Realistic Image Synthesis

- Perception-based Rendering & Advanced Displays-

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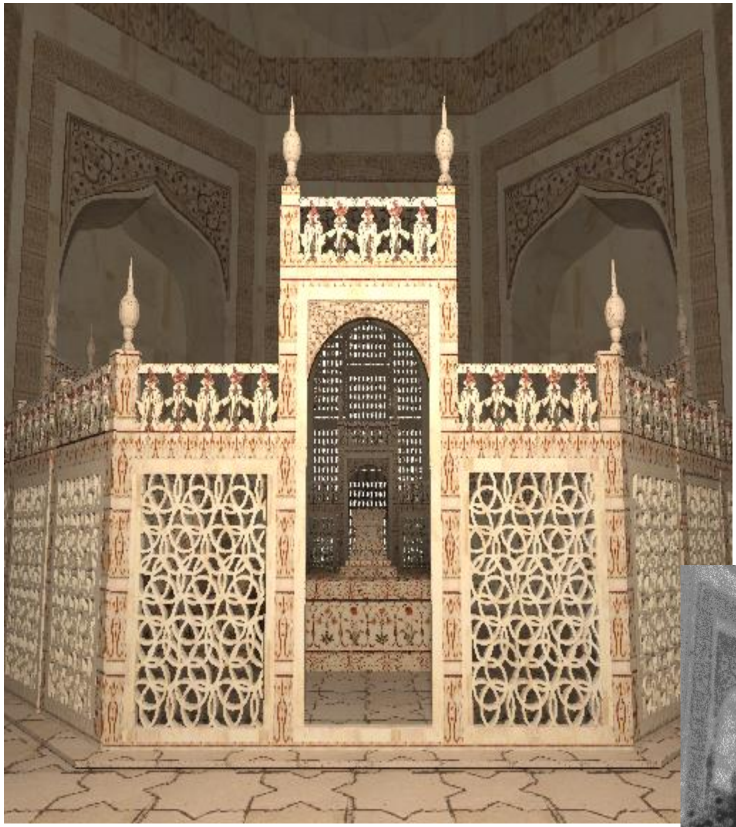
Outline

- **Perceptually based adaptive sampling algorithm**
- **Eye tracking driven rendering**
- **Binocular 3D displays**
- **Autostereoscopic (Glass-free 3D) Displays**
    - Parallax Barriers
    - Integral Imaging
    - Multi-layer displays
    - Holographic displays
- **Head-Mounted Displays with accommodation cues**

Perceptually Based Rendering

6% effort



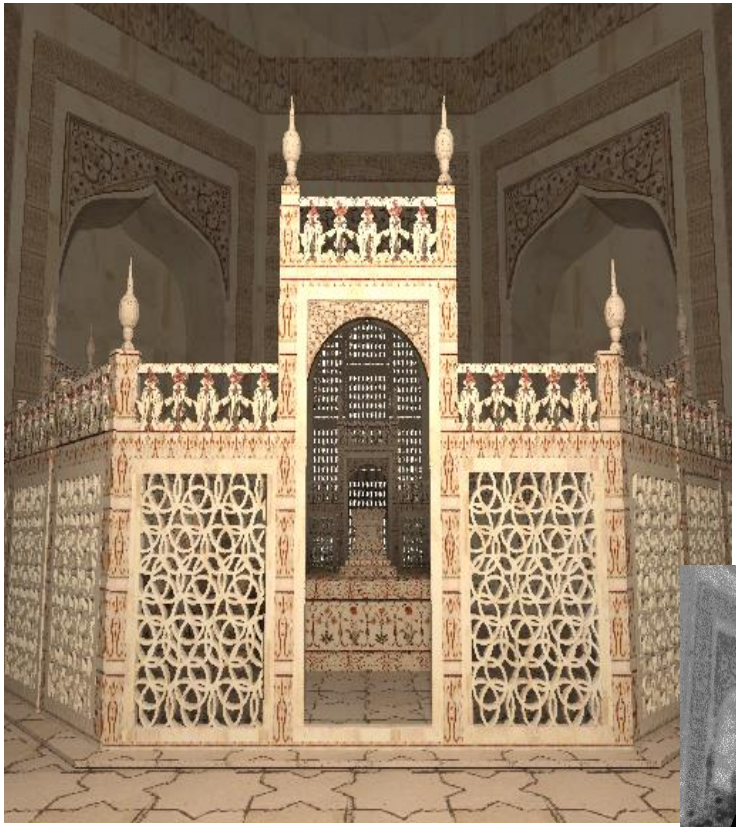
effort distribution (darker regions - less effort)

physically accurate

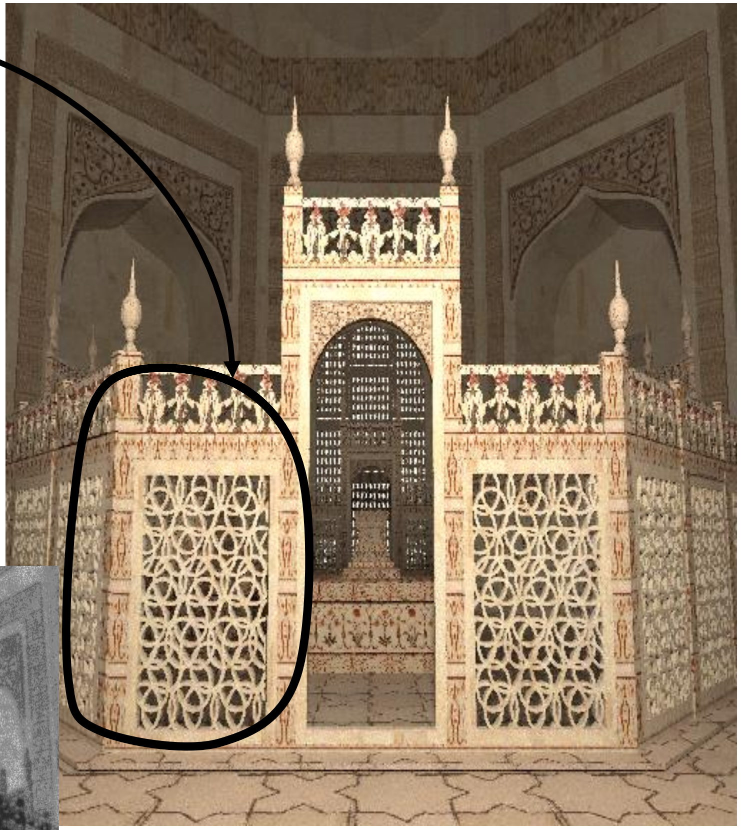
perceptually accurate

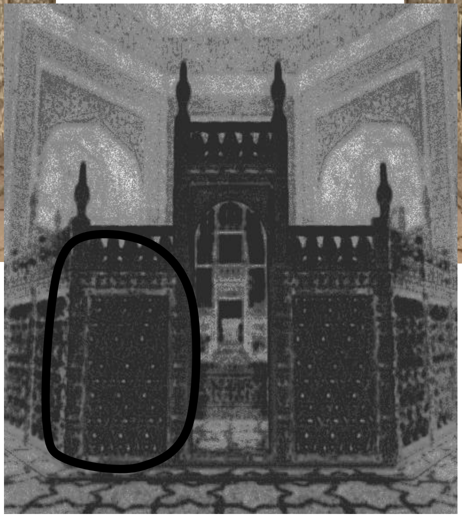
Perceptually Based Rendering

6% effort



effort distribution (darker regions - less effort)





physically accurate

perceptually accurate

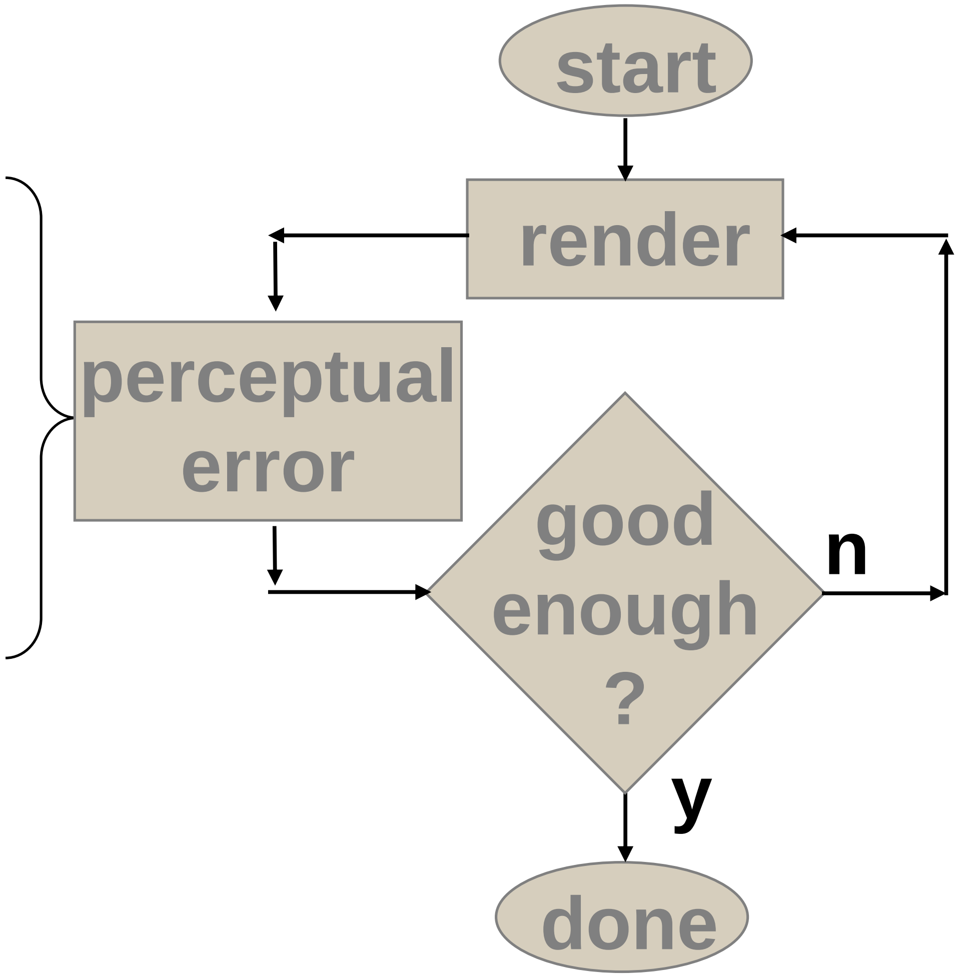
Perceptually Based Rendering

Traditional approach:

Pair of images to compare at each time step

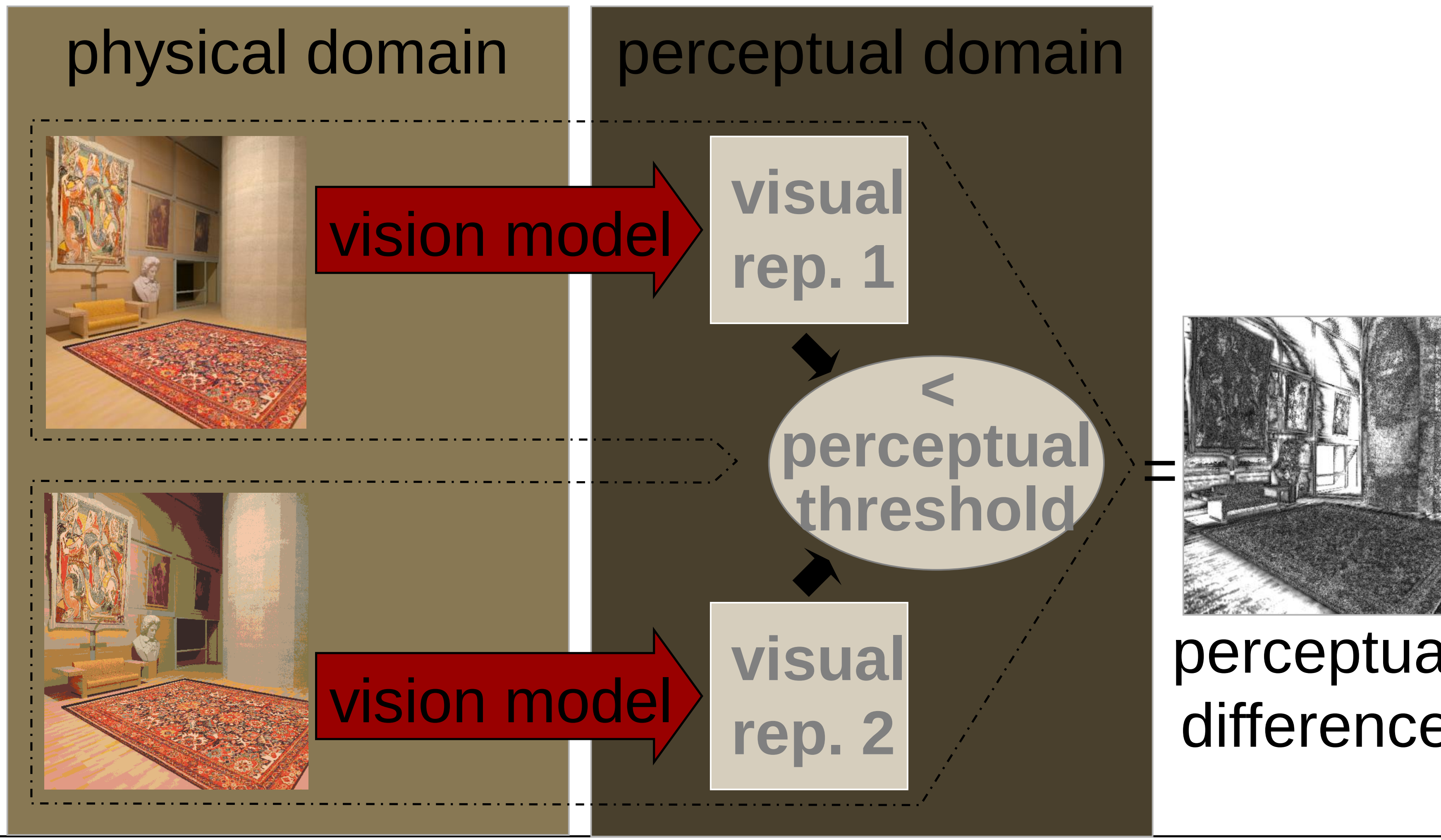
(a) intermediate images at consecutive time steps.

(b) upper and lower bound images at each time step.



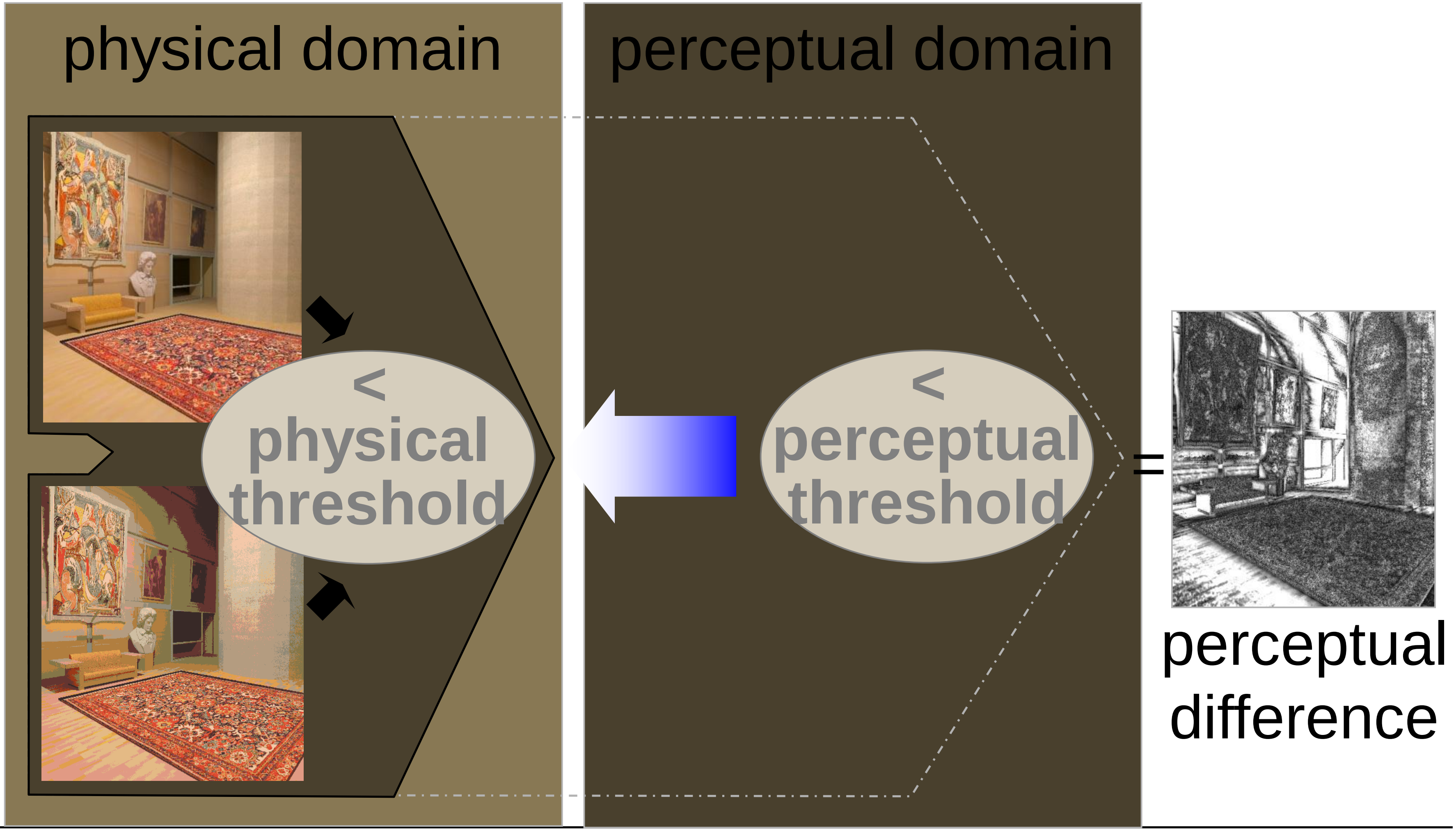
Perceptual Error Metric

Vision model - expensive



Perceptually Based

Physical Error Metric

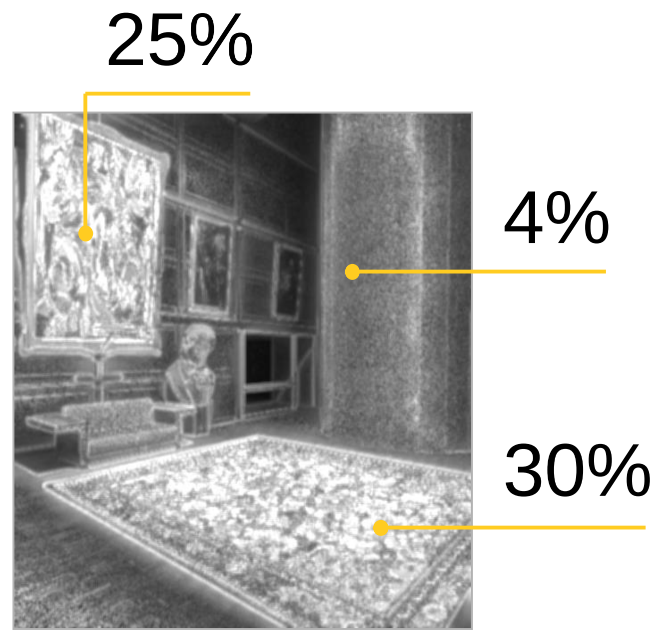


Physical Threshold Map

Predicted bounds of permissible luminance error

input image

threshold model



physical threshold (brighter regions - higher thresholds)

Threshold Model

Components

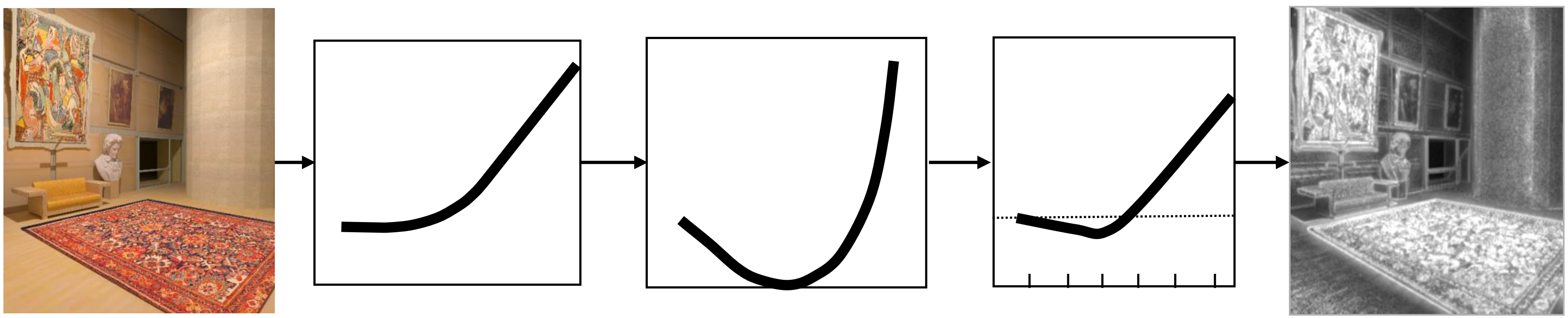
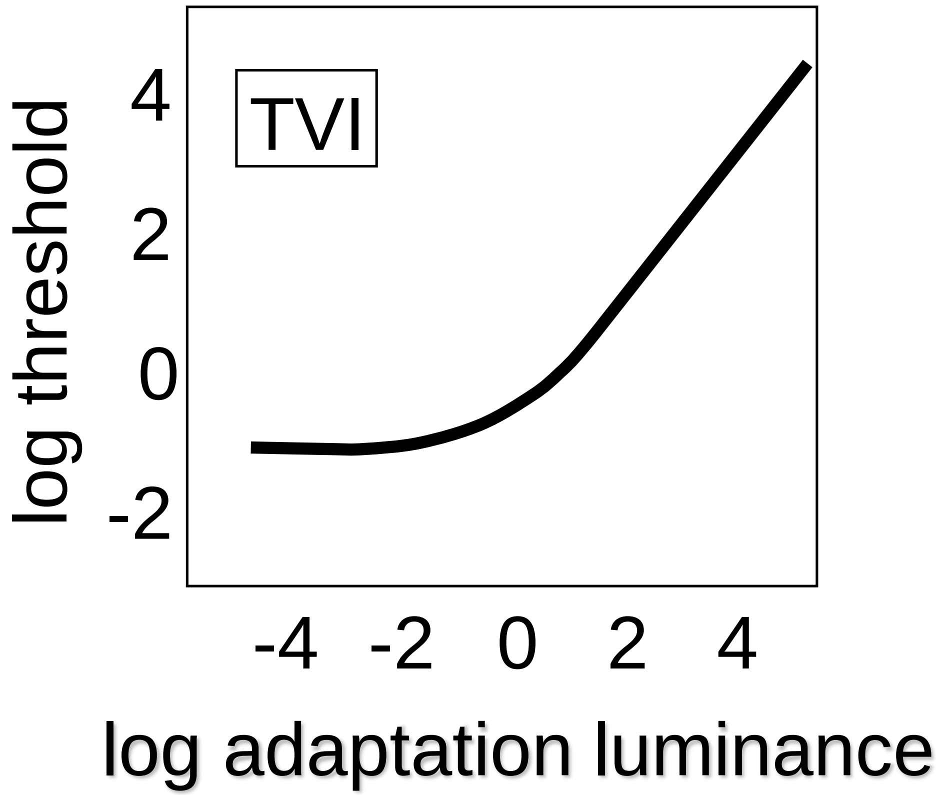


image | luminance component | frequency component | contrast component | threshold map

Threshold Model

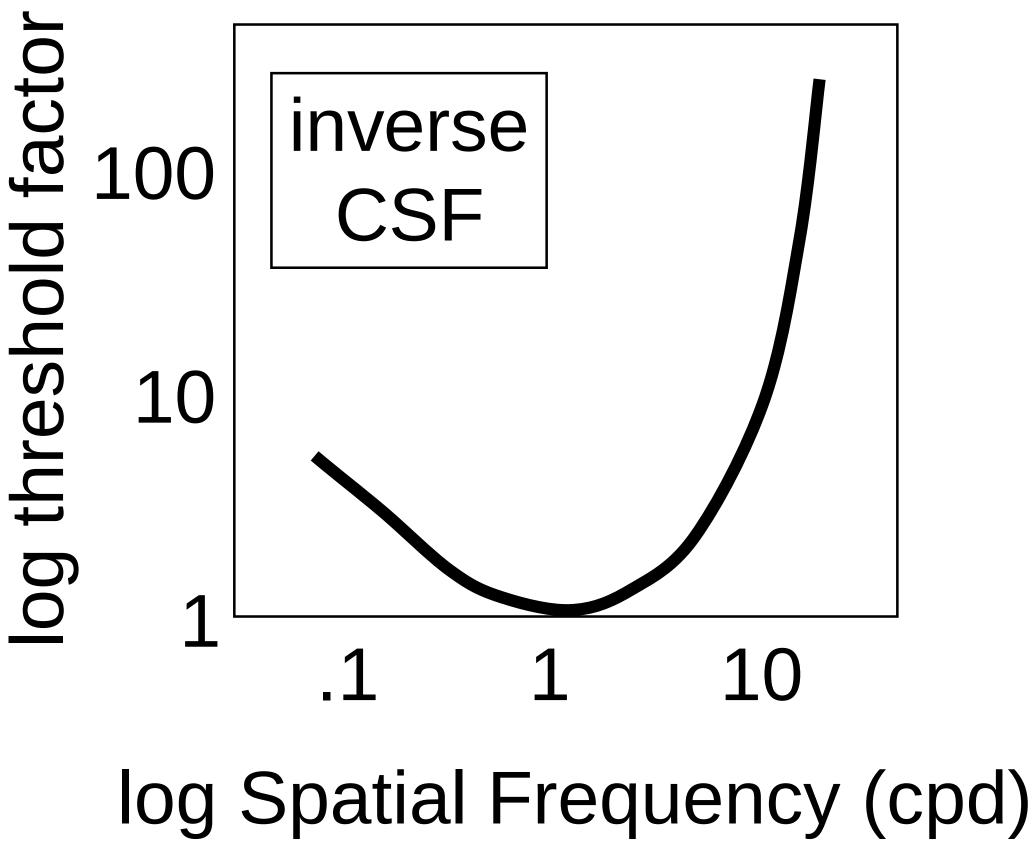
1. Luminance component

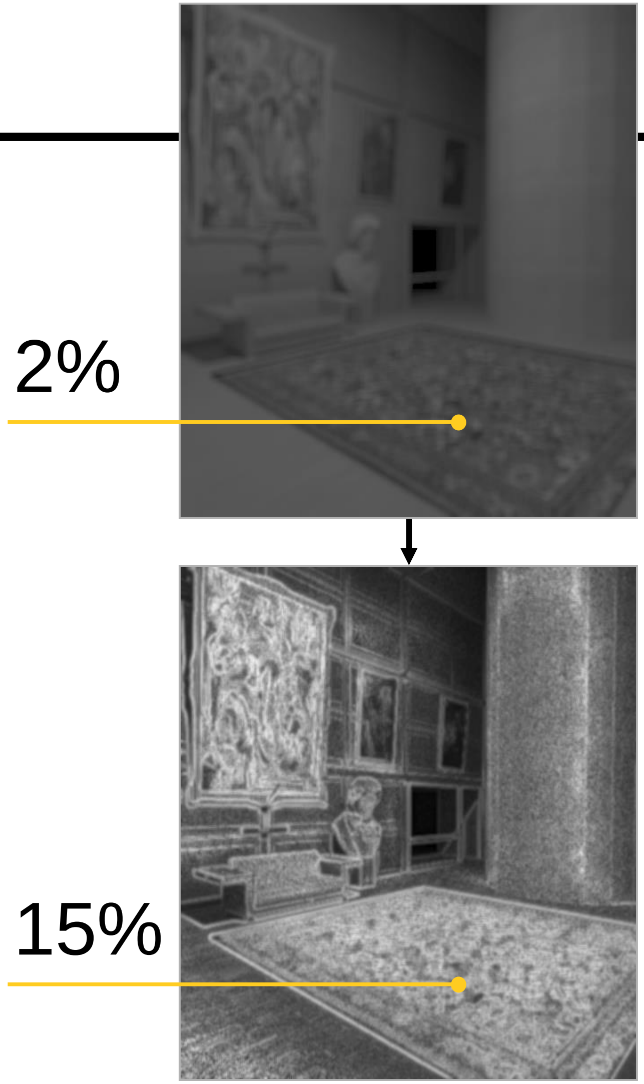


threshold due to luminance

Threshold Model

2. Frequency component

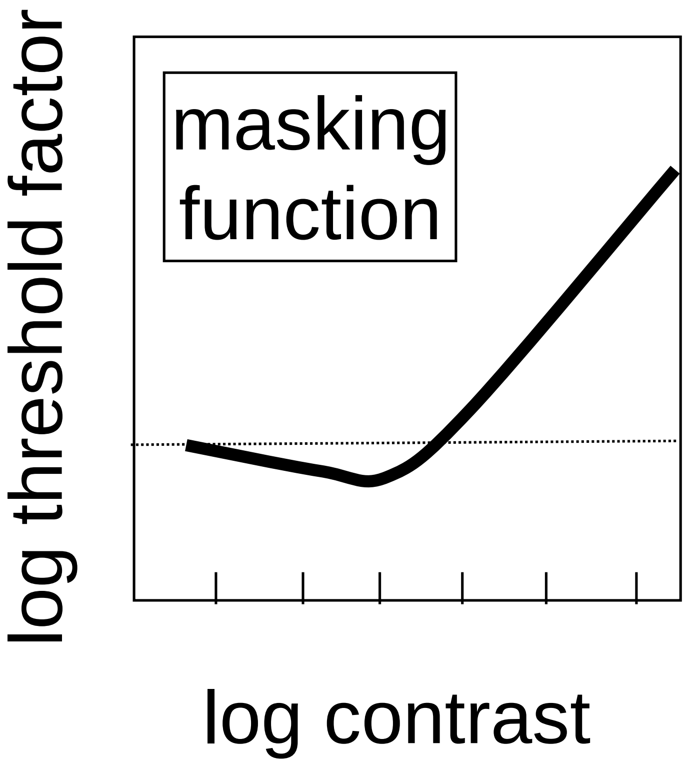


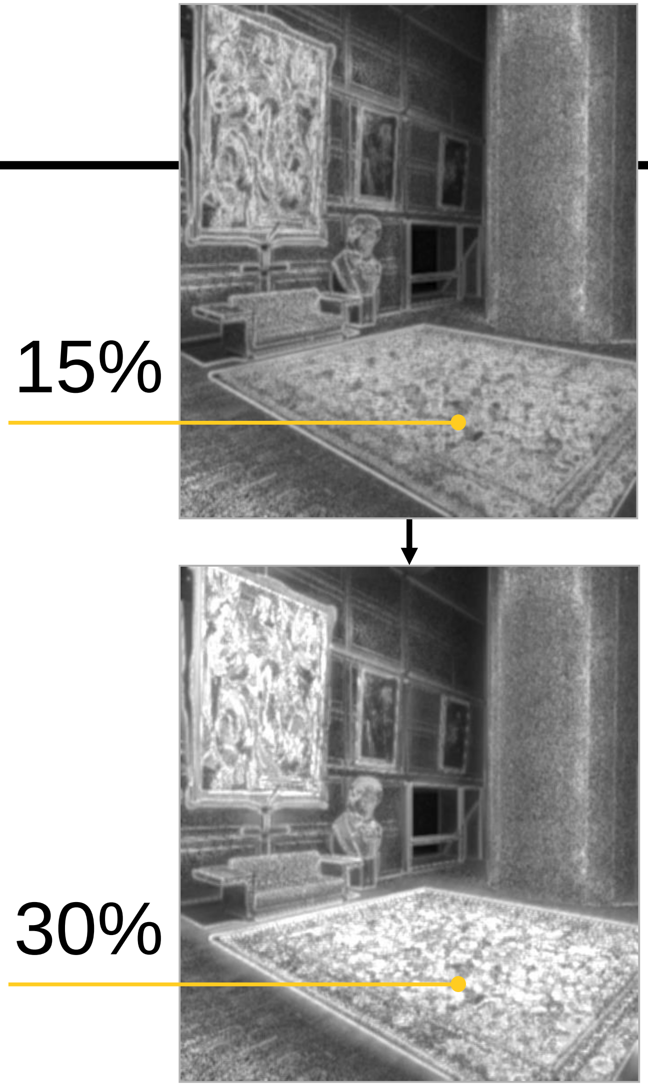


threshold due to luminance + freq.

