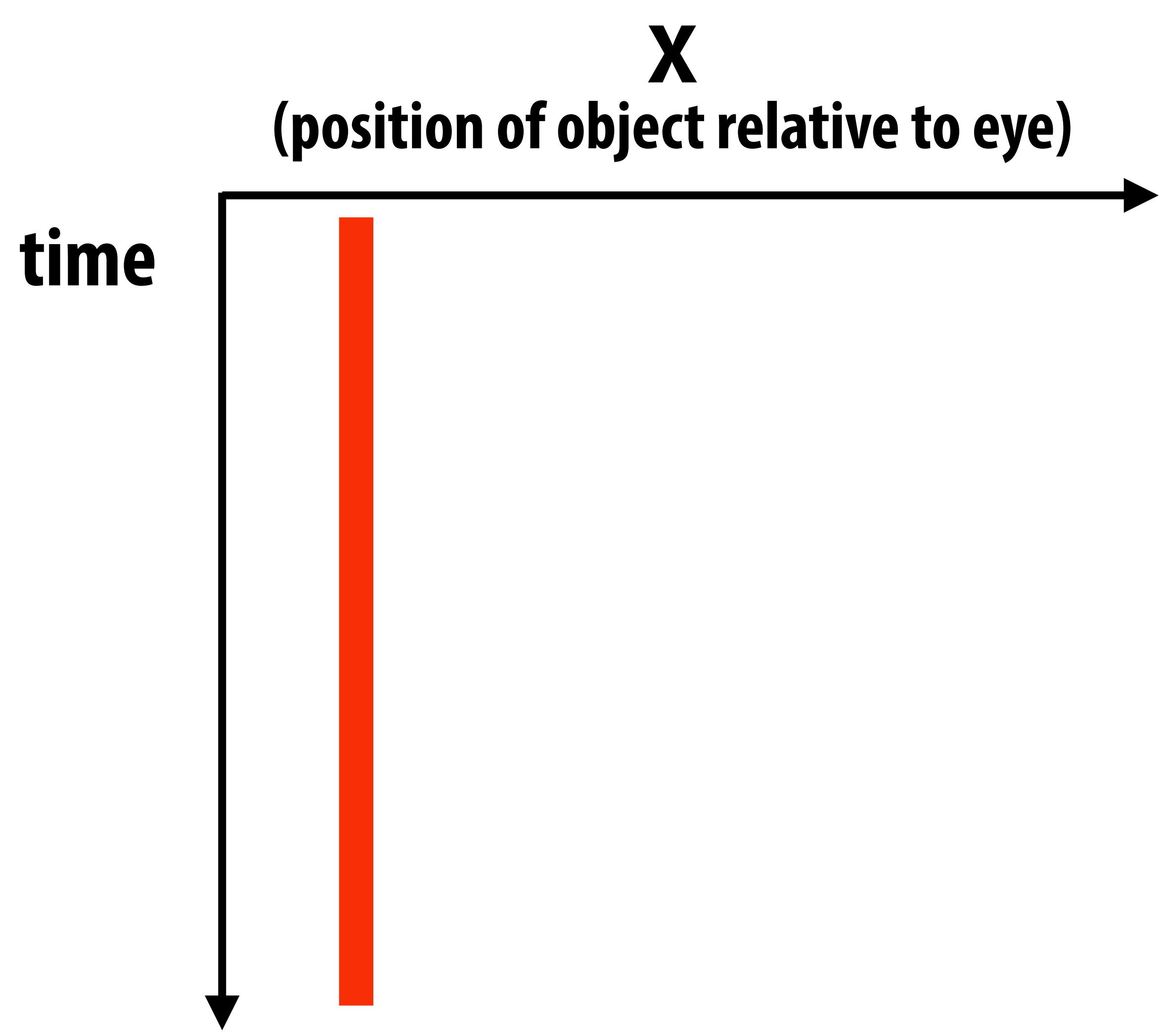
- Effect: time discretization
- OK: same perceptual effect as on regular 2D displays

Spacetime diagrams adopted from presentations by Michael Abrash
Eyes designed by SuperAtic LABS from the thenounproject.com

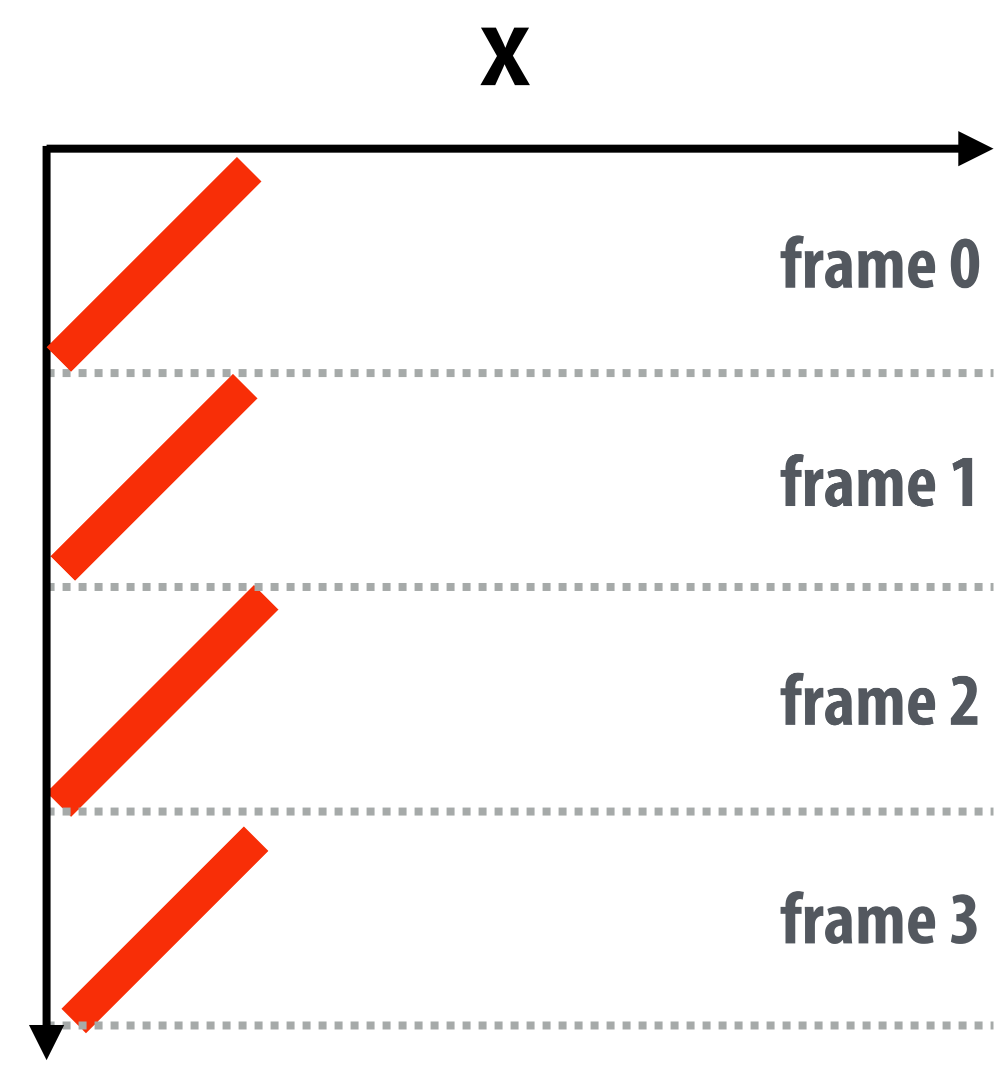
Case 3: Eye Moving to Track Moving Object



Reality (continuous)



VR (discrete display refresh)

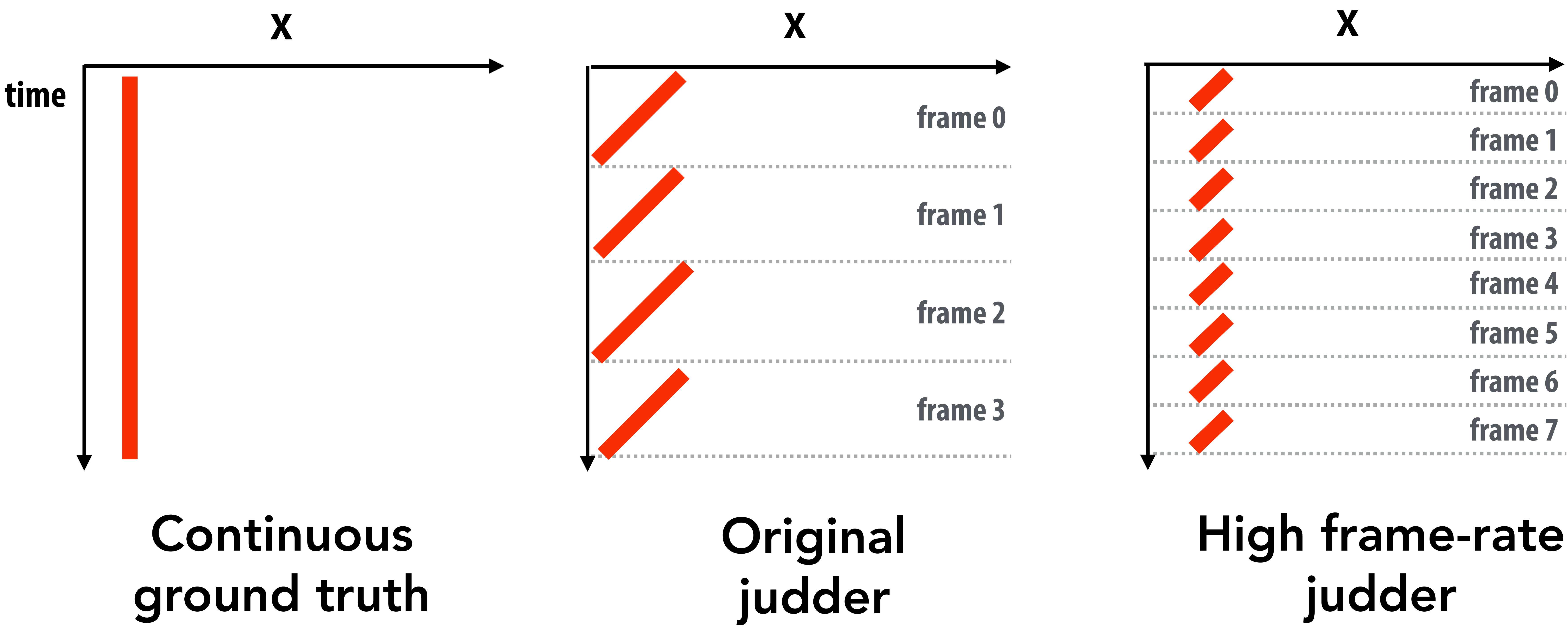


- Red object moving left to right;
- Eye gaze moving left to right to track object

- Eye is moving continuously <u>relative to display</u>
- During each frame, image of object falls behind eye
- Result: smearing/strobing effect ("judder")

Spacetime diagrams adopted from presentations by Michael Abrash
Eyes designed by SuperAtic LABS from the thenounproject.com

Reducing Judder: Increase Frame Rate

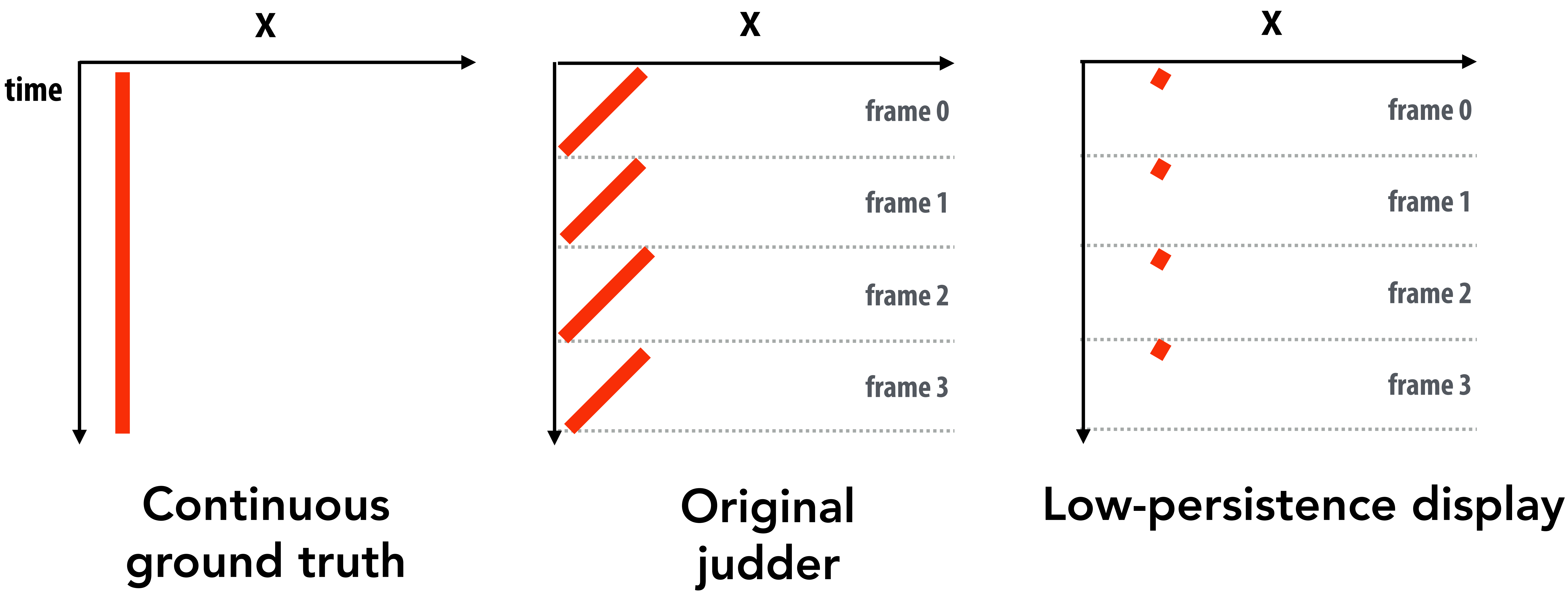


Higher frame rate (right-most diagram)

- Closer approximation of ground truth

Spacetime diagrams adopted from presentations by Michael Abrash

Reducing Judder: Low Persistence Display



Low-persistence display: pixels emit light for small fraction of frame

- Oculus DK2 OLED low-persistence display:
  - 75 Hz frame rate = ~13 ms per frame
  - Pixel persistence = 2-3 ms

Spacetime diagrams adopted from presentations by Michael Abrash

Near-Future VR Rendering System Components

Low-latency image processing
for subject tracking

High-resolution, high-frame rate,
wide-field of view display

Massive parallel computation for
high-resolution rendering

In headset motion/accel
sensors + eye tracker

Exceptionally high bandwidth
connection between renderer and
display:
e.g., 4K x 4K per eye at 90 fps!

