Modern Display Technology

- Rendering Challenges -

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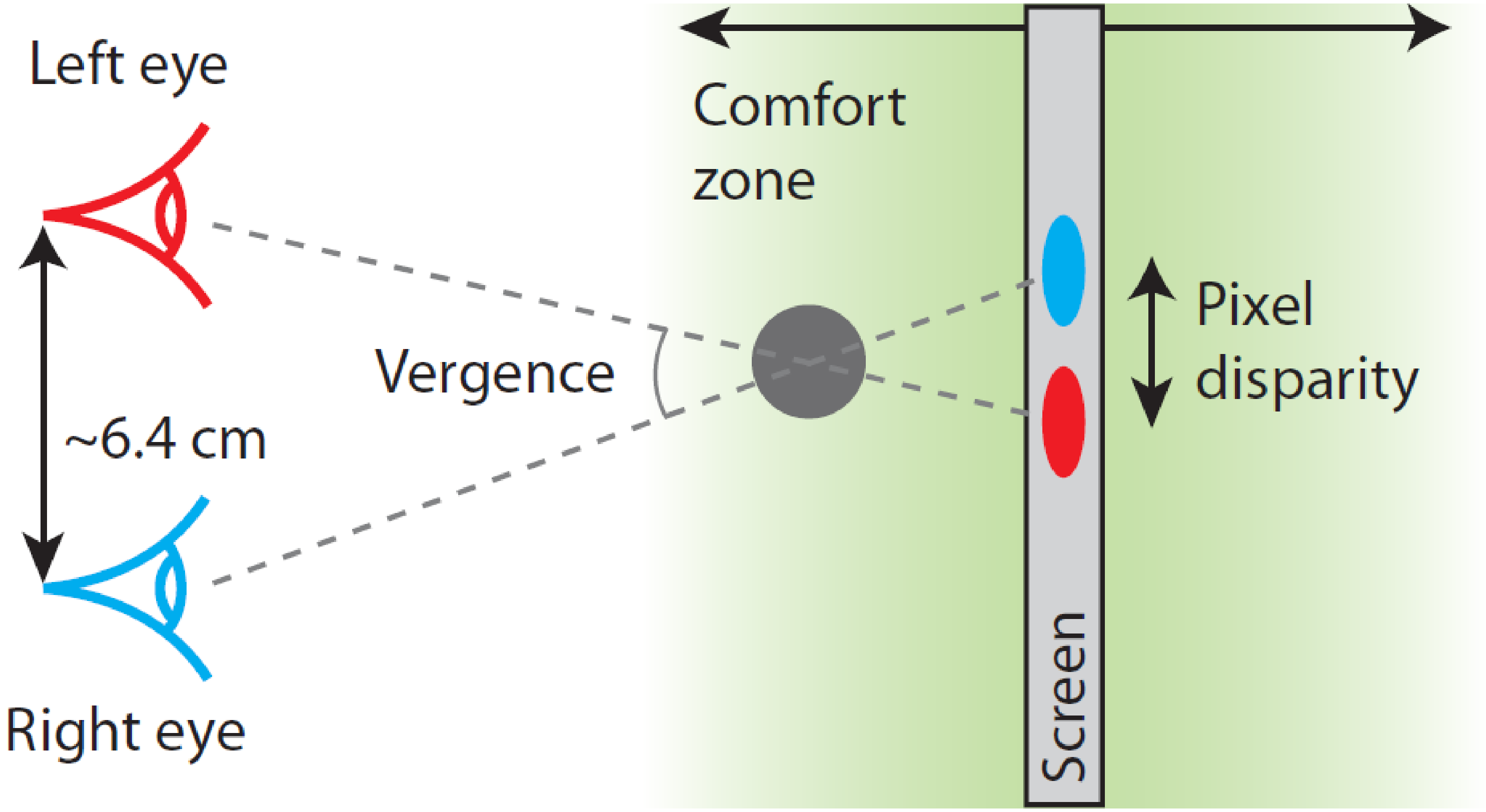
Outline

- Binocular 3D displays
  - Color Anaglyph
  - Polarization
  - Active Shutter Glasses
  - Head-Mounted Displays
- Autostereoscopic (Glass-free 3D) Displays
  - Parallax Barriers
  - Integral Imaging
  - Multi-layer displays
  - Holographic displays
- Head-Mounted Displays with accommodation cues
- Multi-projector displays
- HDR displays

Binocular Stereovision

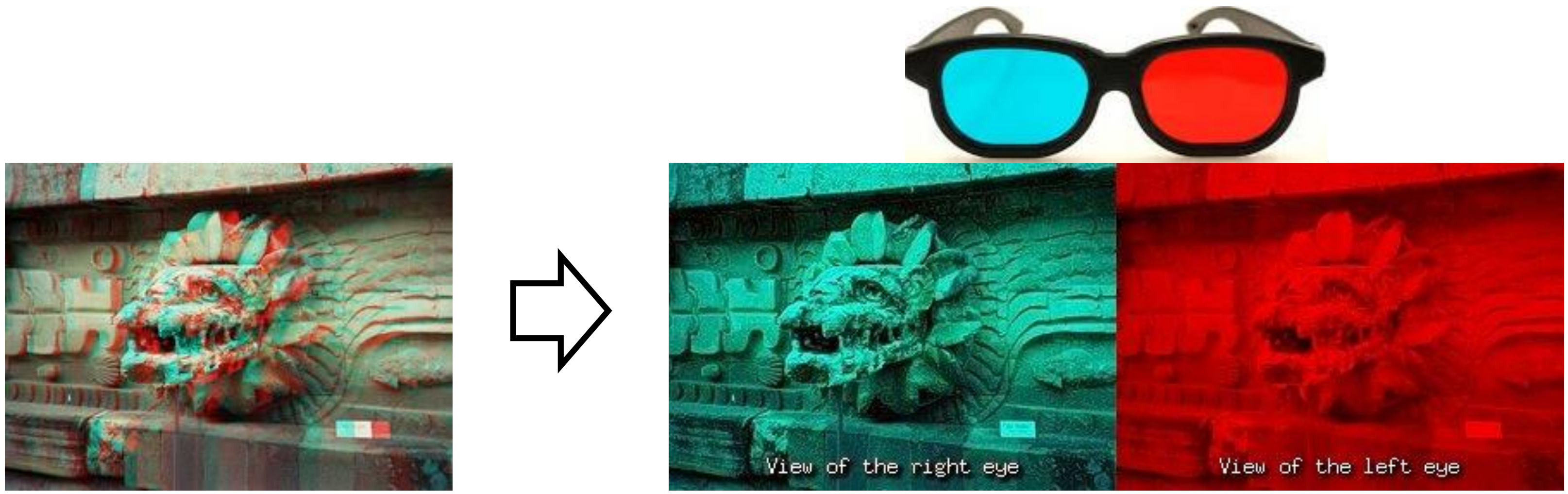


Binocular 3D Displays

- **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

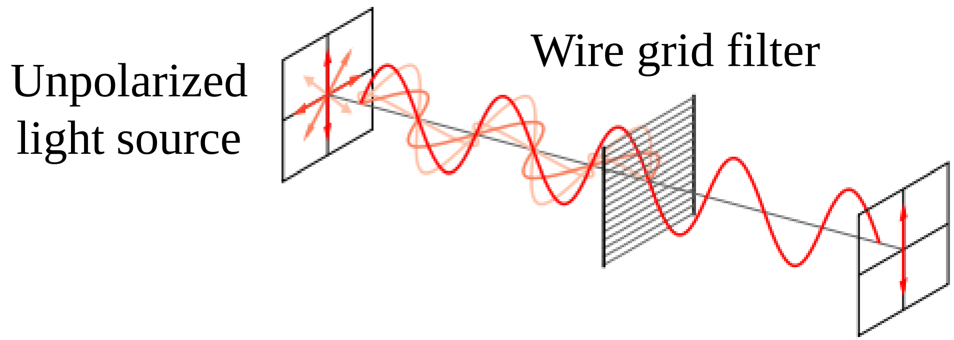
- **Left and right images are filtered using different colors (usually complementary):**
  - Red – Green, Red – Cyan, Green – Magenta
  - Amber – Blue (ColorCode 3D, patented [Sorensen et al. 2004])
- **Limited color perception (since each eye sees only a subset of whole colorspace)**

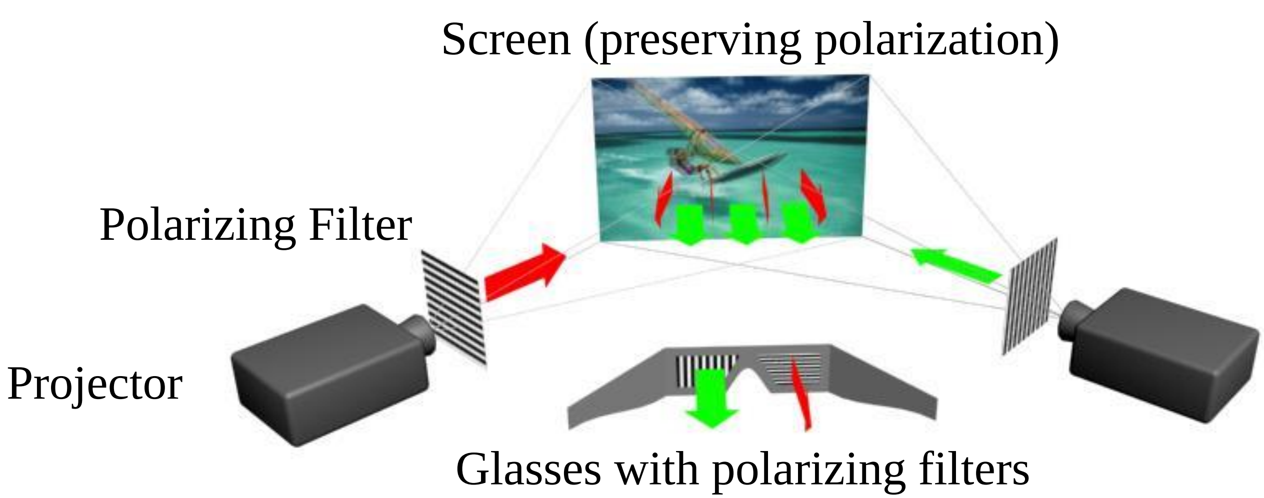


Images adapted from http://axon.physik.uni-bremen.de/research/stereo/color_anaglyph/

Polarization

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

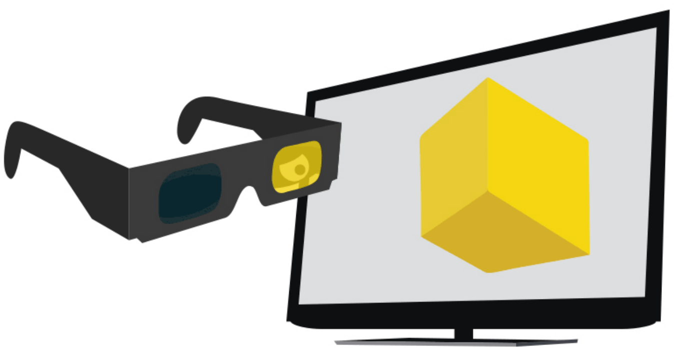


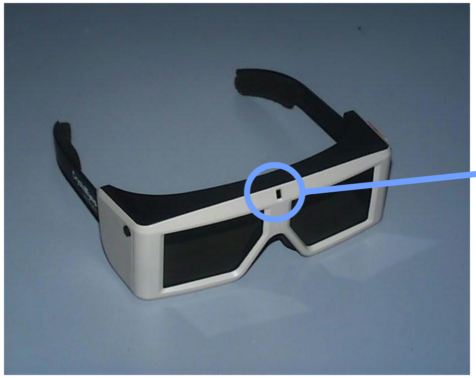


Images adapted from https://cpinettes.u-cergy.fr/S6-Electromag_files/fig1.pdf

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

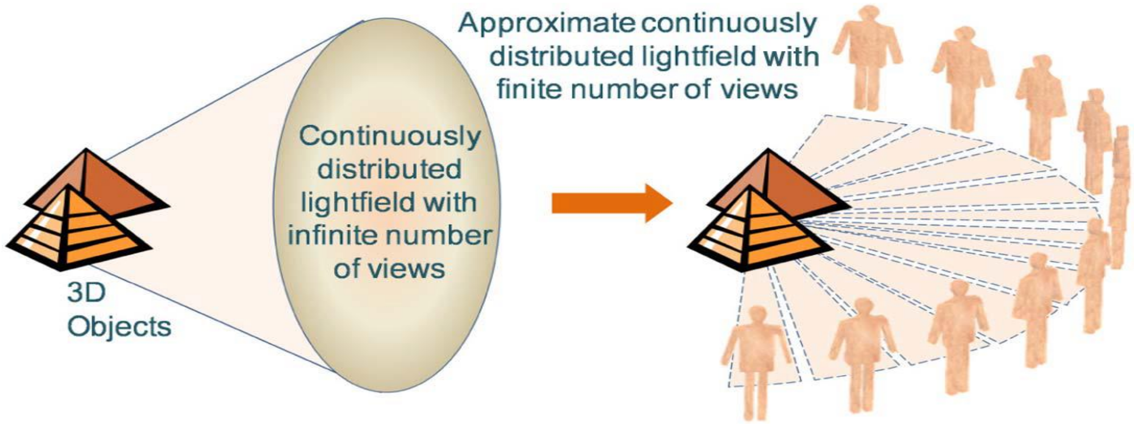
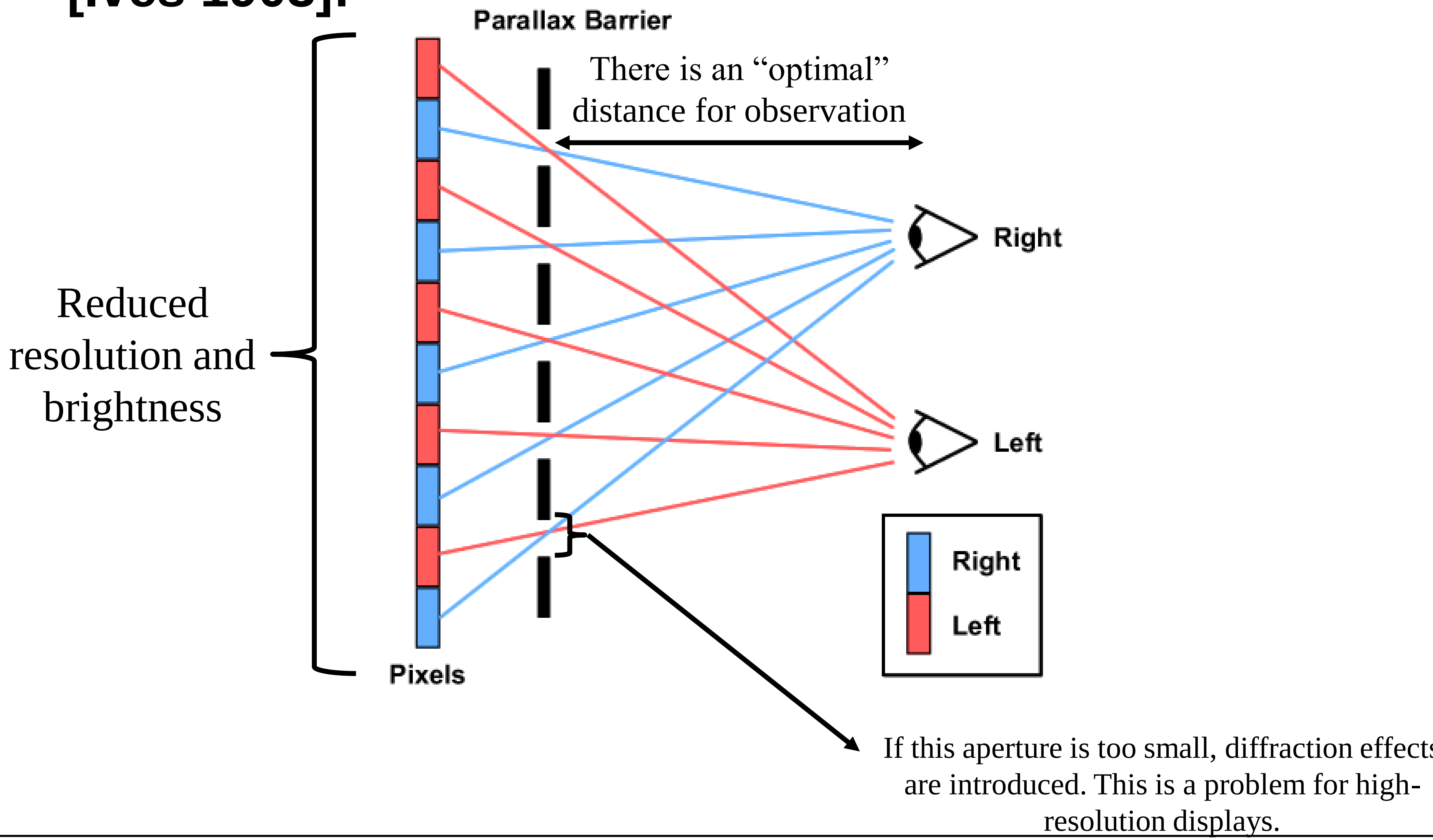