Threshold Model

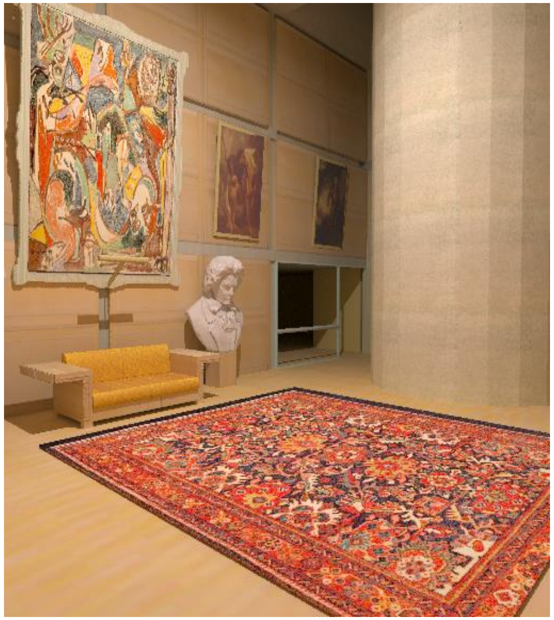
3. Contrast component (visual masking)





threshold due to luminance + freq. + contrast

Validation



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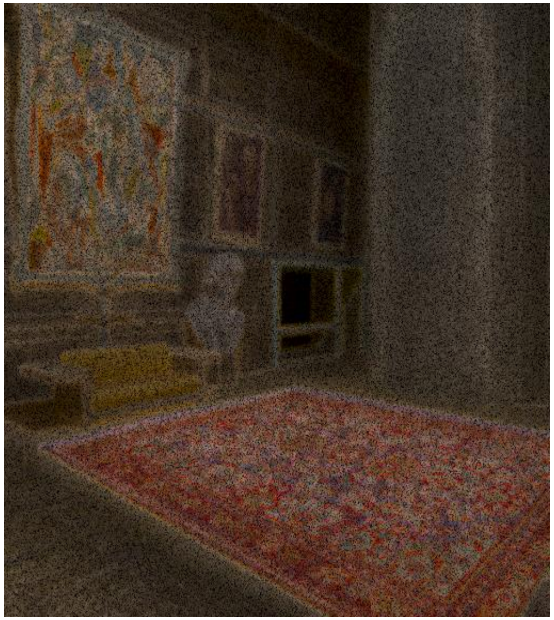

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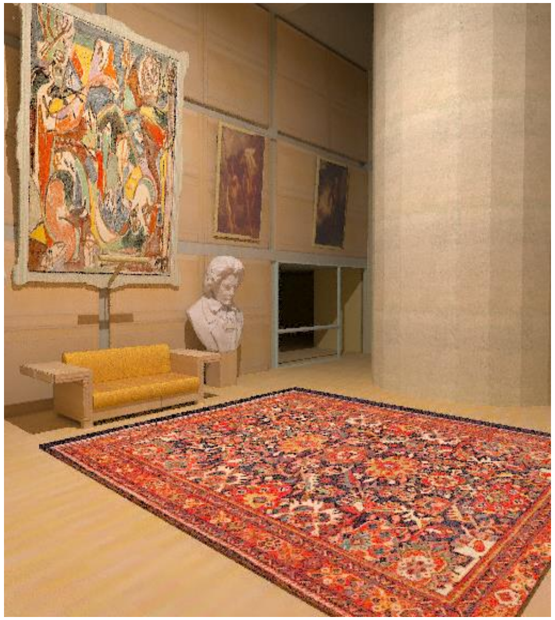
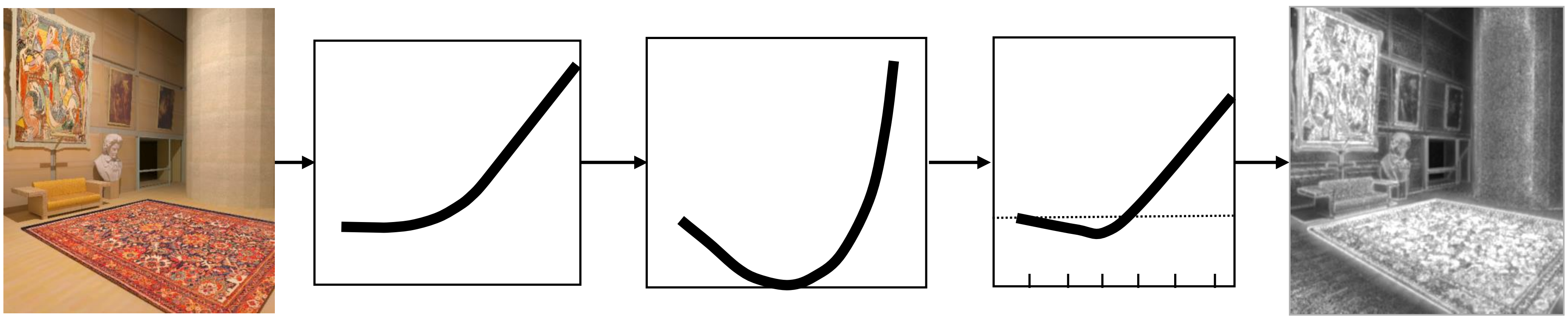


image

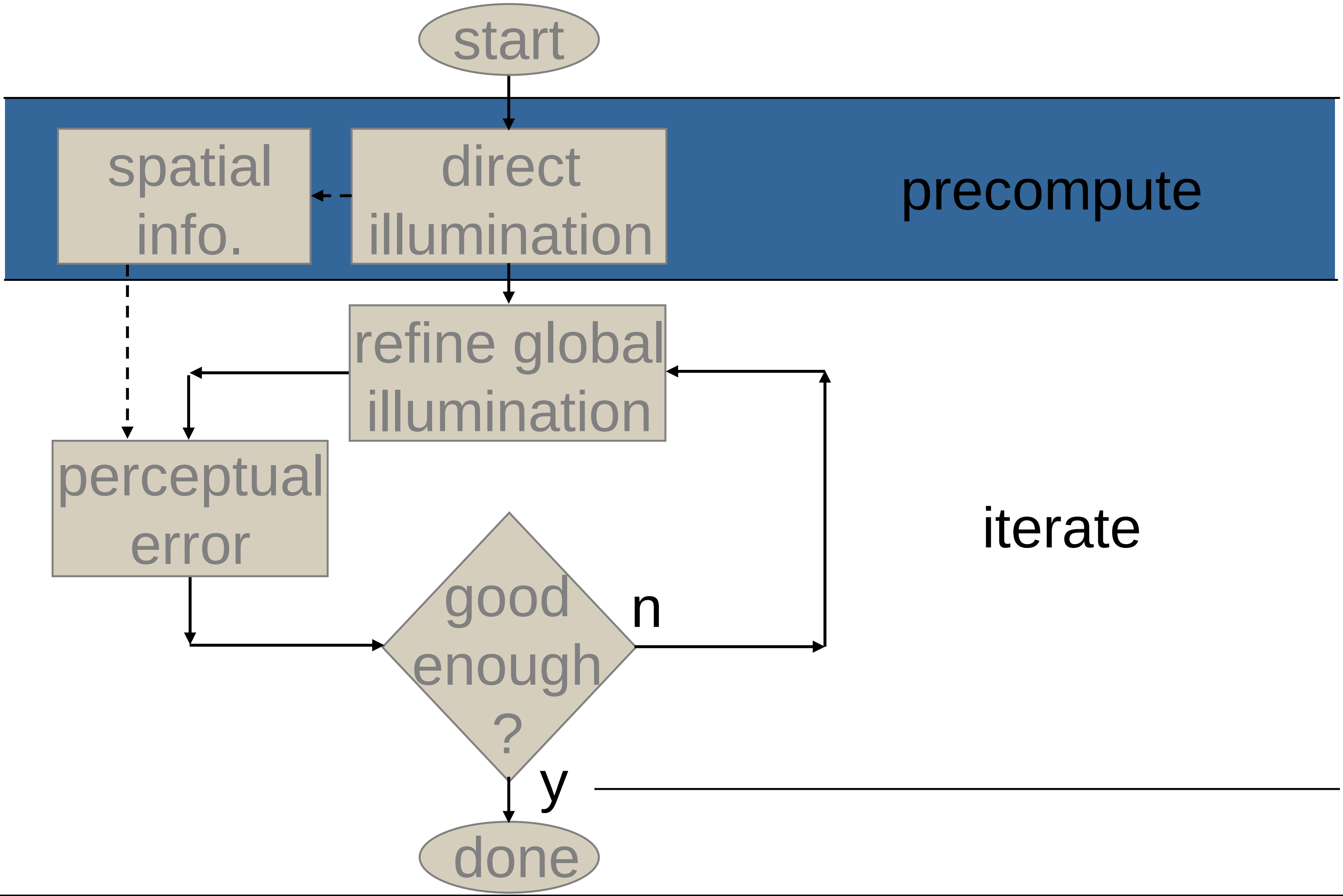
noise

image + noise

Threshold Model

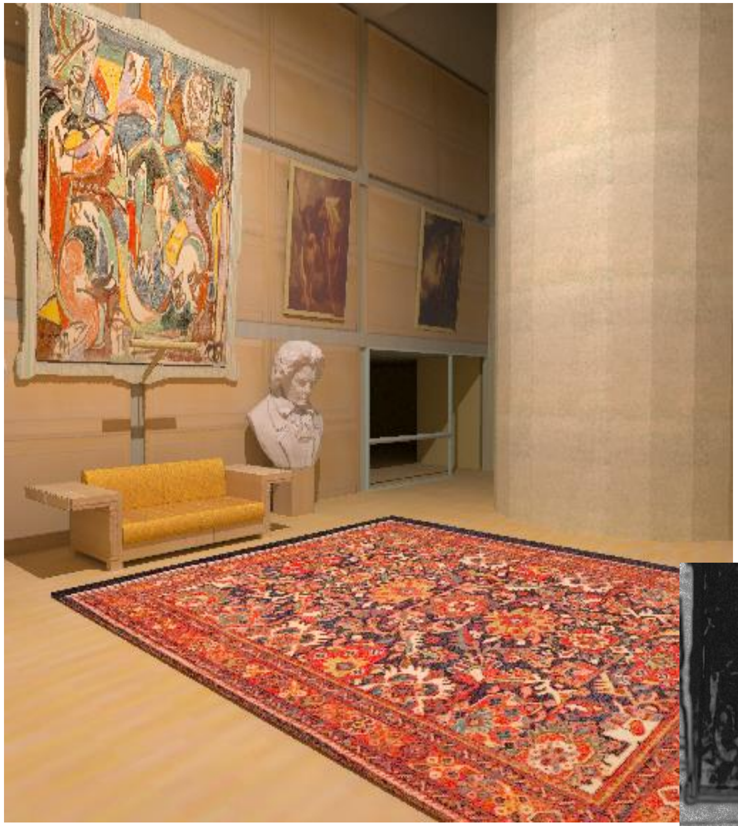


Adaptive Rendering Algorithm

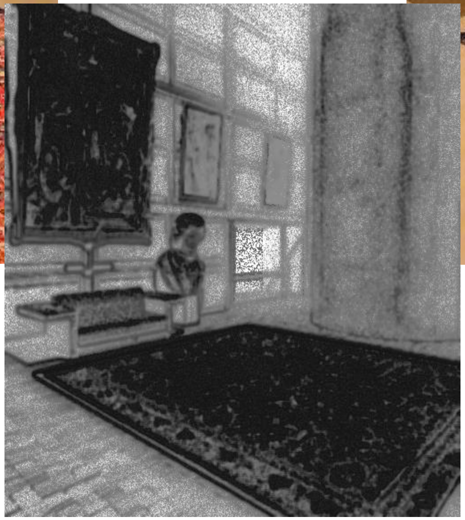


Results

5% effort



effort distribution (darker regions - less effort)



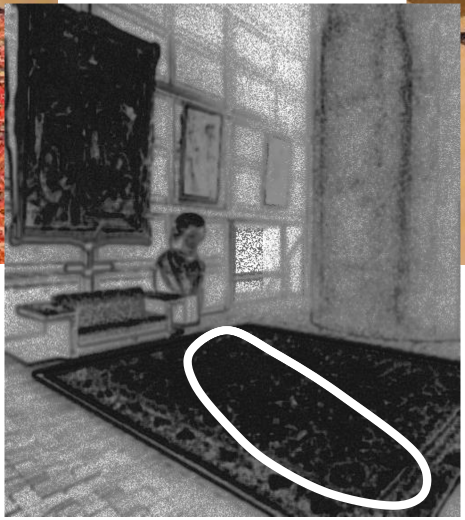
reference solution

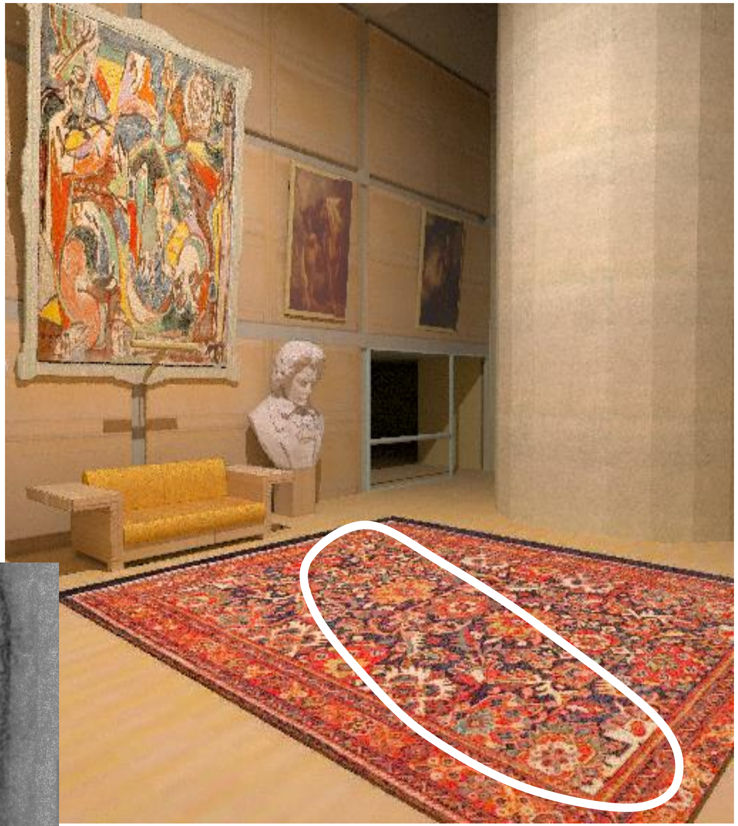
adaptive solution

Results: Masking by Textures

5% effort

effort distribution (darker regions - less effort)



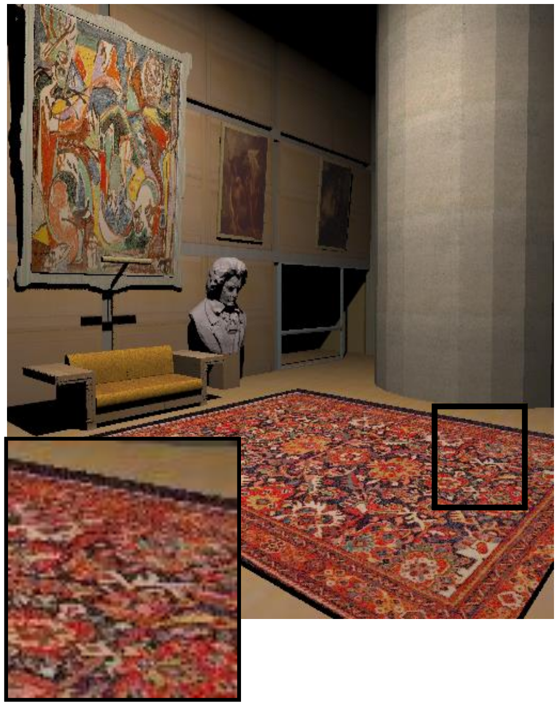


reference solution

adaptive solution

Results

5% effort



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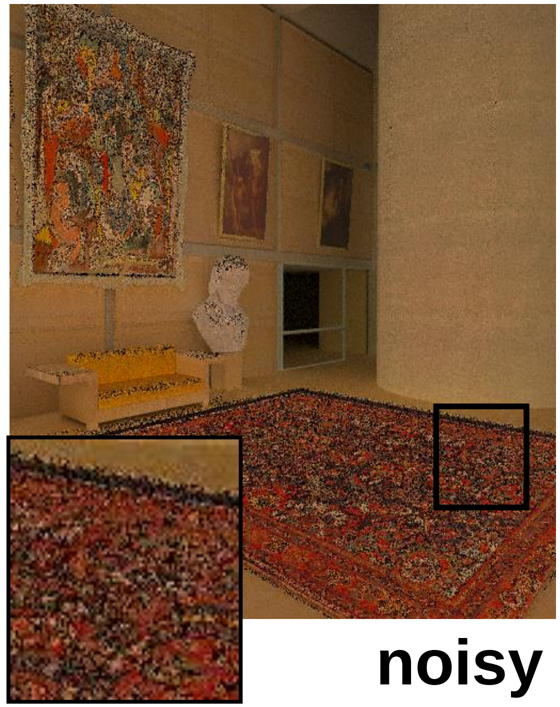


noisy

=

masked

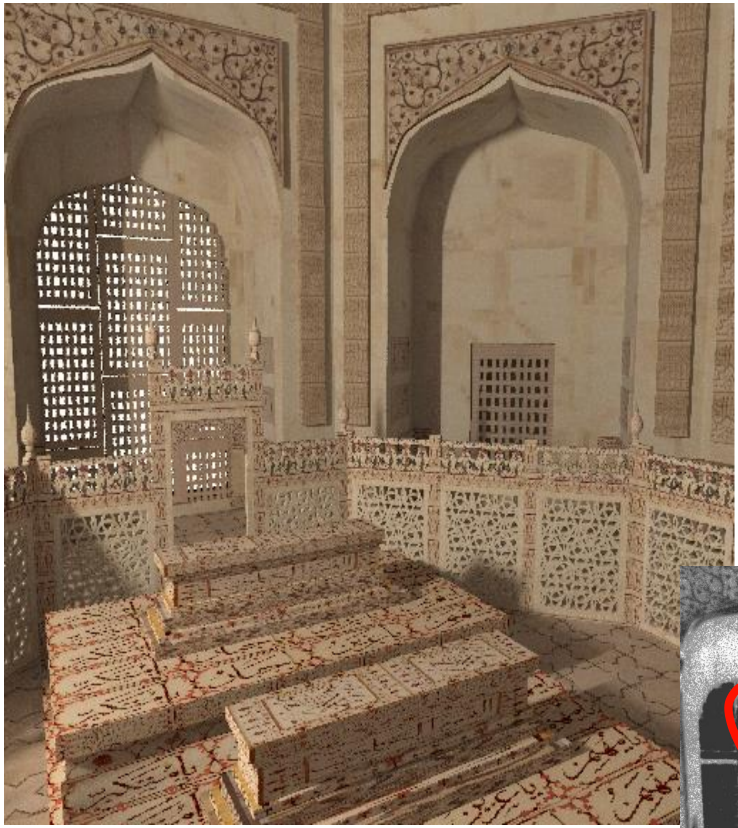
direct illumination

adaptive indirect illumination

adaptive global illumination

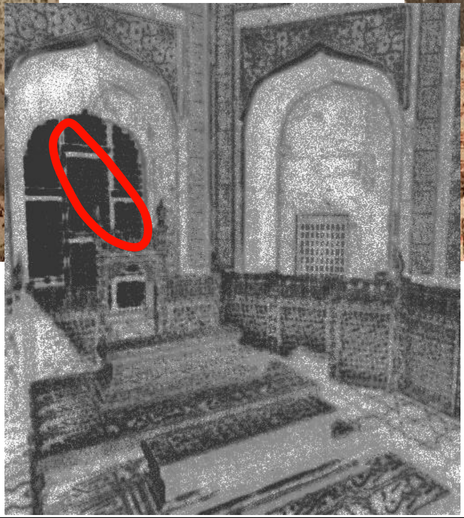
Results: Masking by Geometry

5% effort



reference
solution

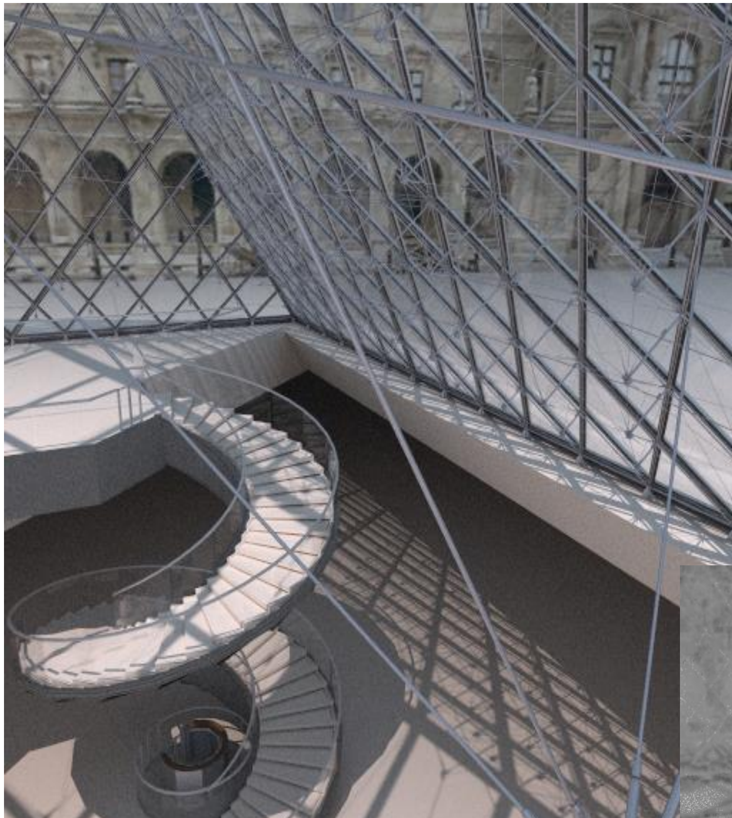
effort
distribution
(darker
regions -
less effort)



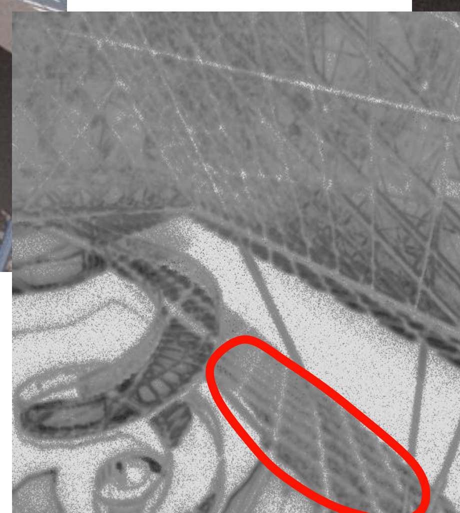
adaptive
solution

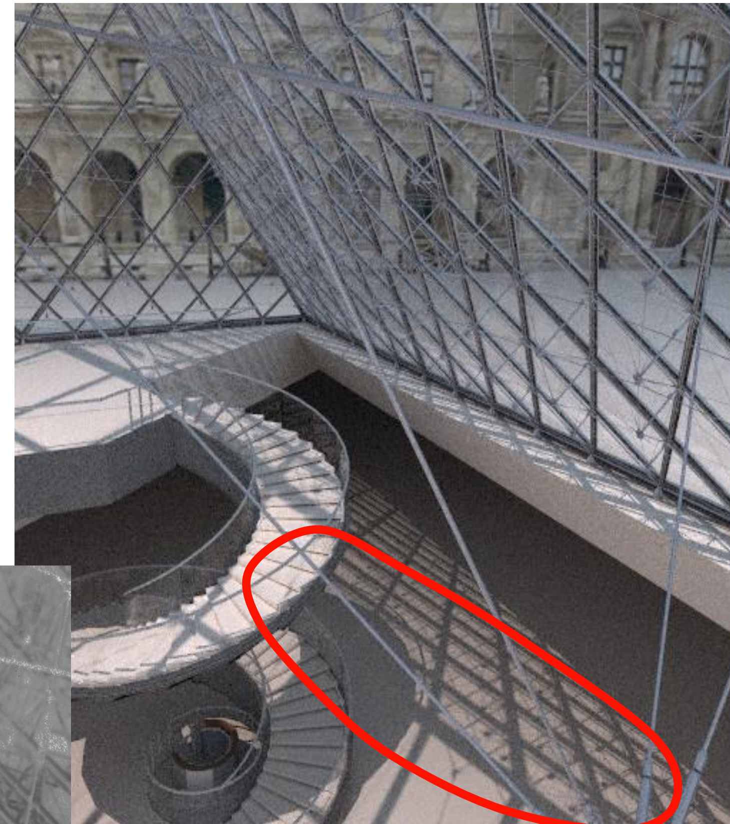
Results: Masking by Shadows

6% effort



effort distribution (darker regions - less effort)