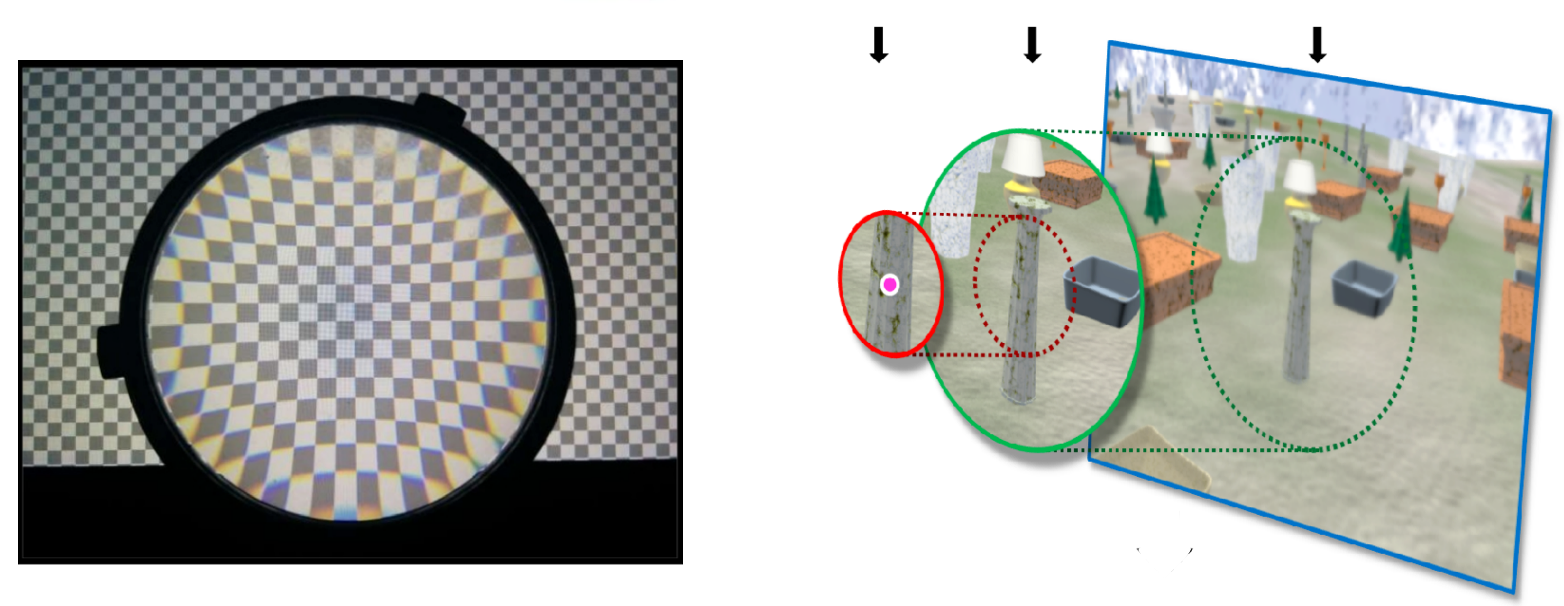
On headset graphics
processor for sensor
processing and re-
projection

Overview of VR Topics

Areas we will discuss over next few lectures

- VR Displays

- VR Rendering

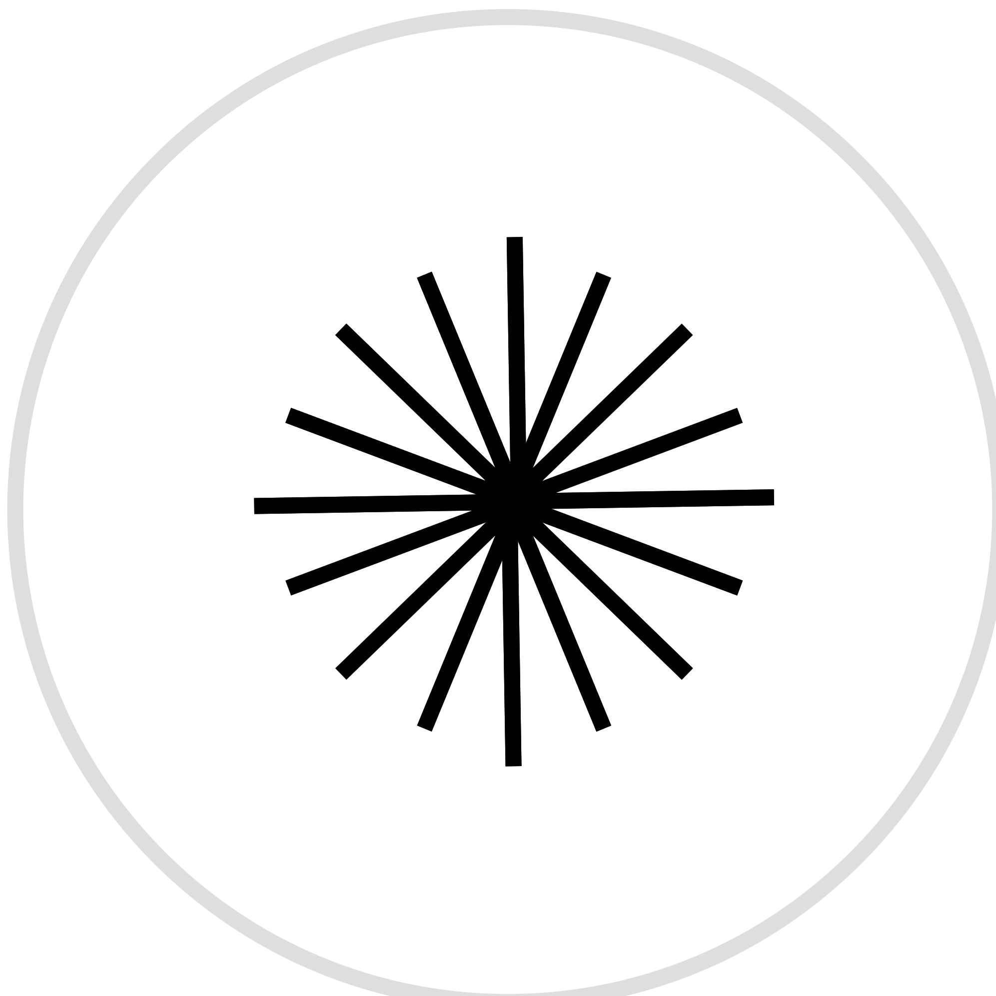


- VR Imaging

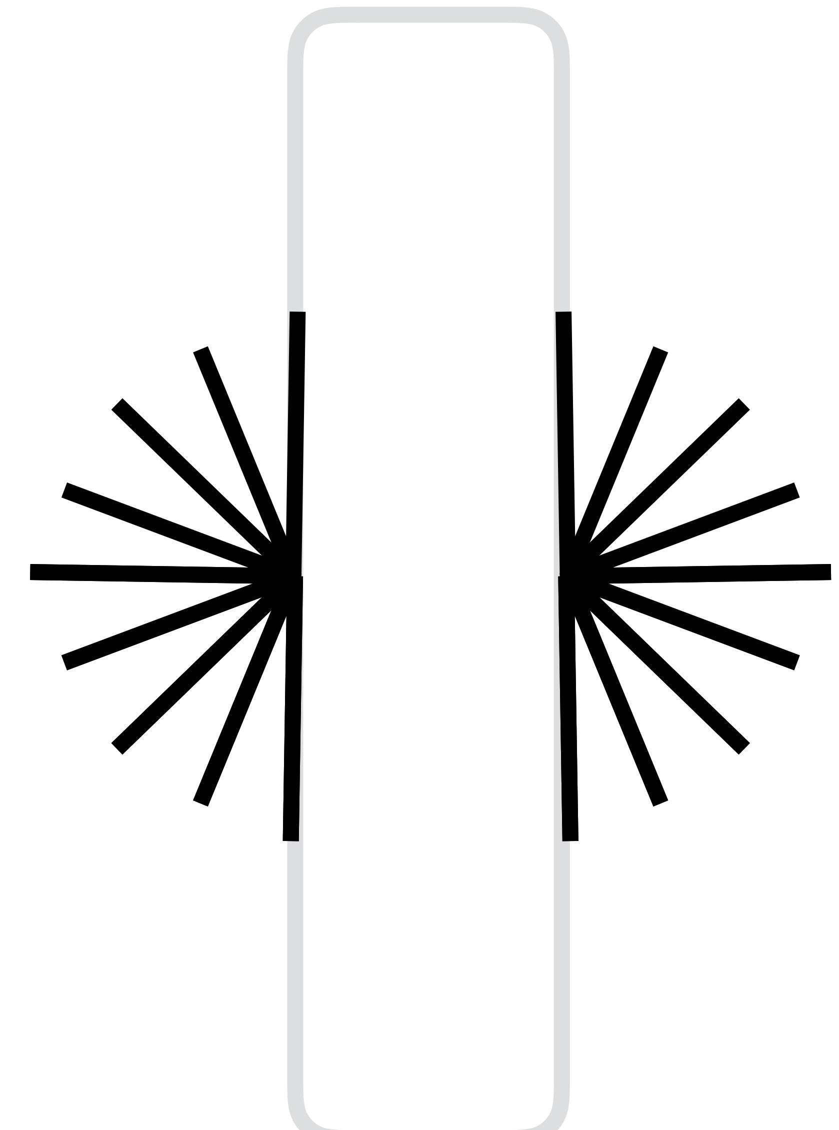
Spherical Imaging
(Monocular 360)