Image adapted from Geng, Jason. "Three-dimensional display technologies." Advances in optics and photonics 5.4 (2013): 456-535.

Parallax Barriers

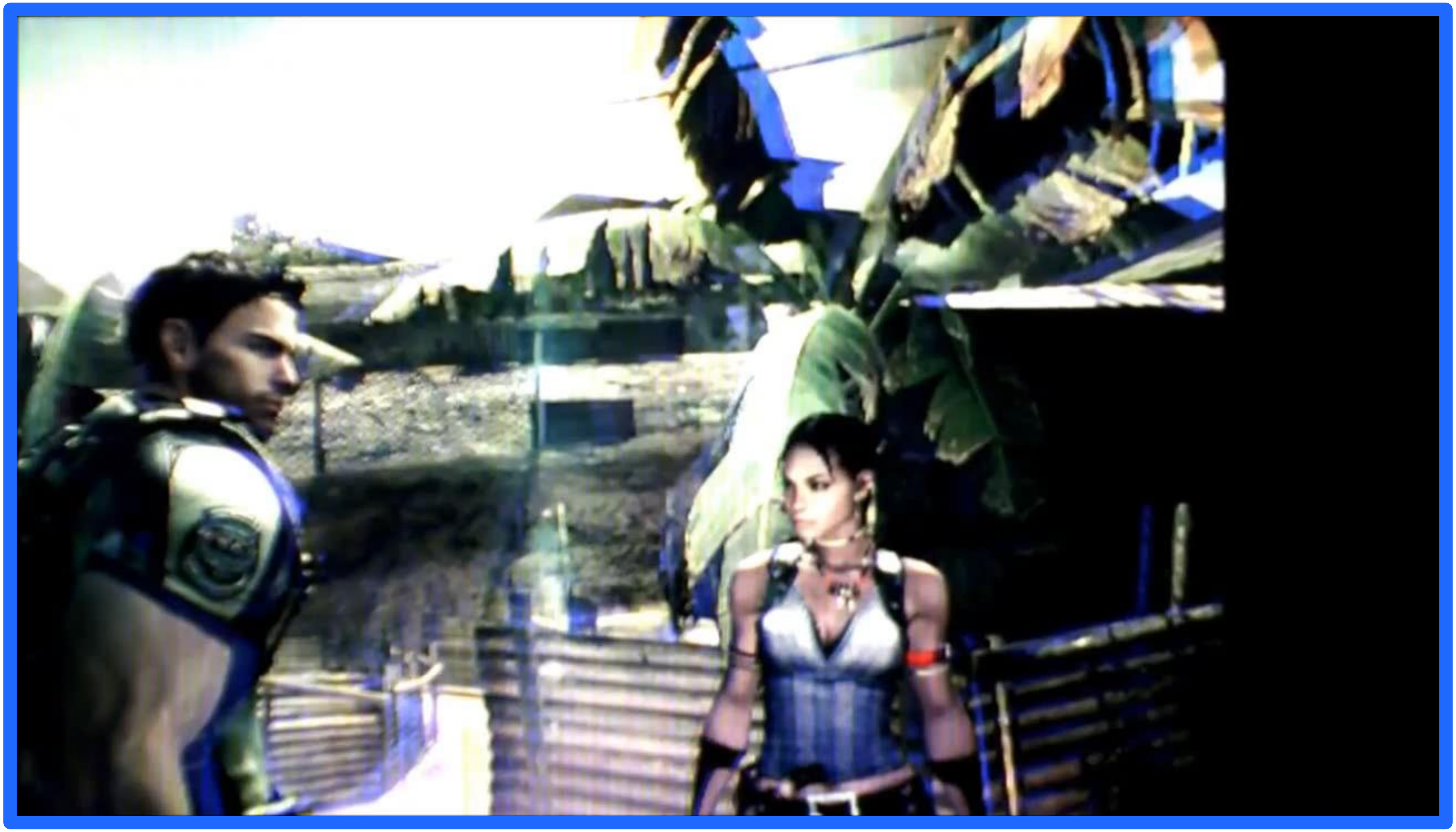
- **Occlusion-based working principle and key features [Ives 1903]:**



Parallax Barriers

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

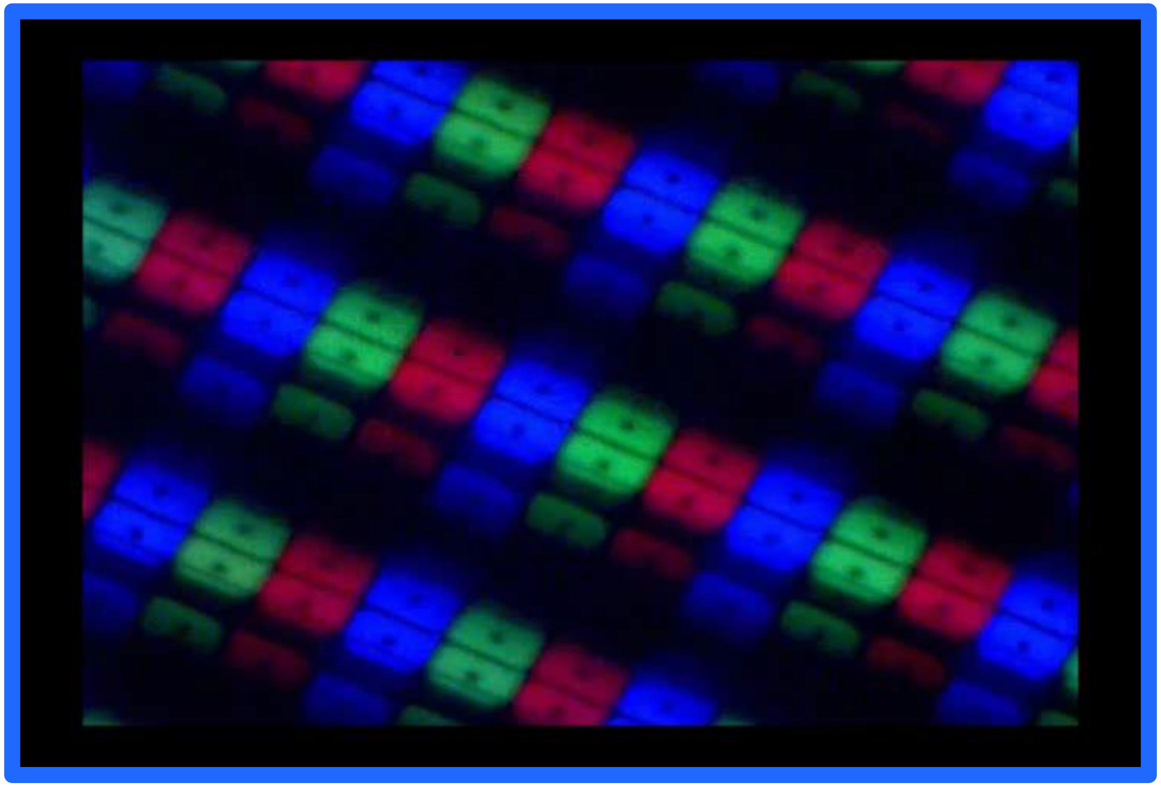
Parallax Barriers



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

Parallax Barriers

- **It is possible to switch between 2D and 3D modes**
- **Parallax barrier of Nintendo 3DS turning on/off under microscope:**

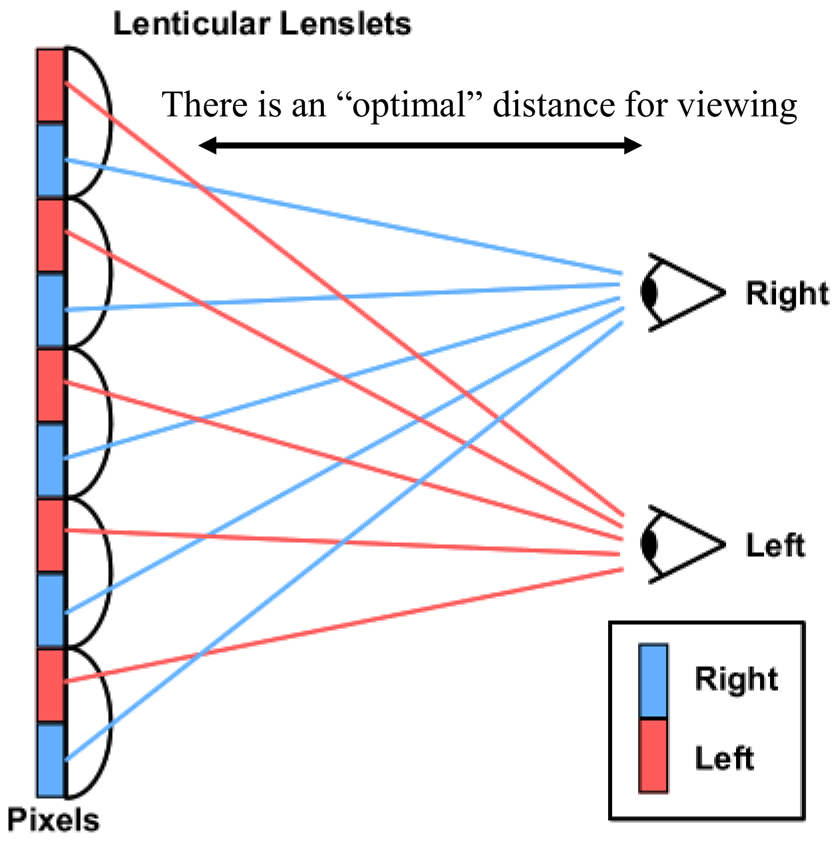


Video adapted from: https://www.youtube.com/watch?v=D-LzRT7Bvc0

Integral Imaging

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

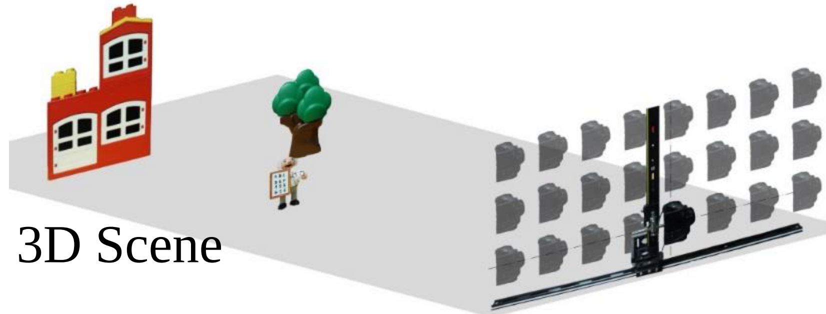
Reduction in resolution and brightness is still a problem.



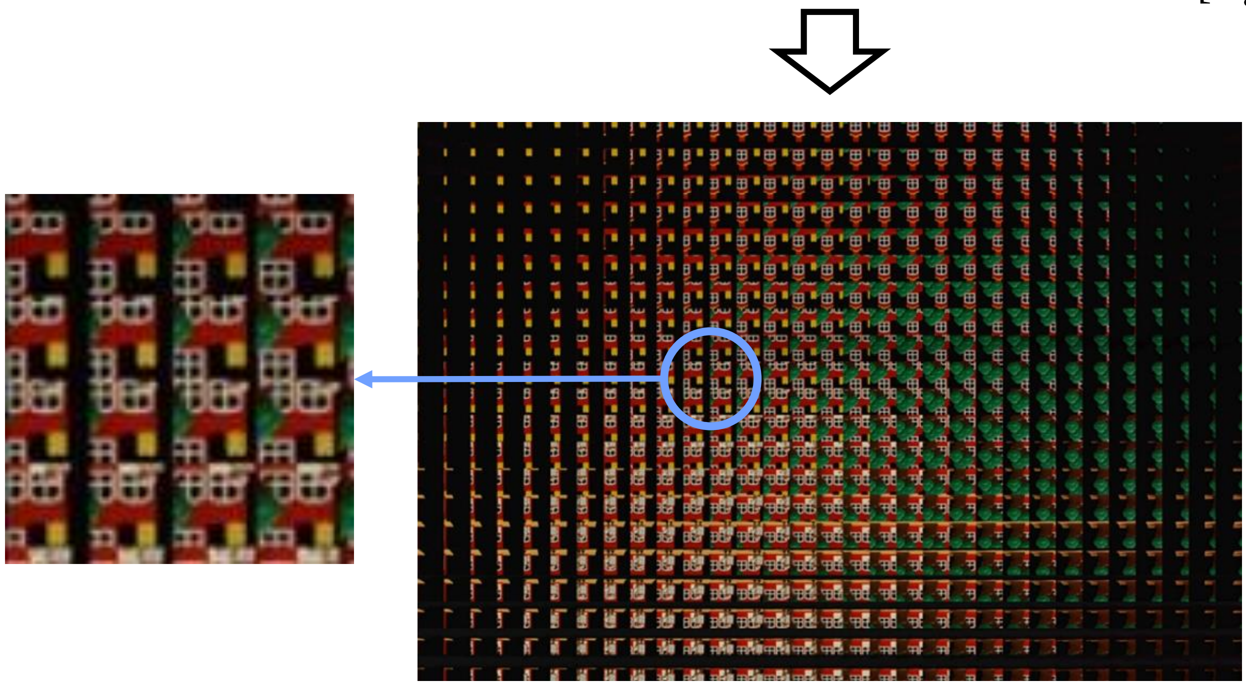
It is possible to reproduce parallax, perspective shift and accommodation depth cues.