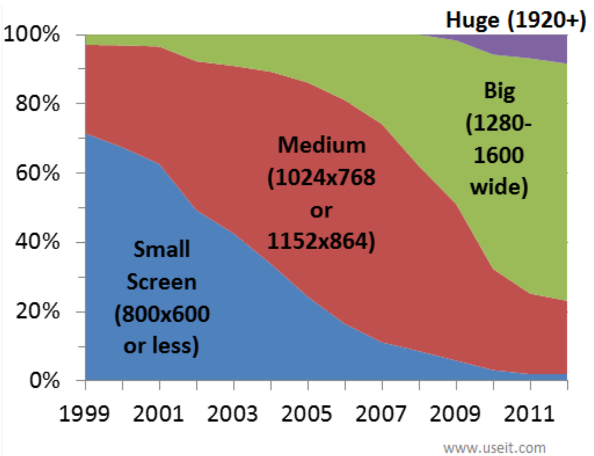


reference solution

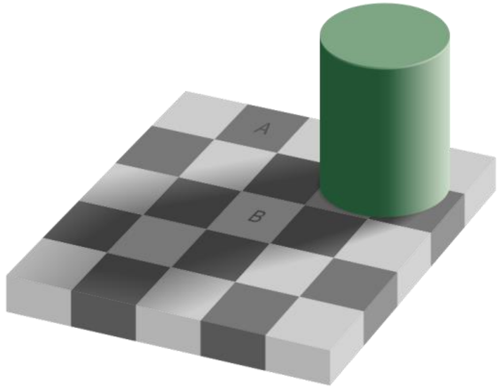
adaptive solution

Eye Tracking - Motivation

1. **Improving computational efficiency**
   - There is a trend towards higher resolution displays
     → Higher computational requirement for 3D rendering
   - Only a fraction of pixels is consciously attended and perceived in the full-resolution
2. **Improving realism**
   - Eye is always focused on the screen plane; nevertheless, it is possible to simulate Depth-of-Field (DoF) effect by artificially blurring out-of-focus regions according to the gaze location
3. **Improve perceived quality**
   - Human Visual System (HVS) has local adaptation property
   - Perception of luminance, contrast and color are not absolute and highly dependent on both spatial and temporal neighborhood of the gaze location



Evolution of computer screen sizes



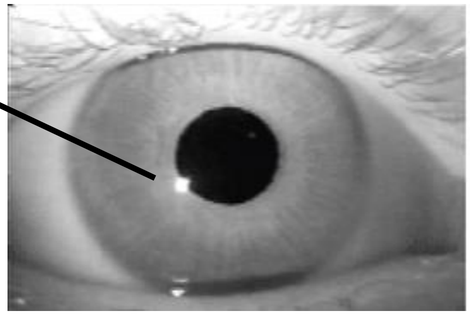
Checker shadow illusion

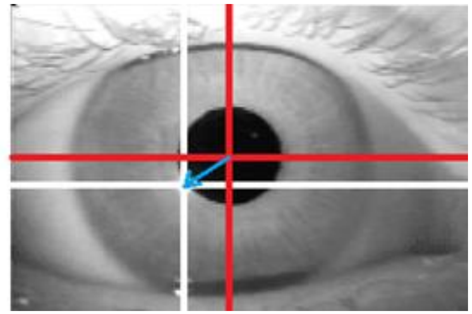
Images adapted from https://www.nngroup.com/articles/computer-screens-getting-bigger/

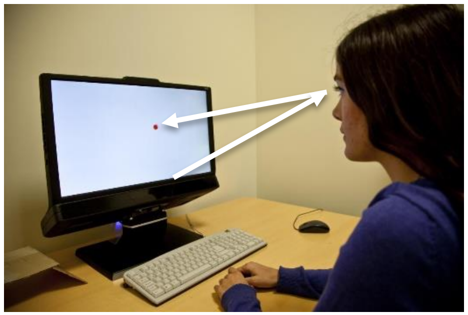
Eye Tracking

- **Basic Technology:**

Corneal Reflection (also known as “glint” or “1st Purkinje Reflection”)



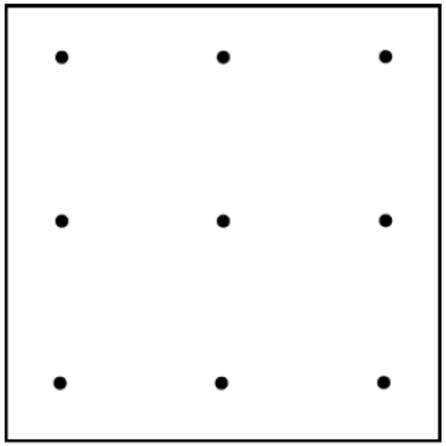




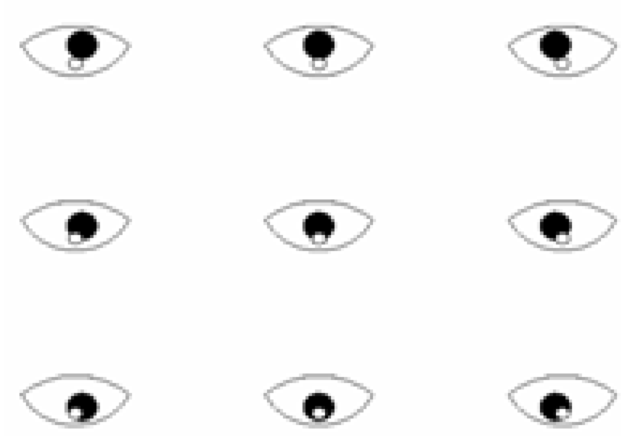
- **Eye trackers mostly operate using infrared imaging technology**
- **Once the pupil is detected the vector between the center of the pupil and the corneal reflection of the infrared light source is translated into the gaze location on screen coordinates**
- **Requires calibration at the beginning**

Images adapted from http://twiki.cis.rit.edu/twiki/bin/view/MVRL/QuadTracker and http://psy.sabanciuniv.edu

Eye Tracking



Sample 9-point calibration grid



Relative positions of the pupil and the corneal reflection

- **Individual calibration is necessary for each observer**
- **Relative location of the corneal reflection and the pupil is different among the population due to**
  - Difference in eye ball radius and shape
  - Eye-glasses

Images adapted from http://wiki.cogain.org

Eye Tracking

Chin-rest (EyeLink 1000/2000)

Glasses (SMI Eye Tracking Glasses)

Head-mounted displays (Oculus Rift)

- **Some of the other types of setups are used only for specific applications since they may be highly intrusive (e.g. chin-rest eye trackers) and not comfortable for the end-users in practice**
- **Head-mounted displays (HMD) offer 3D stereo and augmented reality capabilities in addition to eye tracking**

Images adapted from http://web.ntnu.edu.tw, http://youtube.com and http://techinsider.io

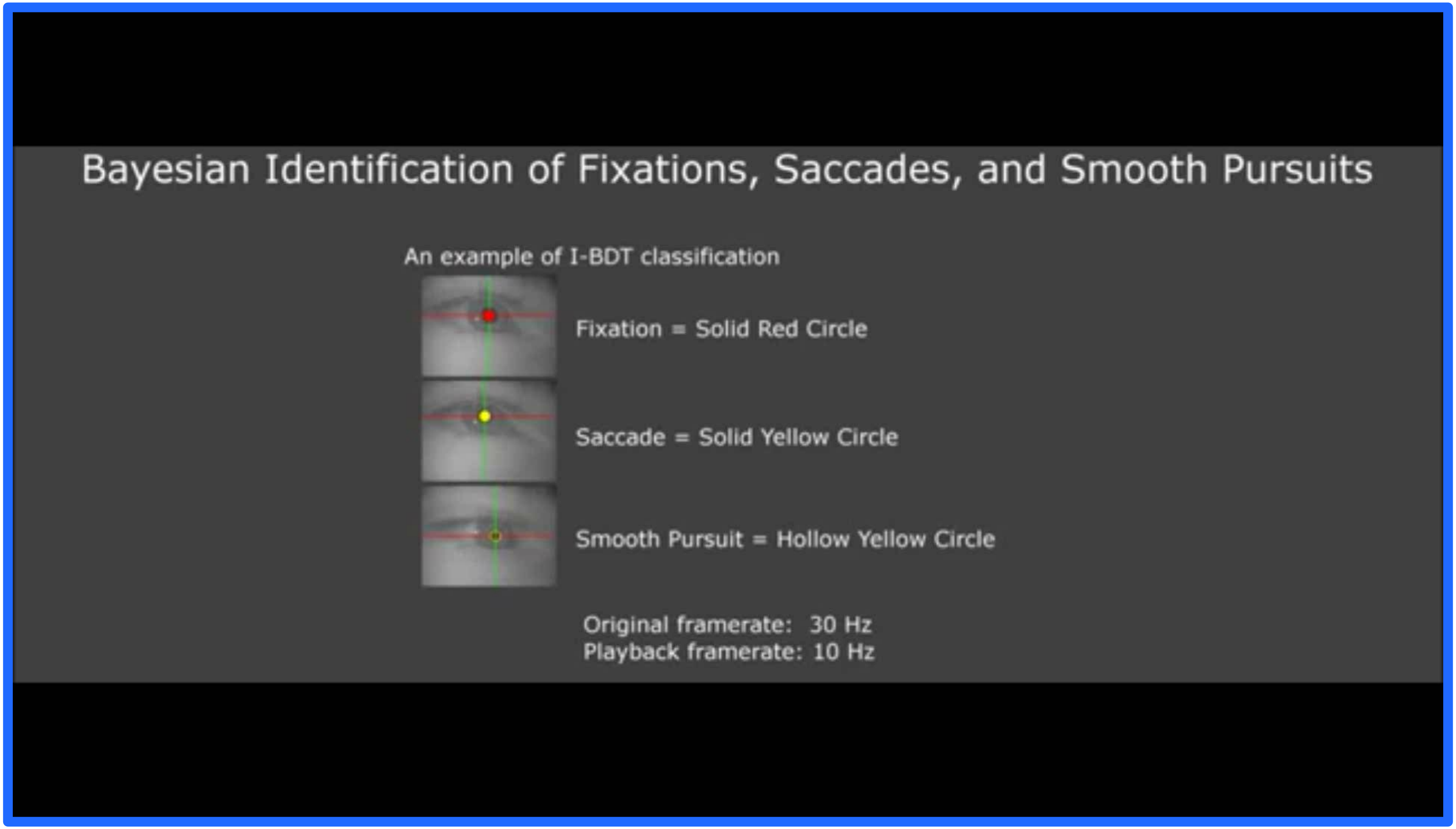
Types of Eye Motion

Type	Duration (ms)	Amplitude (1° = 60’)	Velocity
Fixation	200-300	-	-
Microsaccade	10-30	10-40’	$15\text{-}50^\circ$/s
Tremor	-	<1’	20’/sec
Drift	200-1000	1-60’	6-25’/s
Saccade	30-80	$4\text{-}20^\circ$	$30\text{-}500^\circ$/s
Glissade	10-40	$0.5\text{-}2^\circ$	$20\text{-}140^\circ$/s
Smooth Pursuit	variable	variable	$10\text{-}30^\circ$/s

- While the mechanisms are not exactly known, it is thought that the brain performs visual suppression and compensation during **saccades** and smooth pursuits against motion blur on the retina.

Reference: Holmqvist, K., Nyström, M., Andersson, R., Dewhurst, R., Jarodzka, H., & Van de Weijer, J. (2011). Eye tracking: A comprehensive guide to methods and measures. OUP Oxford.

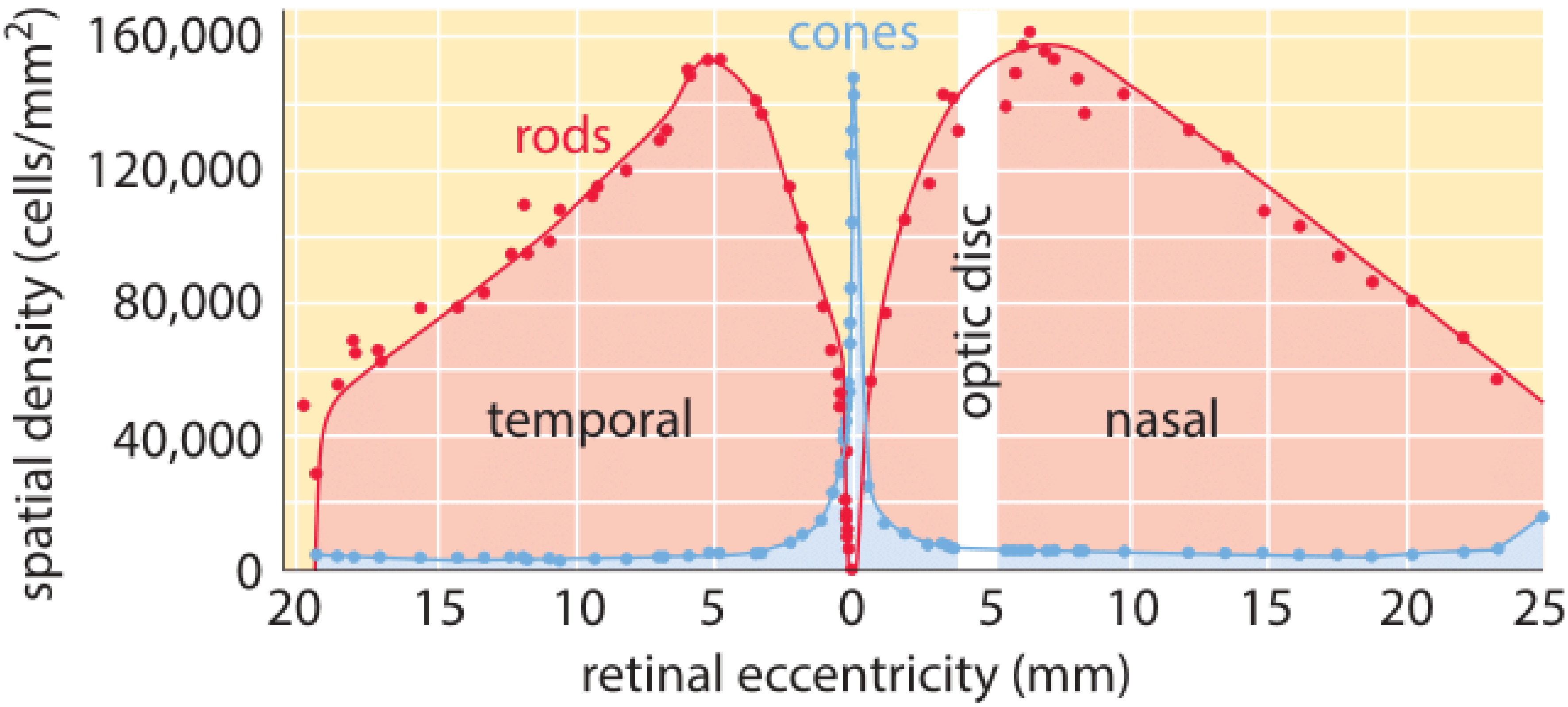
Eye Tracking in Action



Adapted from T. Santini, W. Fuhl, T. Kübler, and E. Kasneci. Bayesian Identification of Fixations, Saccades, and Smooth Pursuits ACM Symposium on Eye Tracking Research & Applications, ETRA 2016.

Visual Acuity

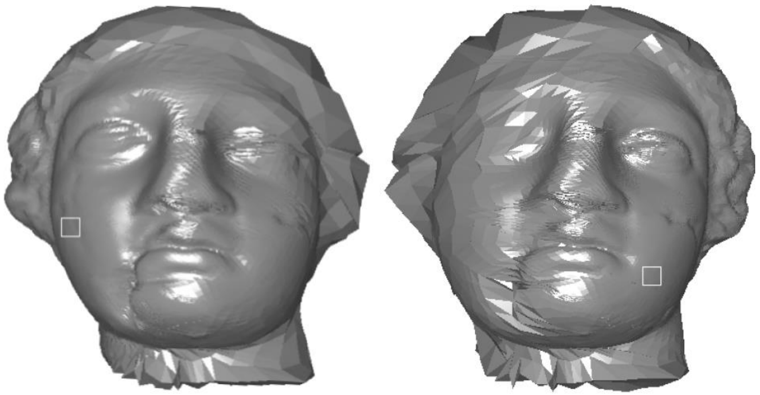
- **Distribution of photoreceptor cells in the retina**



Adapted from R. W. Rodieck, The First Steps of Seeing, Sinauer Associates, 1998.

Level-of-Detail Rendering

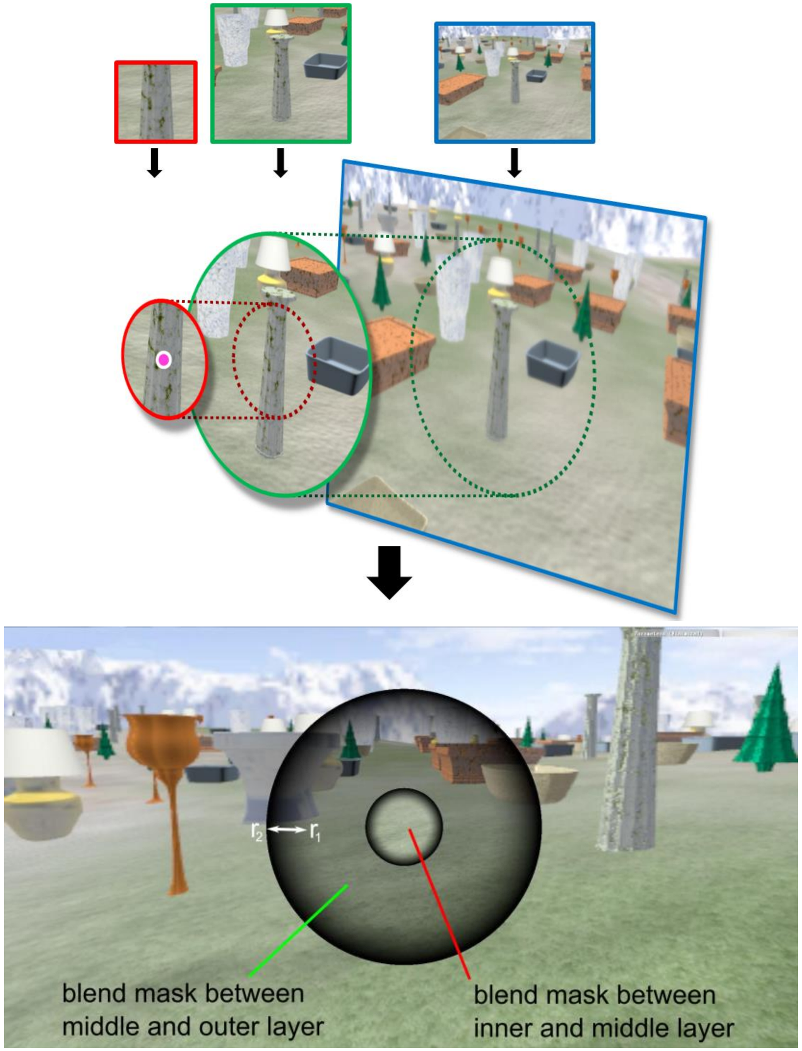
- **The model resolution may be degraded according to the visual angle and the acuity of HVS at the given angle**
  - Mesh structure of the model is partitioned into tiles using Voronoi diagram
  - Tiles are mapped to planar polygons
  - Remeshing into multiresolution form



Adapted from Murphy, Hunter, and Andrew T. Duchowski. "Gaze-contingent level of detail rendering." EuroGraphics 2001 (2001).

Foveated 3D Graphics

- **Screen-based (in contrast to model-based methods)**
- **Human eye has full acuity in around 5° foveal region**
- **The efficiency of image generation can be improved by maintaining high image resolution only around the gaze location**
- **Using** 60Hz **monitor and Tobii X50 eye tracker with** 50Hz **sampling frequency and** 35ms **latency caused artifacts for the observer**
- **Results using** 120Hz **monitor and Tobii TX300 with** 300Hz **sampling frequency and** 10ms **latency were tolerable**



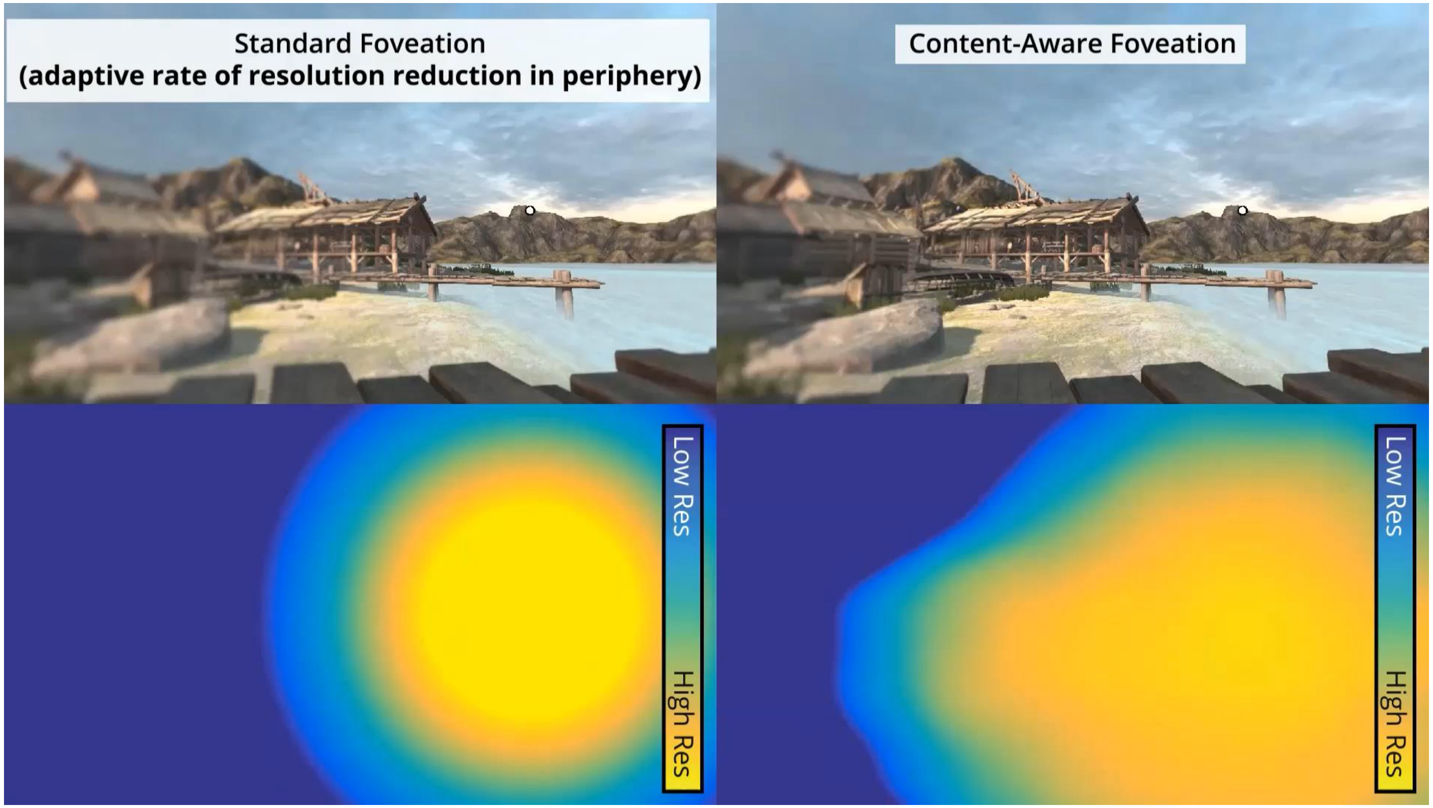
Images adapted from Guenter, B., Finch, M., Drucker, S., Tan, D., & Snyder, J. (2012). Foveated 3D graphics. ACM Transactions on Graphics (TOG), 31(6), 164.

Foveated 3D Graphics

Video adapted from http://research.microsoft.com

Luminance-Contrast-Aware Foveated Rendering

Luminance-Contrast-Aware Foveated Rendering



Effect of Depth-of-Field

- **Improves the rendering realism and enhances the depth perception**

(a) Image focused on objects at shallow depth (flower)

(b) Image focused on objects at large depth (Main Quad)

(c) Image with everything in focus

Images adapted from Gupta, Kushagr, and Suleman Kazi, “Gaze Contingent Depth of Field Display”, 2016. Video adapted from Mantiuk, Radoslaw, Bartosz Bazyluk, and Rafal K. Mantiuk. "Gaze-driven Object Tracking for Real Time Rendering." Computer Graphics Forum. Vol. 32. No. 2pt2. Blackwell Publishing Ltd, 2013.

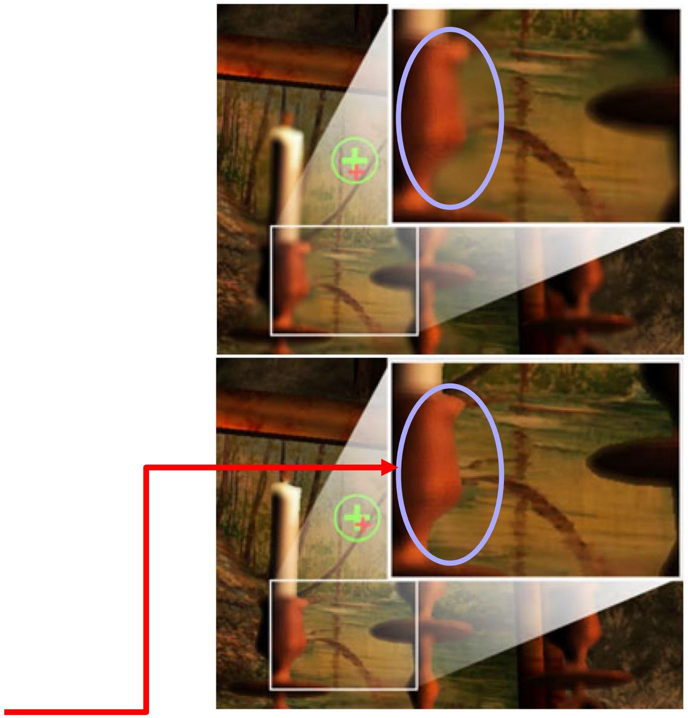
Depth-of-Field Rendering

- **Circle of Confusion :**

$$CoC = a \cdot \left|\frac{f}{d_0 - f}\right| \cdot \left|1 - \frac{d_0}{d_p}\right|$$

a **-** diameter of the lens aperture
f **-** focal length of the lens
d_0**-** distance between the focal plane and lens
d_p **-** distance from an object to the lens

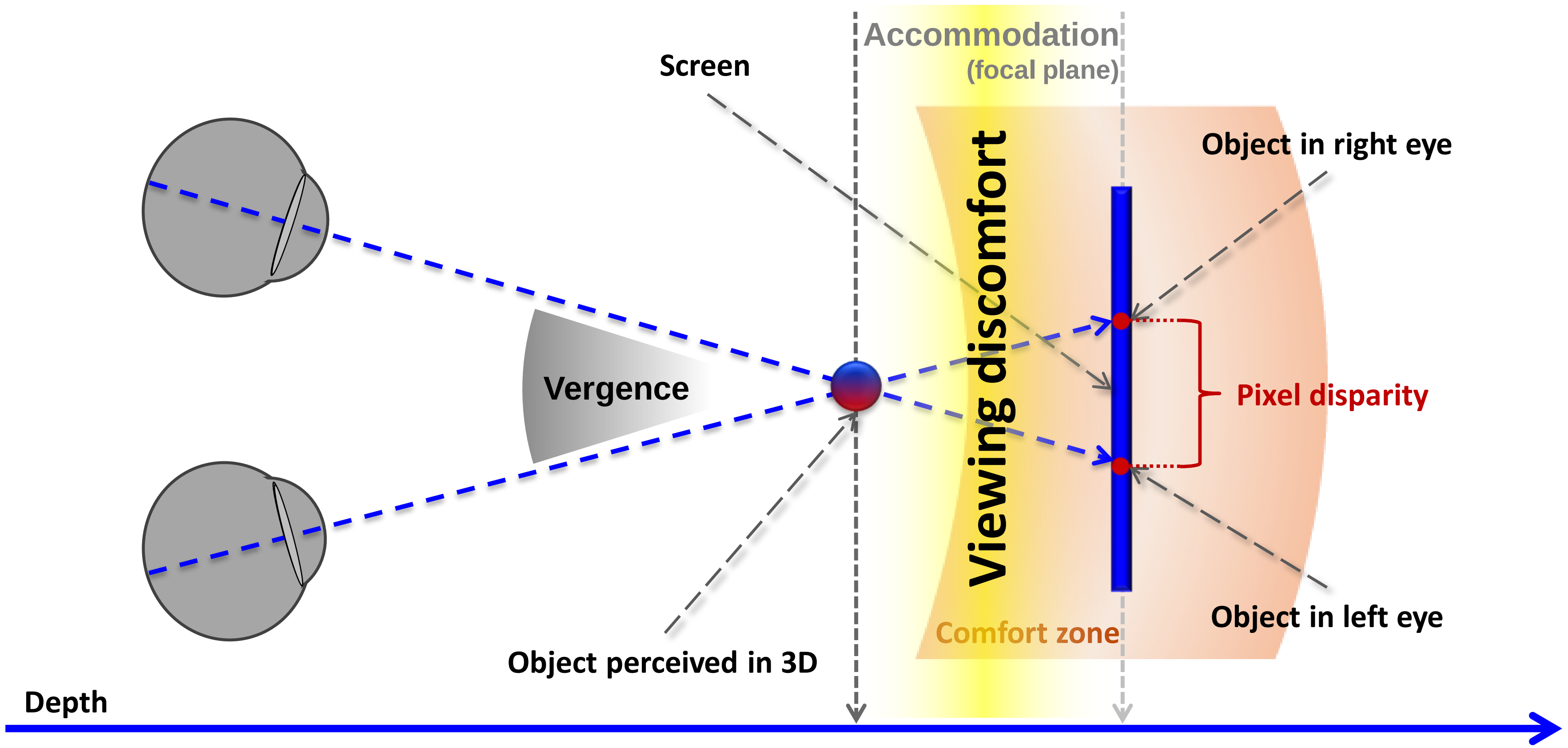
- d_p is obtained from reverse mapping of the z-buffer
- **Addresses the artifacts due to the depth discontinuity near object boundaries by spreading the blur outside the object boundary**



Images adapted from Mantiuk, R., Bazyluk, B., & Tomaszewska, A. (2011). Gaze-dependent depth-of-field effect rendering in virtual environments. In Serious Games Development and Applications (pp. 1-12). Springer Berlin Heidelberg.