Dual Fisheye

Stitching Challenges



Want this
ray sampling



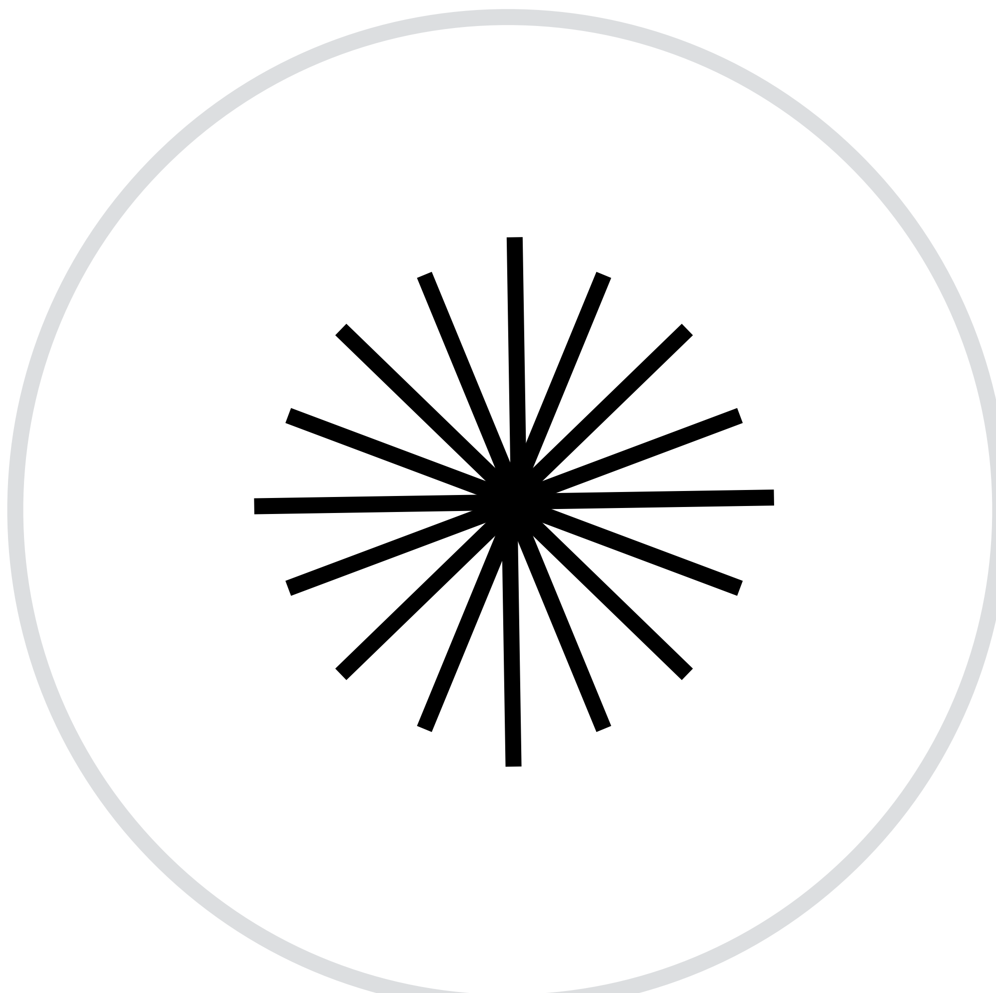
Get this
ray sampling

Spherical Array of Cameras

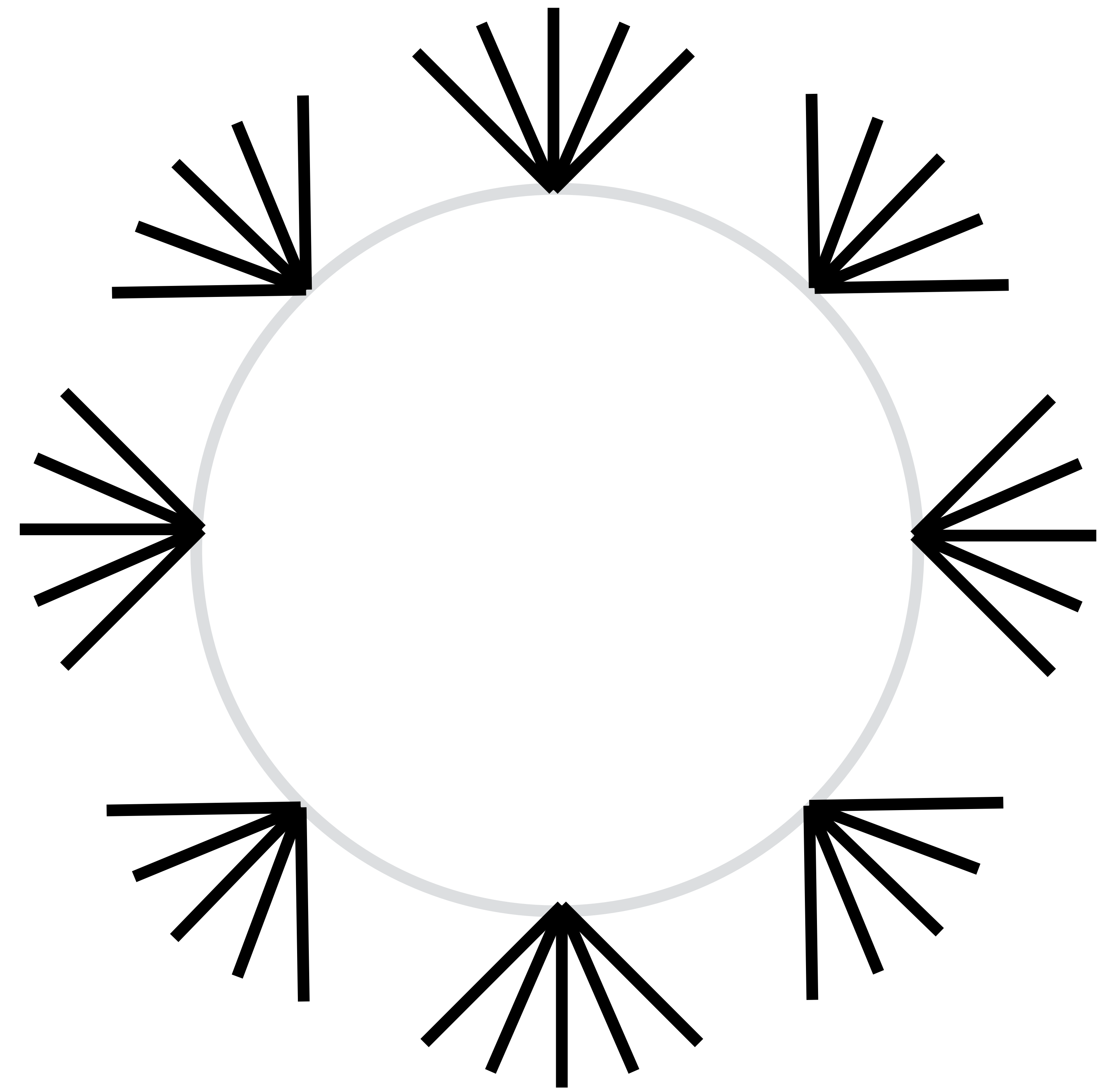
DIAMETER	11 cm
WEIGHT	approximately 480 g
CAMERAS	36 fixed-focus cameras
RESOLUTION	108 megapixels
PANONO APP	iOS 7+ and Android 4.2+
CHARGING	via USB cable
STORAGE CAPACITY	16 GB, approximately 600 Panono shots
CONNECTION	WiFi
SECURITY FEATURES	Theftprotect mode

Panono 360 degree Camera

Stitching Challenges



Want this
ray sampling



Get this
ray sampling

High Quality Stitching Solution Uses Computer Vision

Use computer vision techniques:

- Detect image features (like SIFT features)
- Correlate features across frames (transform)
- Warp to align frames and blend

Spherical Stereo Imaging

What Pairs of Viewpoint Positions Do We Want To Sample?

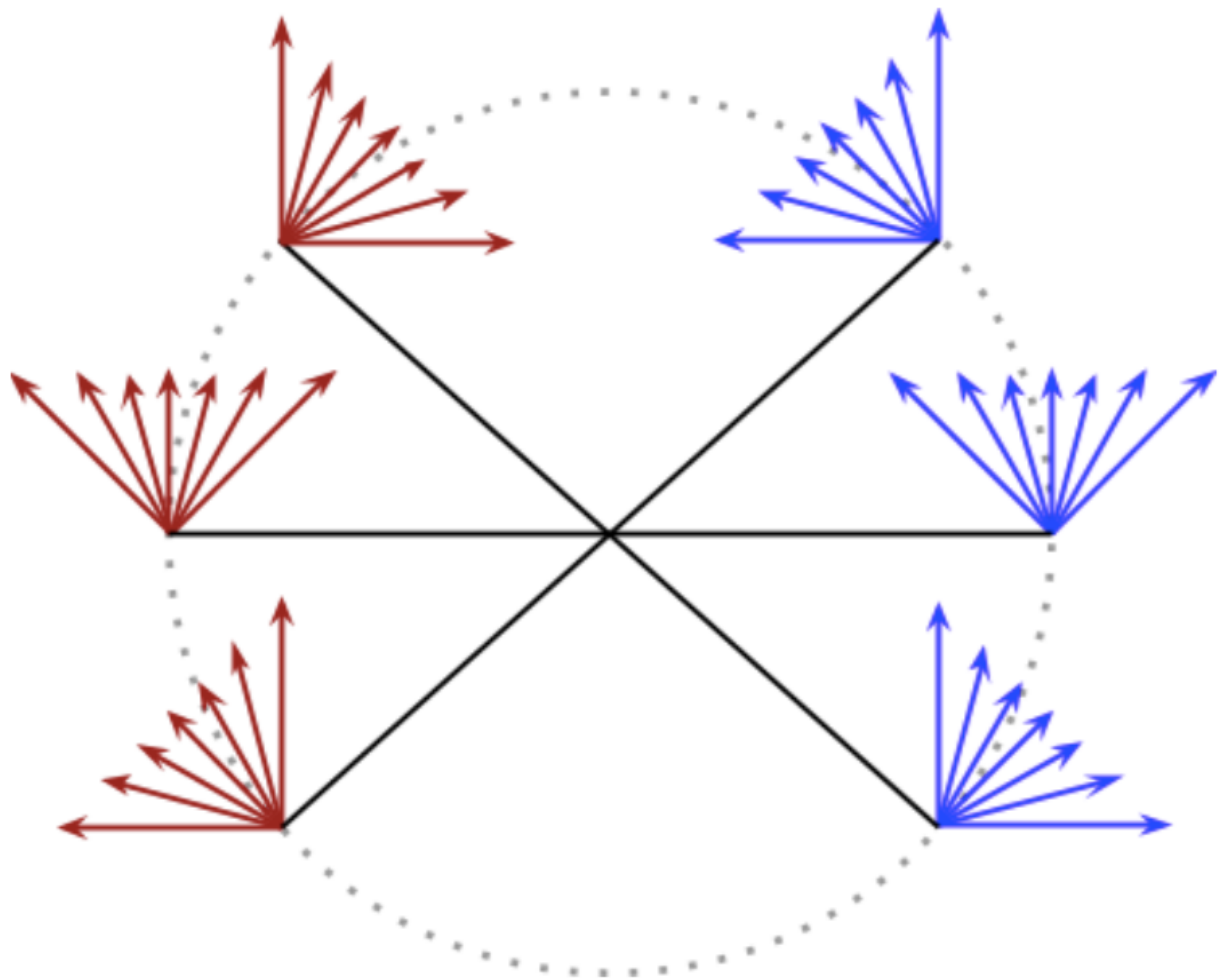
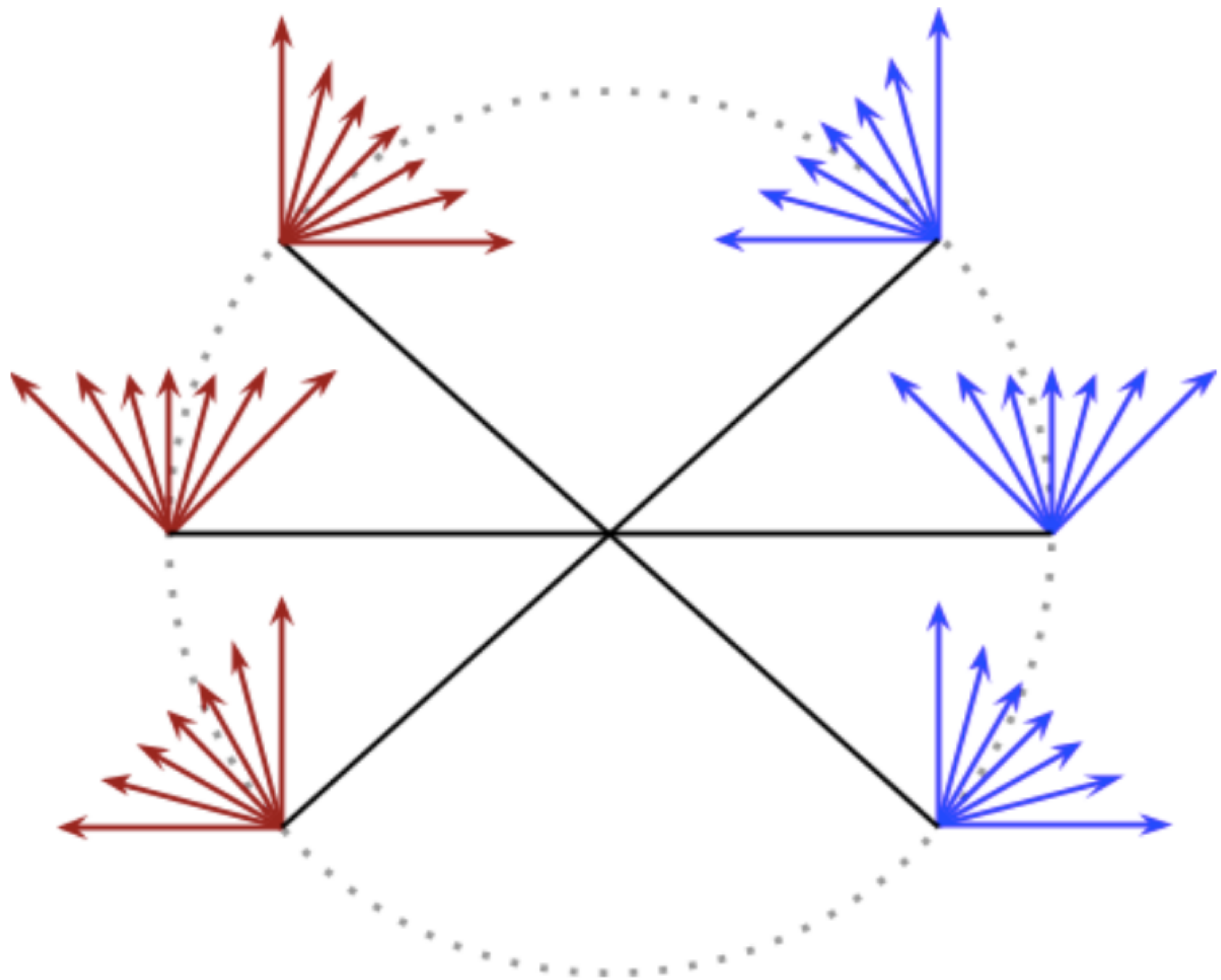


Image Credit: Google Inc.