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

Integral Imaging



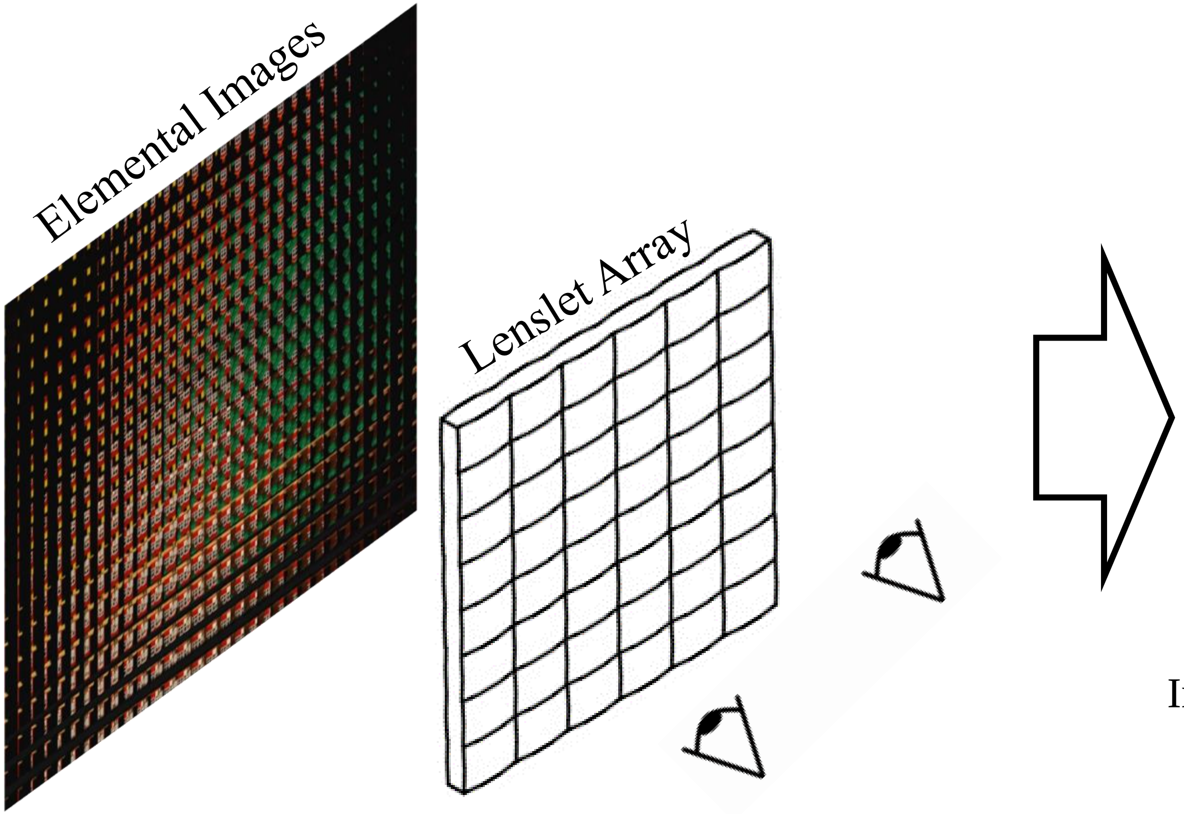
Array of lenses (multiple cameras each with a single lens [Wilburn 2005] or a single camera with multiple lenses in front of the sensor [Ng 2005])

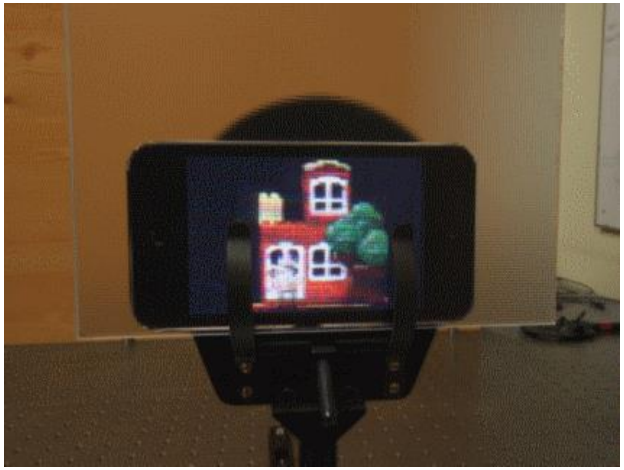


Elemental Images

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

Integral Imaging





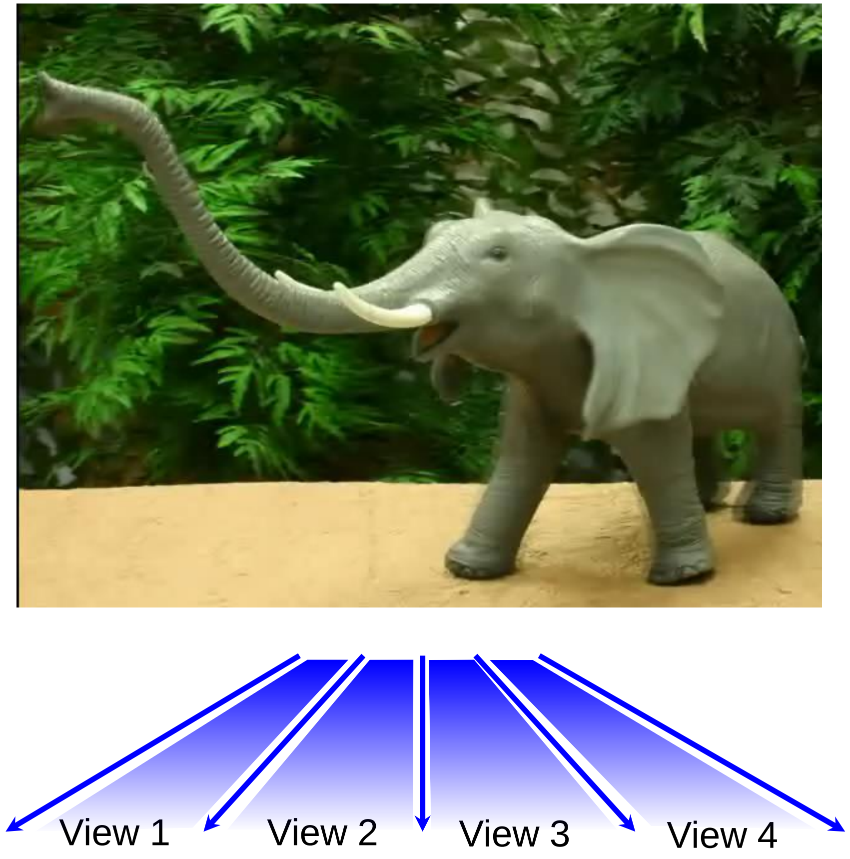
Integral Image as seen by the observer

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



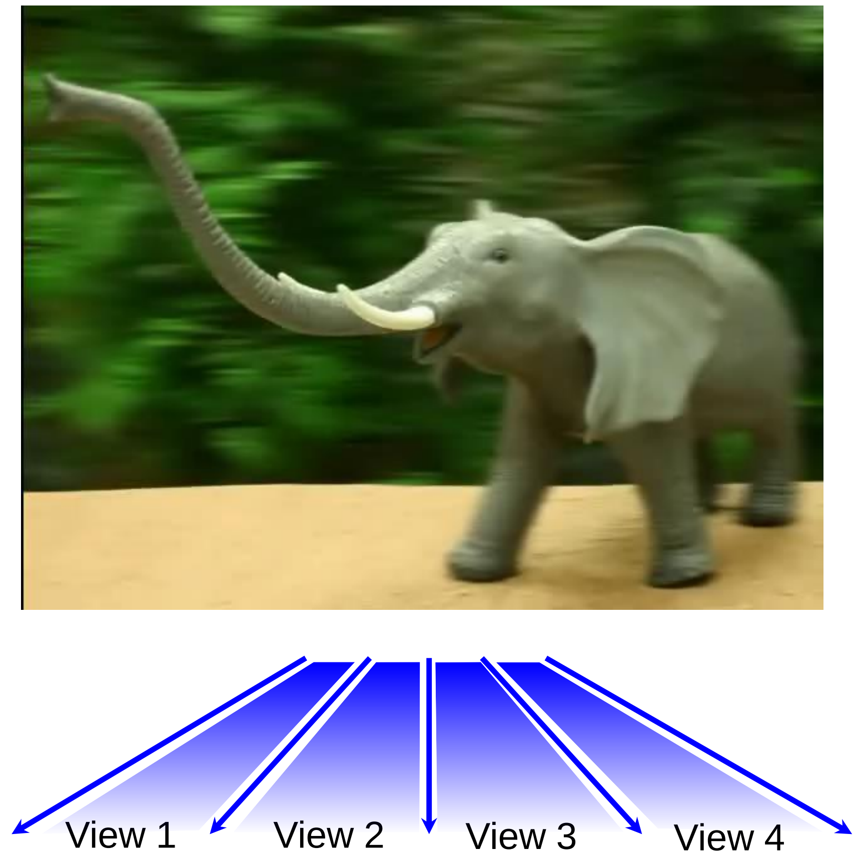
„Antialiasing for automultiscopic 3D displays" [Zwicker et al. 2006]

Multi-view Autostereoscopic Display

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

Weaker depth percept

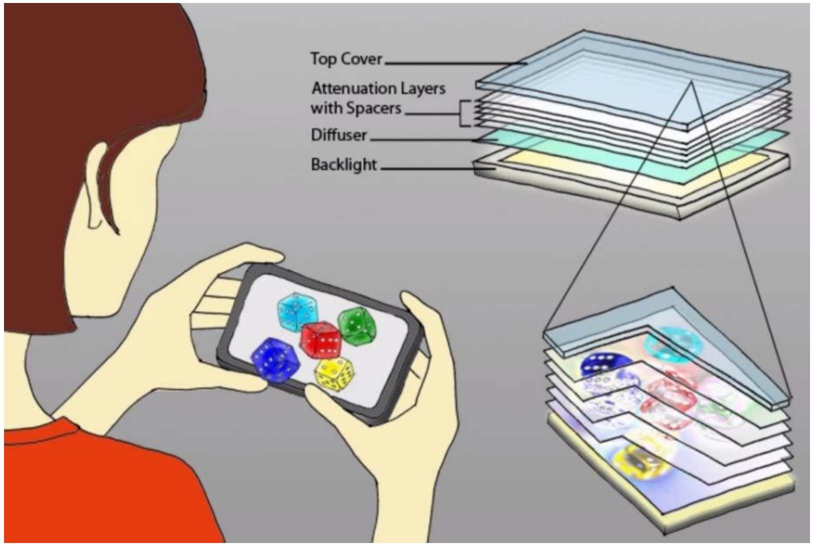
Multi-view autostereoscopic display

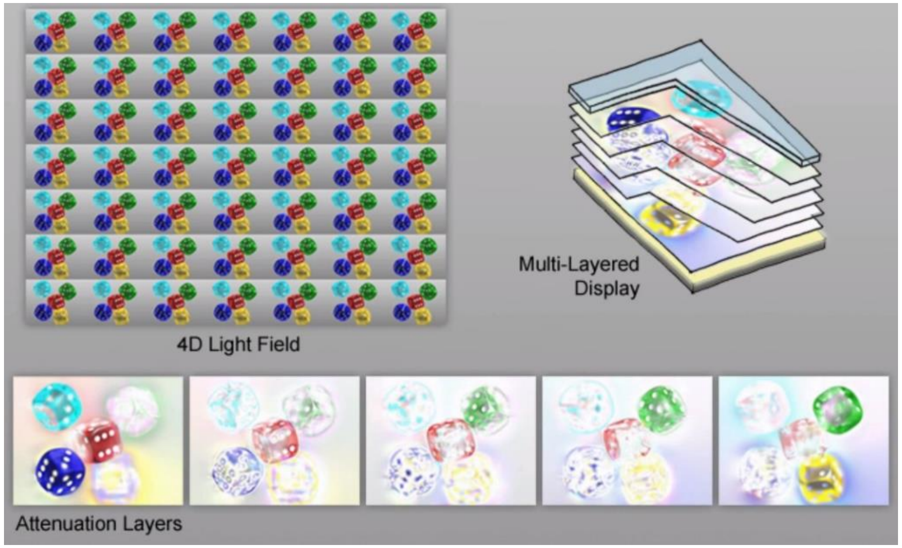


„Antialiasing for automultiscopic 3D displays" [Zwicker et al. 2006]

Multi-layer Displays

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

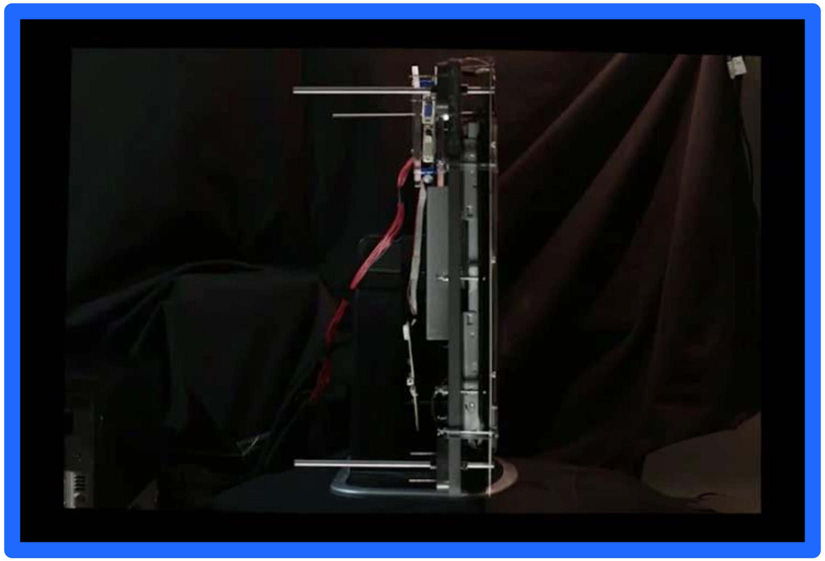




Images adapted from Wetzstein, Gordon, et al. "Layered 3D: tomographic image synthesis for attenuation-based light field and high dynamic range displays." ACM Transactions on Graphics (ToG). Vol. 30. No. 4. ACM, 2011.