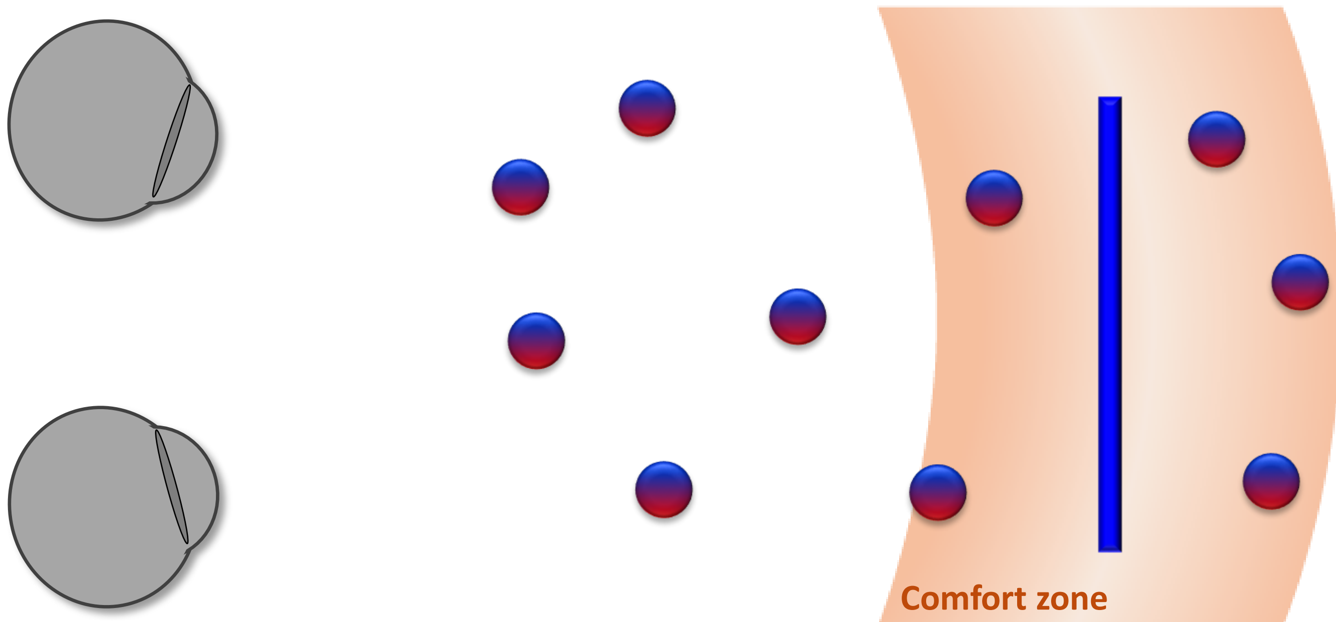
Vergence-accommodation Conflict

Stereo 3D: Binocular Disparity



Vergence-accommodation Conflict

Depth Manipulation



Scene manipulation

Viewing discomfort

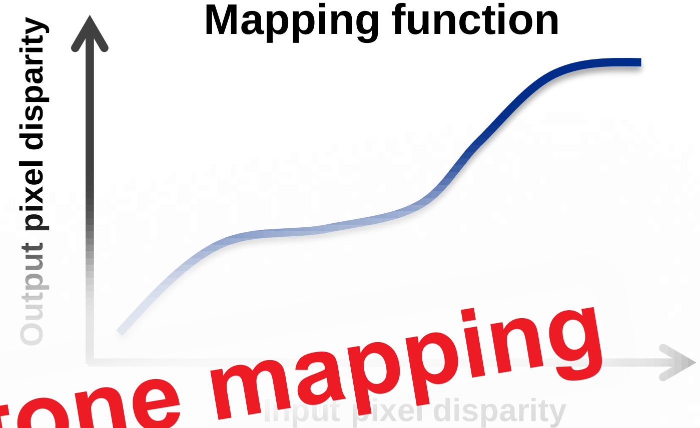
Viewing comfort

Vergence-accommodation Conflict

Depth Manipulation

Pixel disparity map

Modified pixel disparity



Similar to tone mapping

Function:

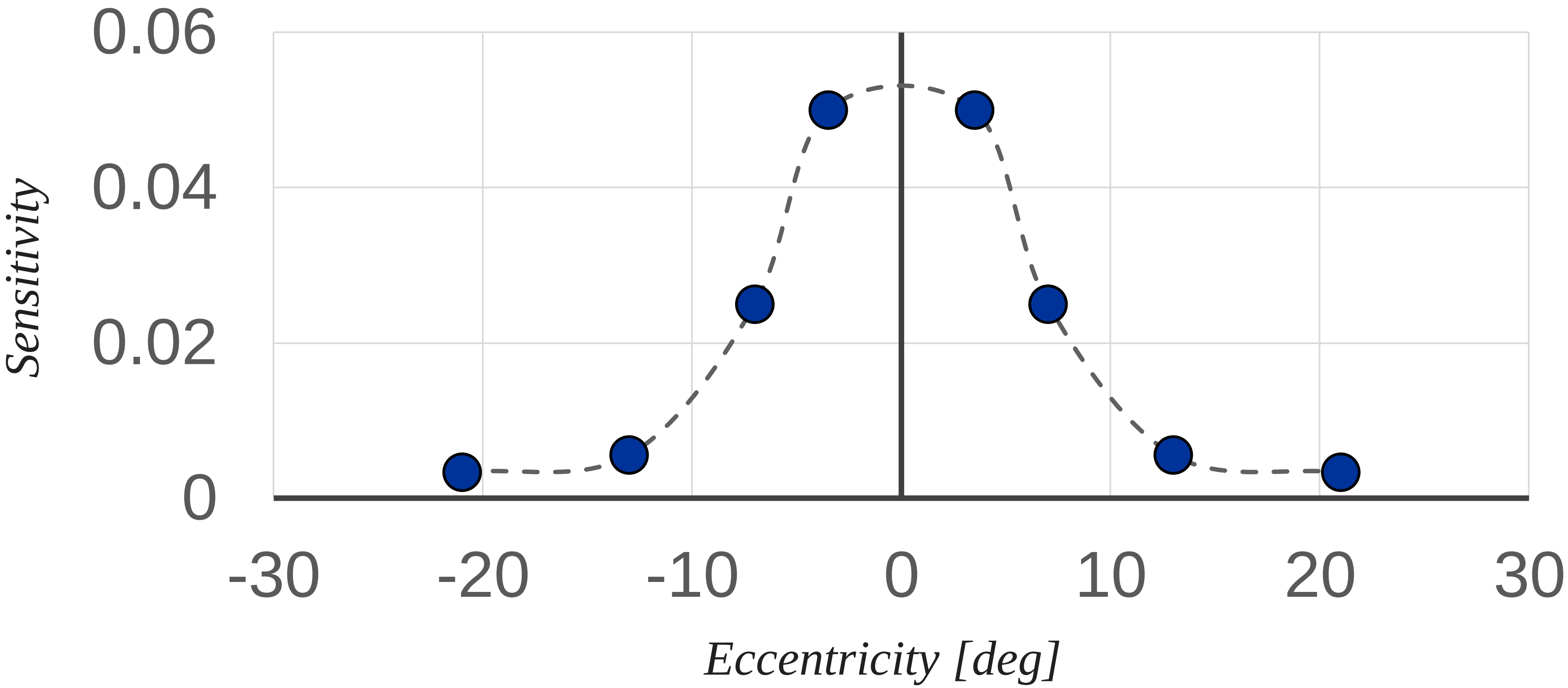
- Linear
- Logarithmic
- Content dependent

Other possibilities:

- Gradient domain
- Local operators

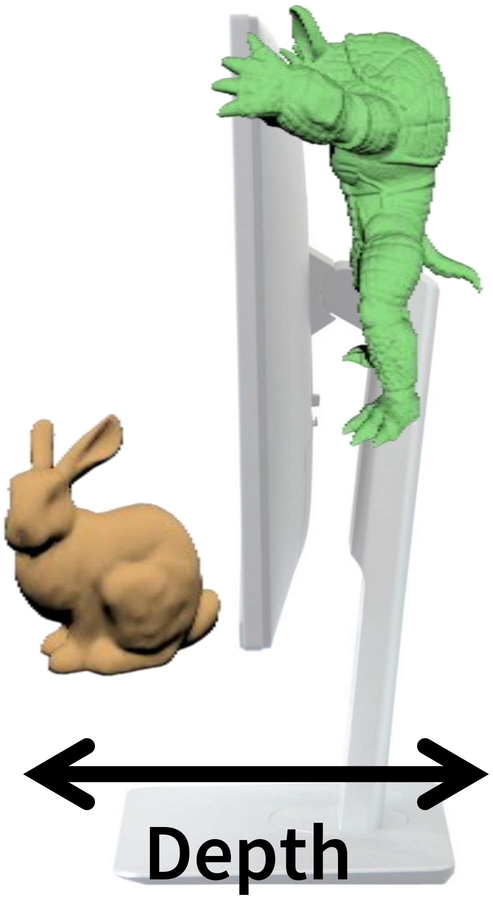
"Nonlinear Disparity Mapping for Stereoscopic 3D" [Lang et al. 2010]

Disparity Perception (Stereo 3D)

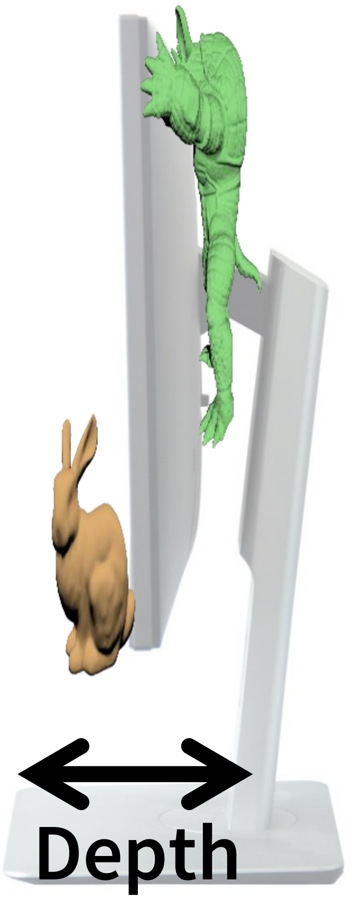


Replotted from Figure 3 of Simon J.D Prince, Brian J Rogers
Sensitivity to disparity corrugations in peripheral vision, Vision Research, Volume 38, Issue 17, September 1998

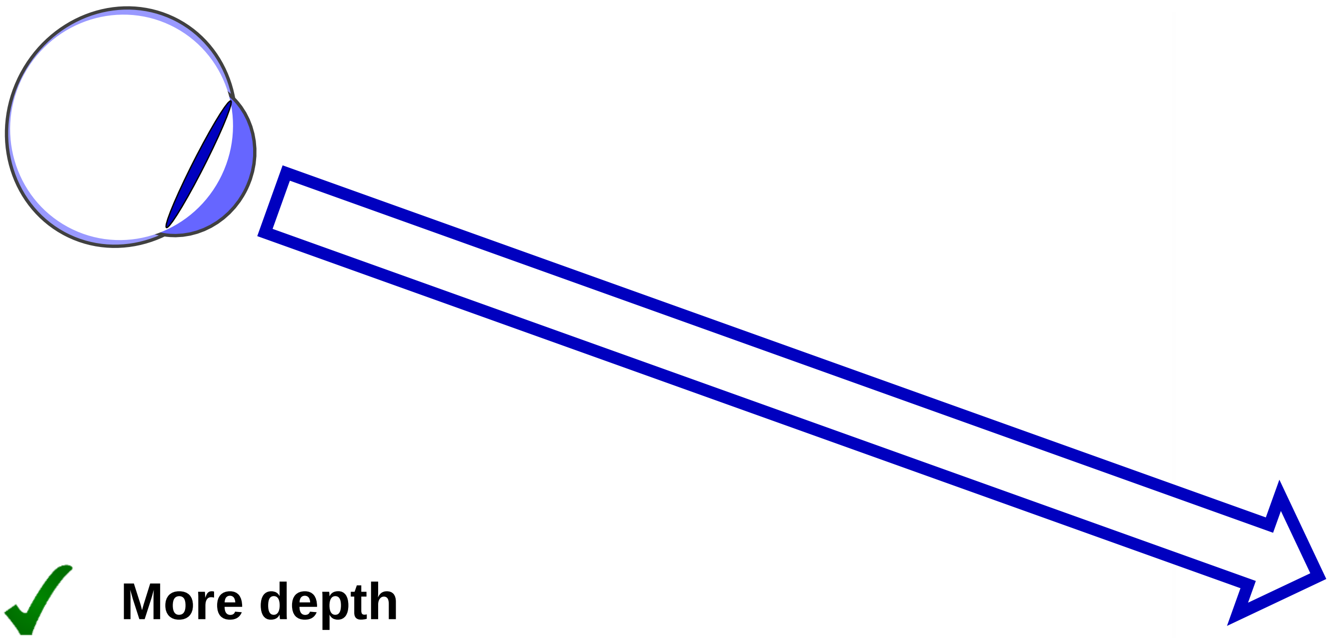
Vergence-accommodation Conflict



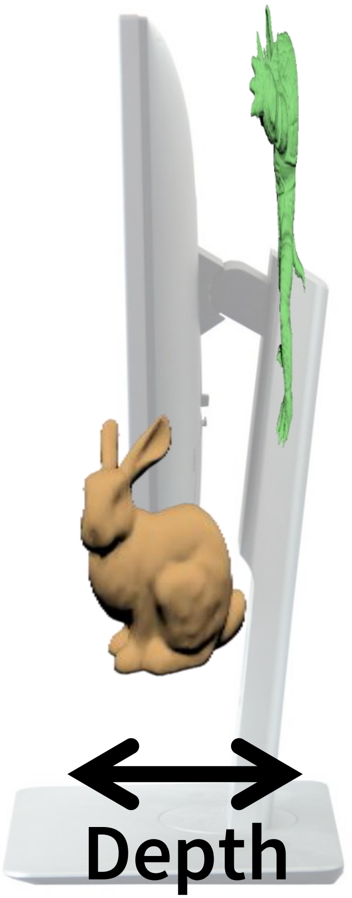
Vergence-accommodation Conflict



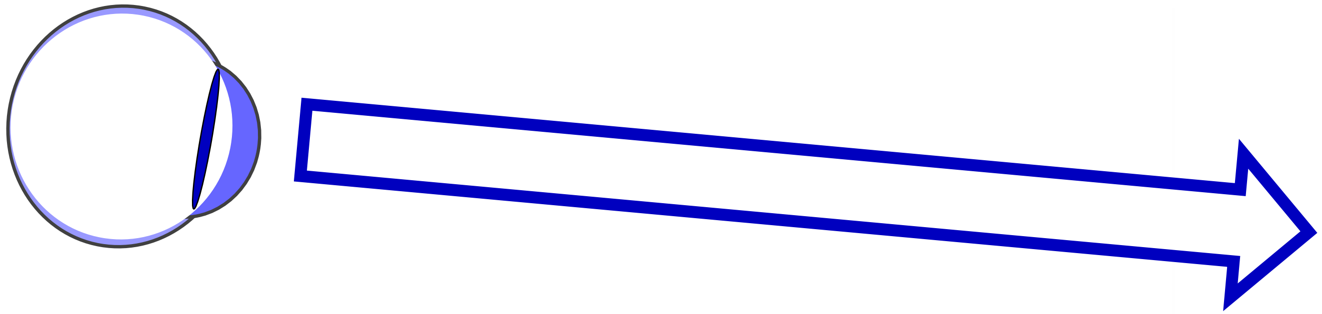
Vergence-accommodation Conflict



✓ **More depth**



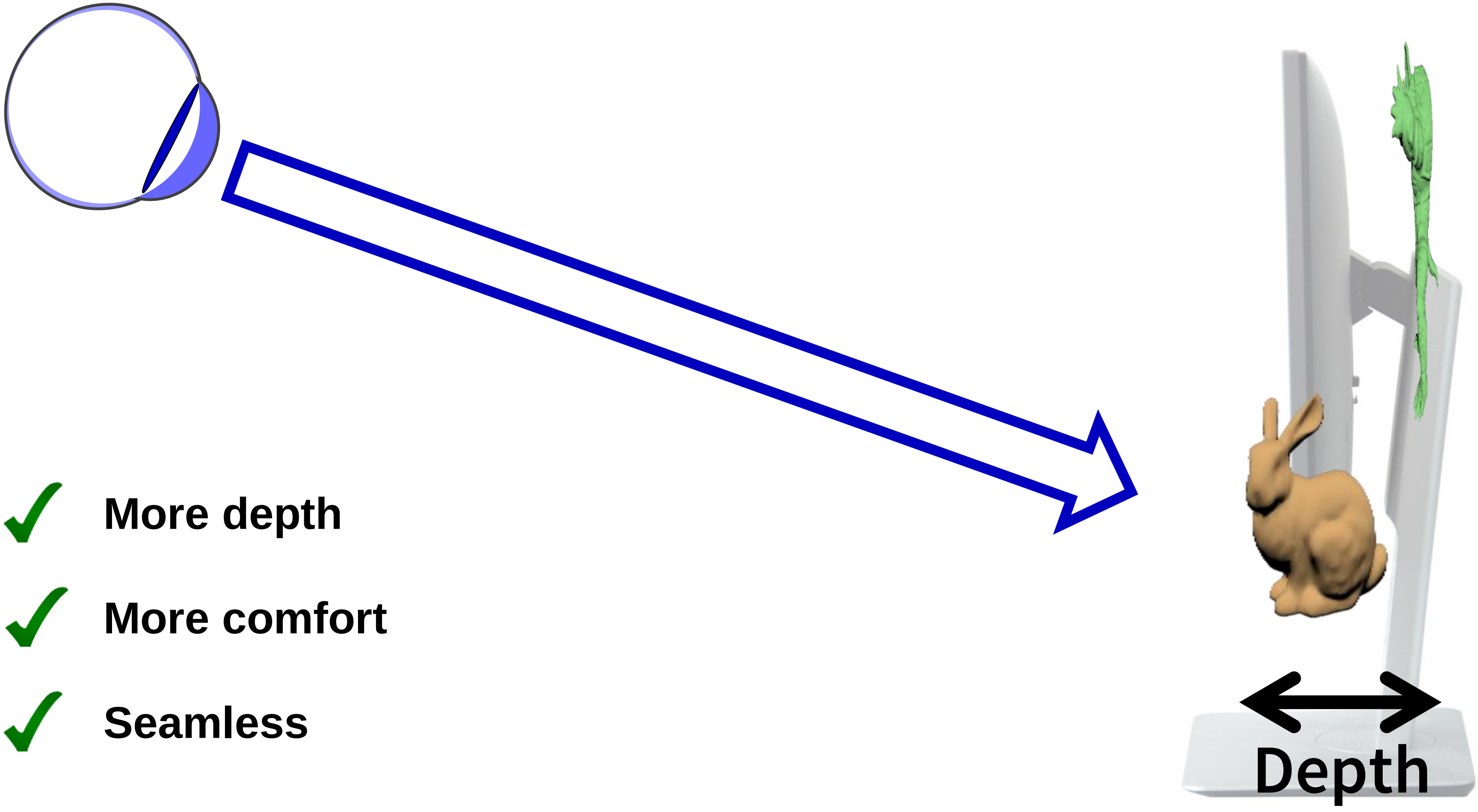
Vergence-accommodation Conflict



✓ **More depth**

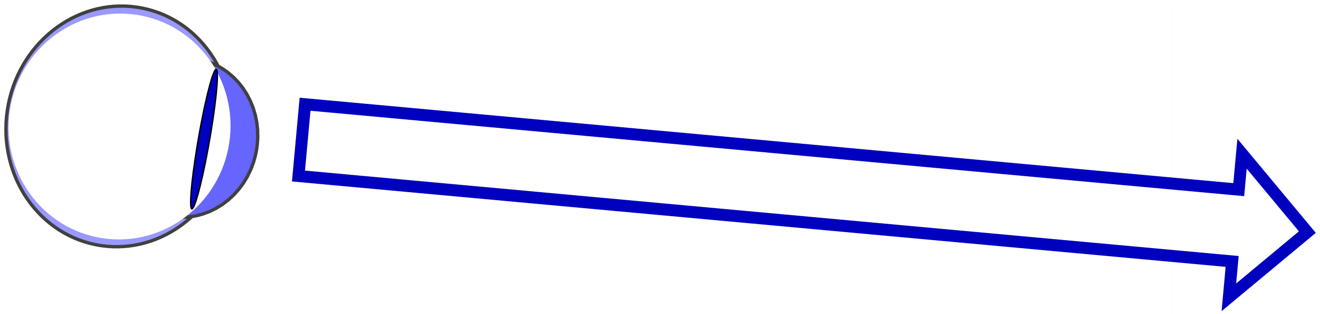
✓ **More comfort**

Vergence-accommodation Conflict



- ✓ **More depth**
- ✓ **More comfort**
- ✓ **Seamless**

Vergence-accommodation Conflict



- ✓ **More depth**
- ✓ **More comfort**
- ✓ **Seamless**
- ✓ **Low cost**

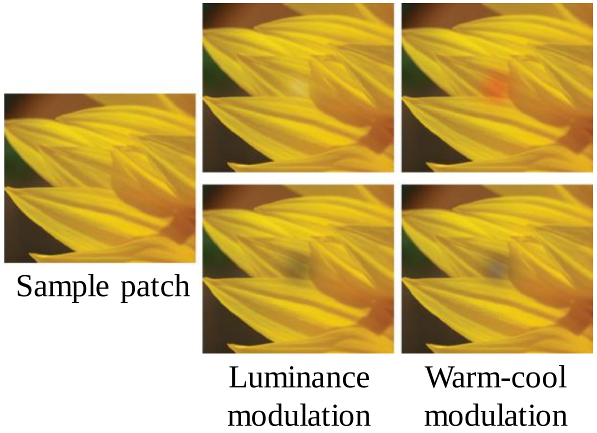
Gaze-contingent Stereo

- The region of attention may be predicted to manipulate disparity for comfortable viewing
- The online predictor uses Decision Forests (DF) to predict the object category that the viewer looks at
- A total of 13 game variables are used for prediction (e.g. Health, Hunger, Thirst, Ammo, Distance to the closest robot, …) which are selected among 300 as the most “informative” ones (ignoring variables with little or no variability)
- The predicted objects in the current scene are placed as close to the plane of zero-disparity as possible

Images adapted from Koulieris, George Alex, et al. "Gaze Prediction using Machine Learning for Dynamic Stereo Manipulation in Games." IEEE Virtual Reality. 2016.

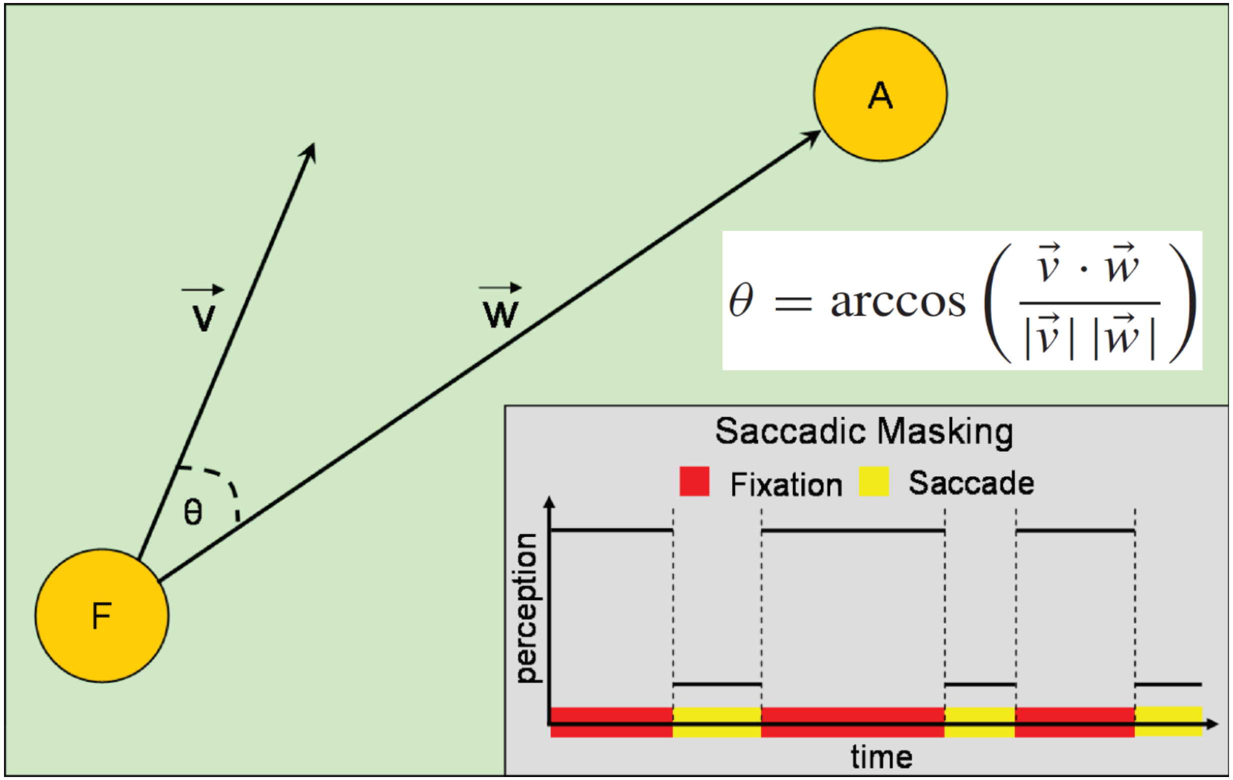
Subtle Gaze Direction

- When viewing an image low-acuity peripheral vision detects areas of interest, then HVS directs gaze to those locations
- HVS is very sensitive to changes in luminance (Spillmann et al. 1990) and opponent color channels (Hurvich and Jameson 1957)
- Introduces subtle image modulation to control the gaze direction of the observer
- Luminance and warm-cool modulations are studied and both are found successful



Images adapted from Bailey, R., McNamara, A., Sudarsanam, N., & Grimm, C. (2009). Subtle gaze direction. ACM Transactions on Graphics (TOG), 28(4), 100.