Idea: Spin a Pair of Cameras About Midpoint

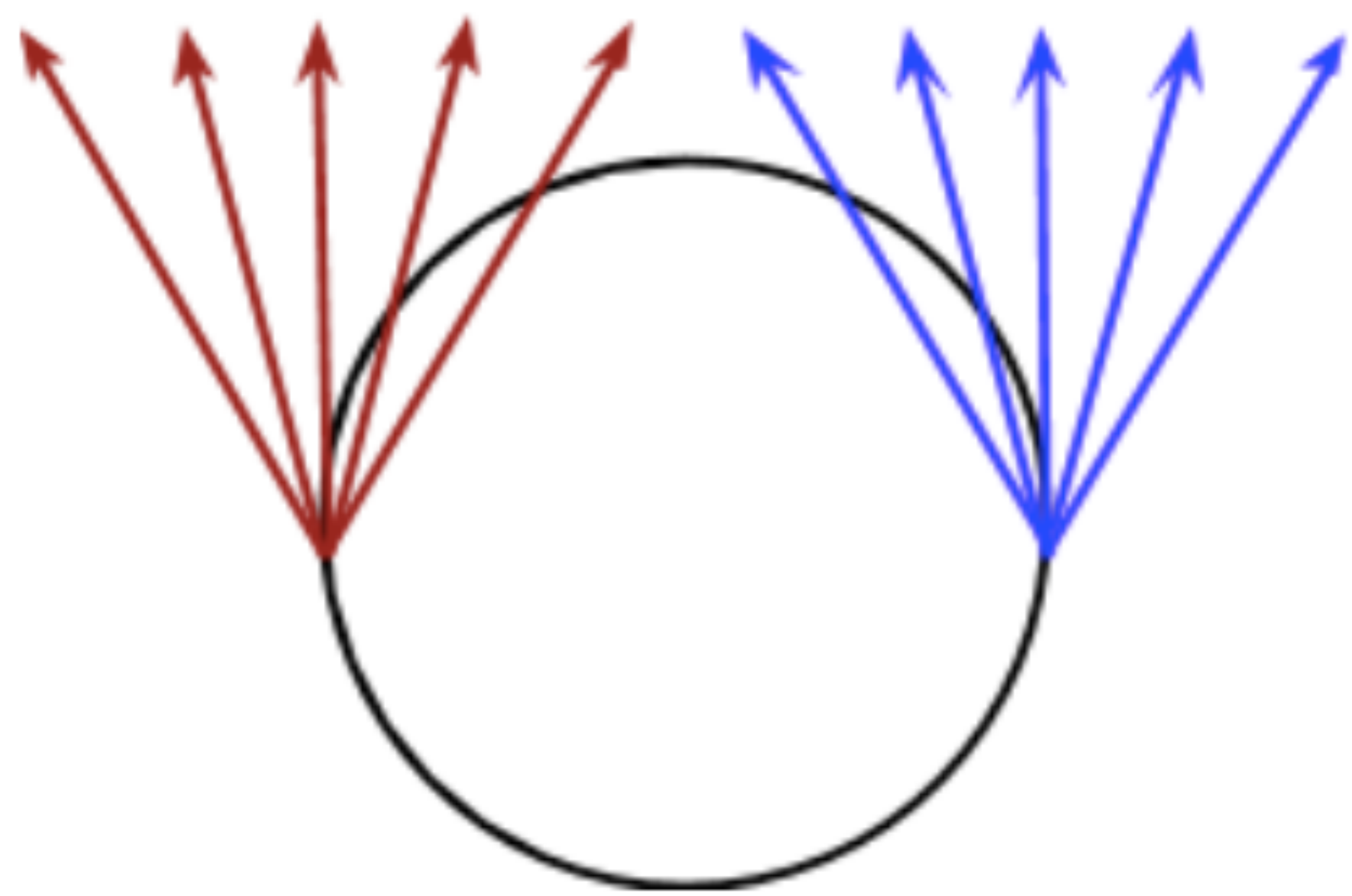


Store a set of movie pairs (one per angle)

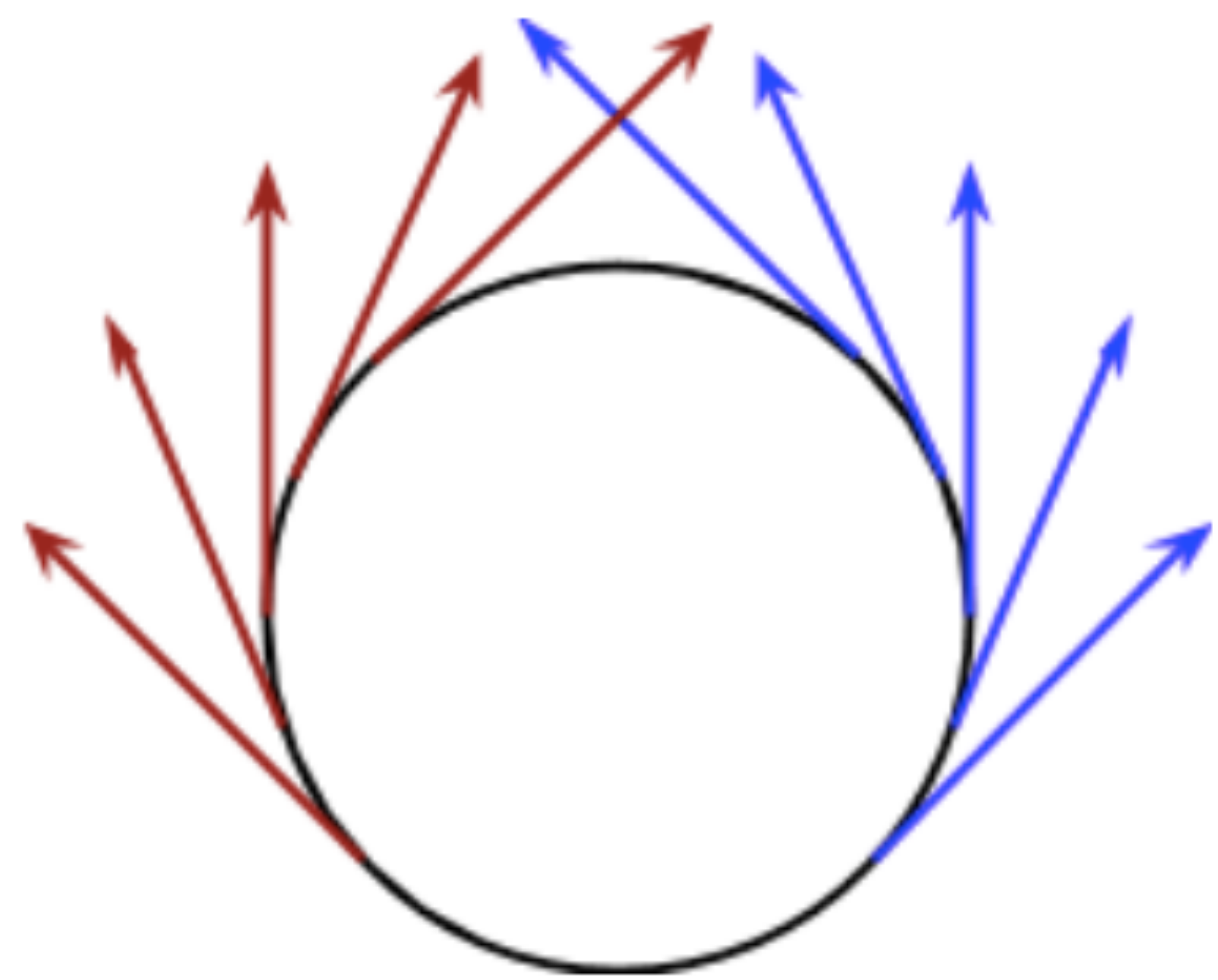
But that's a lot of data

Image Credit: Google Inc.

Omni-Directional Stereo Approximation



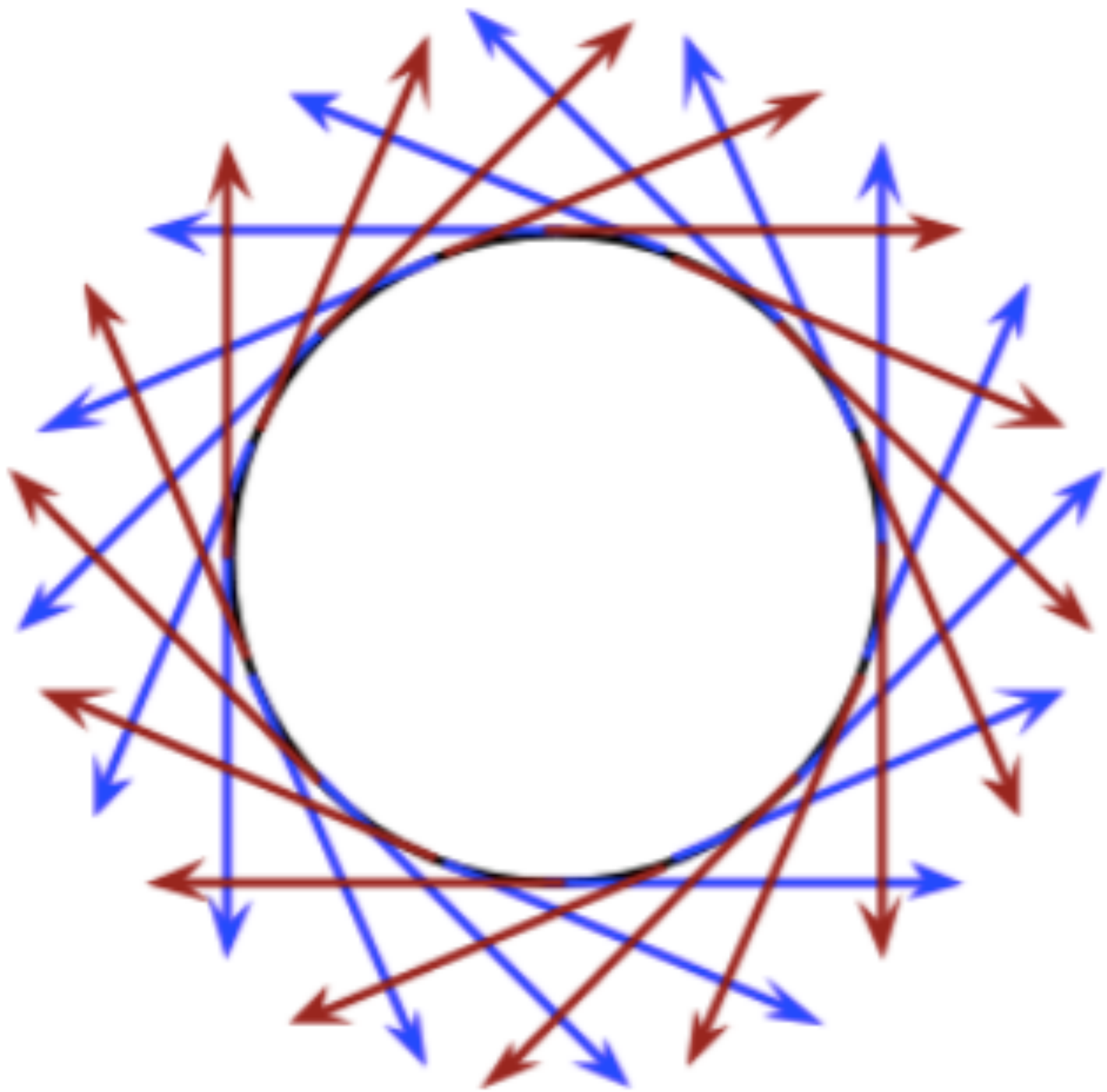
full-frame **left** and **right** eyes



ODS-approximated **left** and **right** eyes

Image Credit: Google Inc.