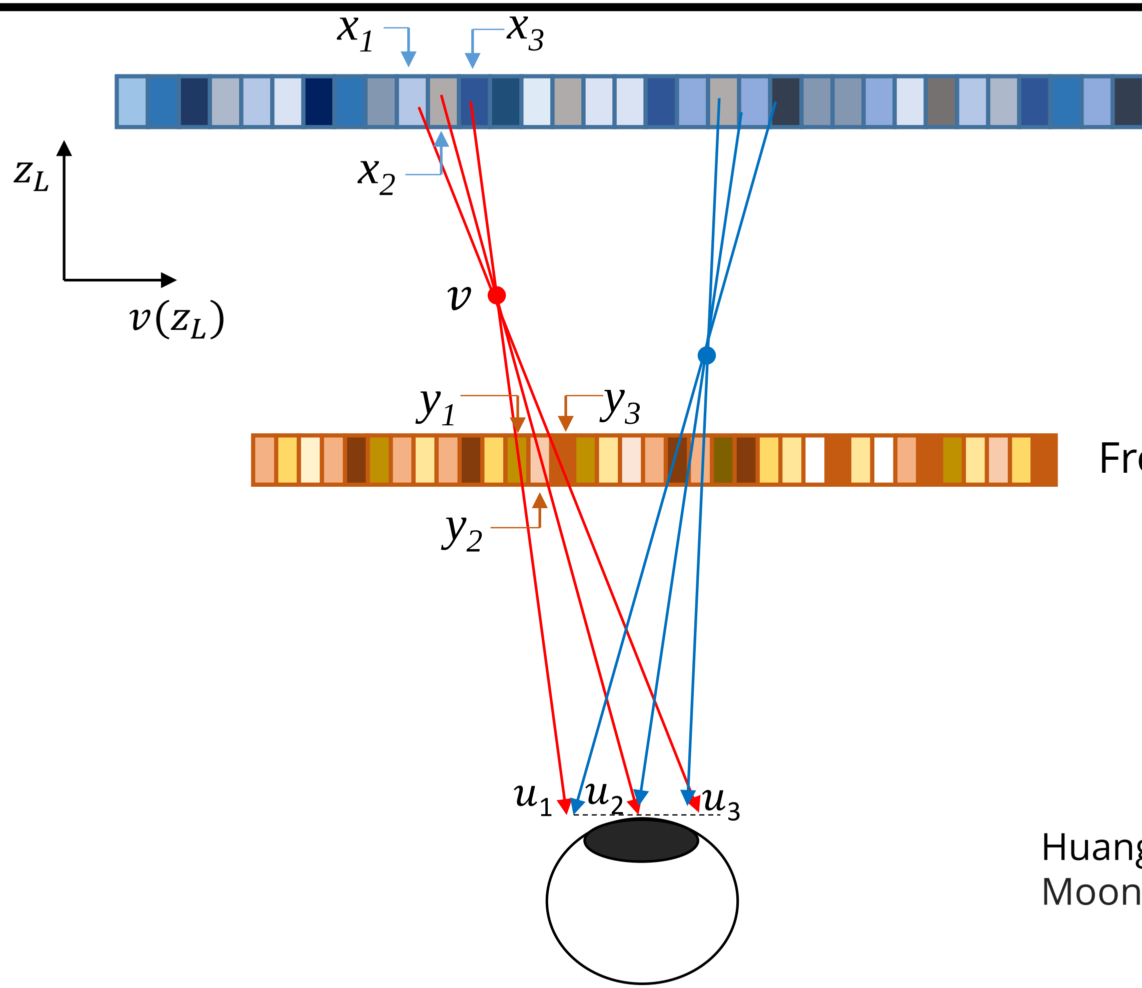
Tensor Displays

- **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 : $L(v,u_1) = x_3 \times y_1$

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

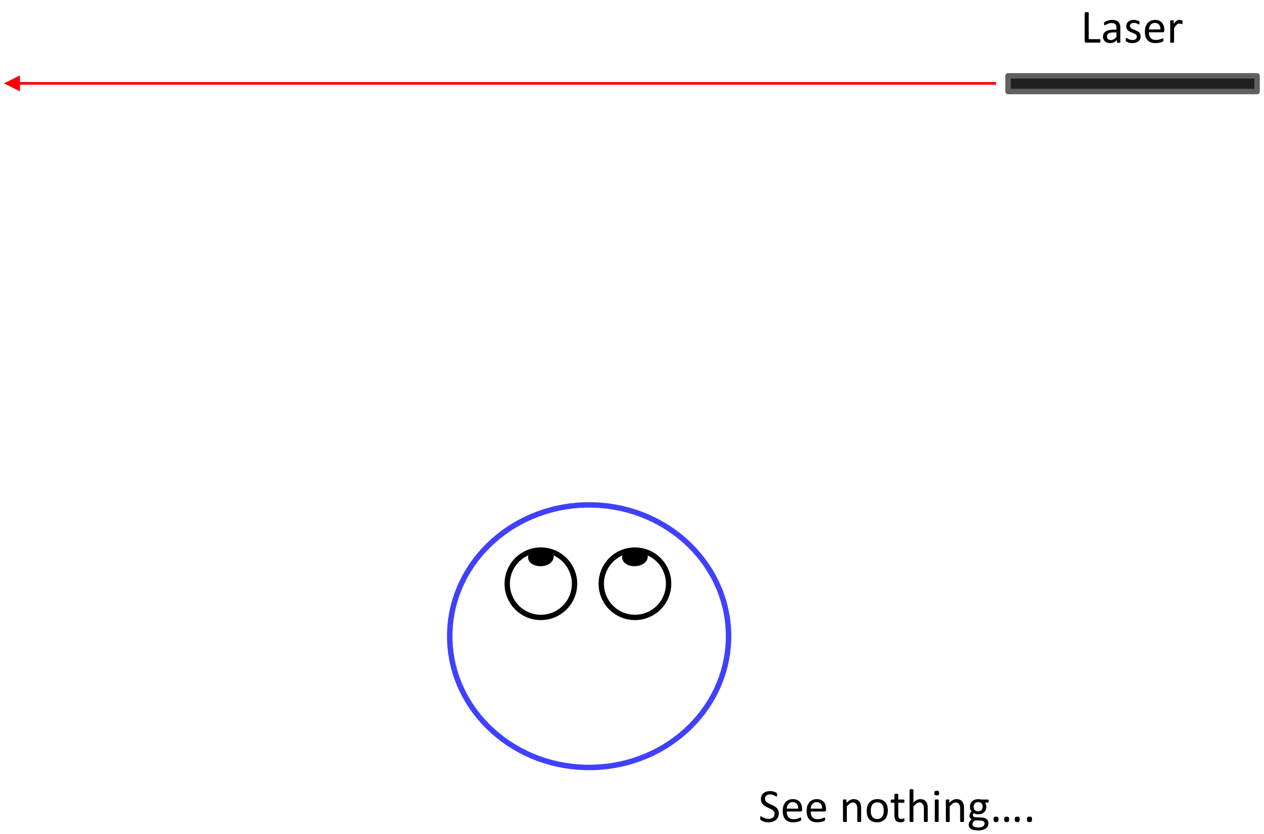
$L(v,u_3) = x_1 \times y_3$

Lightfield Displays

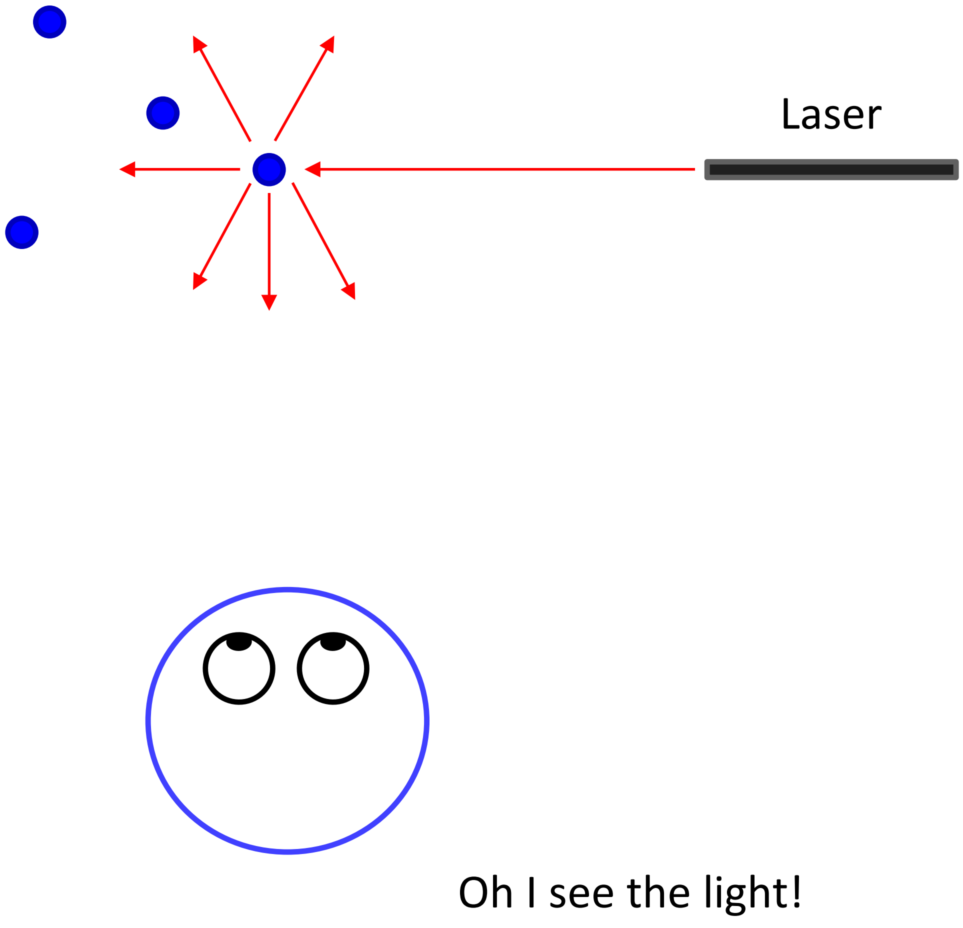
Holographic displays

Does this situation make any sense?

Observing the light

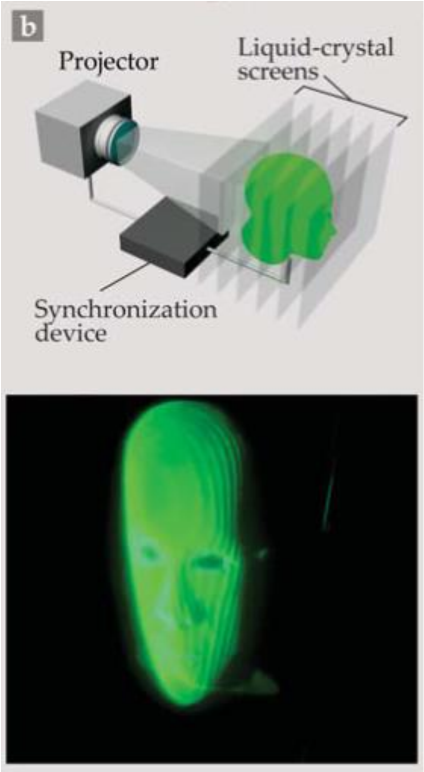


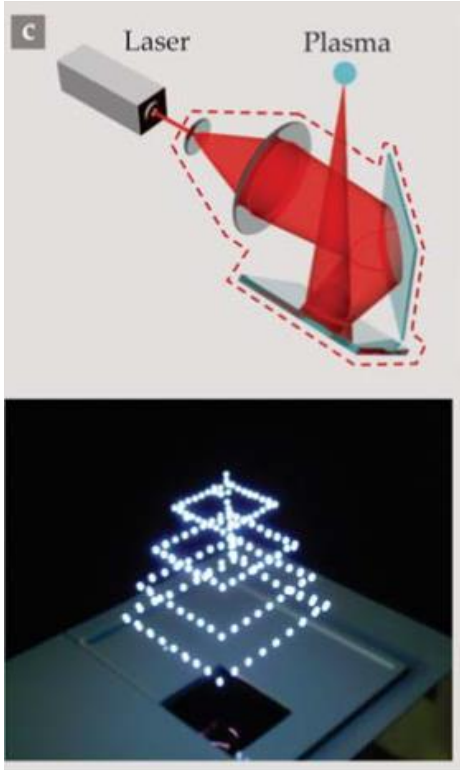
Observing the light



3D displays using scatteres

Yagi et al., SIGGRAPH Asia 2011, Emerging Technologies

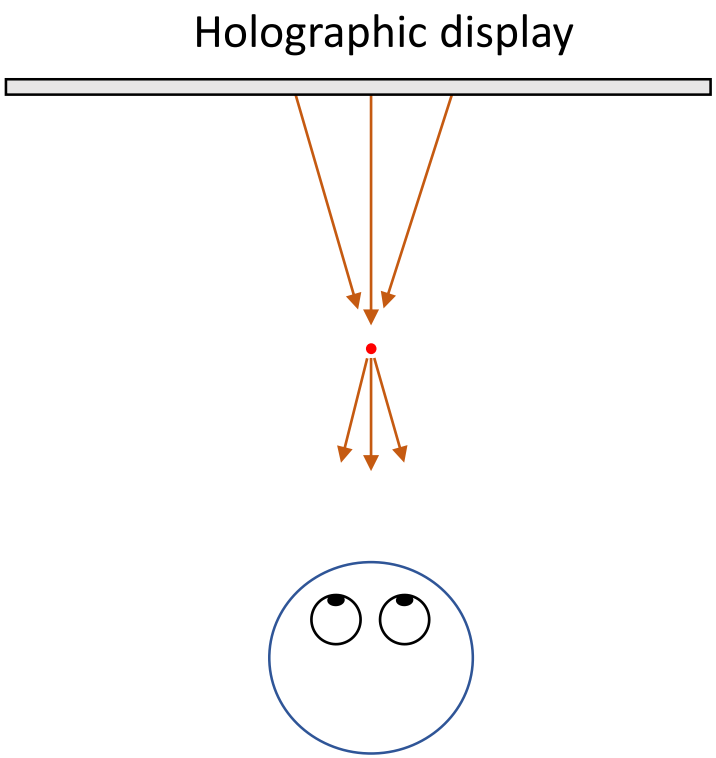




Phys. Today 66(4), 36 (2013)