Subtle Gaze Direction



$$\theta = \arccos\left(\frac{\vec{v} \cdot \vec{w}}{|\vec{v}|\,|\vec{w}|}\right)$$

F: Fixation point**, A:** Predetermined Area of Interest

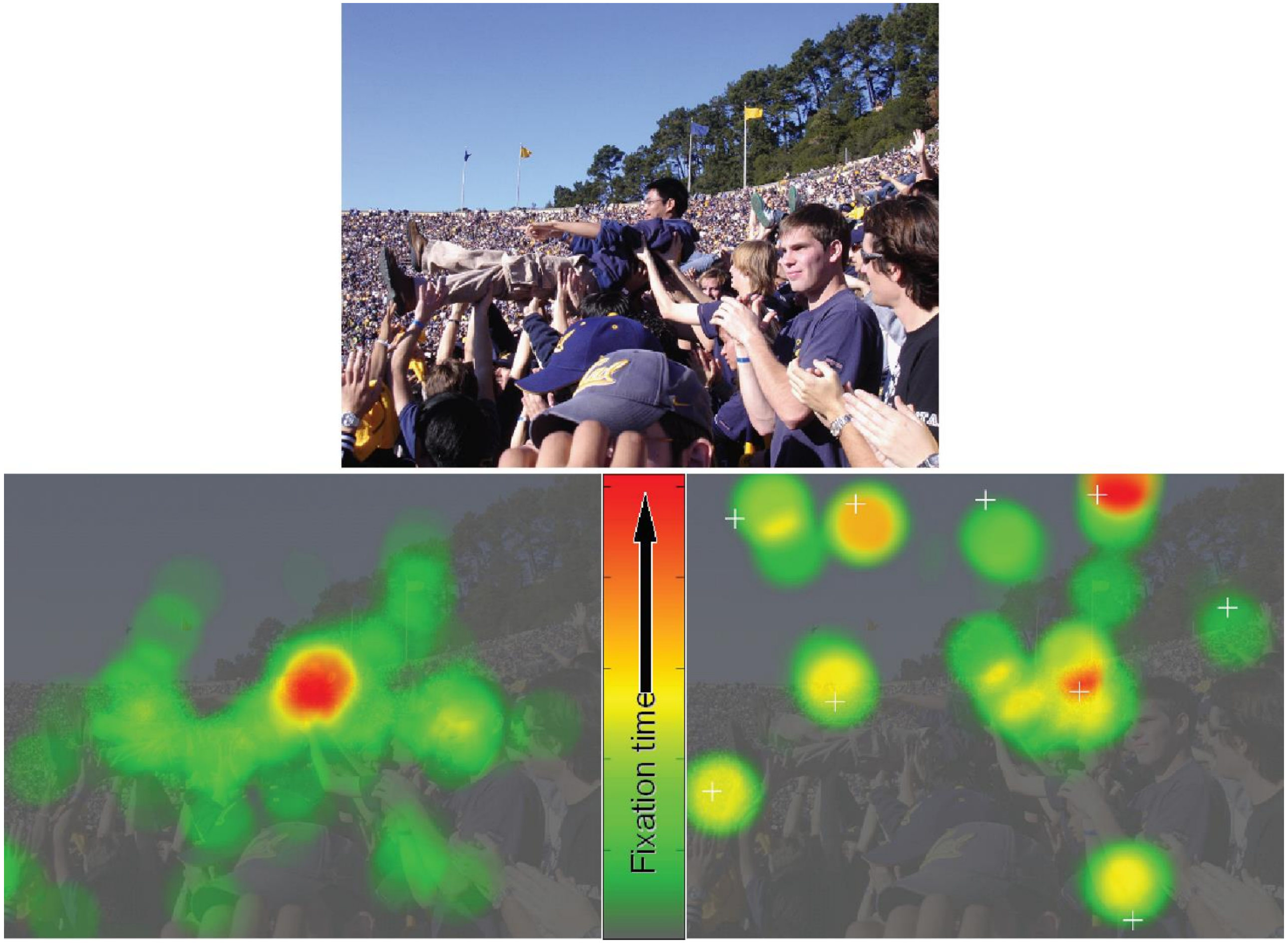
Goal: To direct the user attention to from **F** to **A**

Modulation is applied to A and θ is monitored real-time.

When $\theta \leq 10^{\circ}$, the modulation is terminated immediately.

Images adapted from Bailey, R., McNamara, A., Sudarsanam, N., & Grimm, C. (2009). Subtle gaze direction. ACM Transactions on Graphics (TOG), 28(4), 100.

Subtle Gaze Direction



Top: Input image**, Left:** No modulation**, Right:** Modulation at white crosses

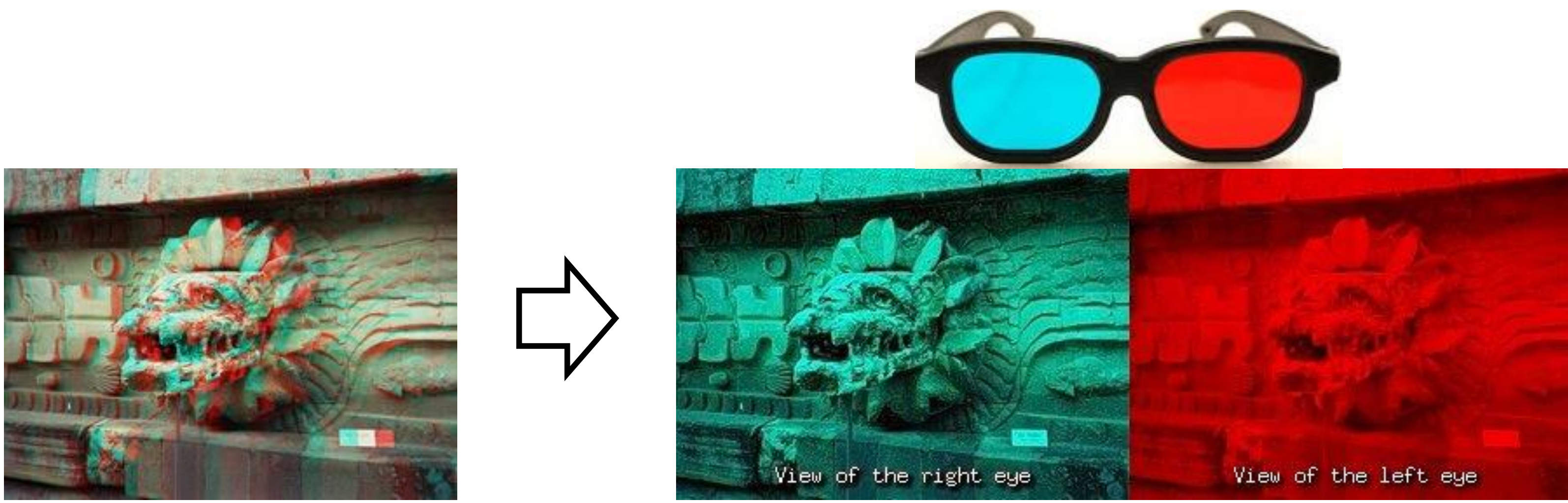
Images adapted from Bailey, R., McNamara, A., Sudarsanam, N., & Grimm, C. (2009). Subtle gaze direction. ACM Transactions on Graphics (TOG), 28(4), 100.

Binocular 3D Displays

- **Capable of providing sense of 3D by simulating binocular disparity**
  - Color Anaglyphs
  - Polarization
  - Shutter Glasses
  - Head-Mounted Displays
- **They mostly do not provide accommodation depth cue**

Color Anaglyphs

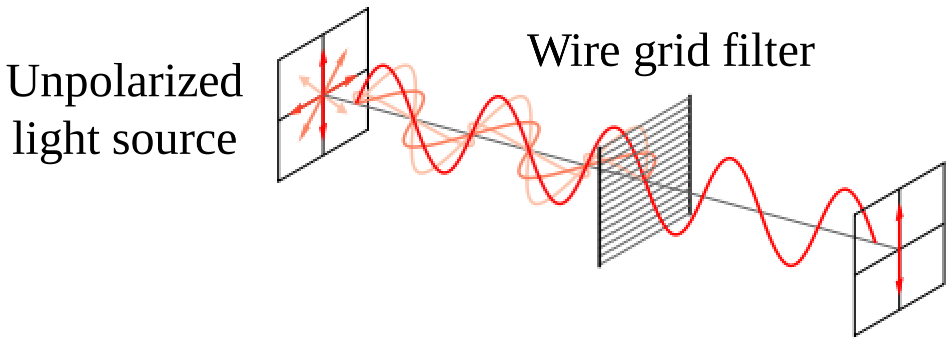
- **Left and right images are filtered using different colors (usually complementary):**
  - Red – Green, Red – Cyan, Green – Magenta
  - Amber – Blue (ColorCode 3D, patented [Sorensen et al. 2004])
- **Limited color perception (since each eye sees only a subset of whole colorspace)**

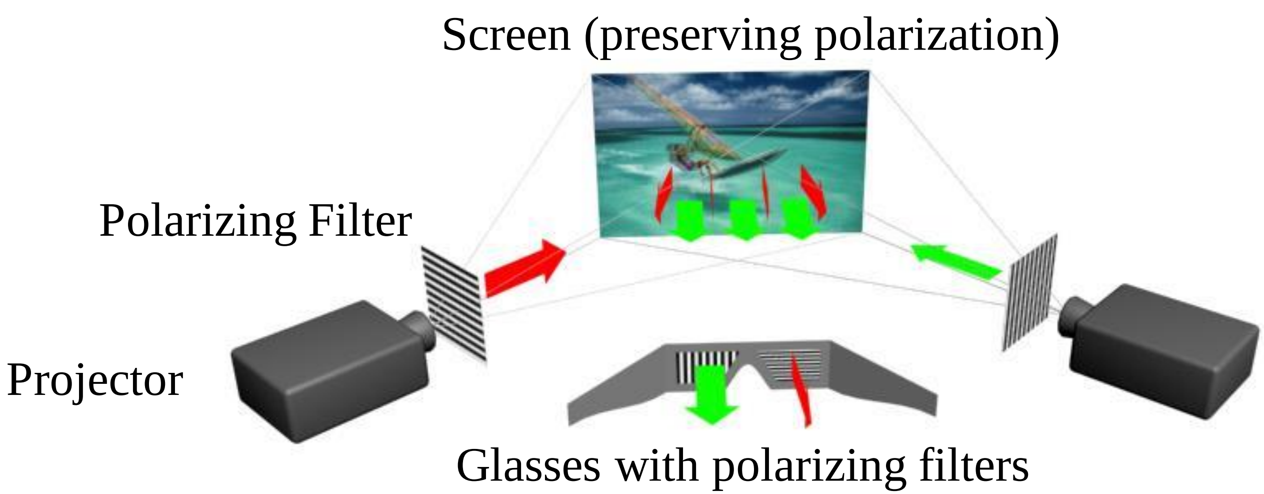


Images adapted from http://axon.physik.uni-bremen.de/research/stereo/color_anaglyph/

Polarization

- **Usually a wire grid filter converts the unpolarized light beam to a polarized one**

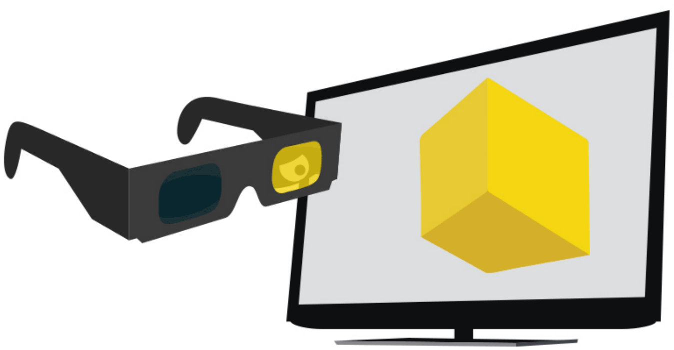


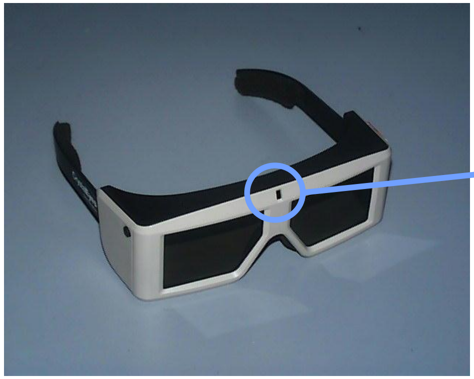


Images adapted from https://cpinettes.u-cergy.fr/S6-Electromag_files/fig1.pdf

Shutter Glasses

- **Exploits the "memory effect" of the Human Visual System [Coltheart 1980]**
- **Glasses have shutters which operate in synchronization with the display system**
- **Left and right eye images are shown in alternation**
- **Color neutral; however, temporal resolution is reduced**





IR receiver for synchronization

Images adapted from https://en.wikipedia.org/wiki/Active_shutter_3D_system

Head-Mounted Displays

- **Separate displays for the left and right eye**
- **May provide current orientation of the head (and update the stimuli accordingly to provide a VR)**

Images adapted from http://www.oculus.com

Autostereoscopic Displays

- **Stereo displays which are viewable without special glasses or head-wear equipment**
- **Simulate an approximate lightfield with a finite number of views**
  - Parallax Barriers
  - Integral Imaging
  - Multi-layer Displays

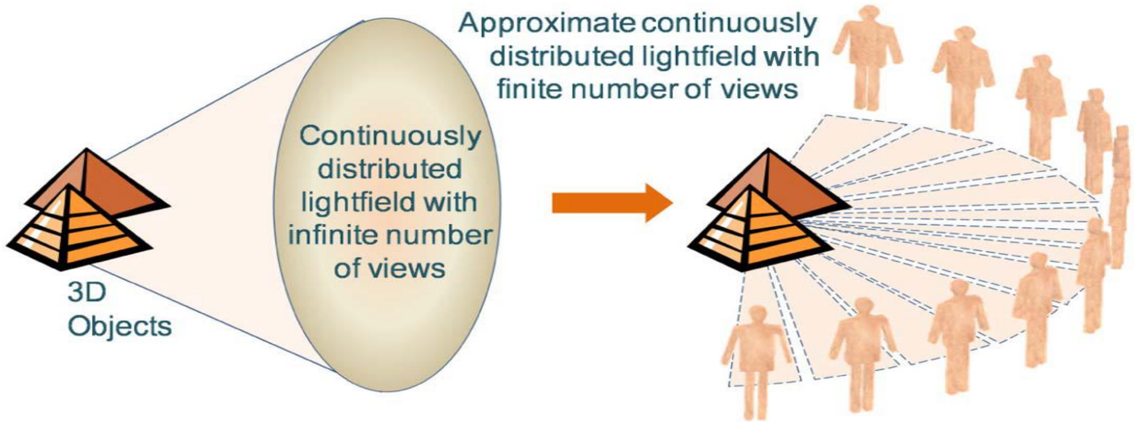
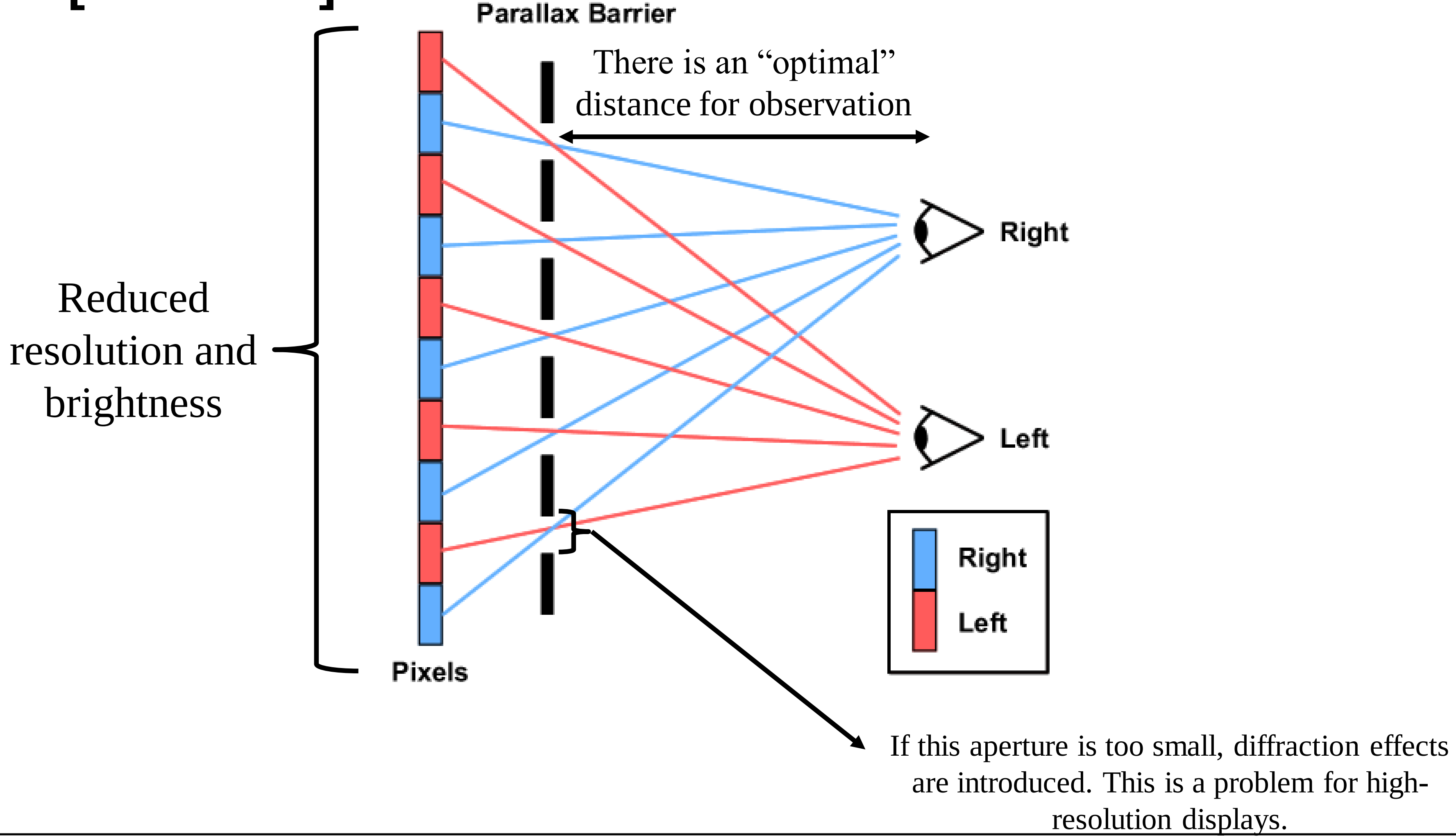


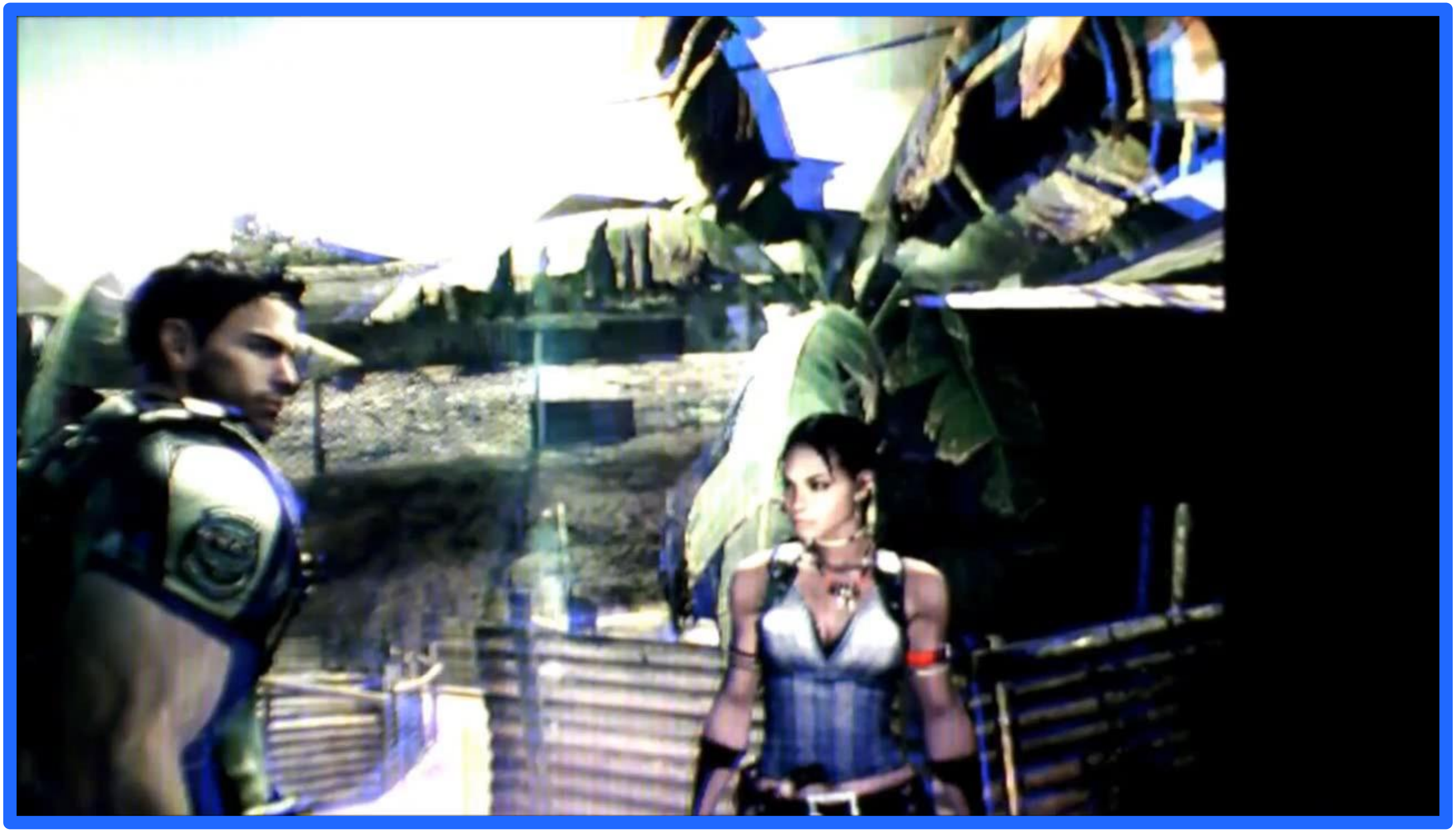
Image adapted from Geng, Jason. "Three-dimensional display technologies." Advances in optics and photonics 5.4 (2013): 456-535.

Parallax Barriers

- **Occlusion-based working principle and key features [Ives 1903]:**



Parallax Barriers

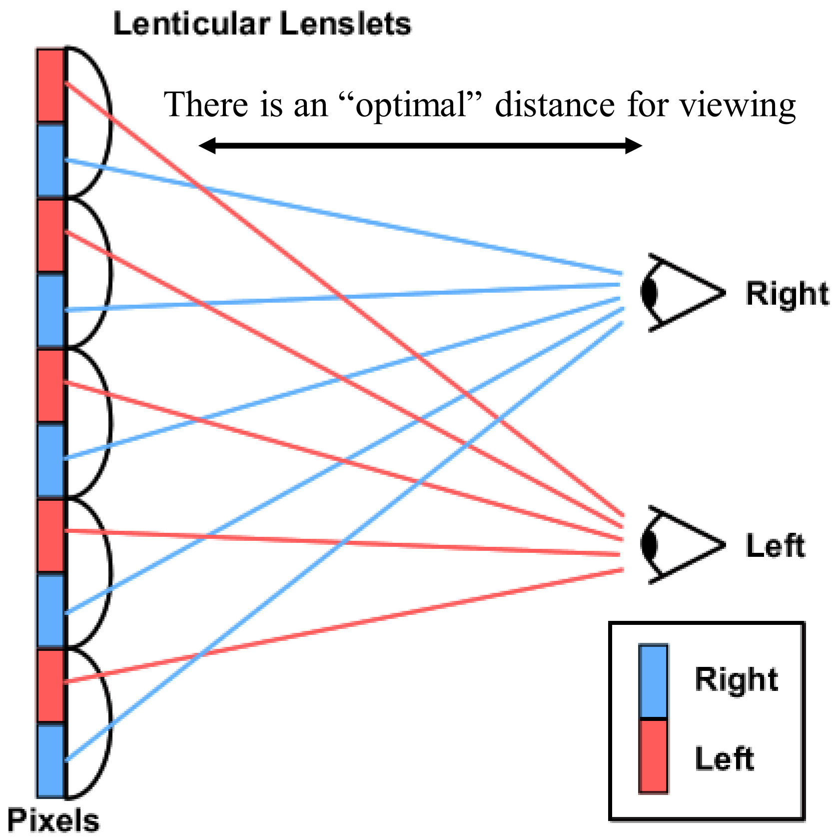


Video adapted from: http://www.youtube.com/watch?v=sxF9PGRiabw "Glasses-Free 3D Gaming for $5 (Parallax Barrier)"

Integral Imaging

- **Refraction-based working principle [Lippmann 1908]:**

Reduction in resolution and brightness is still a problem.



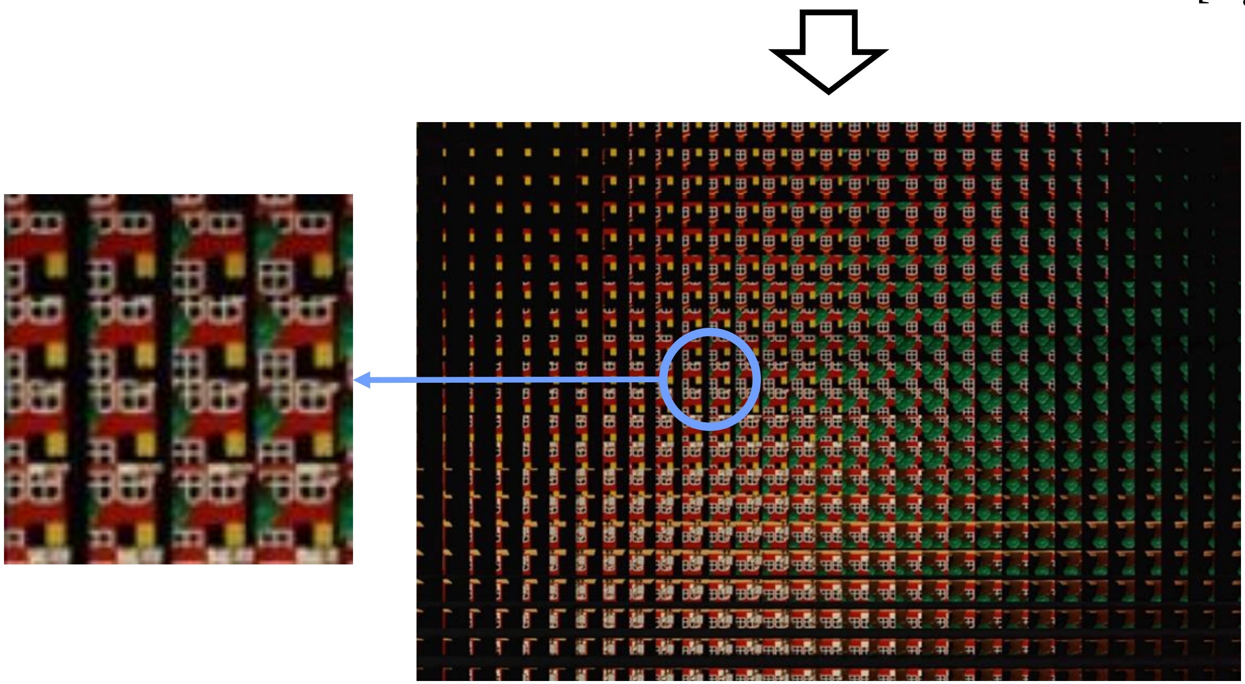
It is possible to reproduce parallax, perspective shift and accommodation depth cues.

Images adapted from http://www.3d-forums.com/threads/autostereoscopic-displays.1/

Integral Imaging

3D Scene

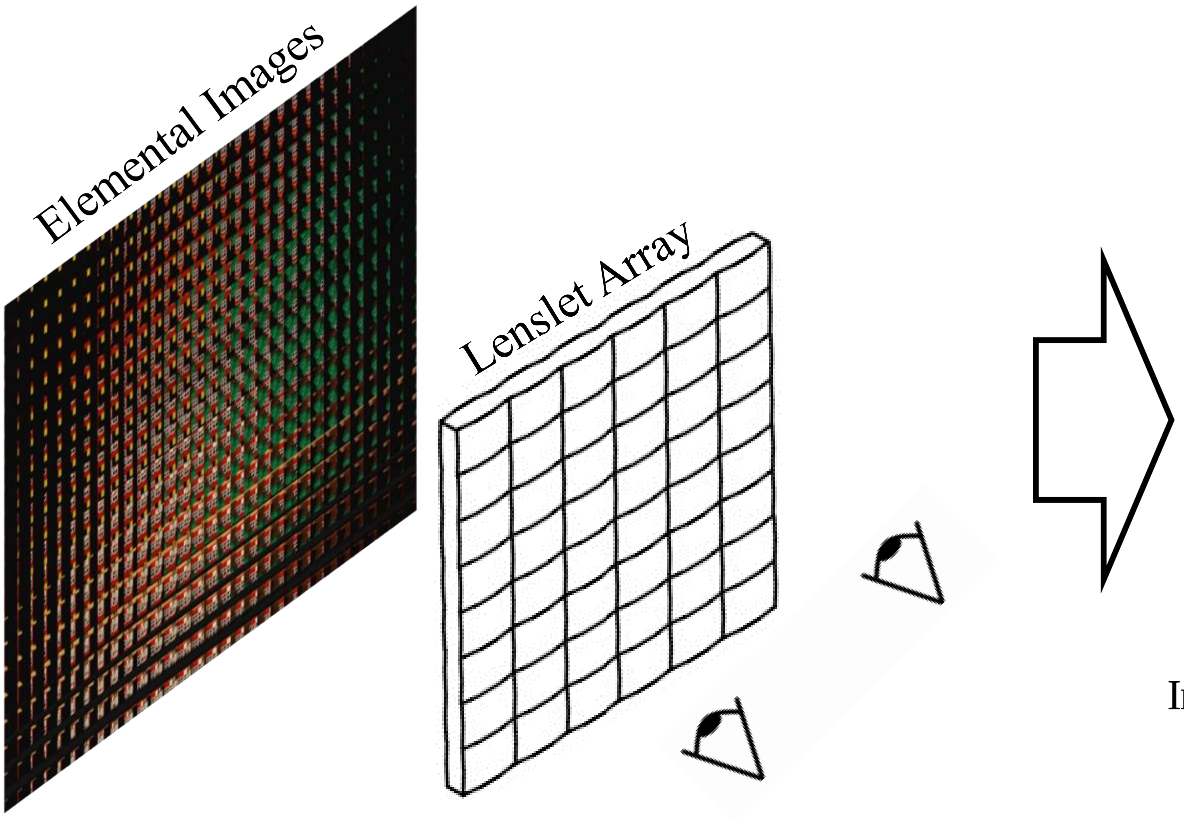
Array of lenses (multiple cameras each with a single lens [Wilburn 2005] or a single camera with multiple lenses in front of the sensor [Ng 2005])

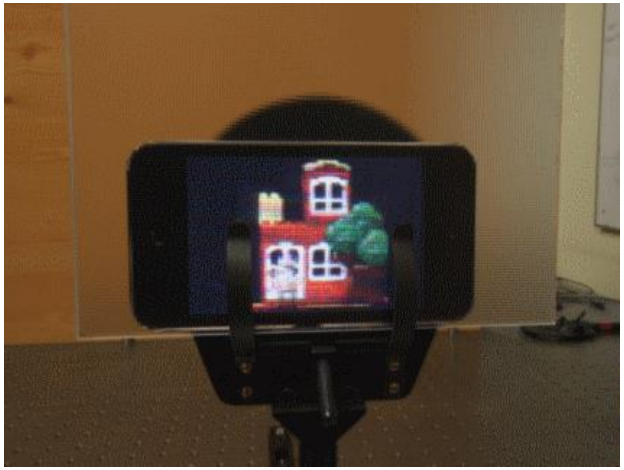


Elemental Images

Images adapted from Martınez-Corral, Manuel, et al. "3D integral imaging monitors with fully programmable display parameters."