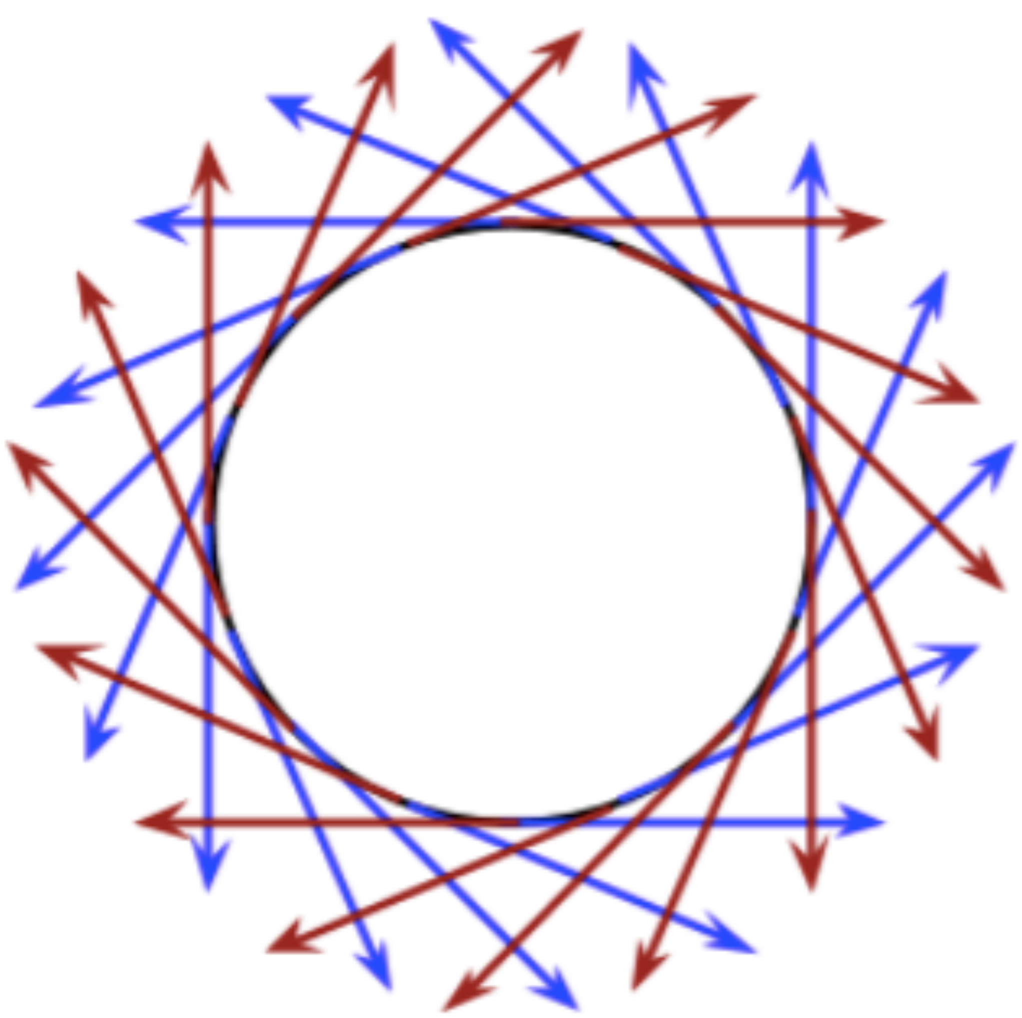
Omni-Directional Stereo Approximation

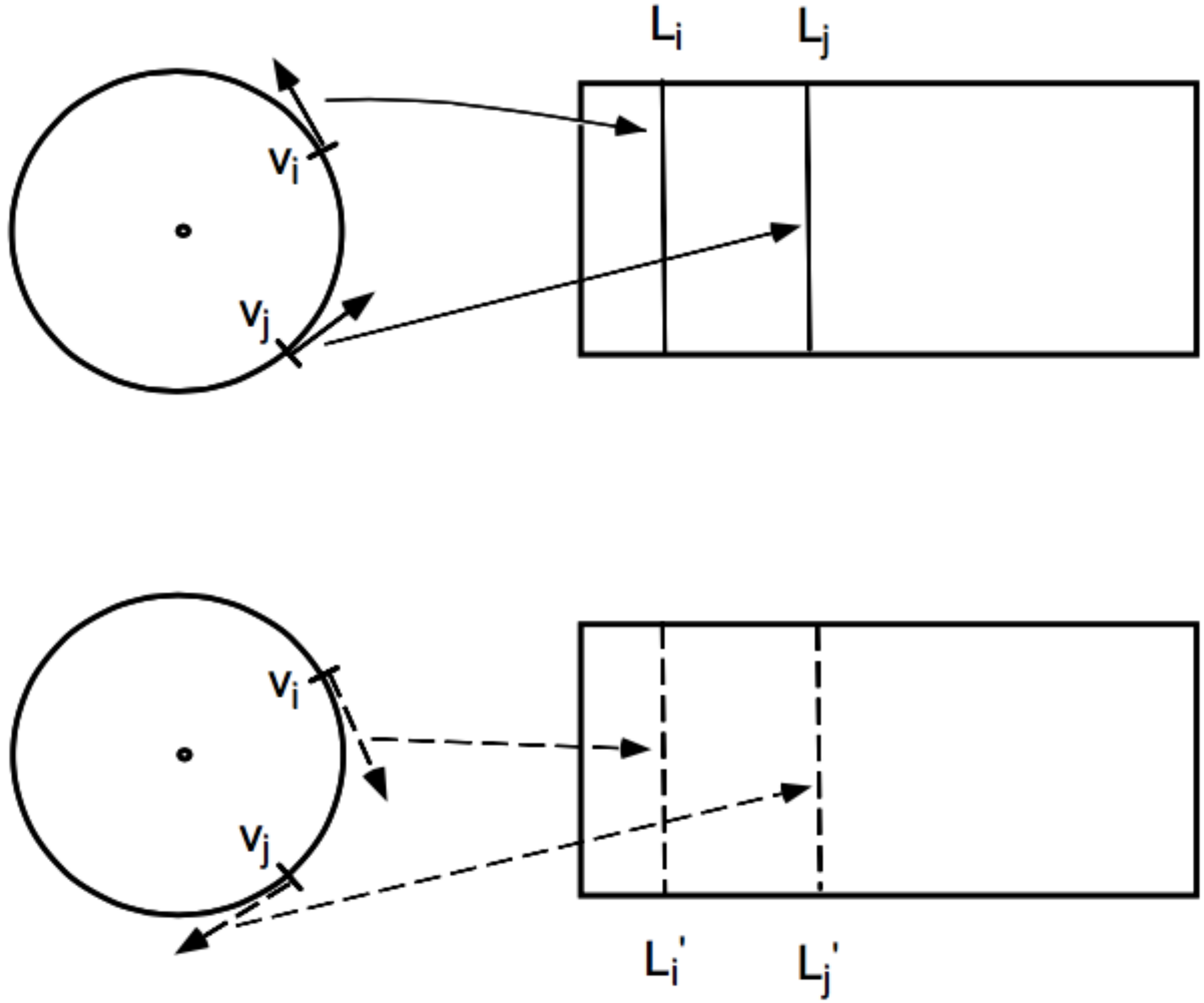


Extended to be omnidirectional

Image Credit: Google Inc.

Spinning Camera





Concentric Mosaics
Shum and He, SIGGRAPH 1999

Omni-Directional Stereo Representation

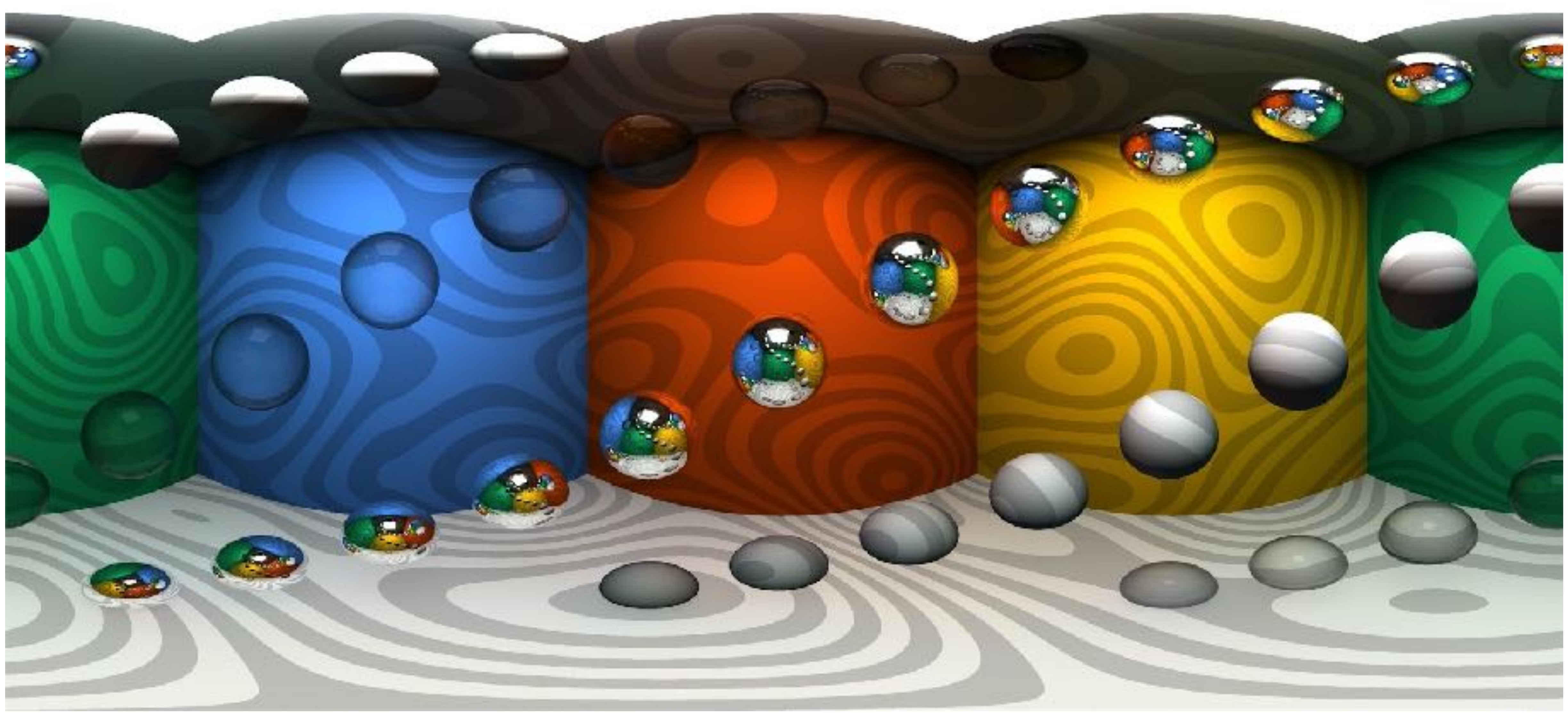
Encode left/right views as just two spherical images

- Render left and right views for each angular view independently, with regular viewing software
- Efficient and compact, but this is an approximation
  - Straight lines may appear slightly curved
  - Vertical disparity for close objects incorrect

Example (Rendered)

Left Eye

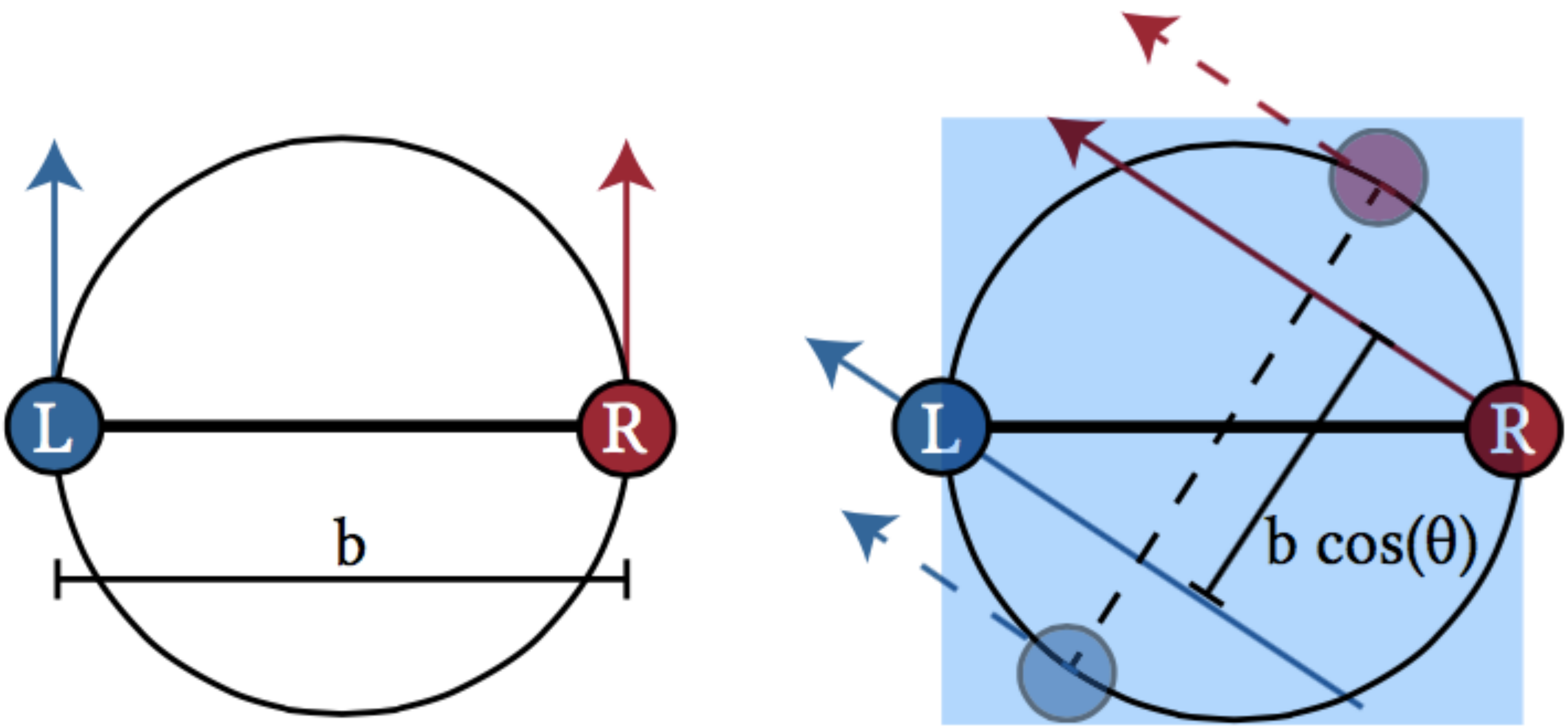
Right Eye



Two Eyes — Two Spherical Cameras?

Matzen et al. SIGGRAPH 2017
Low-Cost 360 Stereo Photography and Video Capture

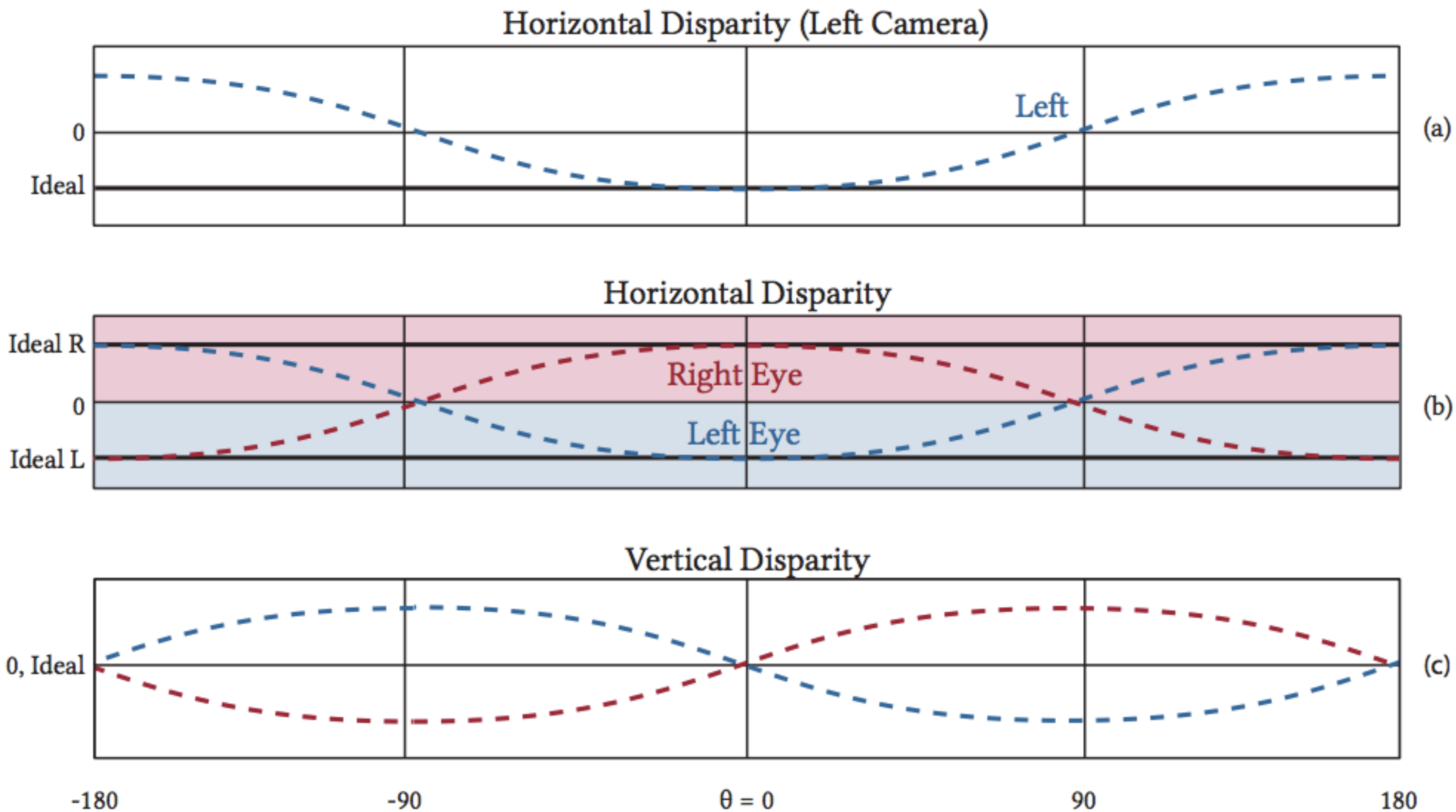
Problem: Stereo Baseline Fluctuates With View Angle



Apparent stereo baseline decreases by cos(θ) if rays are mapped directly

Matzen et al. SIGGRAPH 2017

Problem: Both Horizontal and Vertical Disparities Fluctuate



Matzen et al. SIGGRAPH 2017

Problems

- Disparity: incorrect baseline as view angle changes
- Occlusion: each camera blocks the other's view!