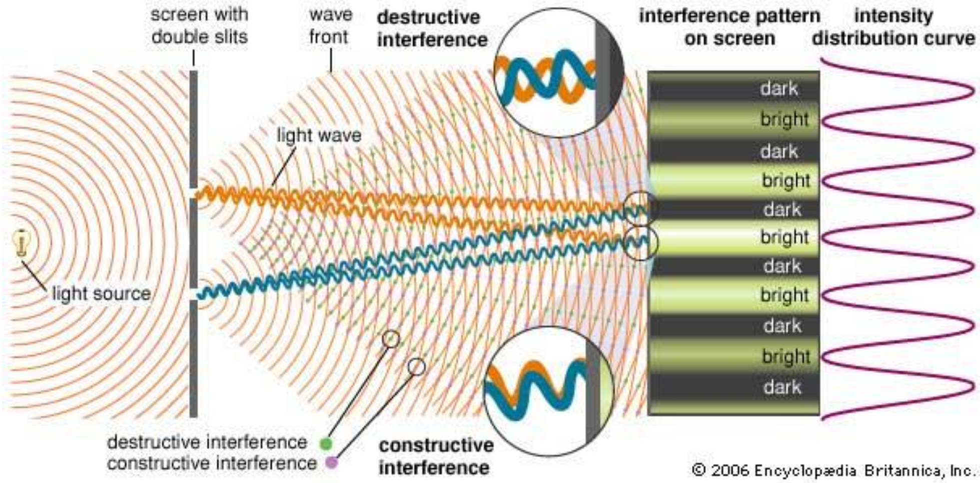
Holographic display

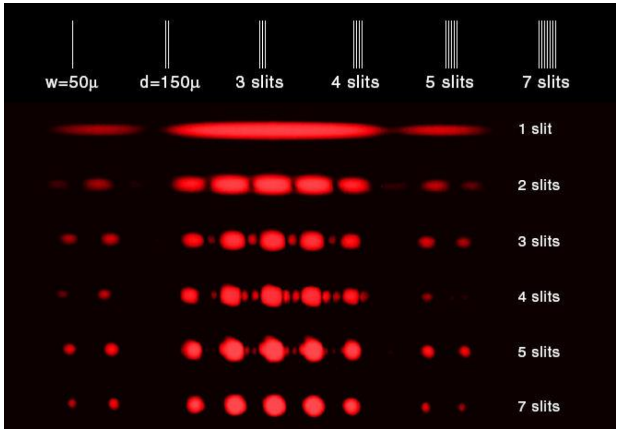
Holographic display : generating 3D images in the air without any scatterer



What is the meaning of “focusing the light”?

Focusing == interference



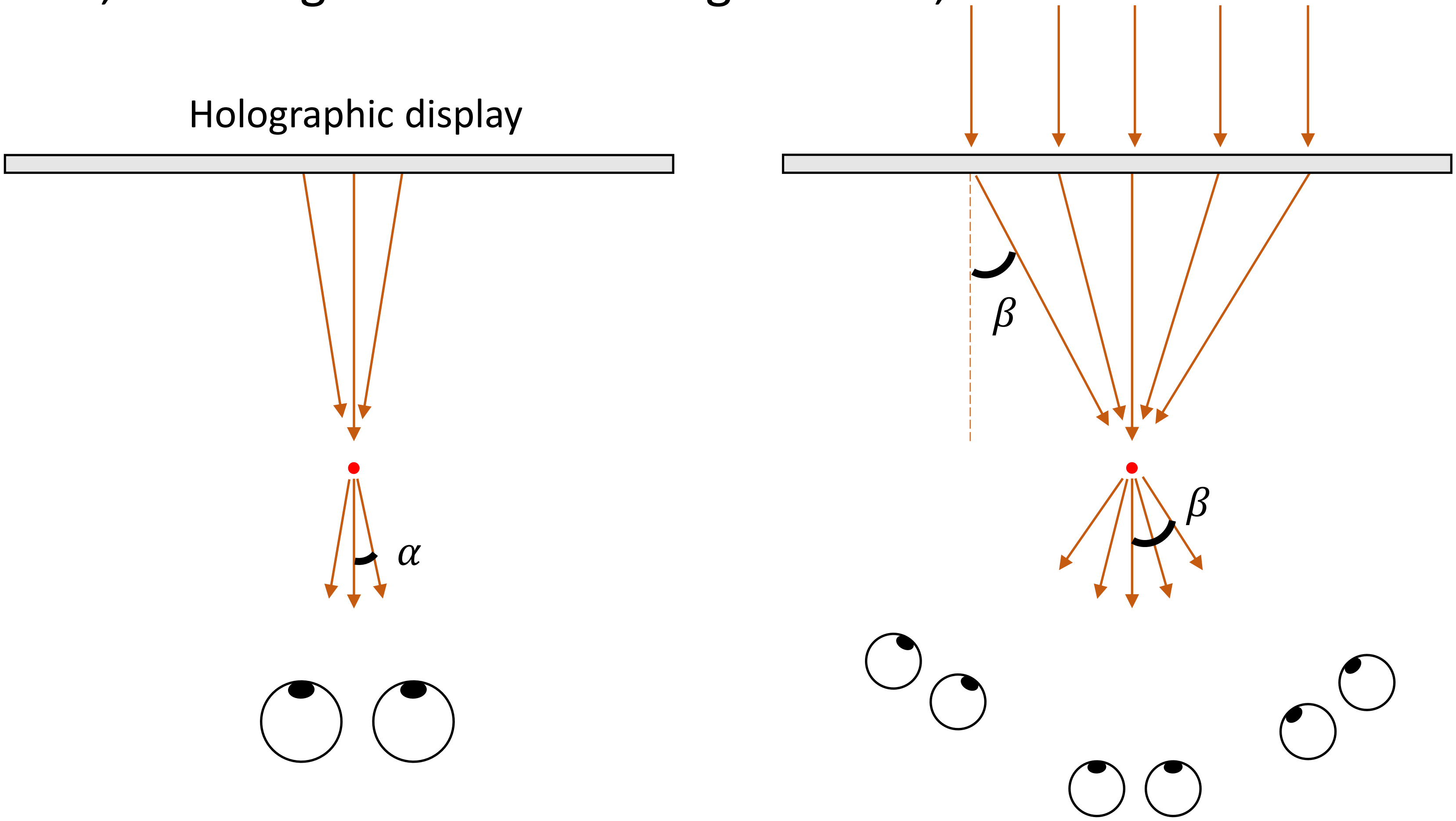


http://labman.phys.utk.edu/phys136

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

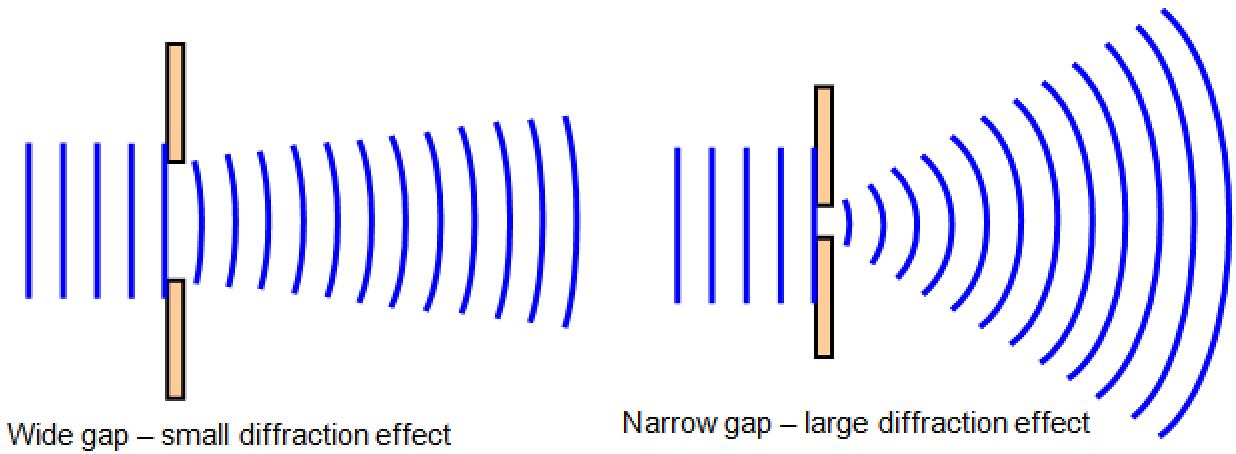
Viewing angle of displays

Let's replace the LED backlight of LCD displays with the laser light.
Then, can we generate the hologram? Yes, but....



A pixel should be able to deflect the light by β degrees

Smaller pixel size == Large diffraction angle

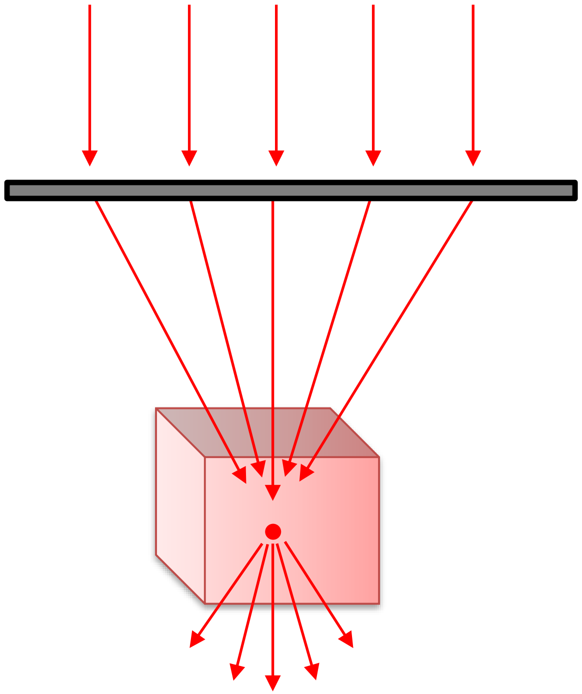


	Pixel size	Viewing angle
LCD monitor	200 μm	0.1°
LCoS Spatial light modulator	16 μm	2°
Ideal pixel size	1 μm	30°

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

Ultimate 3D display: Holographic display

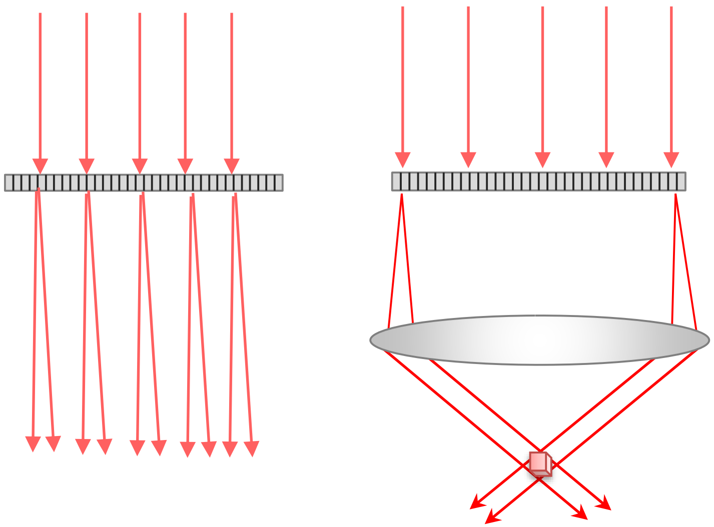
Ideal holographic monitor



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

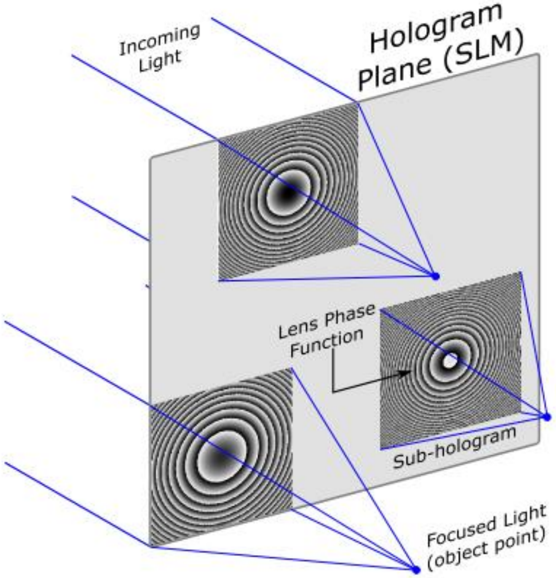
Current holographic monitor



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

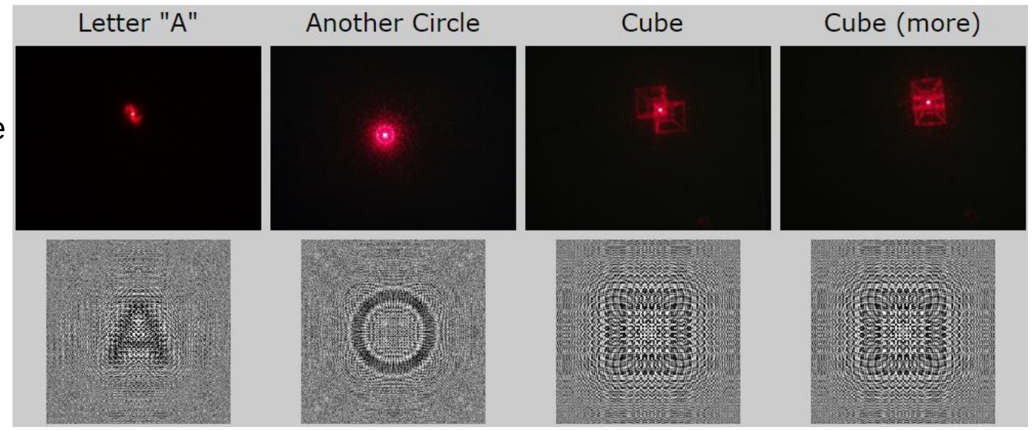
Viewing angle : 2 °
Image size : 1 cm x 1 cm

Rendering holograms



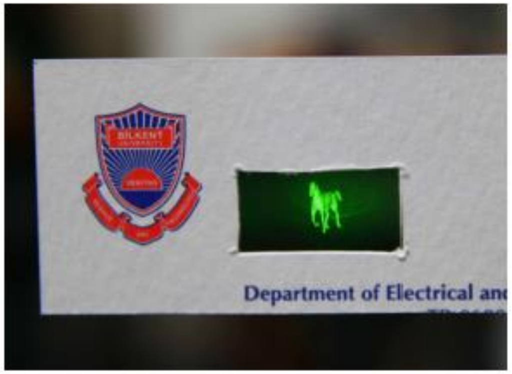
Target image

Displayed image



https://corticalcafe.com/software_onlineCGHinstructions.htm

A Fresnel zone plate pattern generate a focus spot. The target 3D image is first decomposed into a point cloud, and the point cloud is rendered with the combination of multiple zone plate patterns.