Integral Imaging





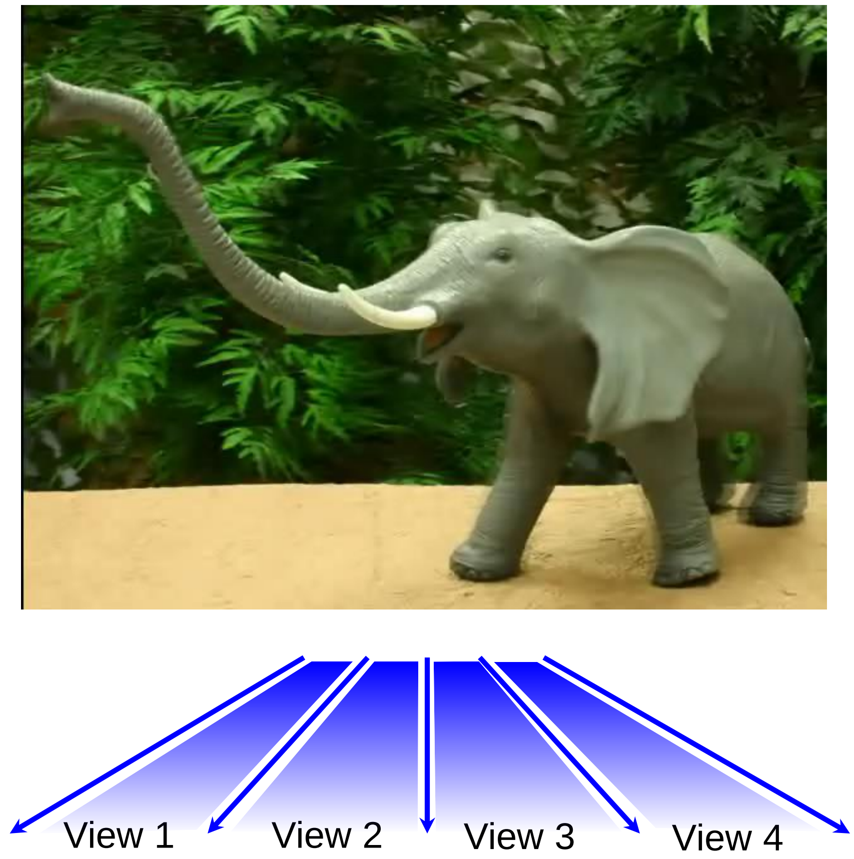
Integral Image as seen by the observer

Images adapted from Martınez-Corral, Manuel, et al. "3D integral imaging monitors with fully programmable display parameters."

Multi-view Autostereoscopic Display

- **Smooth transitions**

Multi-view autostereoscopic display



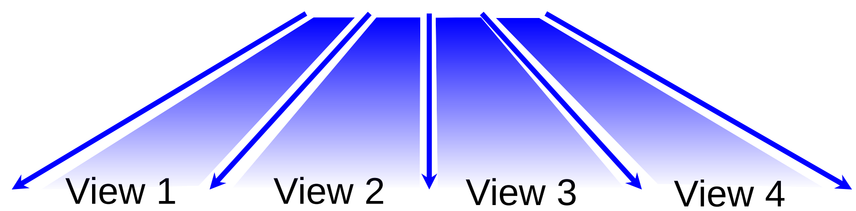
„Antialiasing for automultiscopic 3D displays” [Zwicker et al. 2006]

Multi-view Autostereoscopic Display

- **Smooth transitions**
- **Blur increases with depth**

Weaker depth percept

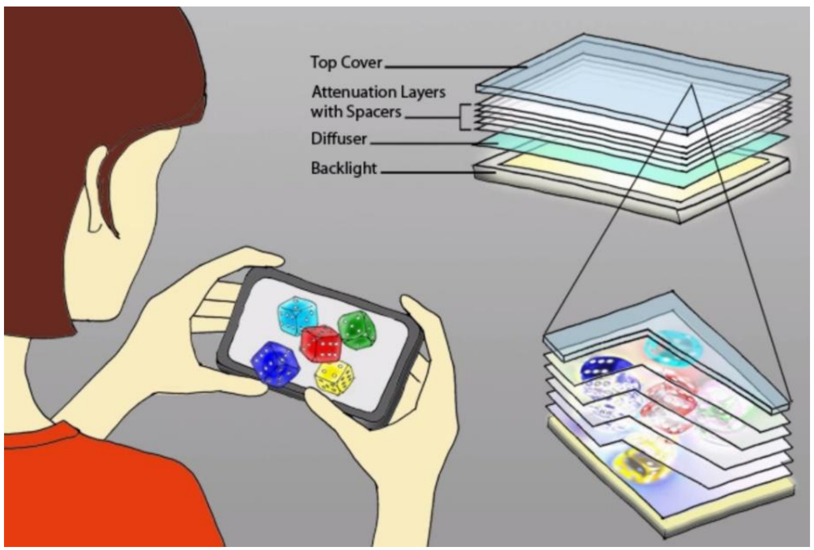
Multi-view autostereoscopic display

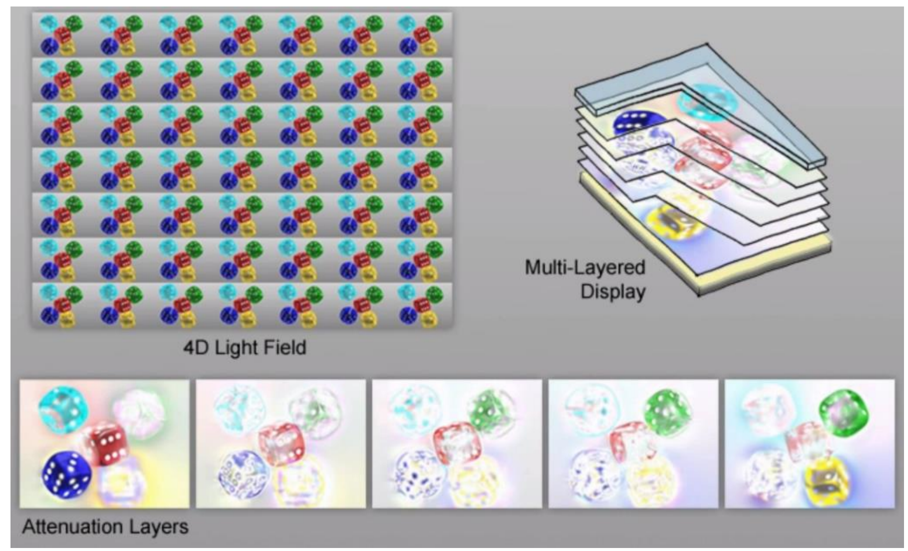


„Antialiasing for automultiscopic 3D displays" [Zwicker et al. 2006]

Multi-layer Displays

- **Improved resolution over parallax barriers and lenslet arrays**
- **Provides a solution to accommodation-vergence conflict**

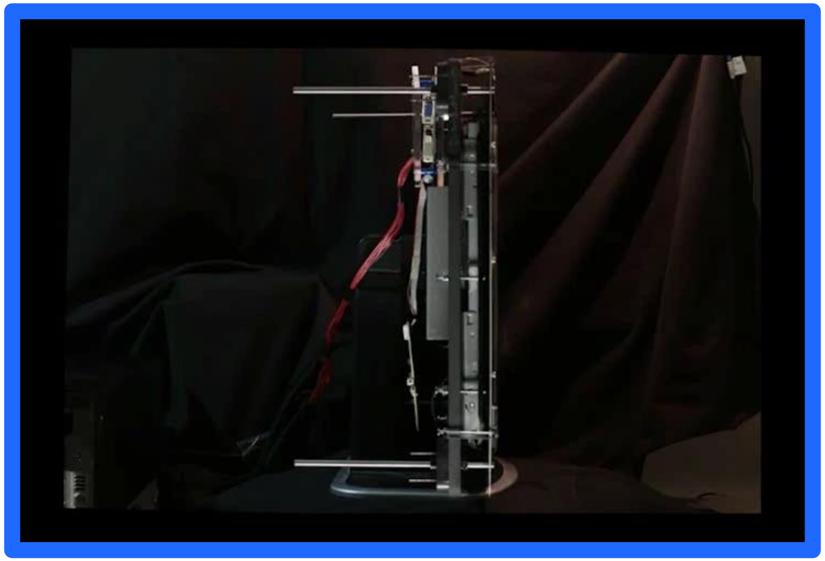




Images adapted from Wetzstein, Gordon, et al. "Layered 3D: tomographic image synthesis for attenuation-based light field and high dynamic range displays." ACM Transactions on Graphics (ToG). Vol. 30. No. 4. ACM, 2011.

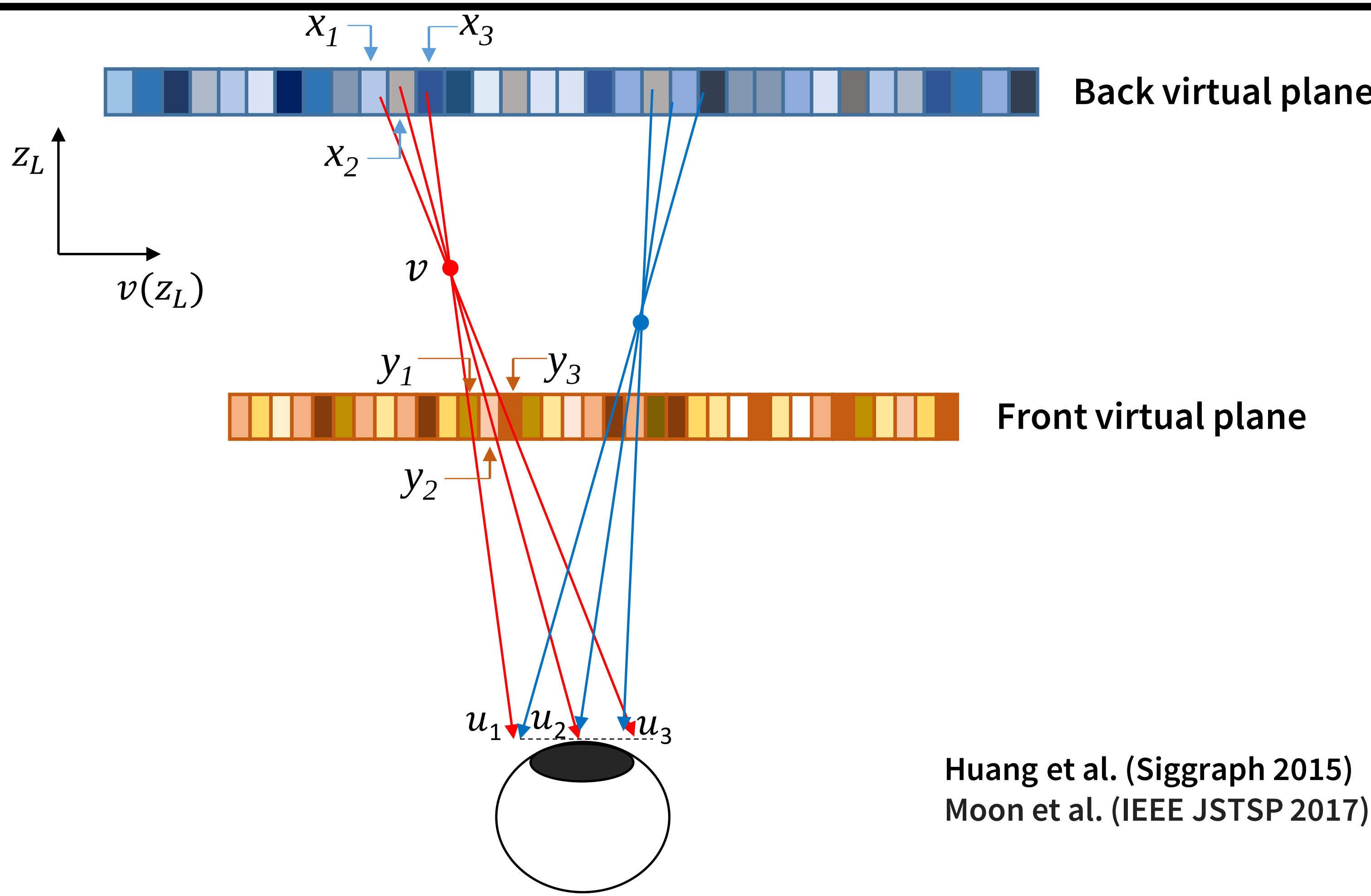
Tensor Displays

- **Lightfield emitted by a multi-layer display is represented by a tensor where rays span a 2D plane in 3D tensor space**
- **Target lightfield is decomposed into Rank-1 tensors using Nonnegative Tensor Factorization**
- **Rank-1 tensors are shown in quick succession with a high refresh rate, which are perceptually averaged over time by the Human Visual System**



Video adapted from Wetzstein, Gordon, et al. "Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting." (2012).

Rendering images in Tensor Displays



Huang et al. (Siggraph 2015)
Moon et al. (IEEE JSTSP 2017)

Target Light-fields: $L(v, u_1) = L(v, u_2) = L(v, u_3) = R$

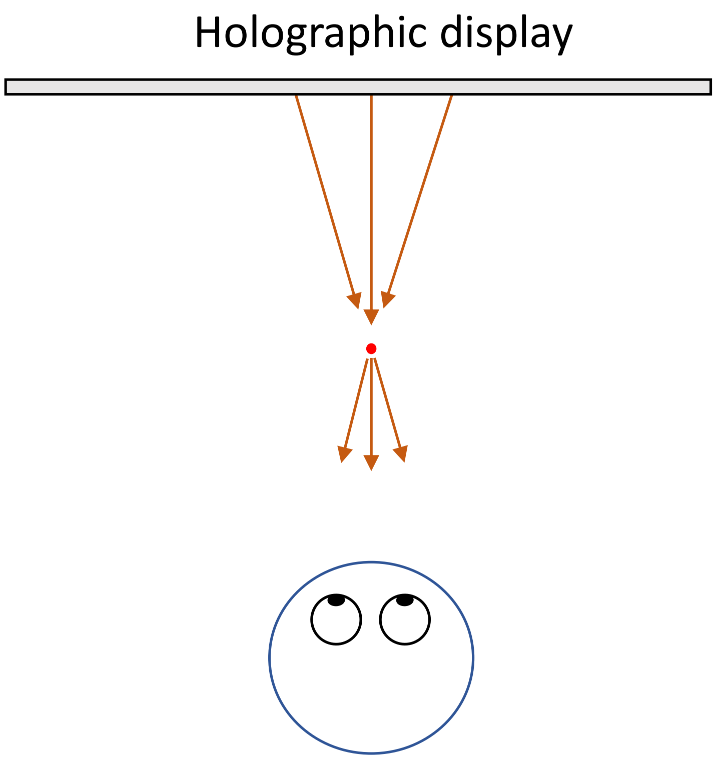
Optimization equation : $L(v, u_1) = x_3 \times y_1$

$$L(v, u_2) = x_2 \times y_2$$
$$L(v, u_3) = x_1 \times y_3$$

Lightfield Displays

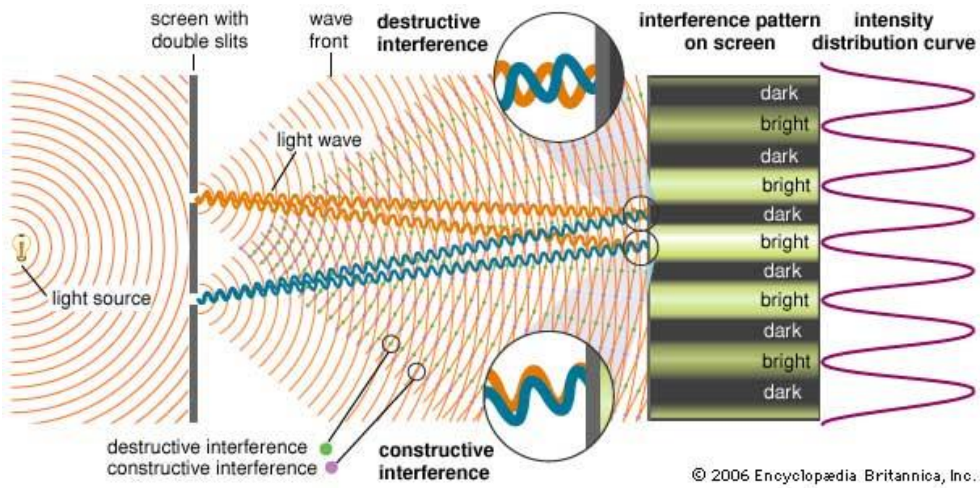
Holographic display

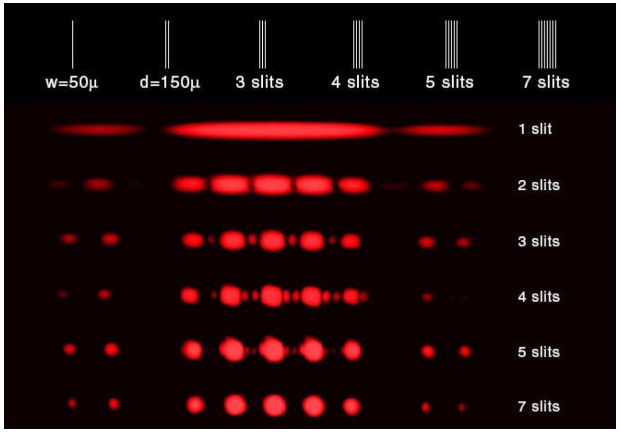
Holographic display : generating 3D images in the air without any scatterer



What is the meaning of “focusing the light”?

Focusing == interference

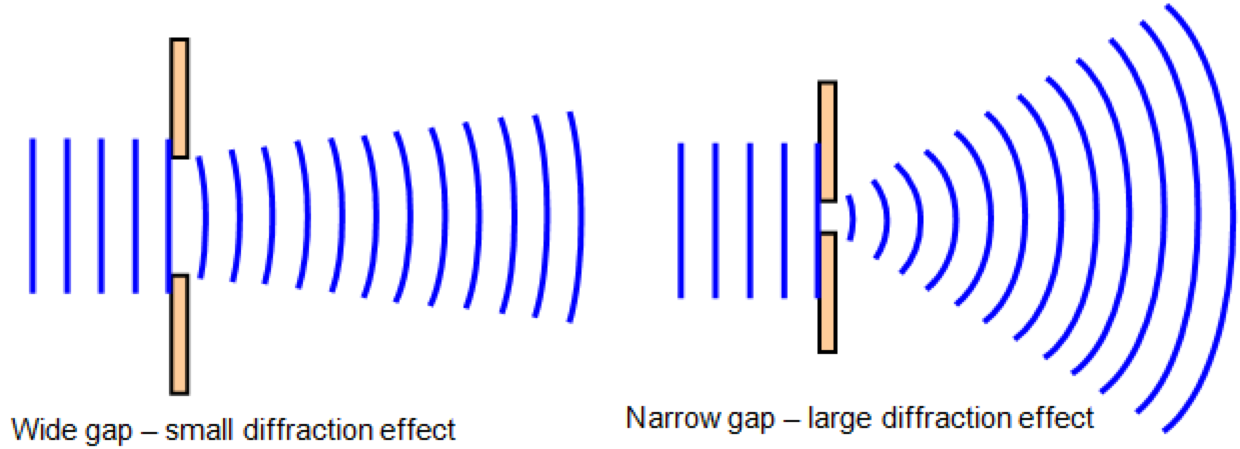




http://labman.phys.utk.edu/phys136

Focusing = constructive interference of multiple pixels
(but it requires coherent light sources such as laser)

Smaller pixel size == Large diffraction angle

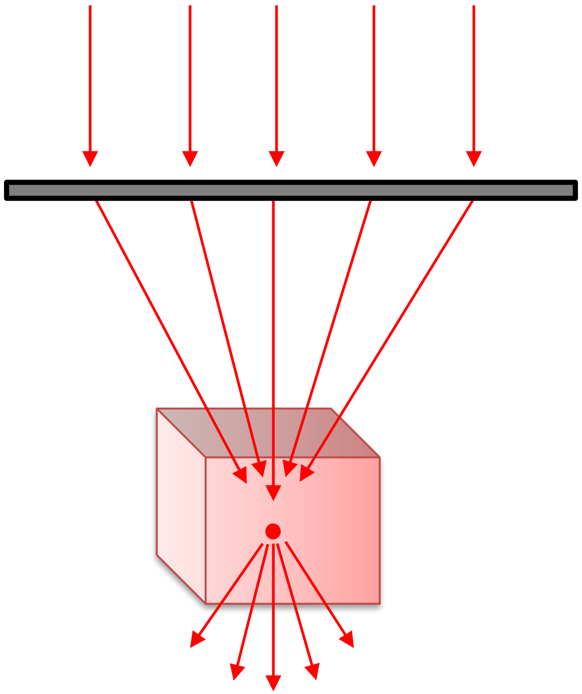


	Pixel size	Viewing angle
LCD monitor	200 μm	0.1°
LCoS Spatial light modulator	16 μm	2°
Ideal pixel size	1 μm	30°

http://www.schoolphysics.co.uk/age14-16/Wave%20properties/text/Diffraction_/index.html

Ultimate 3D display: Holographic display

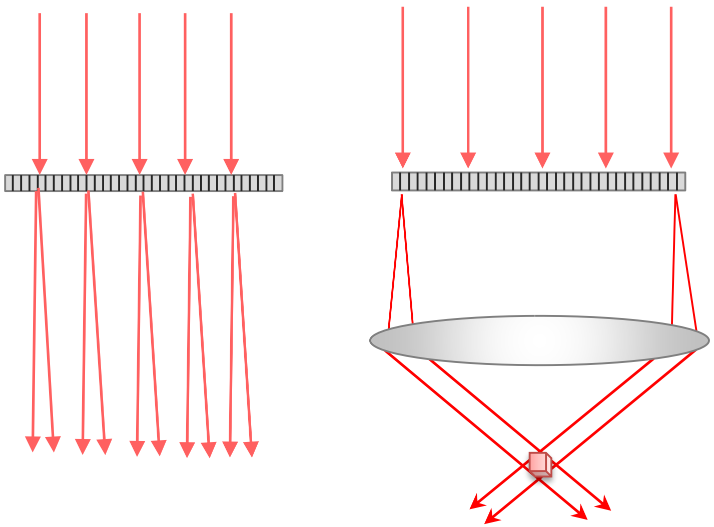
Ideal holographic monitor



Pixel size : 1 μm
Screen size : 30 cm x 30 cm
Resolution : 300000 x 300000

Viewing angle : 30 °
Image size : 30 cm x 30 cm

Current holographic monitor



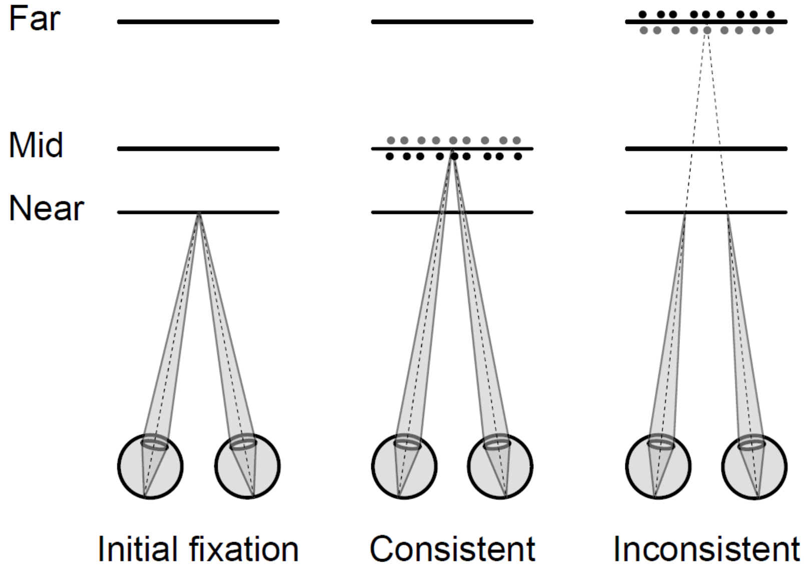
Pixel size : 16 μm
Screen size : 1 cm x 1 cm
Resolution : 1024 x 768

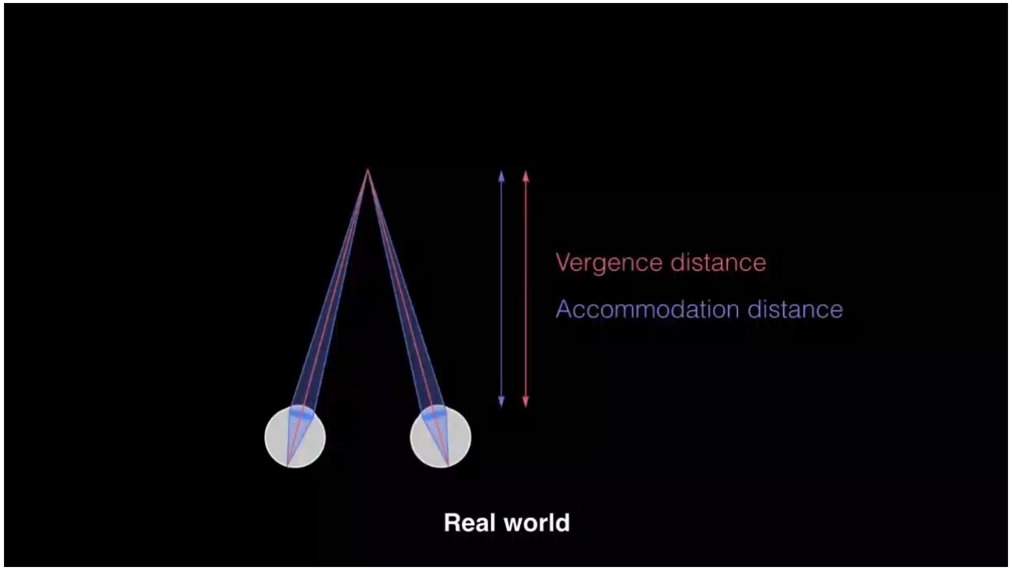
Viewing angle : 2 °
Image size : 1 cm x 1 cm

Displays Comparison

	Pictorial Cues	Disparity	Motion Parallax	Glasses-free	Accommodation
2D Display	✓	✗	✗	✓	✗
Stereoscopic Display	✓	✓	✗	✗	✗
Head-mounted Display	✓	✓	✓	✗	✗
Autostereoscopic Display	✓	✓	✓	✓	✗
Light field Display	✓	✓	✓	✓	✓
Holographic Display	✓	✓	✓	✓	✓