Matzen et al. SIGGRAPH 2017

Solution: Computational Photography

3D reconstruction

- Computer vision on stereo views

Disparity correction

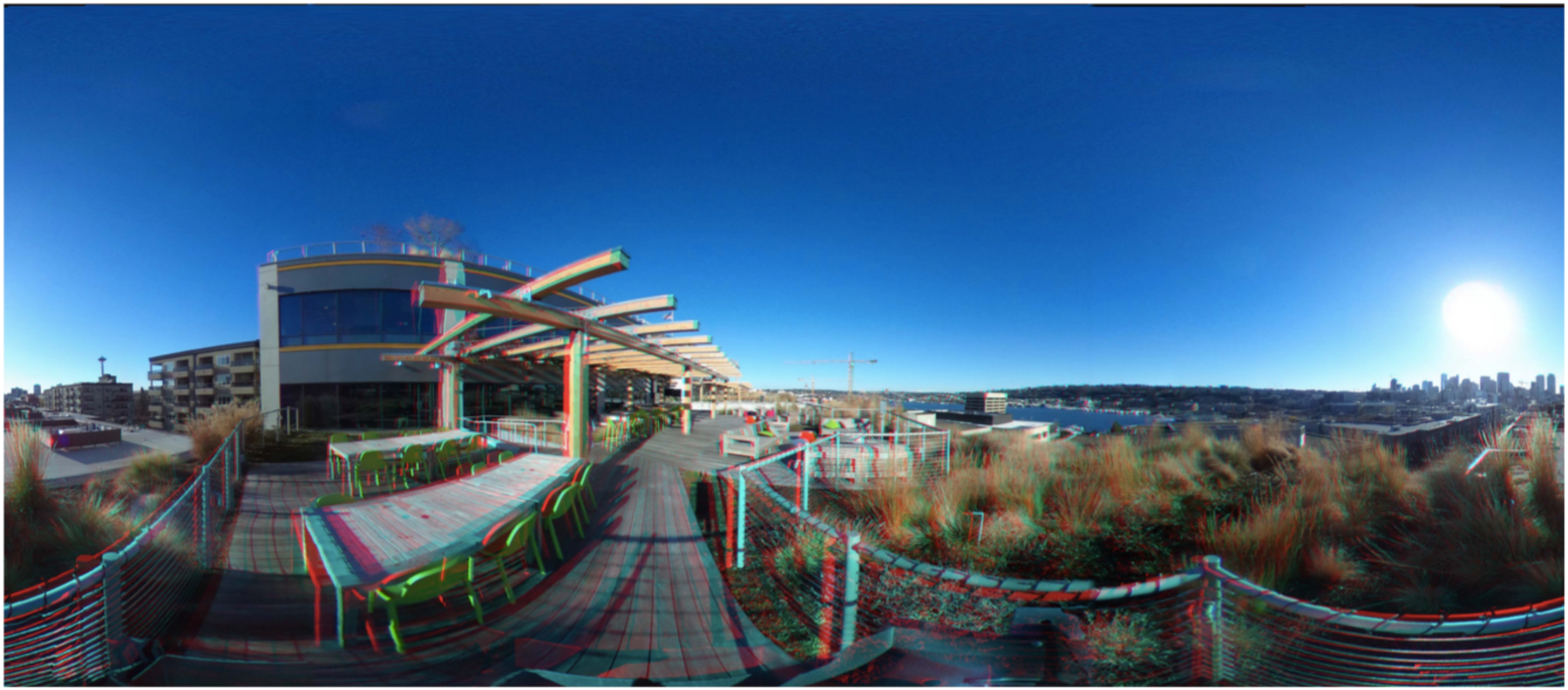
- Use 3D model to correct stereo disparities
  - e.g. amplify horizontal disparities by $1/\cos(\theta)$
- Flip views when facing backwards

Hole filling

- Cut out view of other camera, and fill hole with pixels from other camera, as best possible

Matzen et al. SIGGRAPH 2017

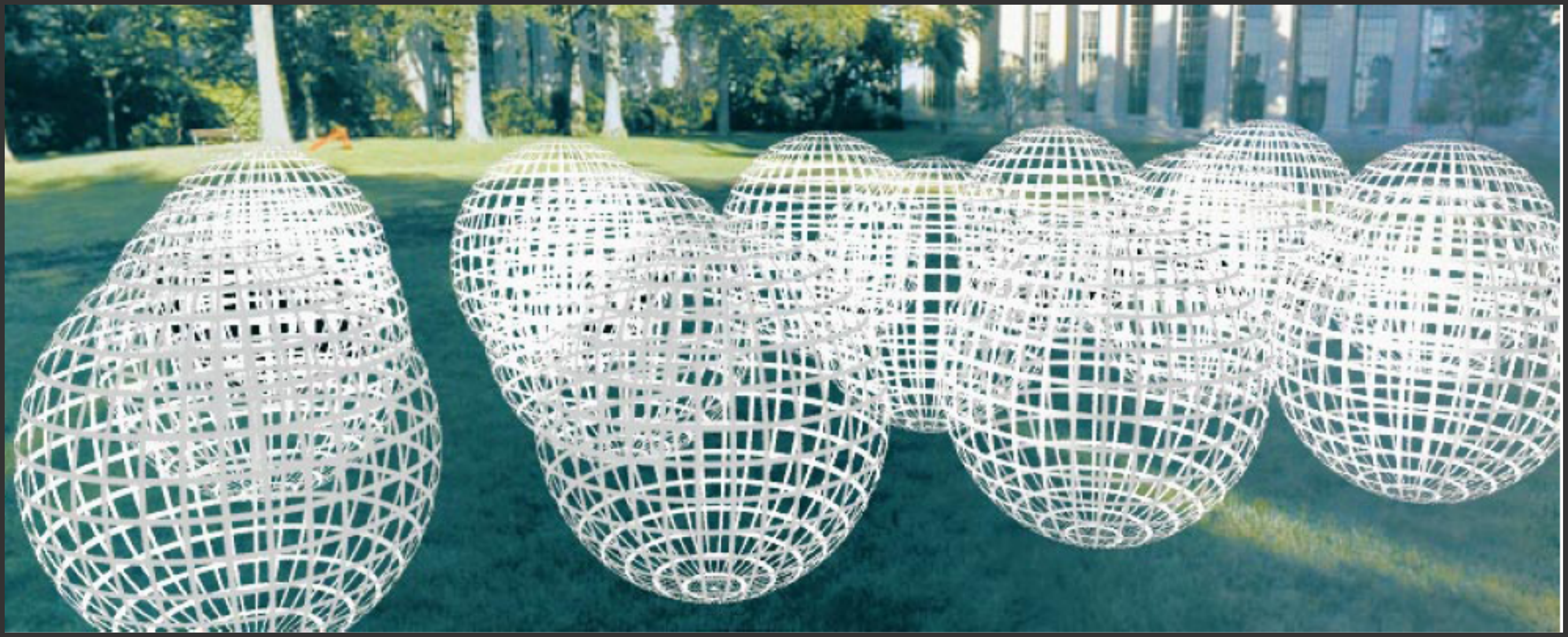
Spherical Stereo Result



Matzen et al. SIGGRAPH 2017

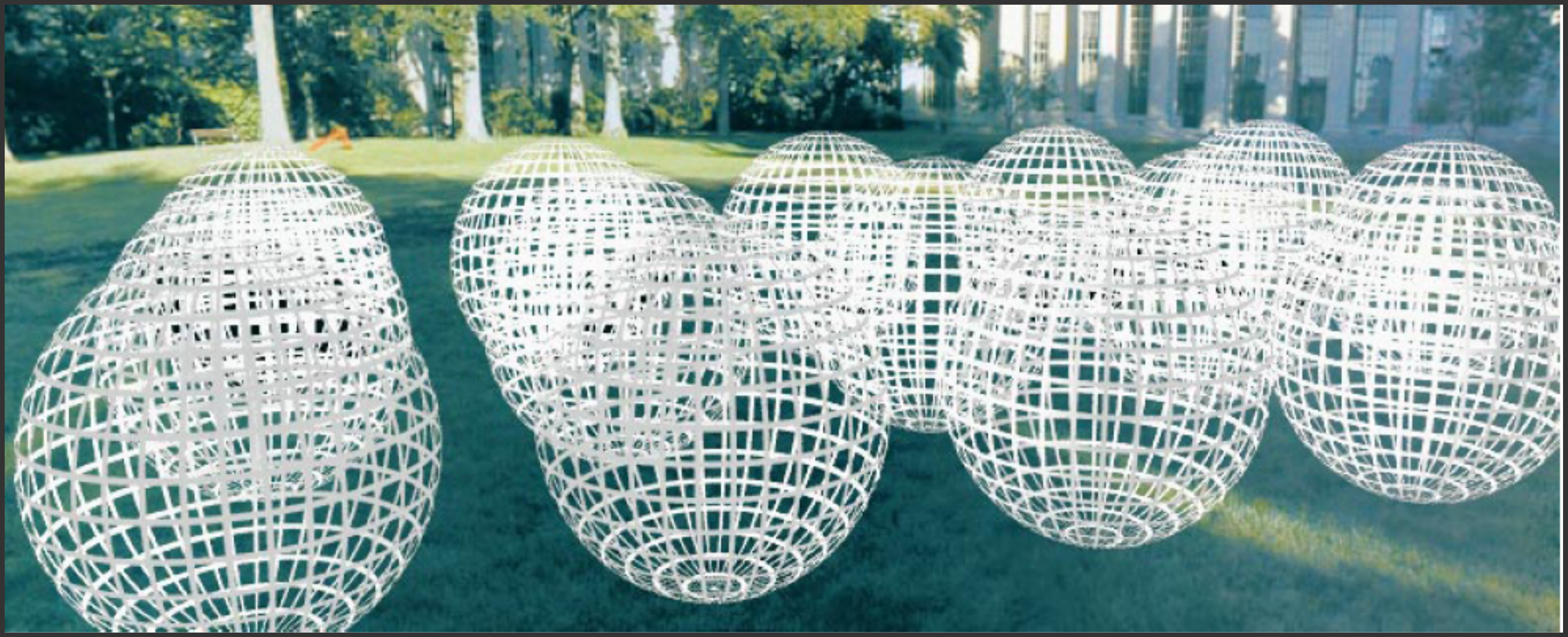
Moving-Viewpoint Imaging
(Full Plenoptic Function?)

The 5D Plenoptic Function



$$P(\theta, \phi, V_x, V_y, V_z)$$

4D Light Field



$$P(\theta, \phi, V_x, V_y) = P(u, v, s, t)$$

- In a region of free-space, 5D plenoptic function simplifies to 4D because light is constant along a ray