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	✓	✓	✓	✓	✓

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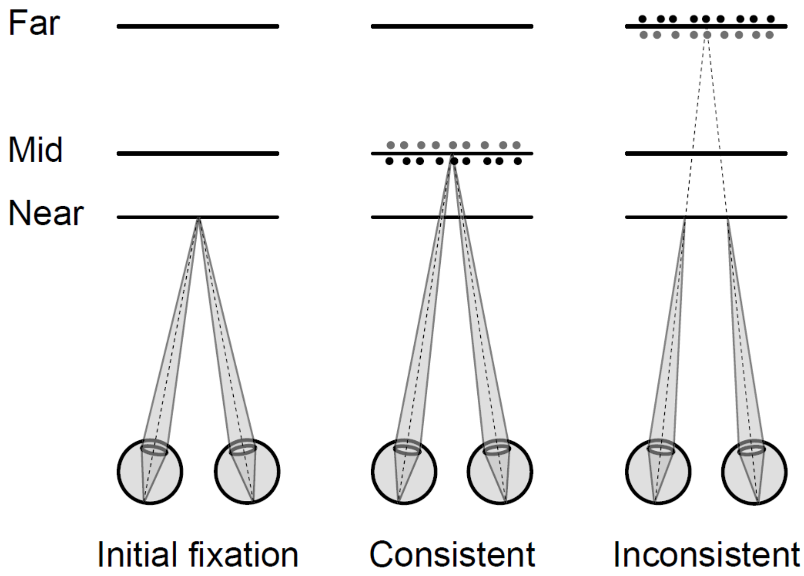
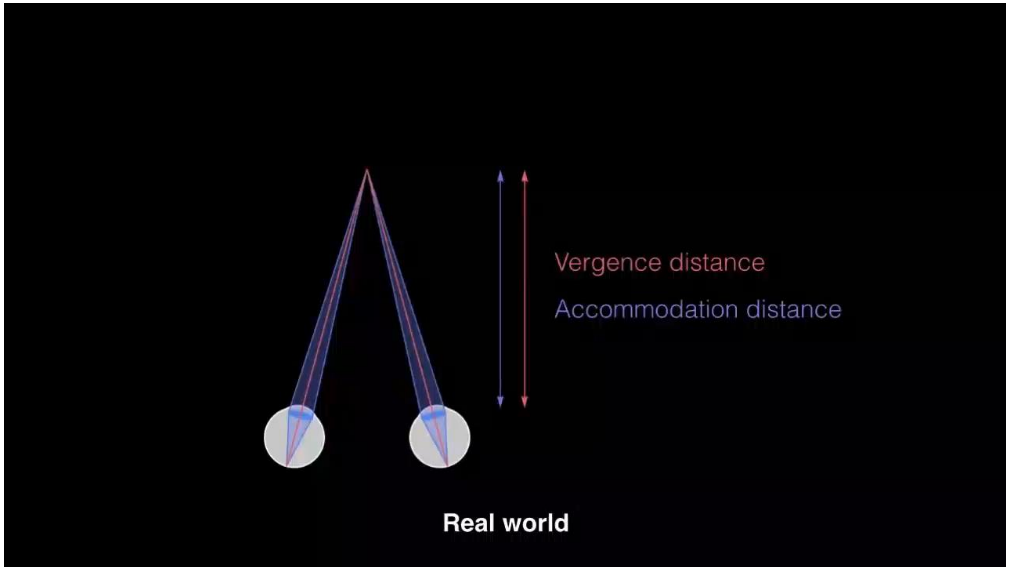
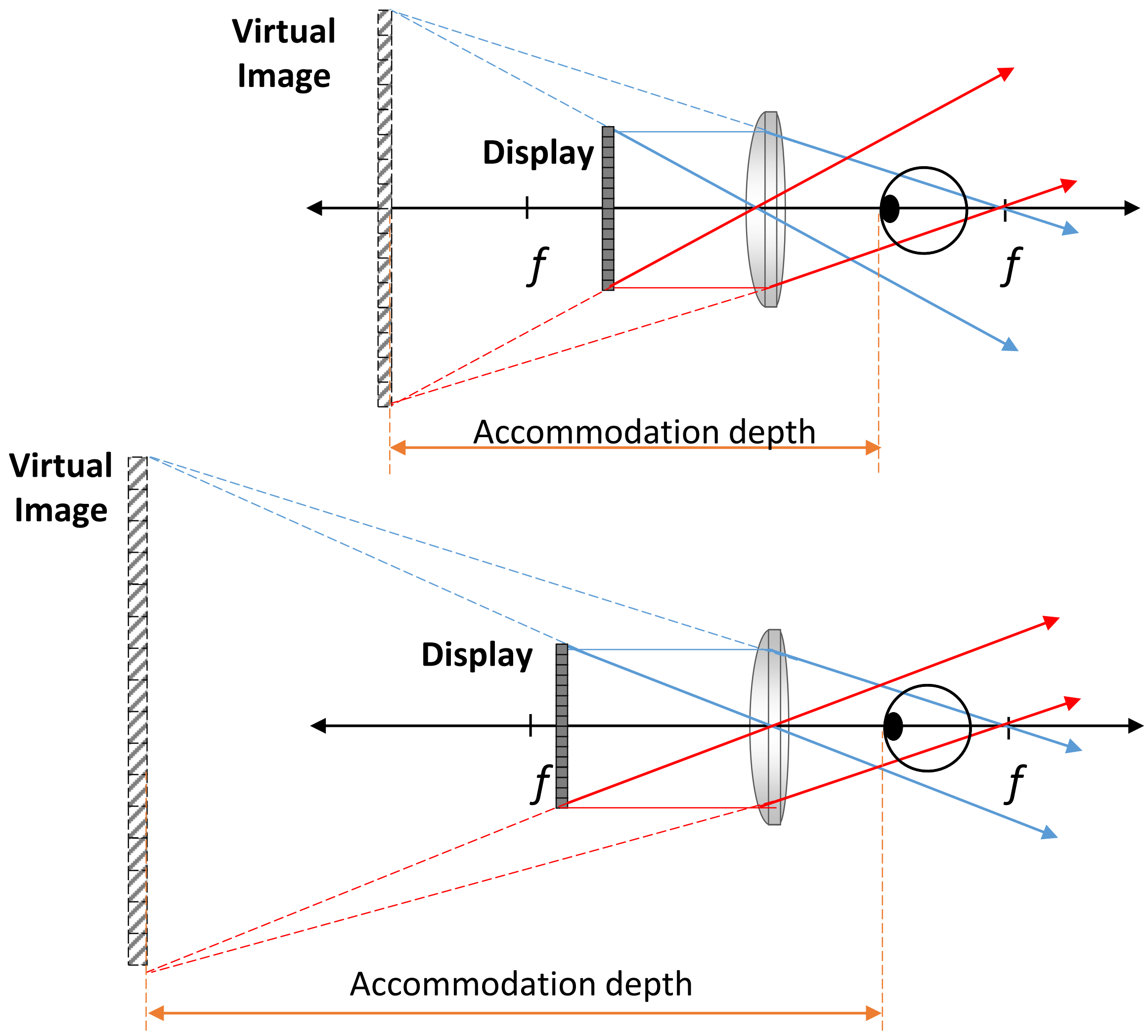
Accomodation-Vergence Conflict



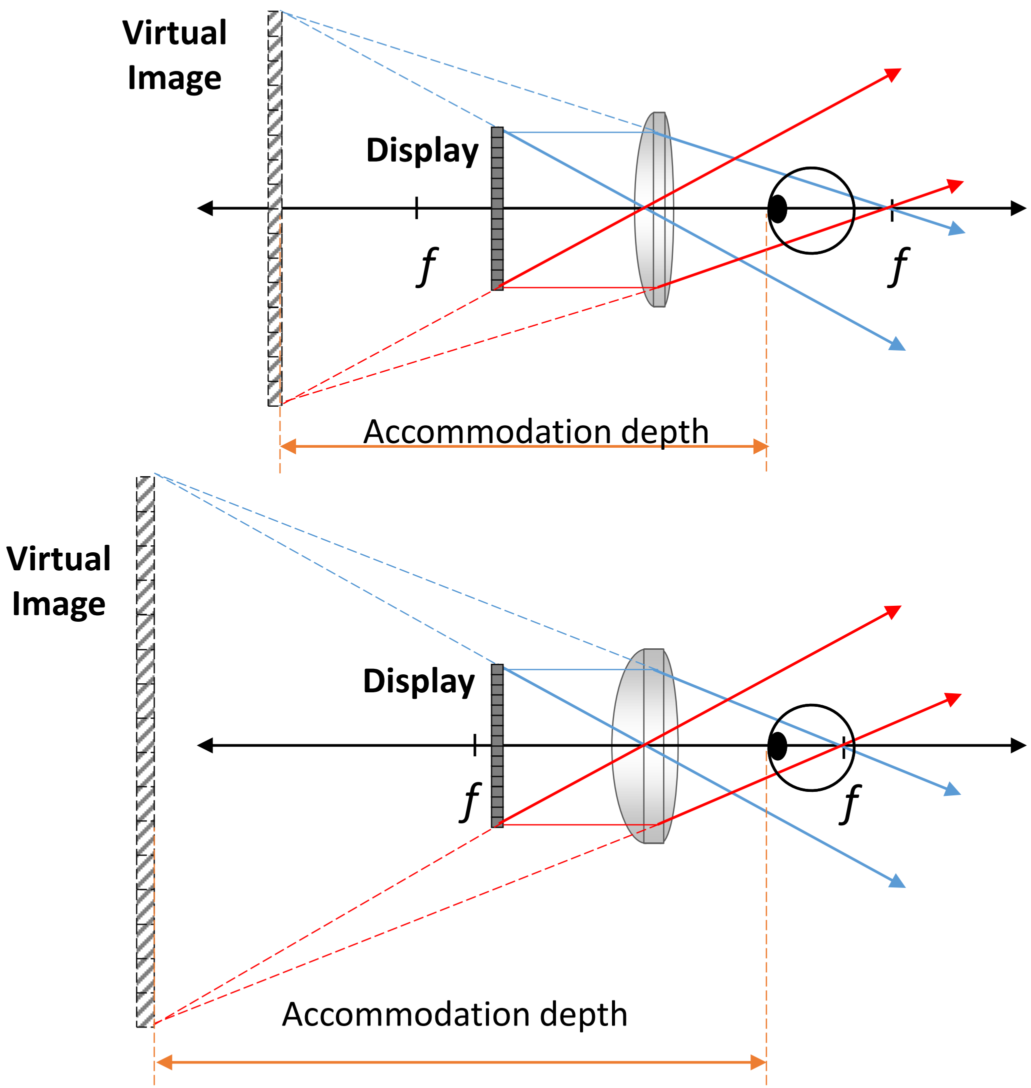


Visuals adapted from Akeley, Kurt, et al. "A stereo display prototype with multiple focal distances." ACM transactions on graphics (TOG). Vol. 23. No. 3. ACM, 2004. and Narain, Rahul, et al. "Optimal presentation of imagery with focus cues on multi-plane displays." ACM Transactions on Graphics (TOG)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

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

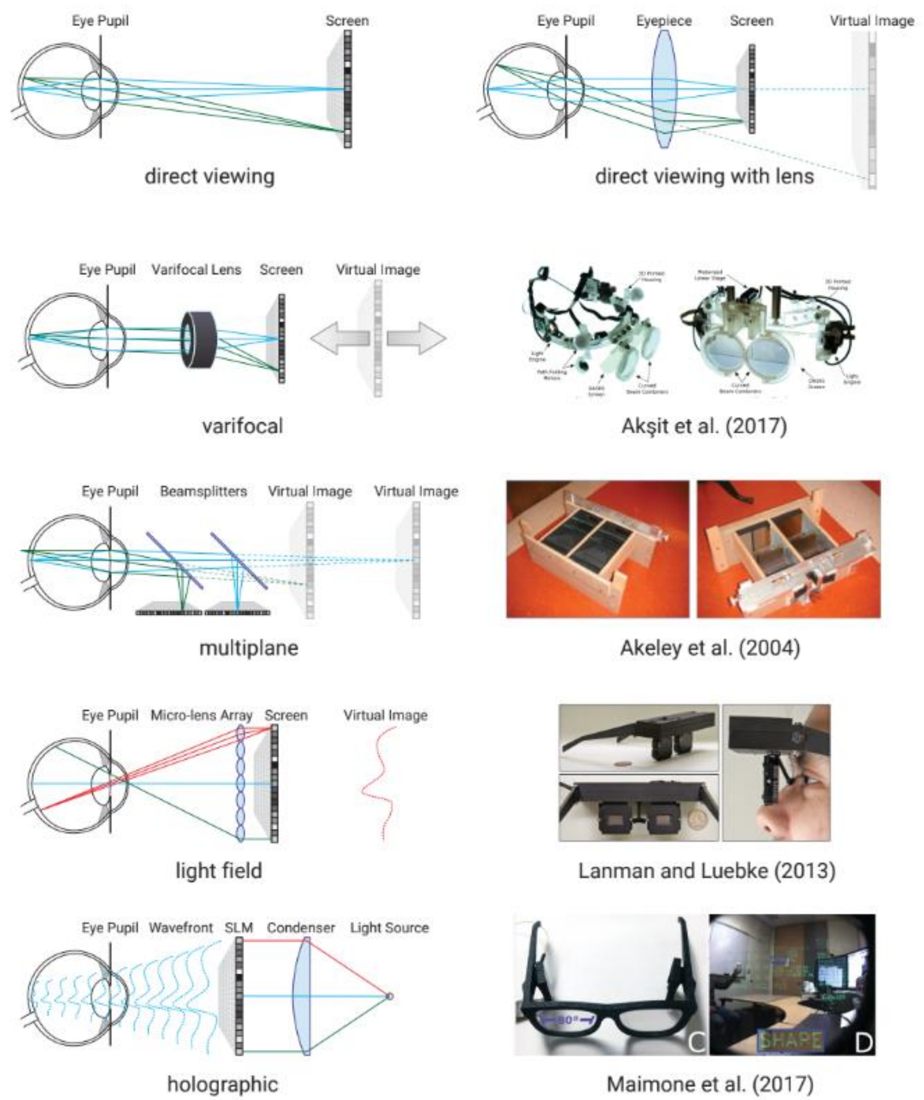


How to change accommodation? : (2) the lens focal length



HMD with accommodation cues

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



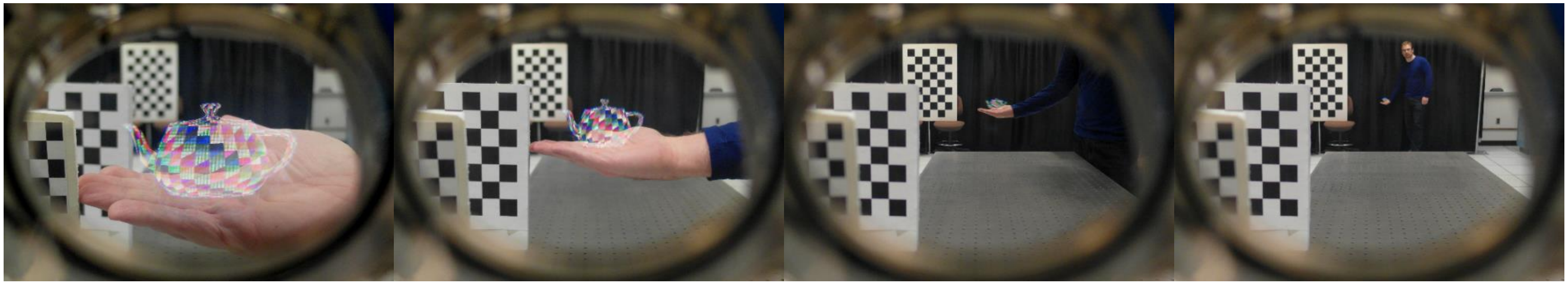
Varifocal display: Deformable Beamsplitter