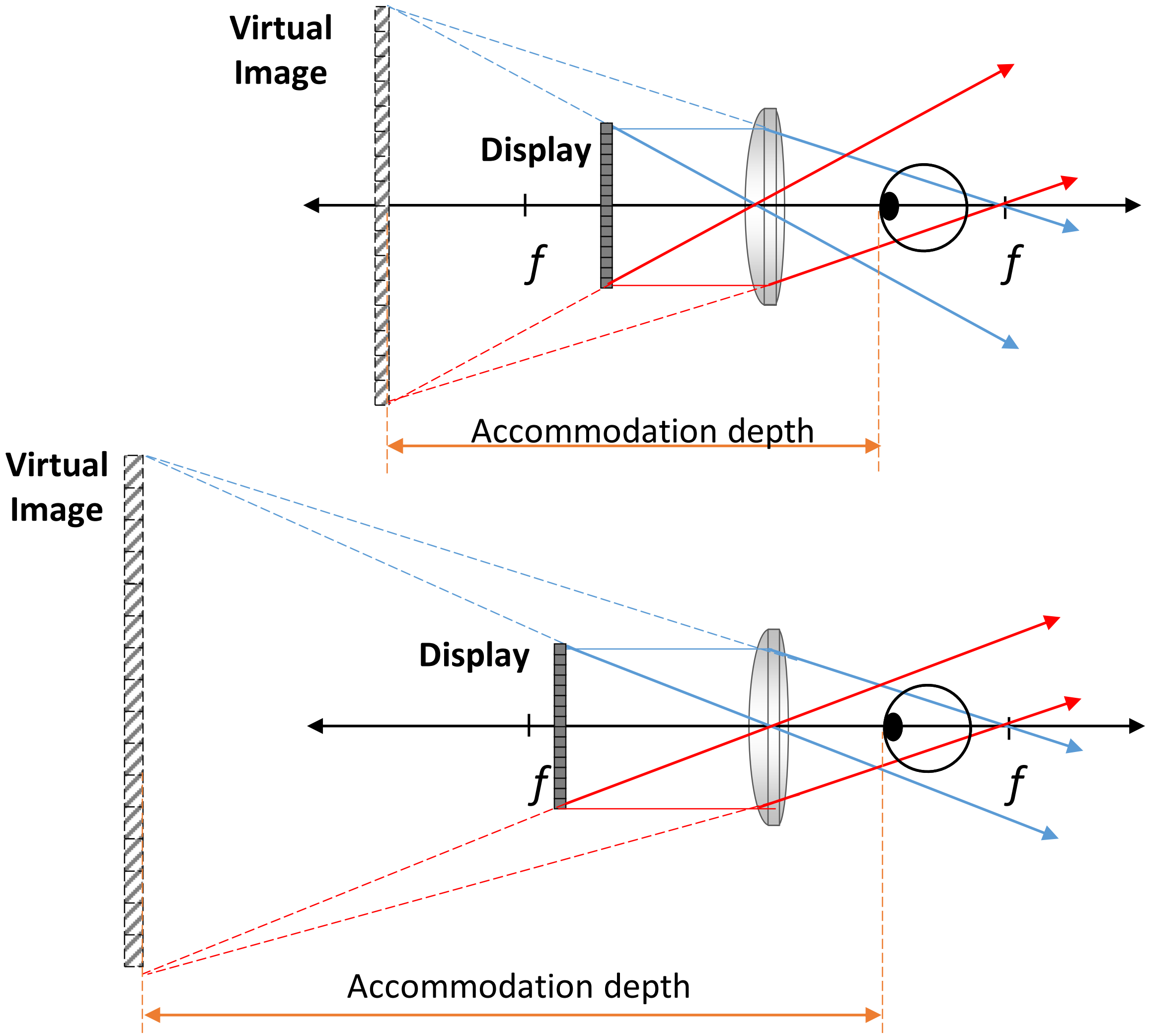
Accomodation-Vergence Conflict



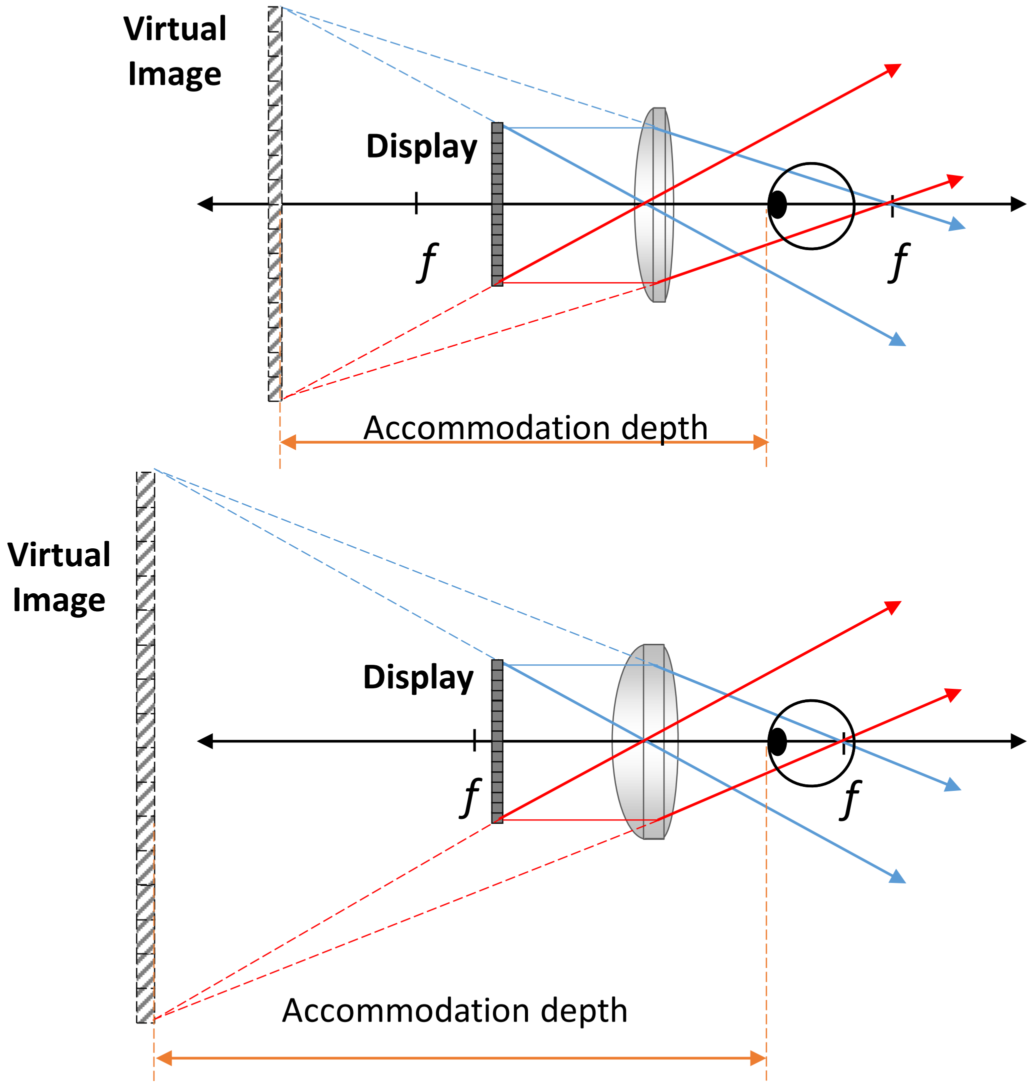


Visuals adapted from Akeley, Kurt, et al. "A stereo display prototype with multiple focal distances." ACM transactions on graphics (TOG). Vol. 23. No. 3. ACM, 2004. and Narain, Rahul, et al. "Optimal presentation of imagery with focus cues on multi-plane displays." ACM Transactions on Graphics (TOG) 34.4 (2015): 59.

How to change accommodation? : (1) the display position

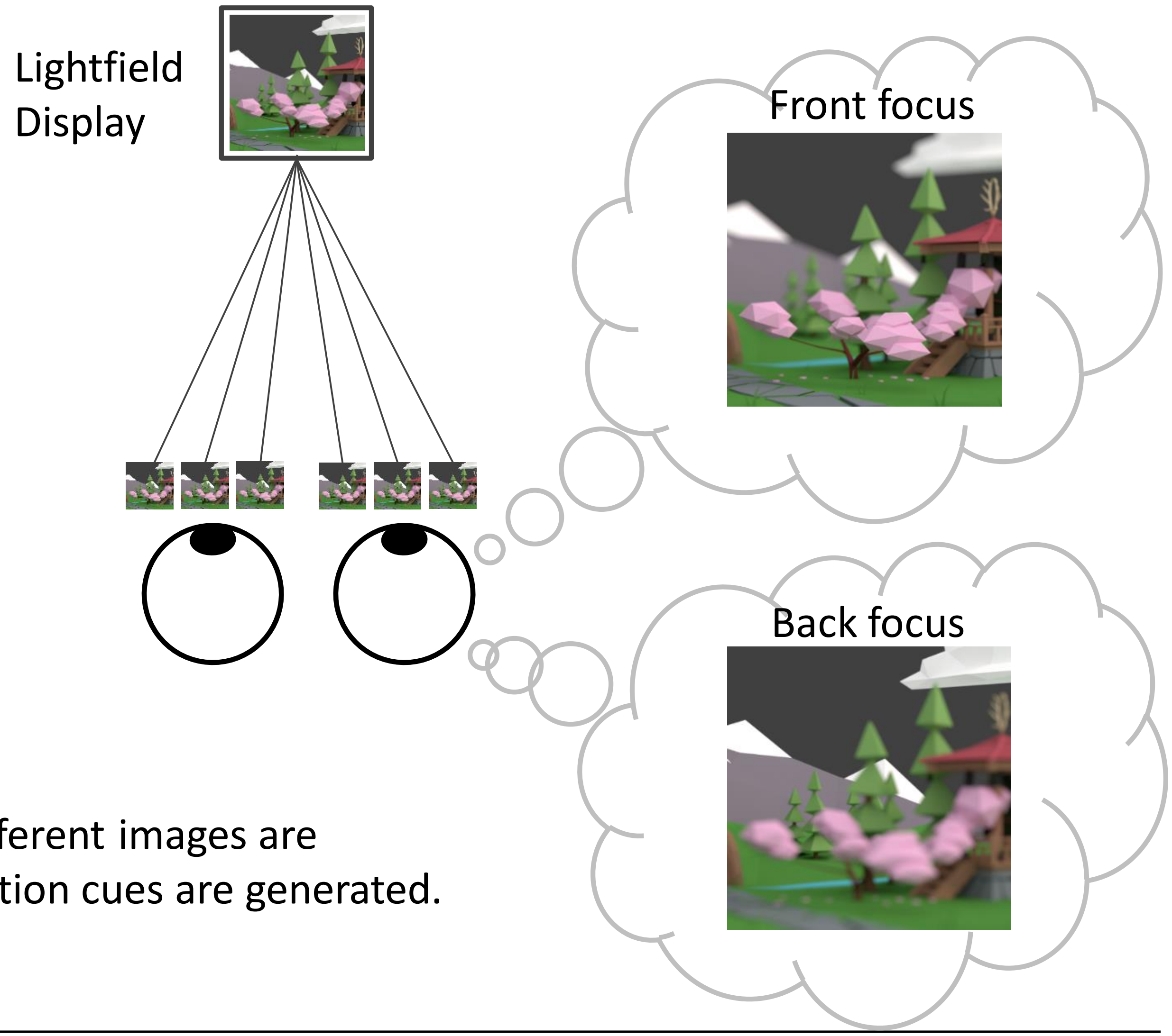


How to change accommodation? : (2) the lens focal length



Requirement for supporting accommodation

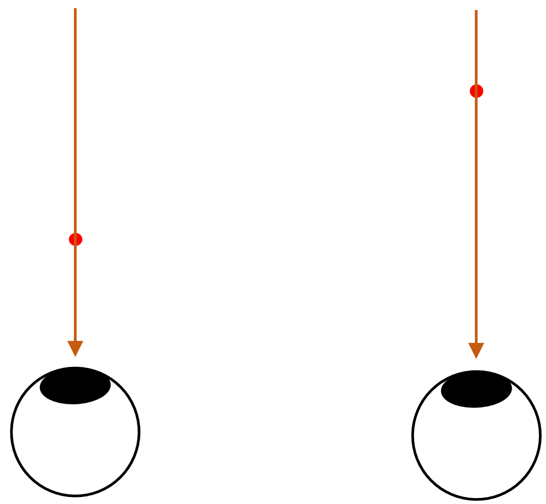
High angular resolution or dense light fields: Accommodation



Towards each eye, multiple different images are projected: proper accommodation cues are generated.

Requirement for supporting accommodation

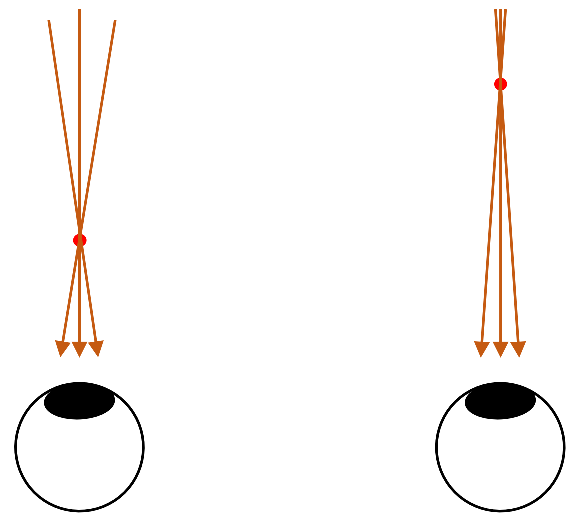
Single ray is not enough
(depth ambiguity)



Mathematically, minimum two rays
should be projected inside the pupil
In practice,

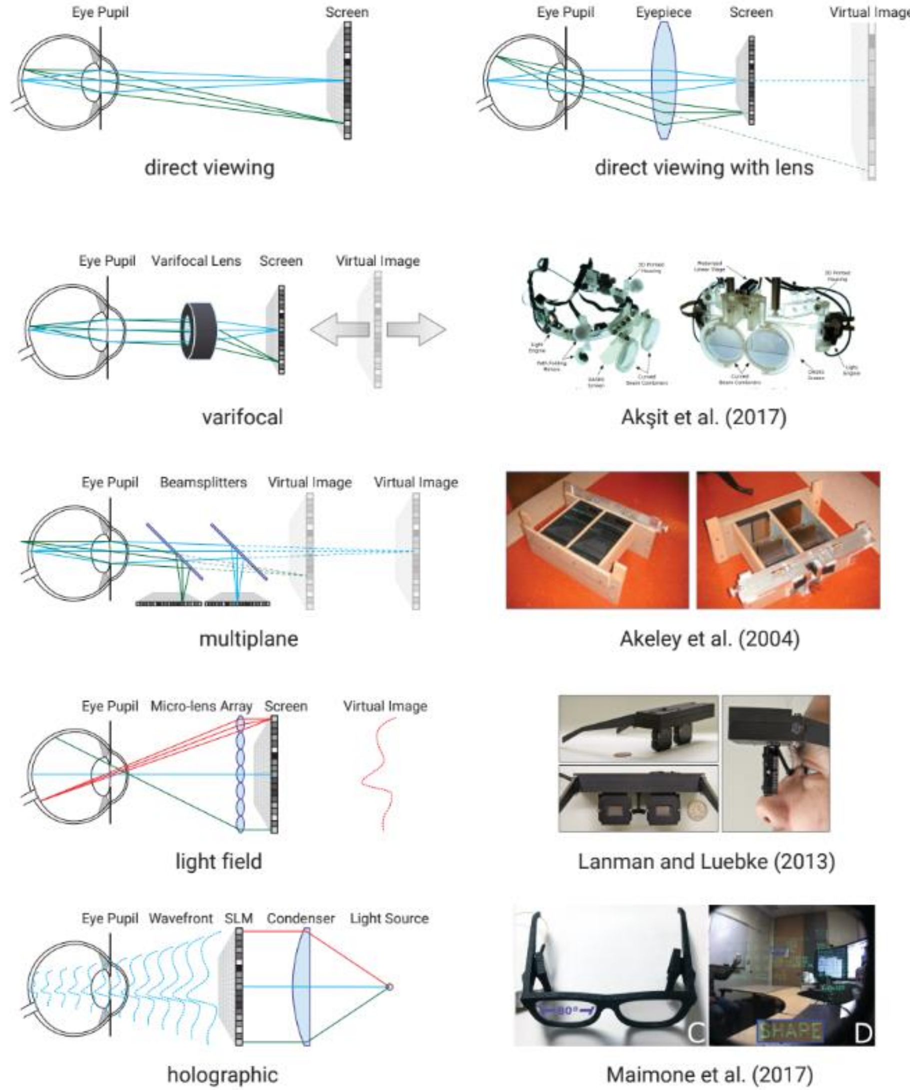
3 rays for 1-D

3 x 3 rays for 2-D



HMD with accommodation cues

- **Varifocal display**
- **Multi-focal displays**
- **Light field displays**
- **Holographic displays**



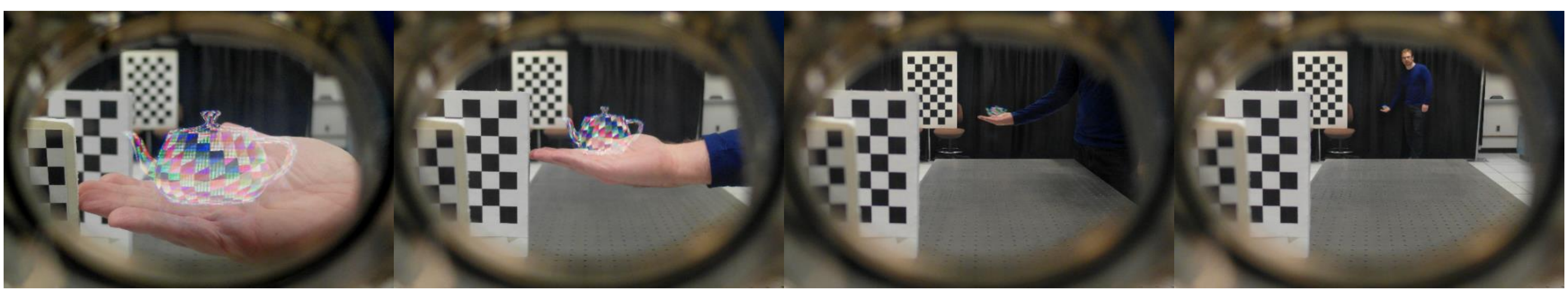
Varifocal display: Deformable Beamsplitter

See-through

Dynamic focal depth: objects at any depth

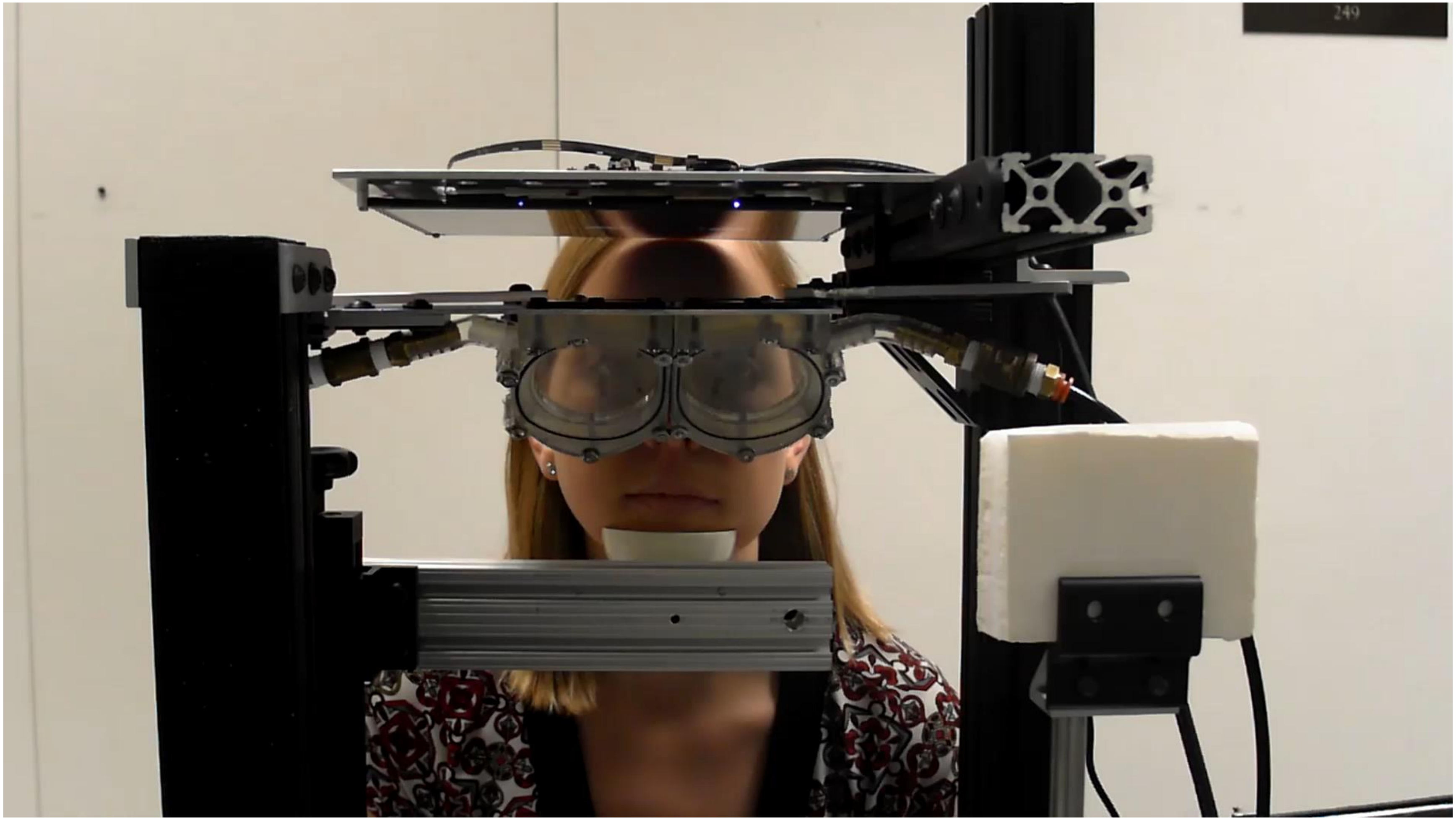
Wide field of view

Optics are simple



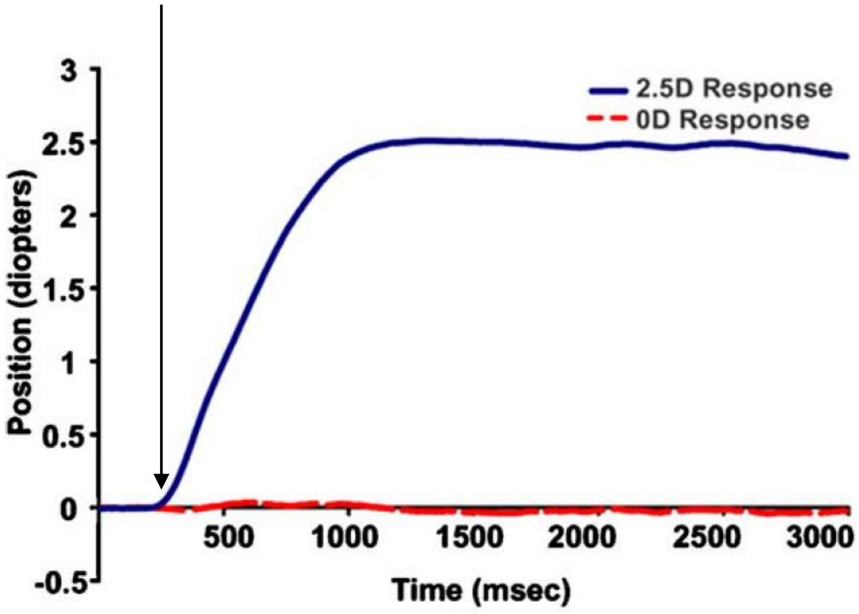
Membrane AR – Dunn et al.

Varifocal display: Deformable Beamsplitter



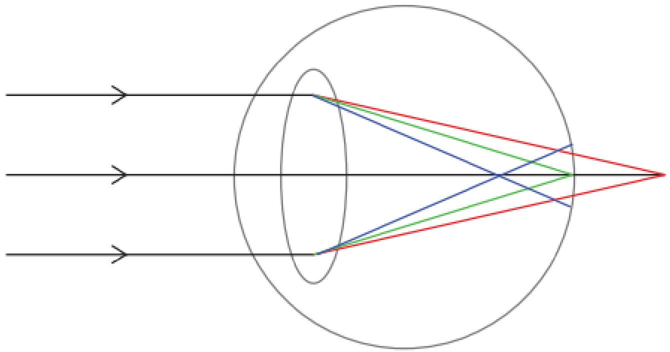
Accommodation Response

- Step change of fixated object depth
  - Smooth and steady accommodation increase
    - up to 1 second to achieve the full accommodation state
    - ~300 ms latency



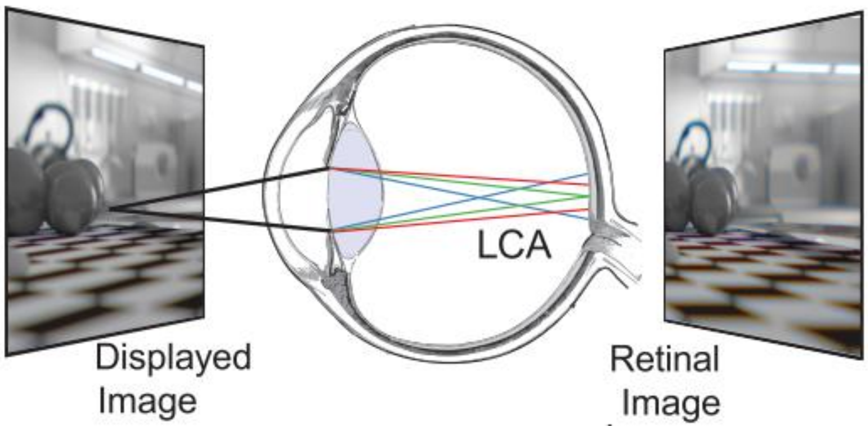
Bharadwaj and Schor, Vision Research 2004

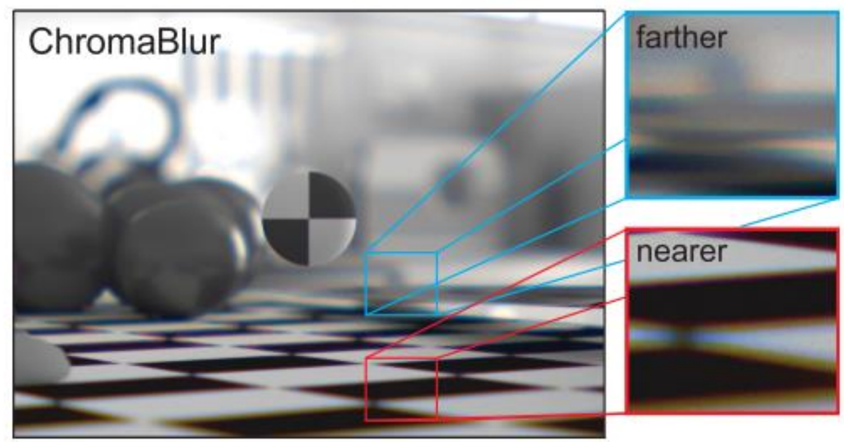
Rendering Chromatic Eye Aberration



$$D(\lambda) = 1.731 - \frac{633.46}{\lambda - 214.10}$$

Short wavelengths (blue) are refracted more than long (red). Medium wavelengths are generally in best focus for broadband lights.