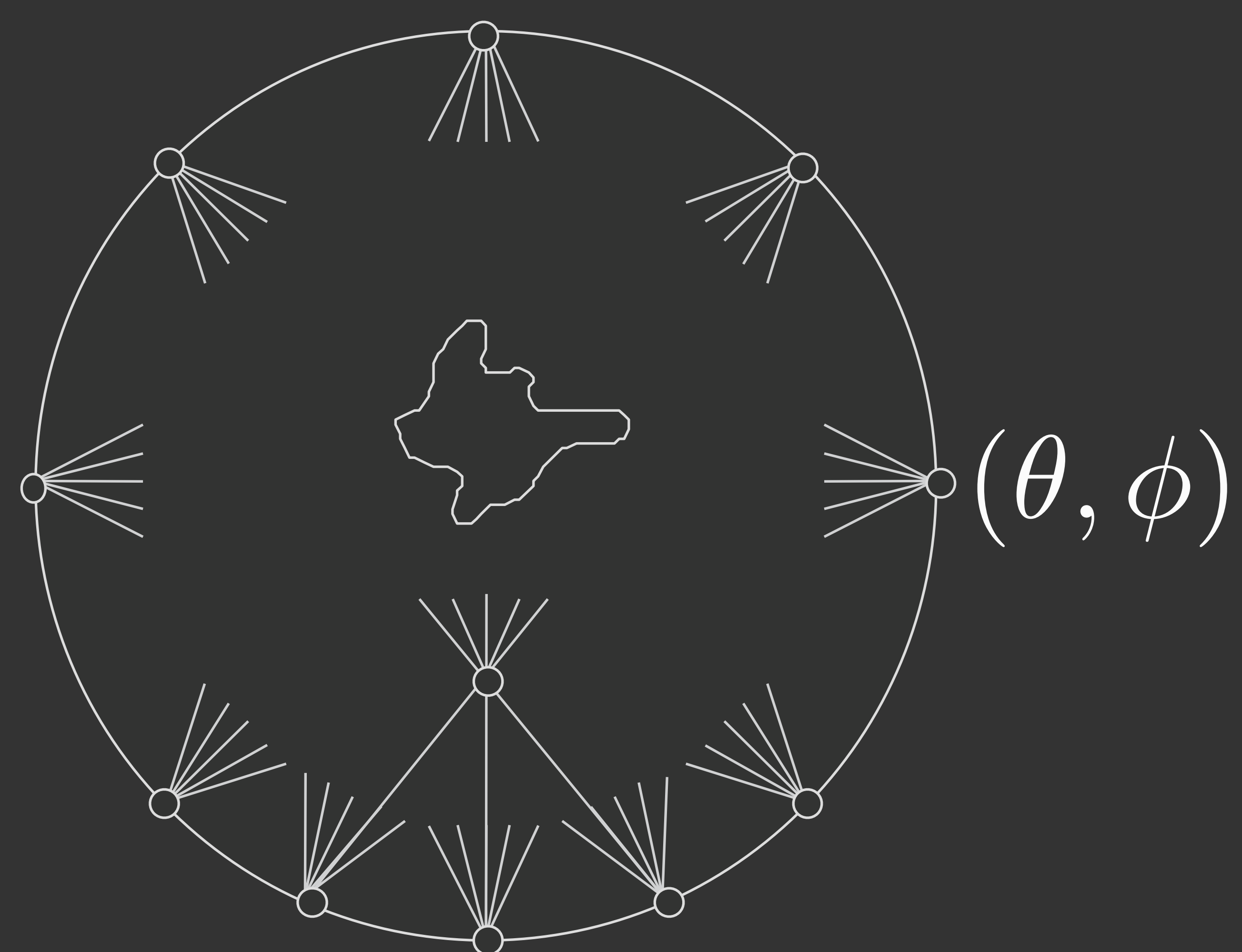
Light Field Capture Robot

Original light field rendering paper

Take photographs of an object from all points on an enclosing sphere

Captures all light leaving an object – like a hologram

$L(x, y, \theta, \phi)$



[Levoy & Hanrahan 1996] [Gortler et al. 1996]

Slide credit: Pat Hanrahan

Multi-Camera Array ⇒ 4D Light Field

[Wilburn et al. SIGGRAPH 2005]

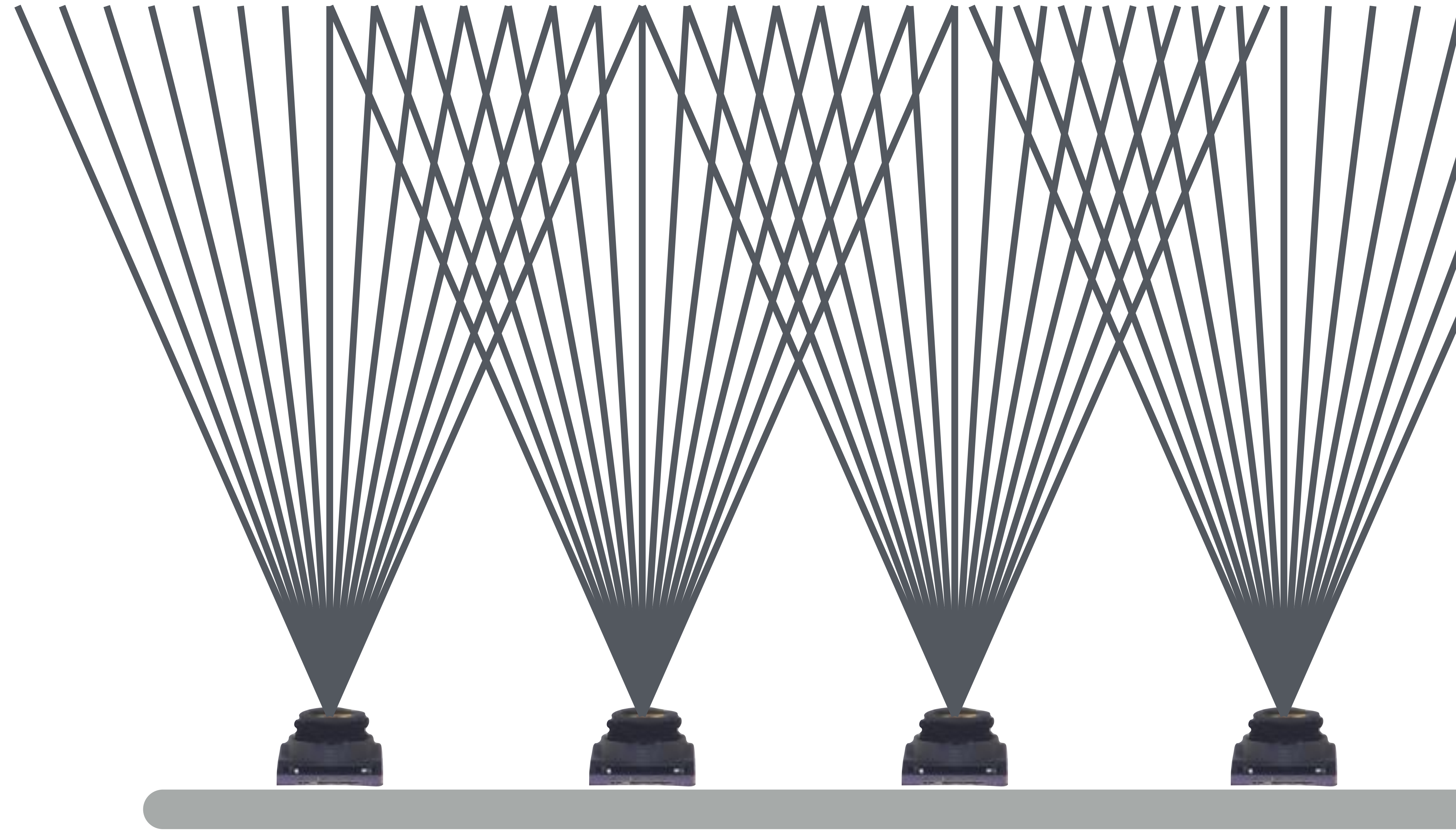
Slide credit: Pat Hanrahan

[Wilburn et al. SIGGRAPH 2005]

Handheld 4D Light Field Camera (Plenoptic Camera)

Lytro Gen-2 Light Field Camera

Handheld Light Field Camera vs Camera Array



Camera array: e.g. 10x10 views distributed across large planar support

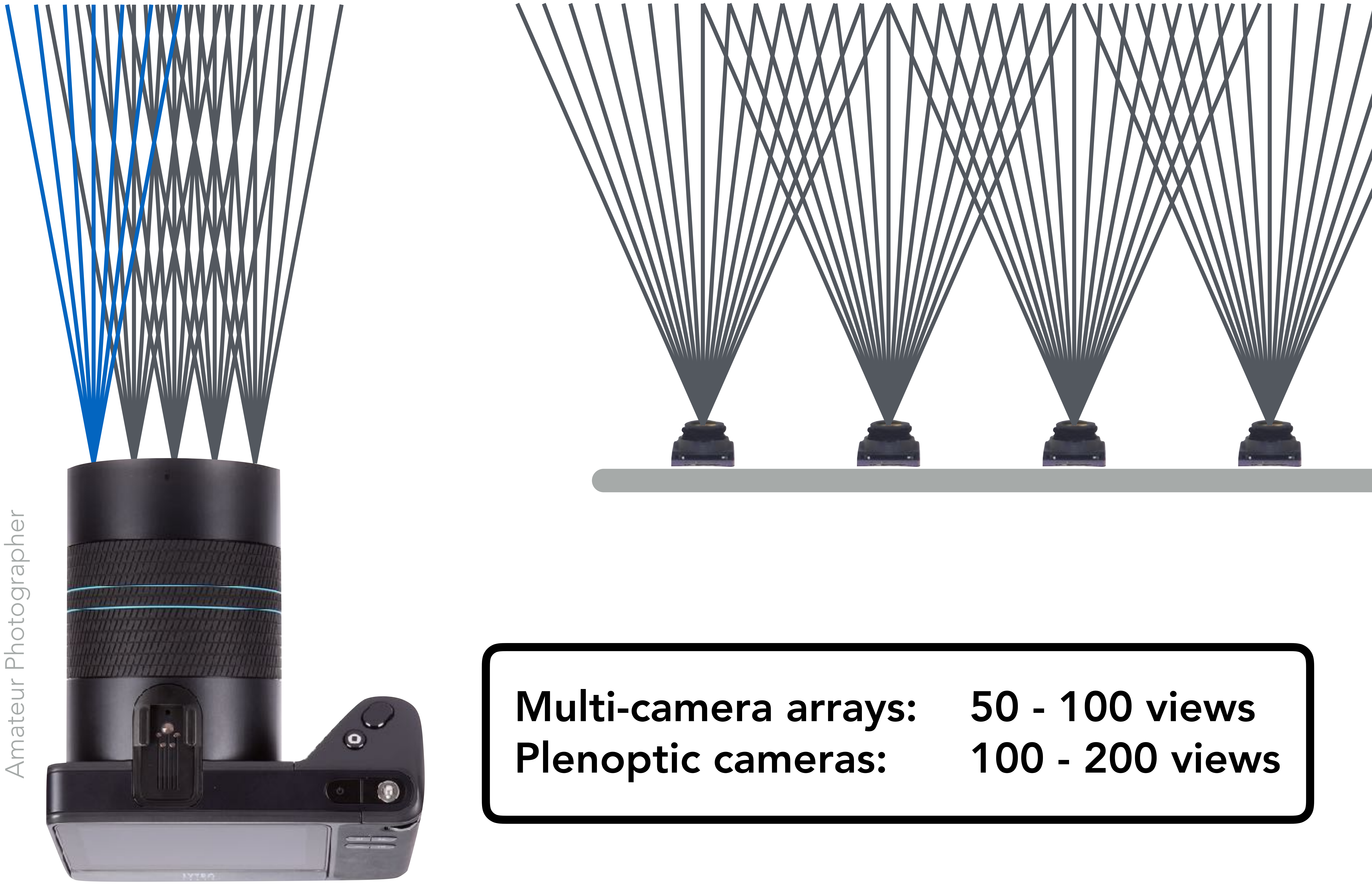
Plenoptic camera: e.g. 14x14 views distributed across small lens pupil
Note: antialiased across views, unlike camera array

The Intimacy of VR Graphics

Google’s Tilt Brush on HTC Vive


A Challenge: Intimate Proximity in VR Imaging

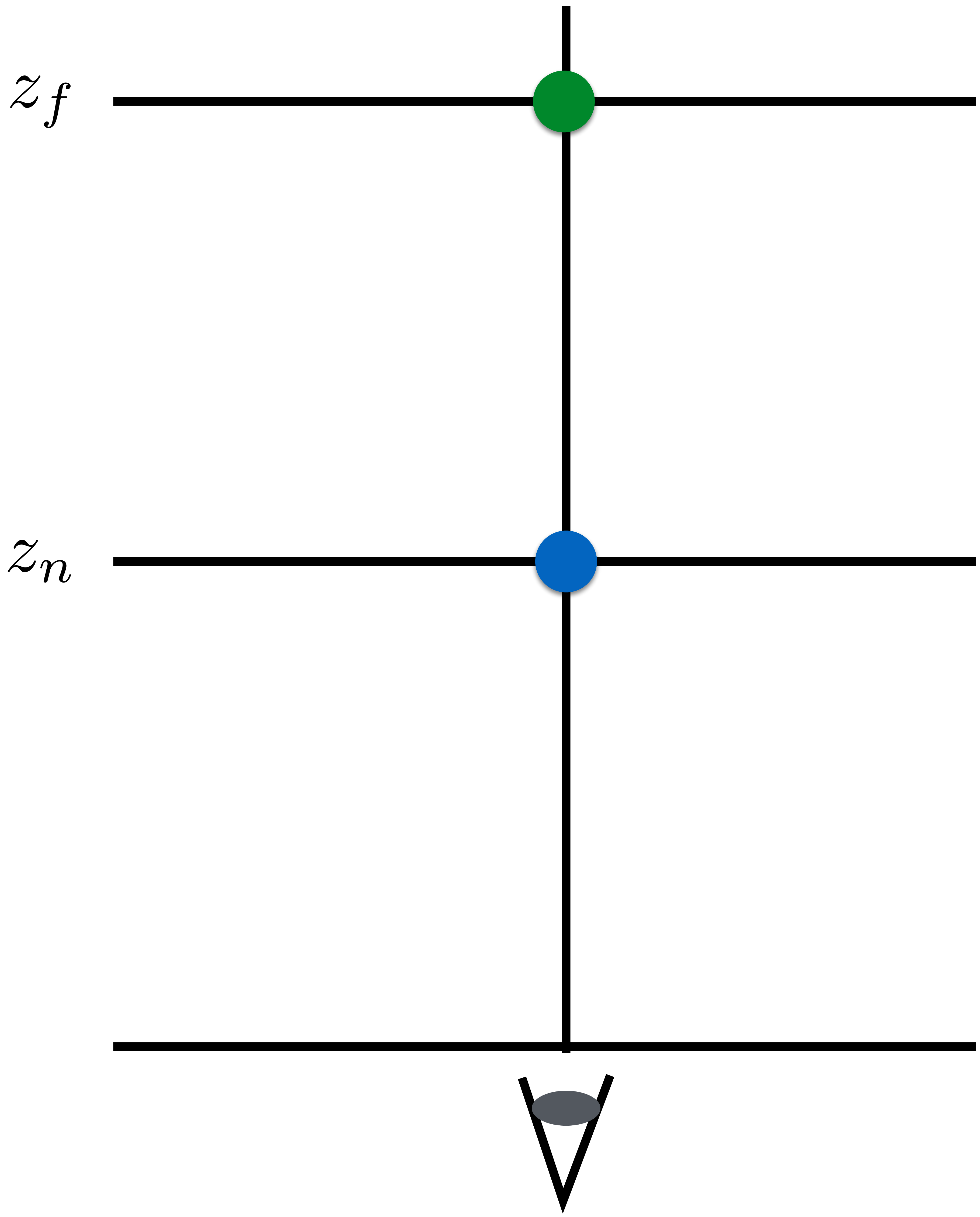
How Dense Are Camera Views Today?