See-through

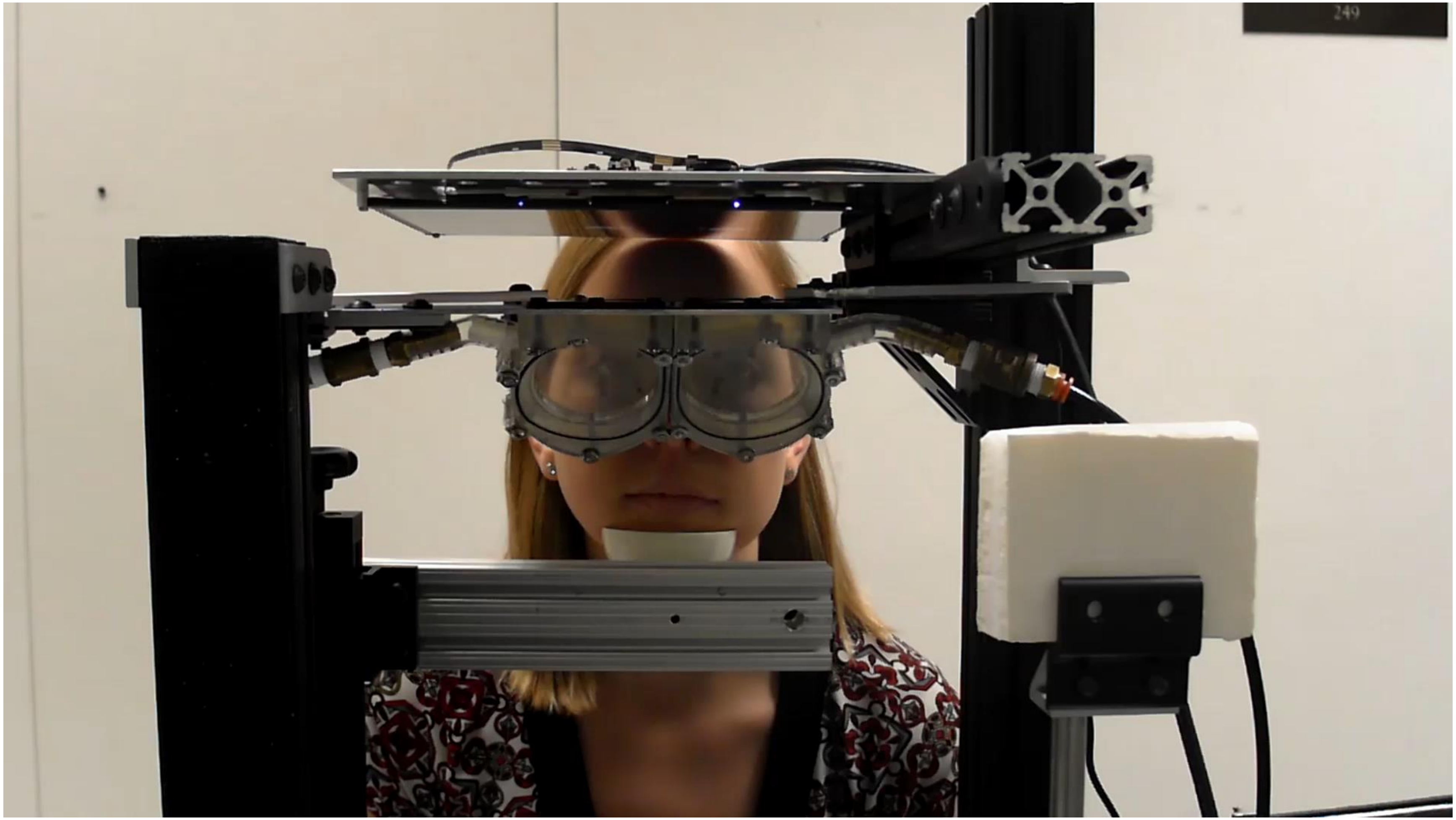
Dynamic focal depth: objects at any depth

Wide field of view

Optics are simple

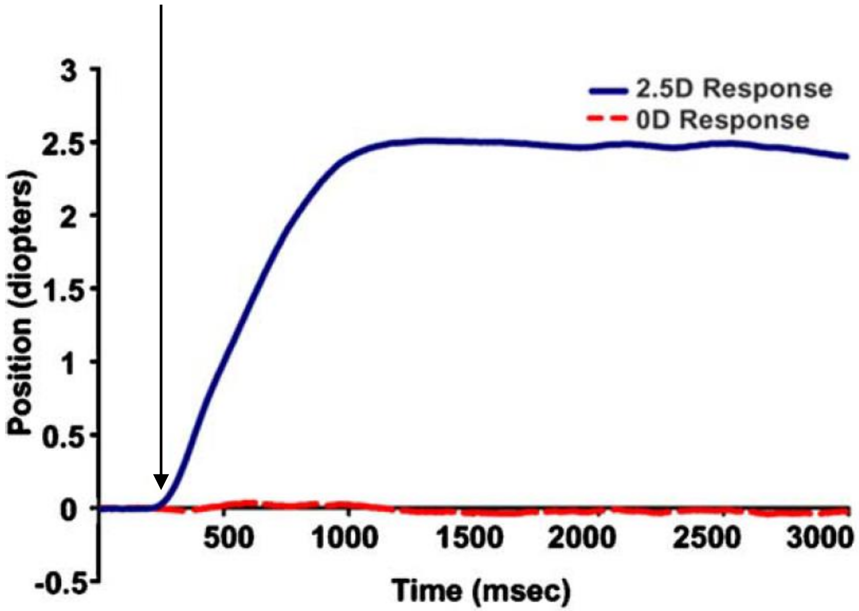


Varifocal display: Deformable Beamsplitter



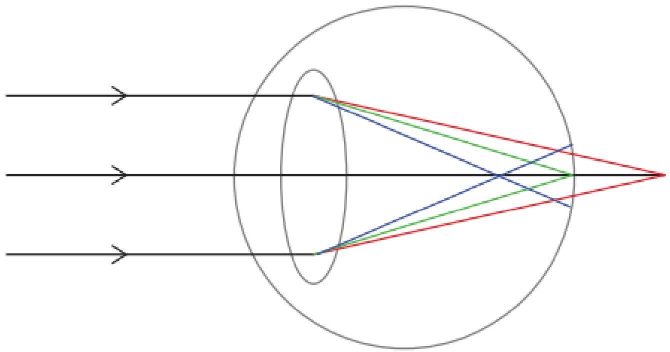
Accommodation Response

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



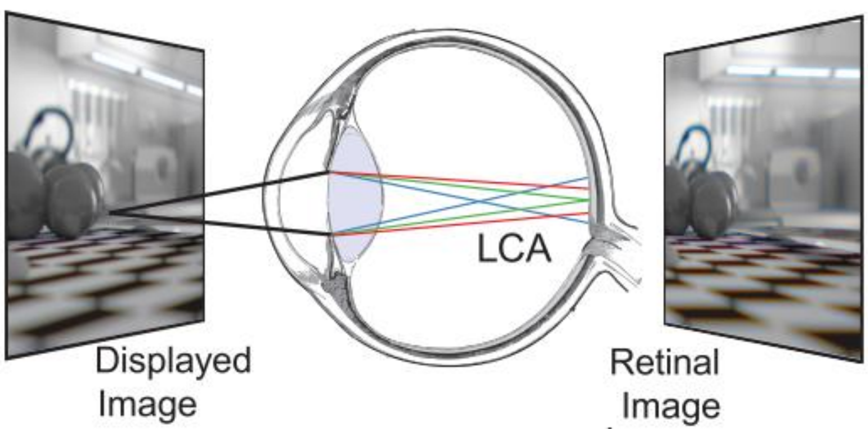
Bharadwaj and Schor, Vision Research 2004

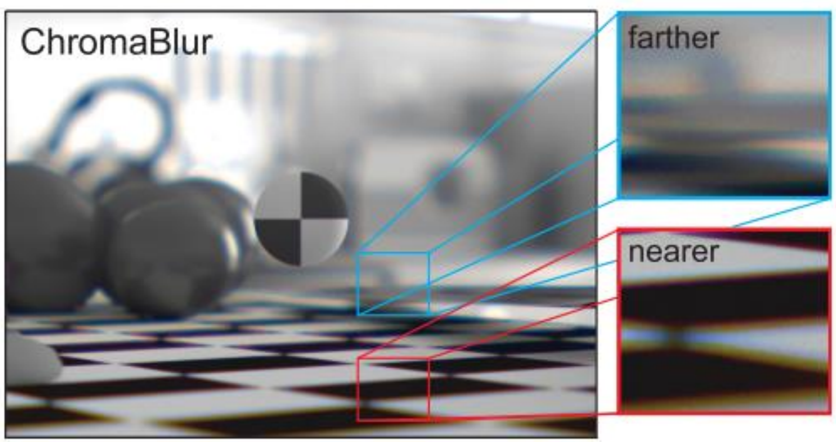
Rendering Chromatic Eye Aberration



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

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



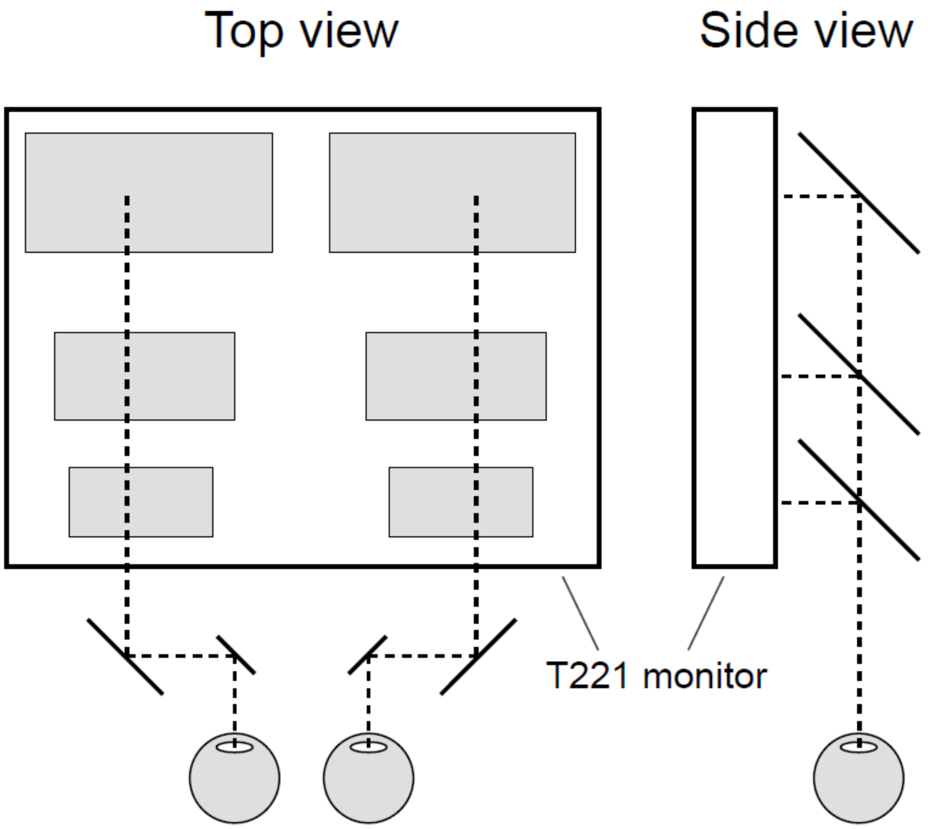


Rendering chromatic blur can provide accommodation effect (but not fully) and improve the realism

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

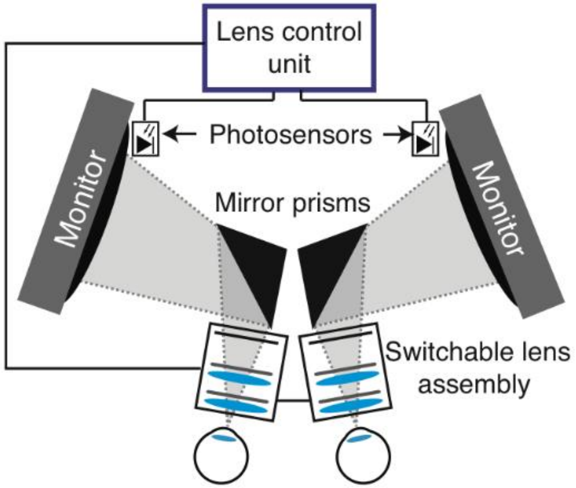
Multi-focal Plane Displays

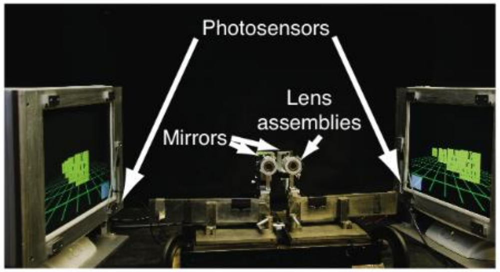
- **A display prototype with multiple focal distances using beam-splitters**



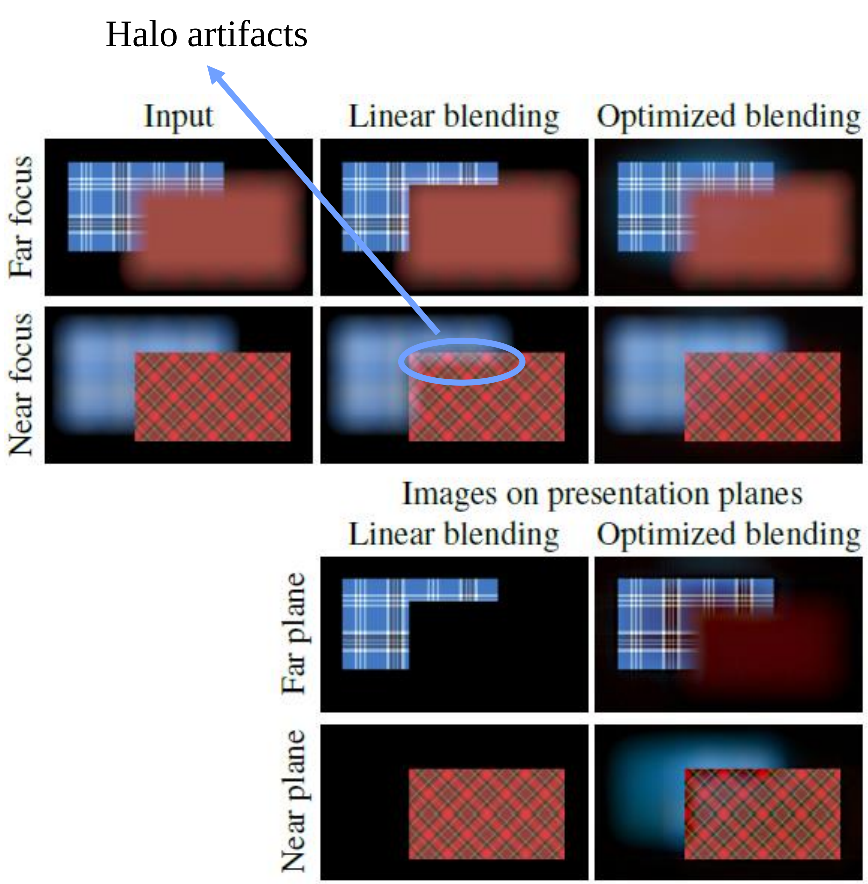
Images adapted from Akeley, Kurt, et al. "A stereo display prototype with multiple focal distances." ACM transactions on graphics (TOG). Vol. 23. No. 3. ACM, 2004.