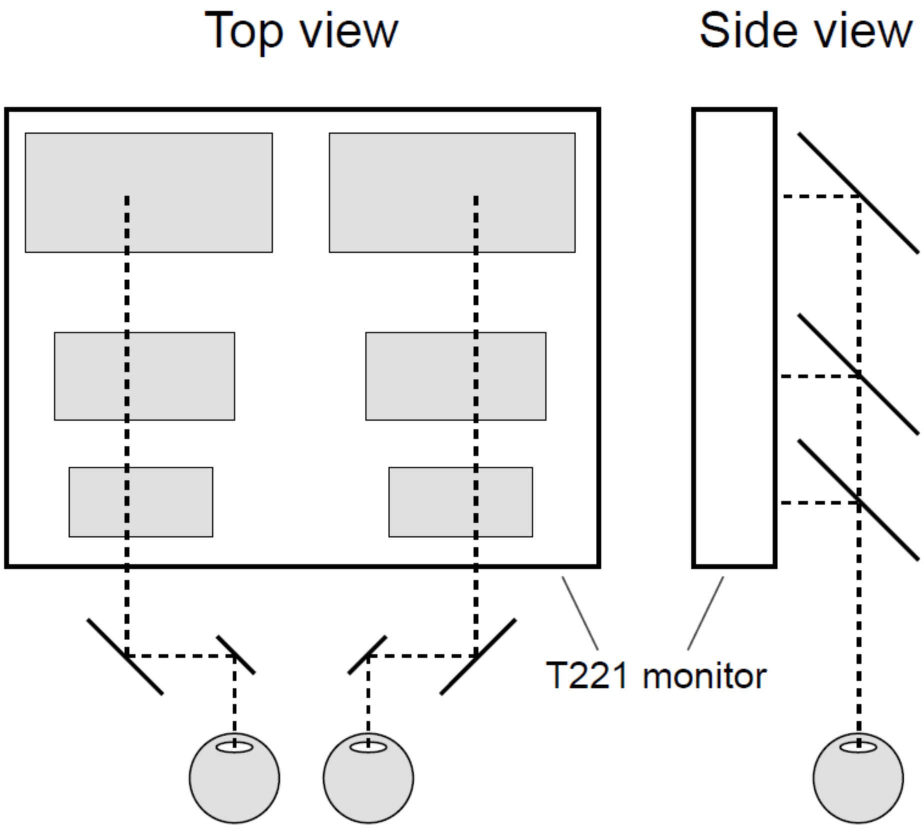


Rendering chromatic blur can provide accommodation effect (but not fully) and improve the realism

CHOLEWIAK ET AL, 2017. ChromaBlur: Rendering Chromatic Eye Aberration Improves Accommodation and Realism in HMDs. *Siggraph*

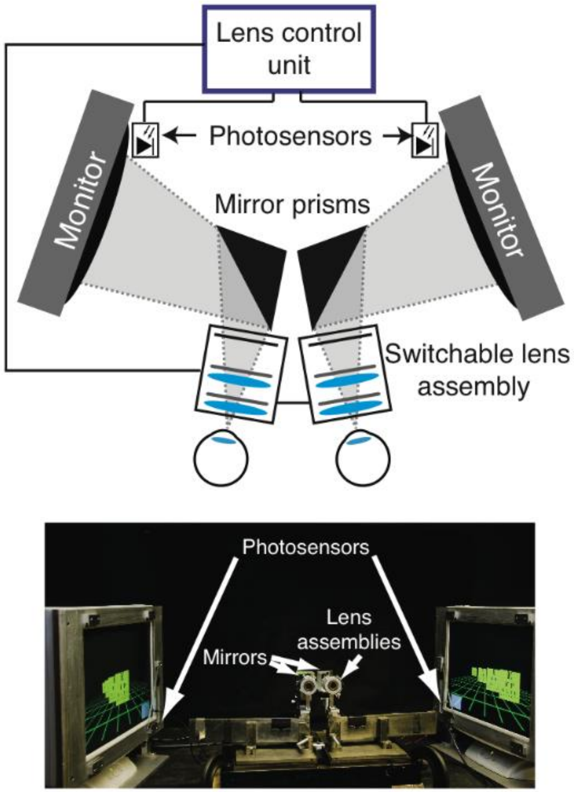
Multi-focal Plane Displays

- **A display prototype with multiple focal distances using beam-splitters**

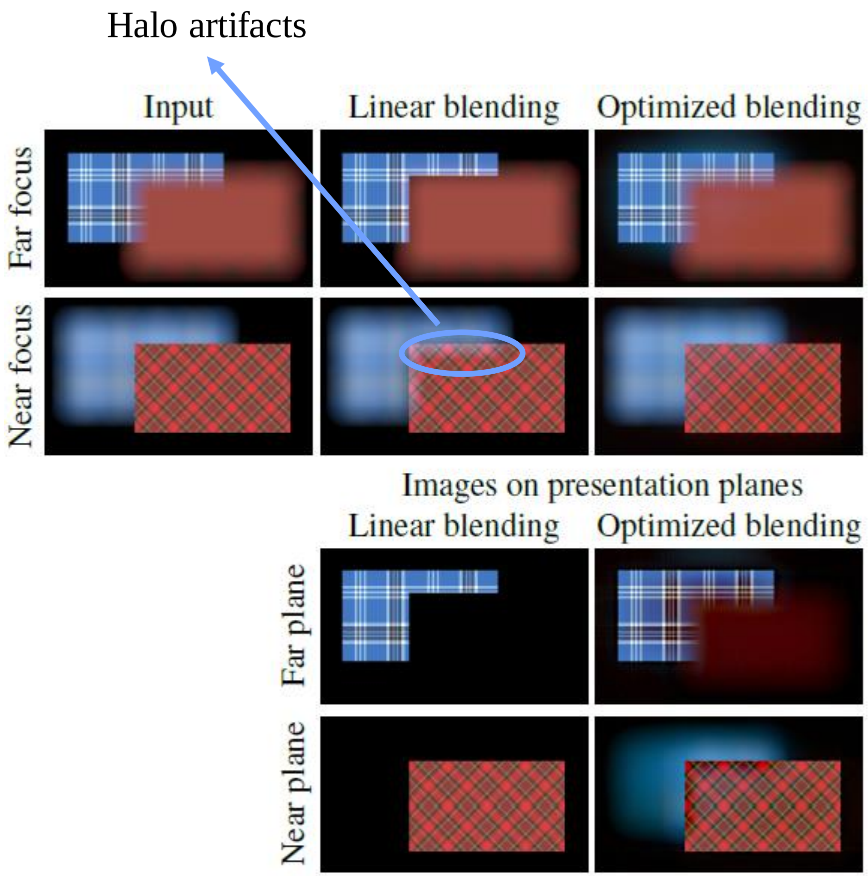


Images adapted from Akeley, Kurt, et al. "A stereo display prototype with multiple focal distances." ACM transactions on graphics (TOG). Vol. 23. No. 3. ACM, 2004.

Multi-focal Plane Displays



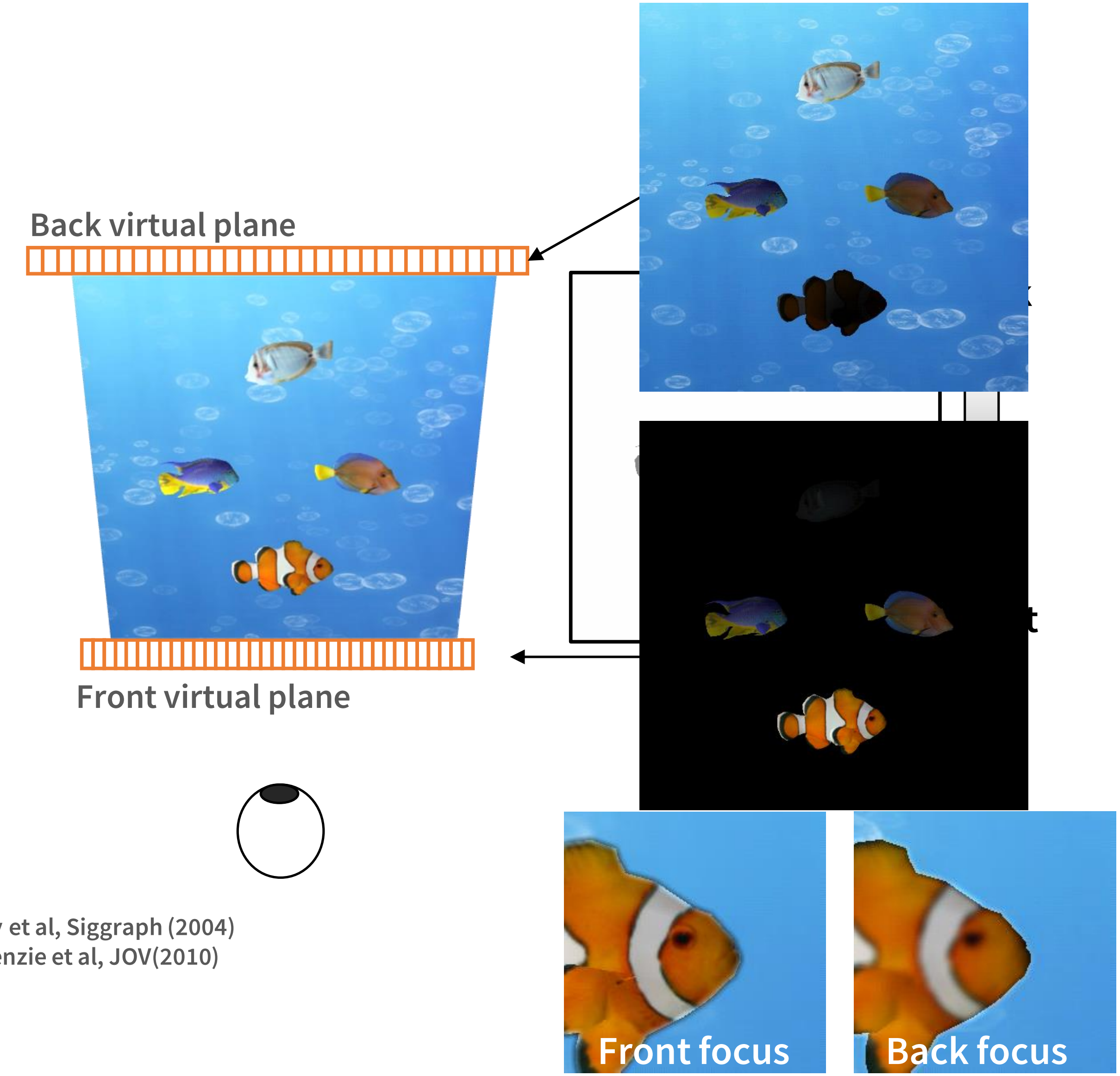
Prototype introduced by Love et al [2009]



Narain et al. [2015] optimize the focus cues for improved realism.

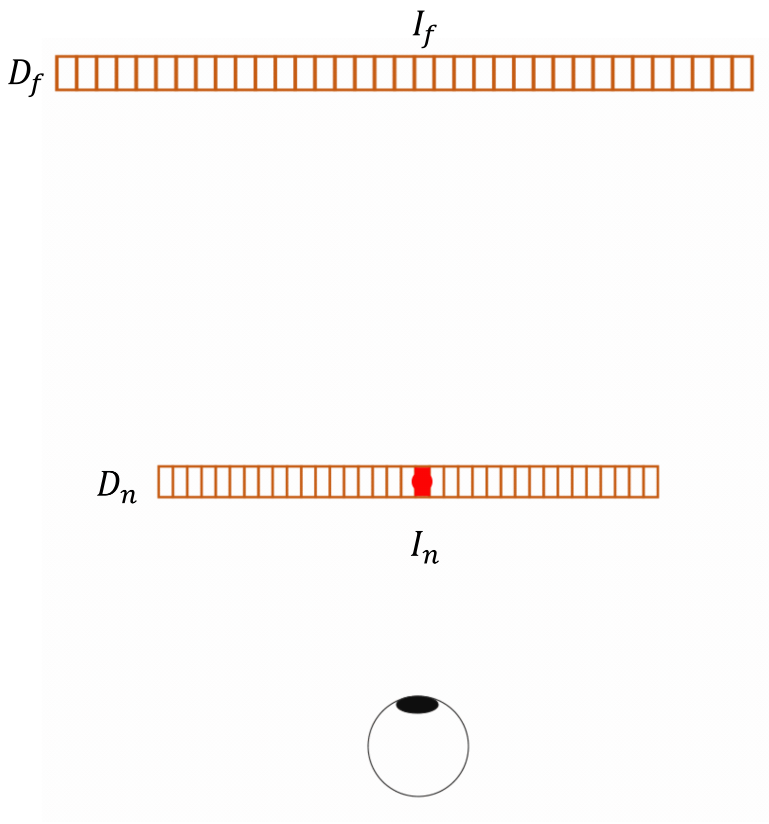
Images adapted from Narain, Rahul, et al. "Optimal presentation of imagery with focus cues on multi-plane displays." ACM Transactions on Graphics (TOG) 34.4 (2015): 59.

Rendering for multi plane displays: (1) linear Blending Rule



Akeley et al, Siggraph (2004)
MacKenzie et al, JOV(2010)

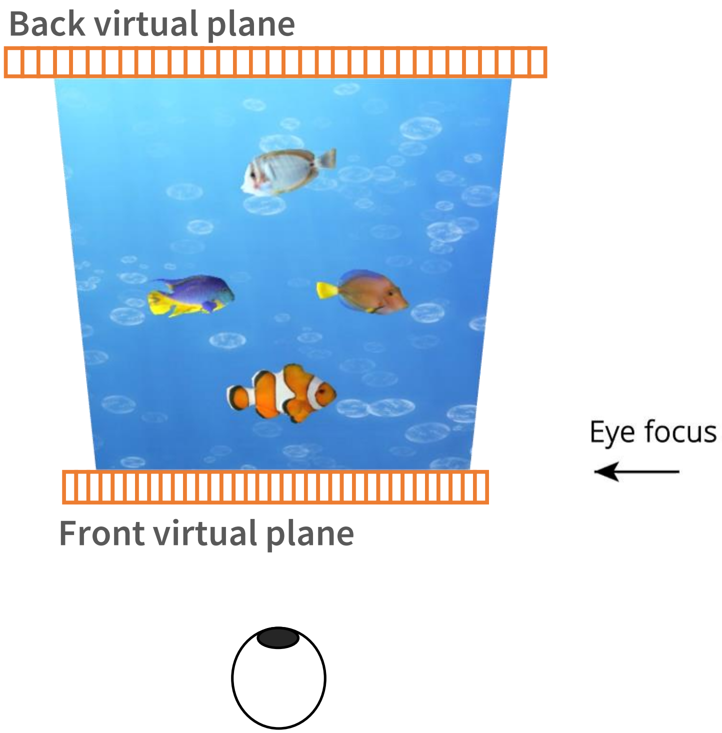
Rendering for multi plane displays: (1) linear Blending Rule



$$I_n = \left[1 - \frac{(D_n - D_s)}{(D_n - D_f)}\right] I_s \qquad I_f = \left[\frac{(D_n - D_s)}{(D_n - D_f)}\right] I_s .$$

Akeley et al, Siggraph (2004)
MacKenzie et al, JOV(2010)

Rendering for multi plane displays: (2) Retinal Optimization

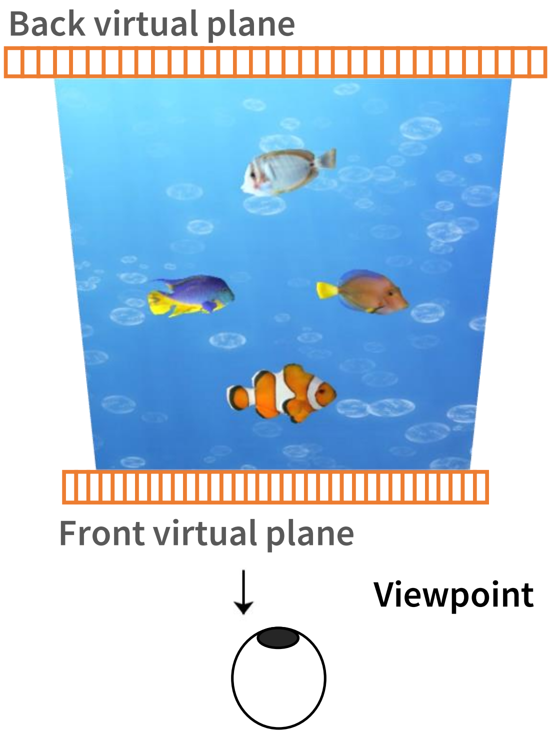


Narain et al (Siggraph 2015)
Mercier et al (Siggraph Asia 2017

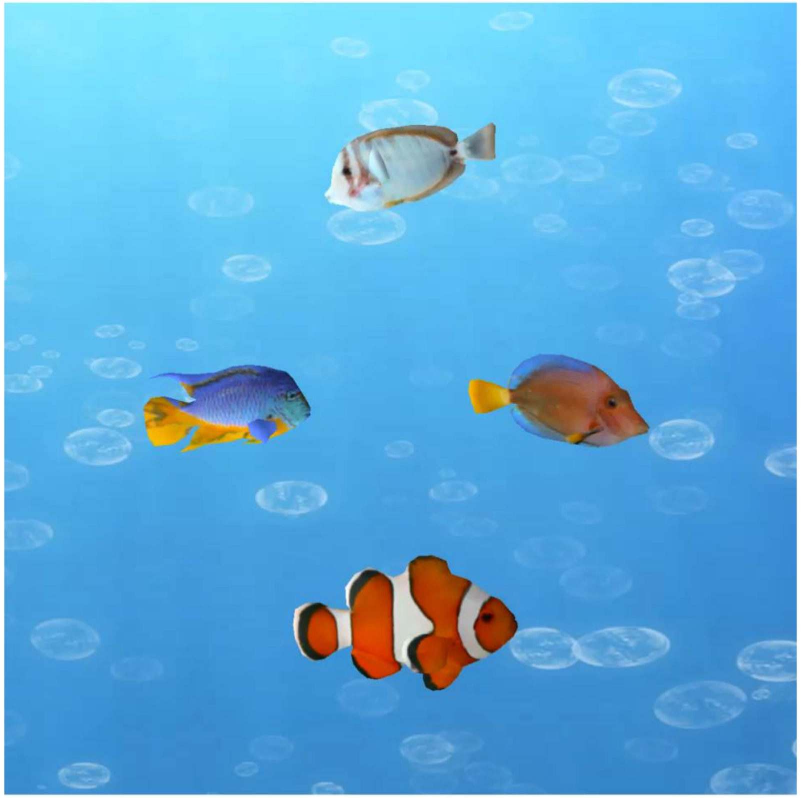
Optimization objective

A focal stack

Rendering for multi plane displays: (3) Light field synthesis



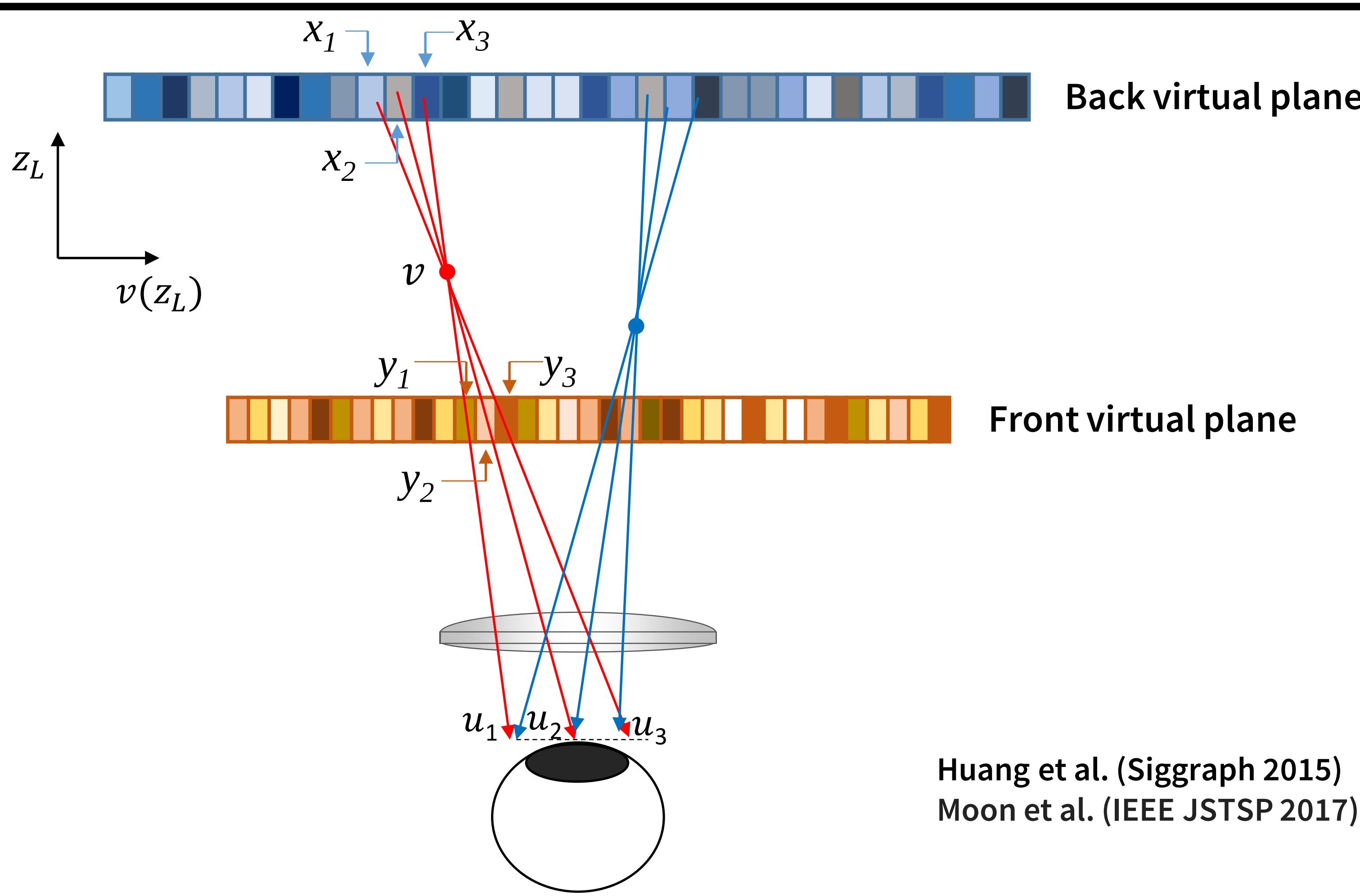
Optimization objective



Light field

Huang et al. (Siggraph2015)
Moon et al. (IEEE JSTSP 2017)

Rendering for multi plane displays
(3) Light field synthesis



Huang et al. (Siggraph 2015)
Moon et al. (IEEE JSTSP 2017)

Target Light-fields: $L(v, u_1) = L(v, u_2) = L(v, u_3) = R$

Optimization equation : $L(v, u_1) = x_3 + y_1$

$$L(v, u_2) = x_2 + y_2$$

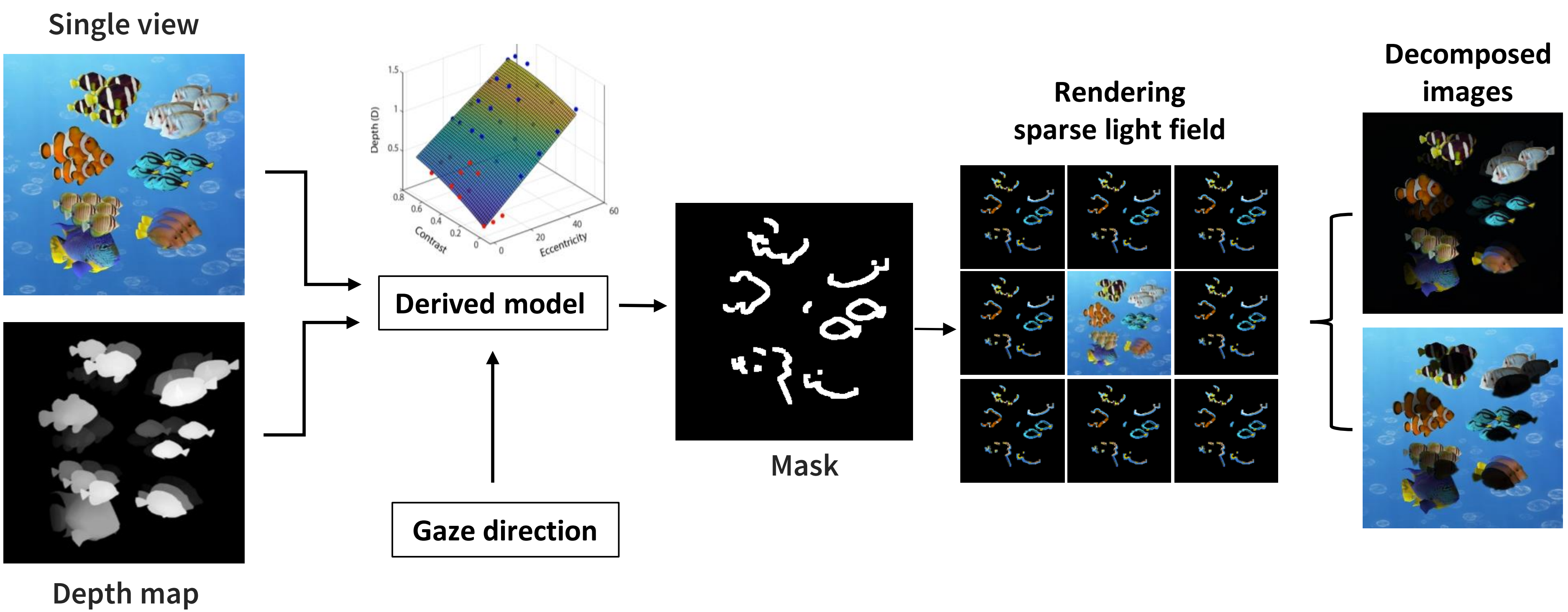
$$L(v, u_3) = x_1 + y_3$$

Comparison

	Initial input	Optimization Algorithm	Occlusion & Non-Lambertian surfaces
Linear Blending [1]	Single image + depth map	Fast	Incorrect
Retinal Optimization [2,3]	Focal stack	Slow	Correct
Light-field synthesis [4]	Light field	Slow	Correct
Ours	Sparse light field	Fast	Correct

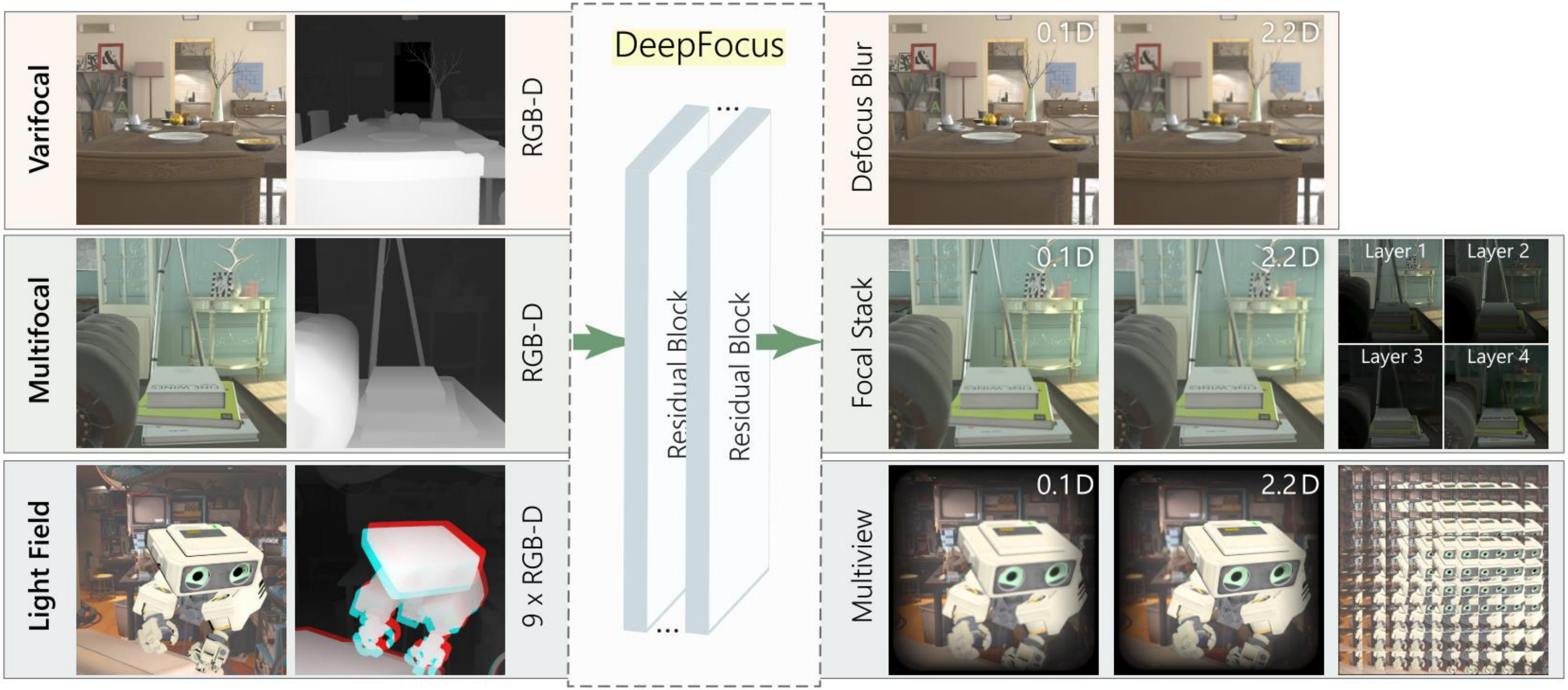
[1] Akeley et al, Siggraph (2014)
[2] Narain et al (Siggraph 2015)
[3] Mercier et al, Siggraph Asia (2017)
[4] Moon et al, IEEE JSTSP (2017)

Hybrid optimization



Yu et al, "A Perception-driven Hybrid Decomposition for Multi-layer Accommodative Displays" IEEE Transactions on Visualization and Computer Graphics (2019)

Deep learning solution for various displays



XIAO ET AL, 2018. DeepFocus : Learned Image Synthesis for Accommodation-Supporting Displays. *Siggraph Asia*

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