Multi-camera arrays:	50 - 100 views
Plenoptic cameras:	100 - 200 views


How Dense Must Cameras Views Be?

How Dense Must Camera Views Be?

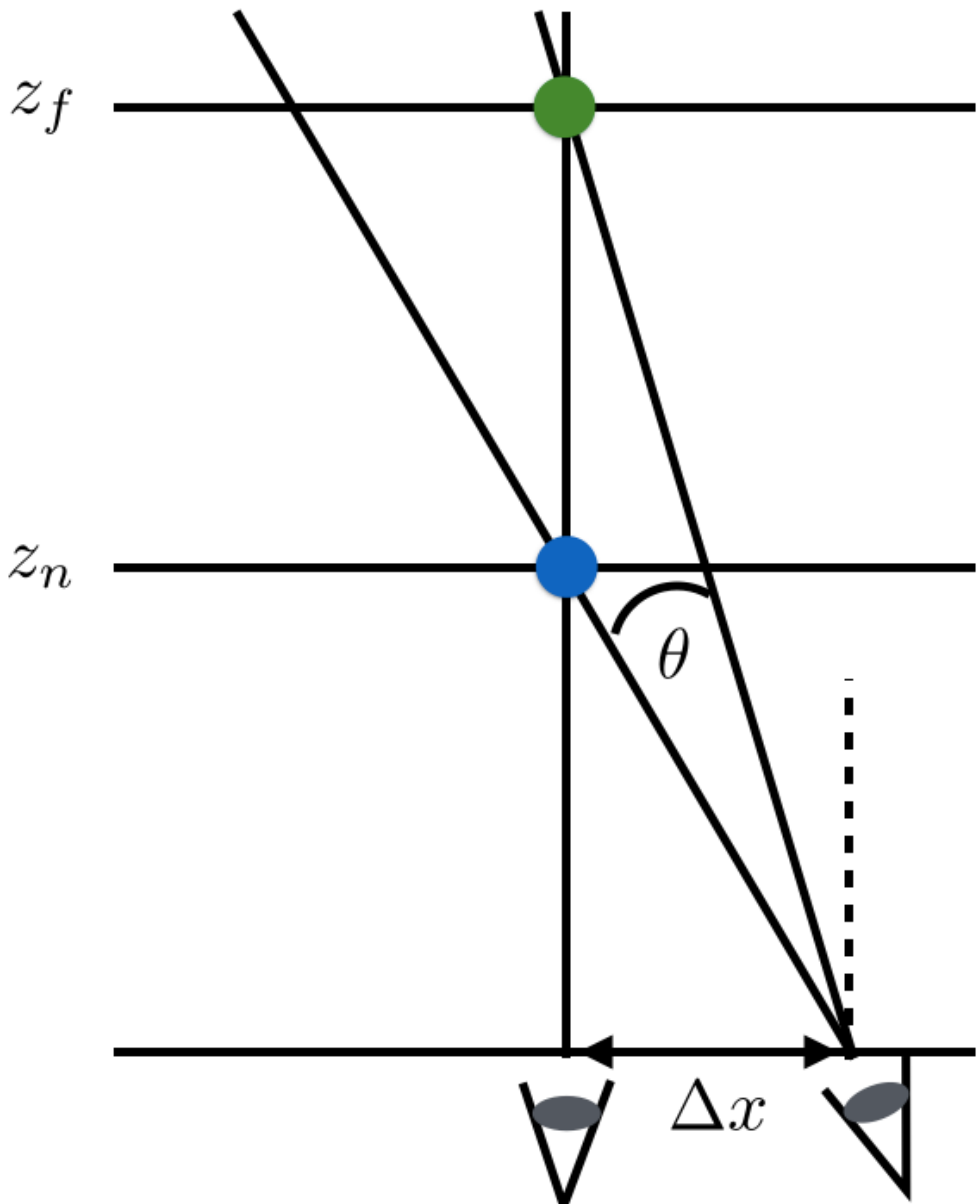


Child in lap, front to back of head

$$z_n = 0.3\mathrm{m}$$

$$z_f = 0.6\mathrm{m}$$

How Dense Must Camera Views Be?



20/20 vision: $\theta \approx (1/60)^\circ$

Curent HMDs: $\theta \approx (1/10)^\circ$

How Dense Must Camera Views Be?

Solving for minimum lateral motion:

$$\Delta x = \frac{(z_f - z_n) - \sqrt{(z_f - z_n)^2 - 4\tan^2\theta z_n z_f}}{2\tan\theta}$$

Child in lap, front to back of head

$z_n = 0.3\mathrm{m}$

$z_f = 0.6\mathrm{m}$

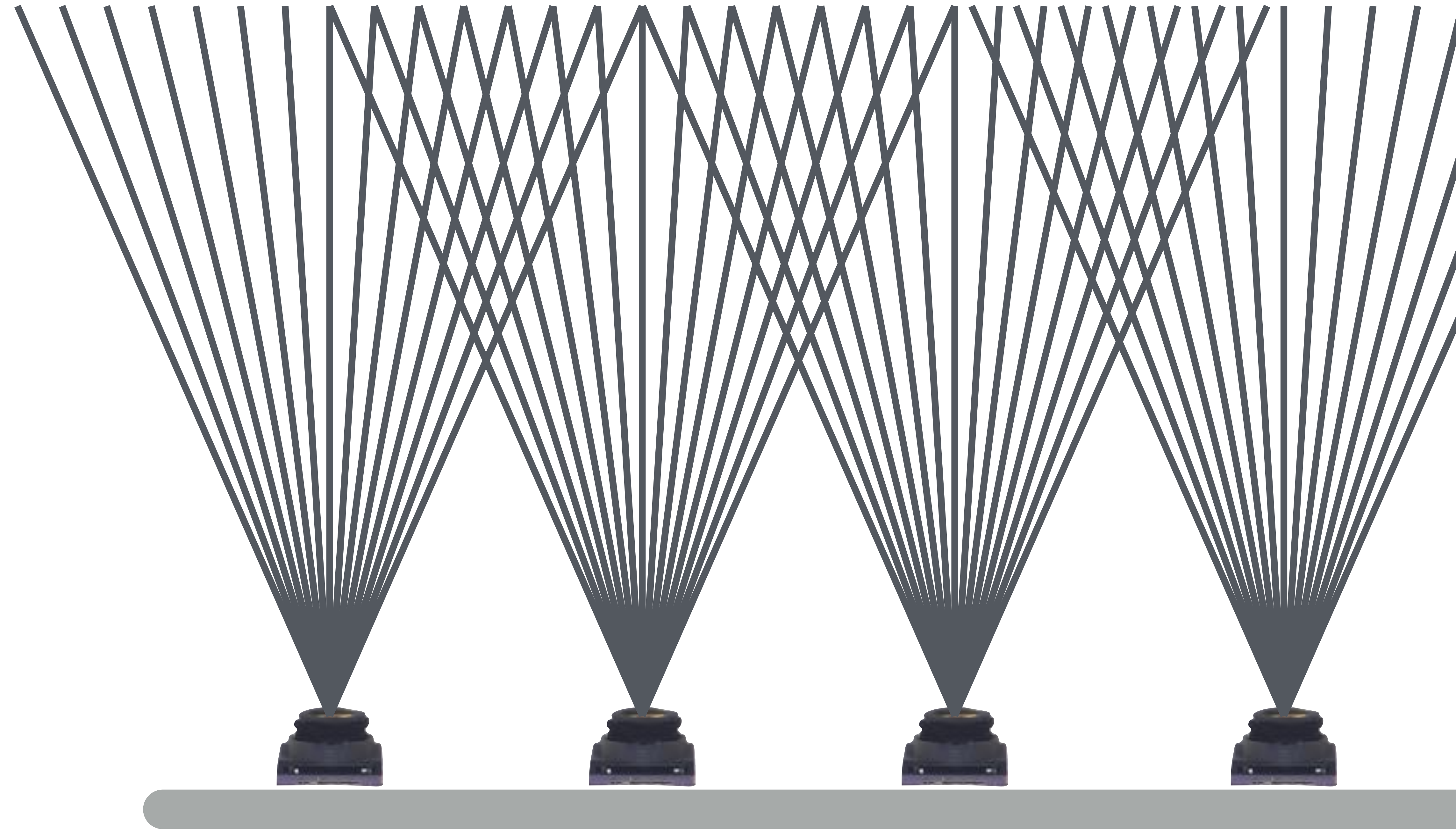
20/20 vision: $\theta \approx (1/60)^\circ \implies \Delta x \approx (1/1719)\mathrm{ft}$

Curent HMDs: $\theta \approx (1/10)^\circ \implies \Delta x \approx (1/286)/\mathrm{ft}$

20/20 vision: millions of views per square foot
Current HMDs: a hundred thousand views per square foot

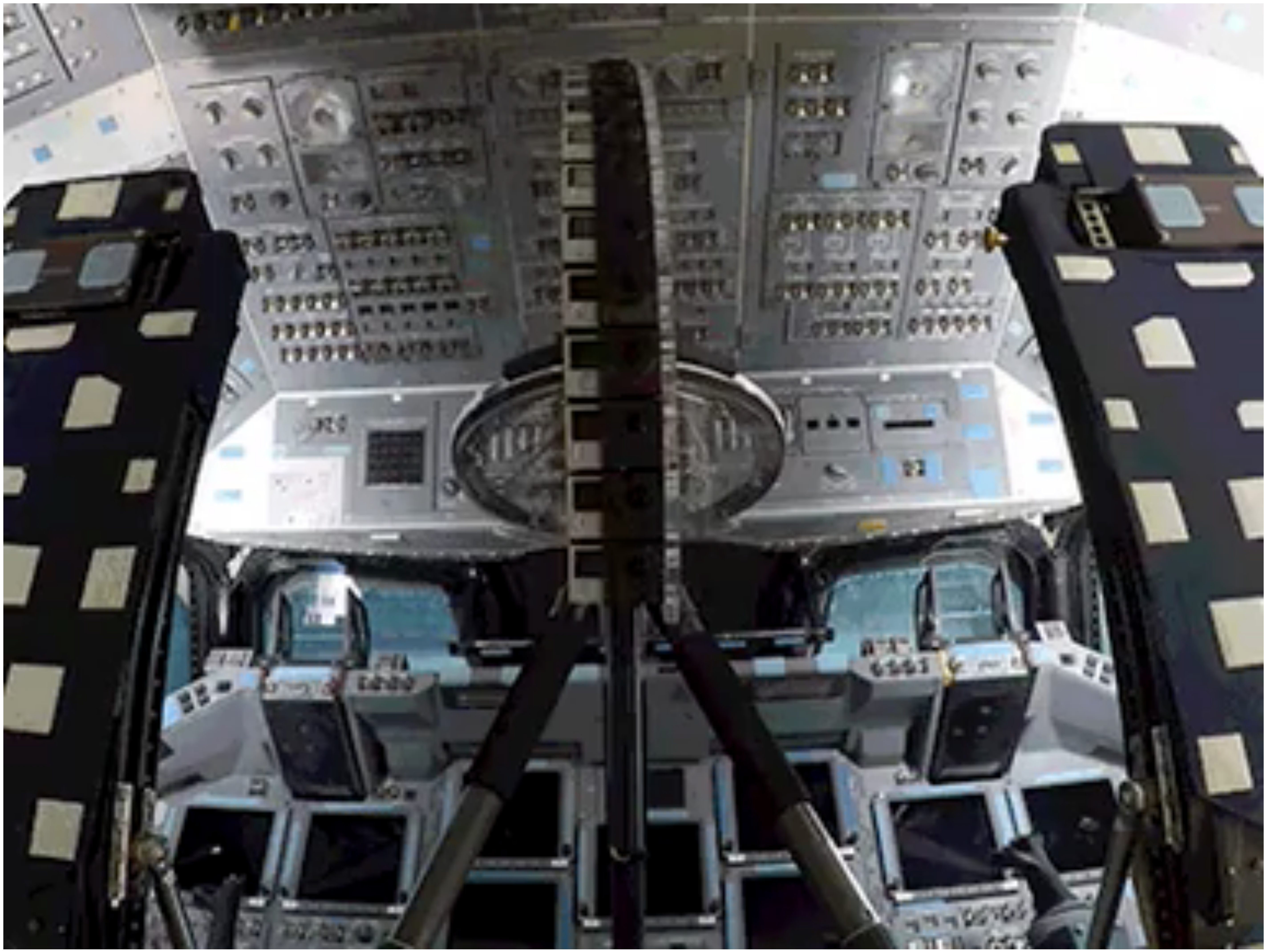
How Dense Are Camera Views Today?

Amateur Photographer



Multi-camera arrays:	50 - 100 views
Plenoptic cameras:	100 - 200 views

Google VR Camera Rig



Paul Debevec, Google

Active Area of Research

One important theme is applying machine learning to intelligently up-sample from tens of camera views to the very high sampling rates required for Nyquist-sampled VR rendering.

See research from my grad students Pratul Srinivasan, Ben Mildenhall and Matt Tancik in recent years on this topic.

Things to Remember

VR presents many new graphics challenges!

Displays

- Head-pose tracking with high accuracy and low latency

Rendering

- Low-latency, high resolution & frame-rate, wide field of view, …

Imaging

- 360 spherical, stereo, light field

Acknowledgments

Thanks to Kayvon Fatahalian, Alyosha Efros, Brian Wandell and Pratul Srinivasan for lecture resources and slides!