Multi-focal Plane Displays





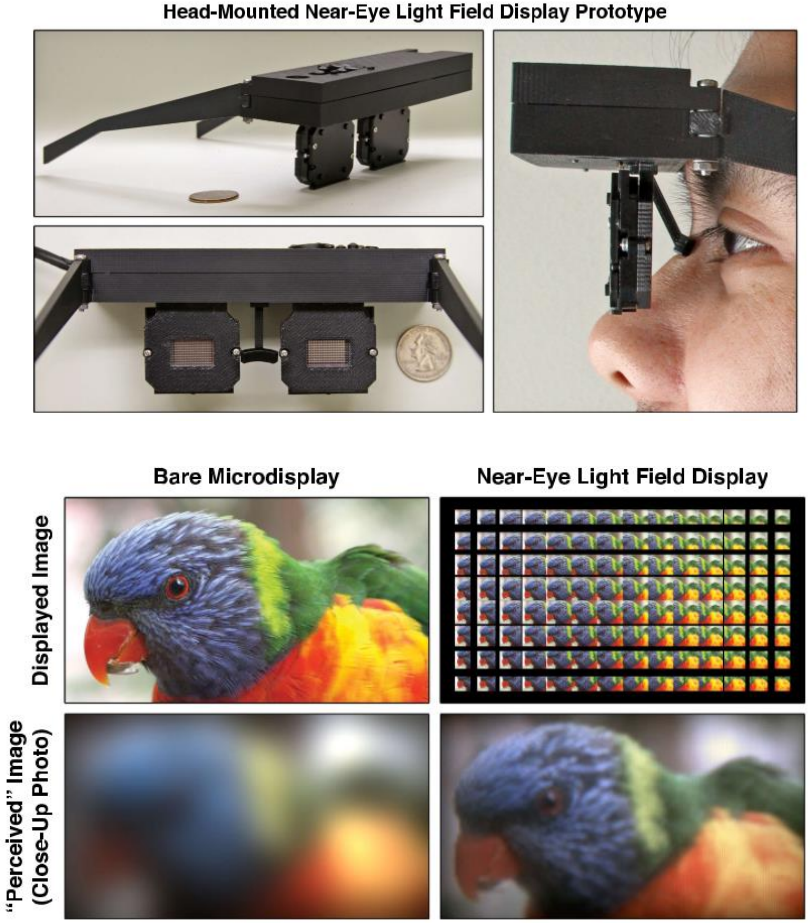
Prototype introduced by Love et al [2009]

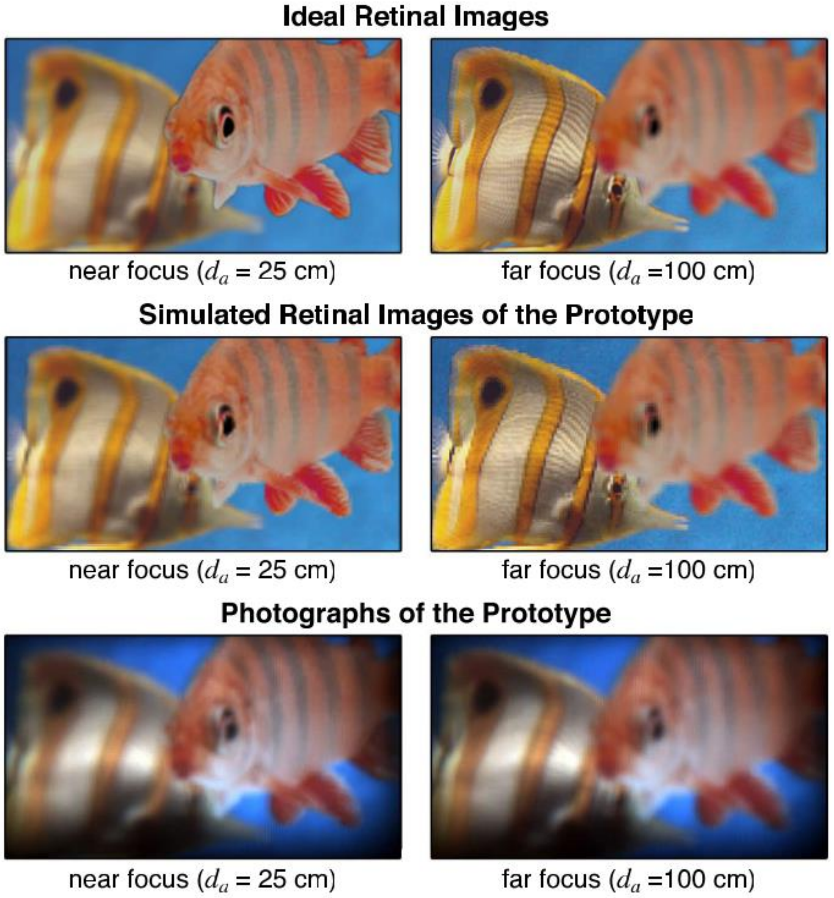


Narain et al. [2015] optimize the focus cues for improved realism.

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.

Light-field Displays

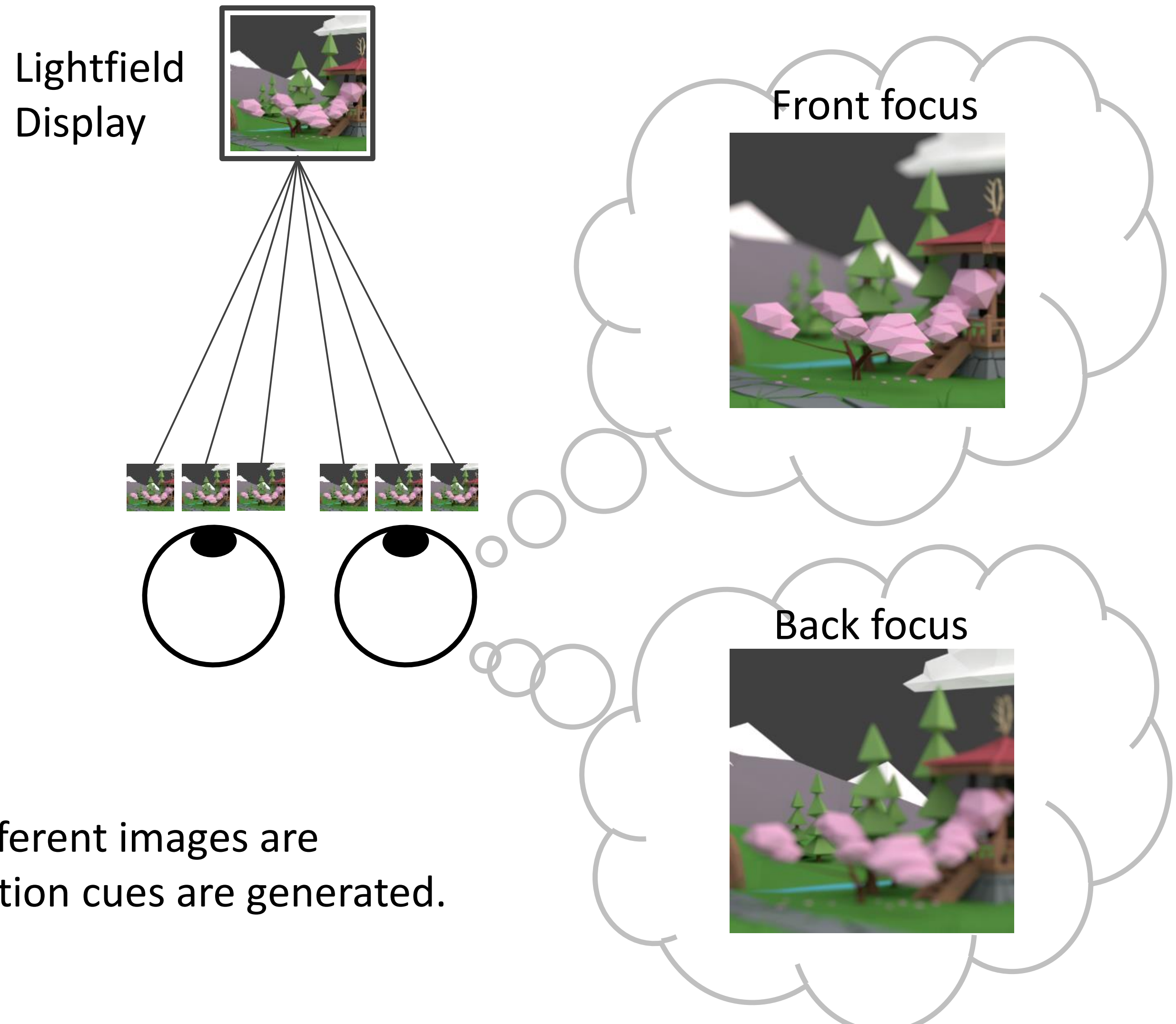




LANMAN, D. AND LUEBKE, D. 2013. Near-eye light field displays. *ACM Transactions on Graphics 32*, 6, 1–10.

Requirement for supporting accommodation

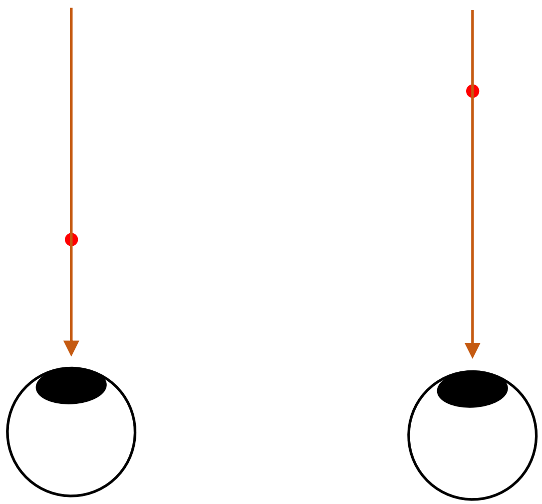
High angular resolution or dense light fields: Accommodation



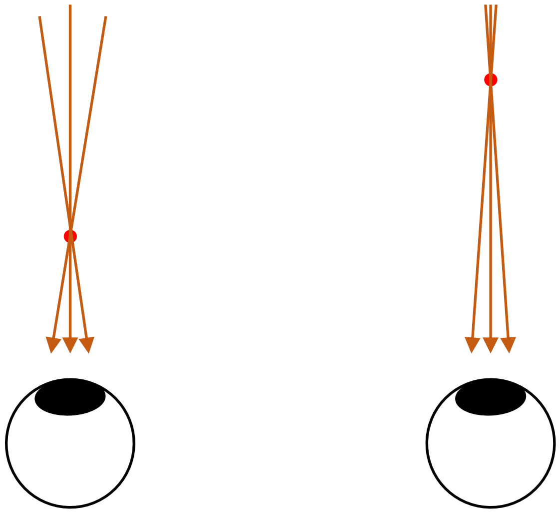
Towards each eye, multiple different images are projected: proper accommodation cues are generated.

Requirement for supporting accommodation

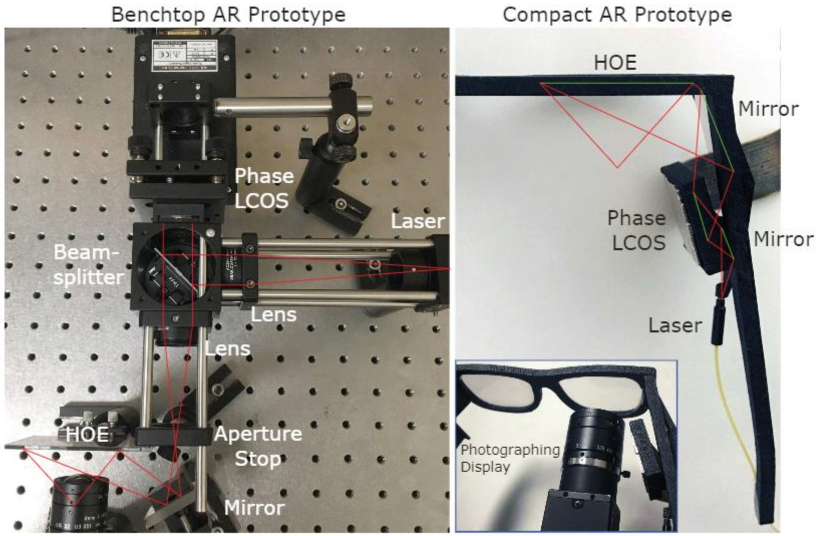
Single ray is not enough
(depth ambiguity)

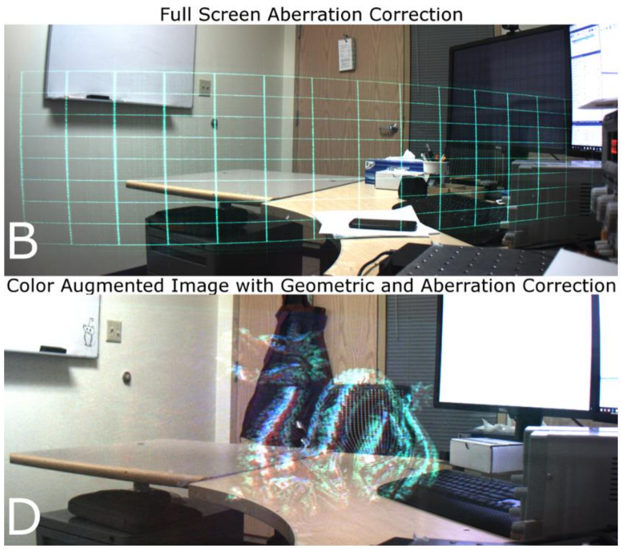


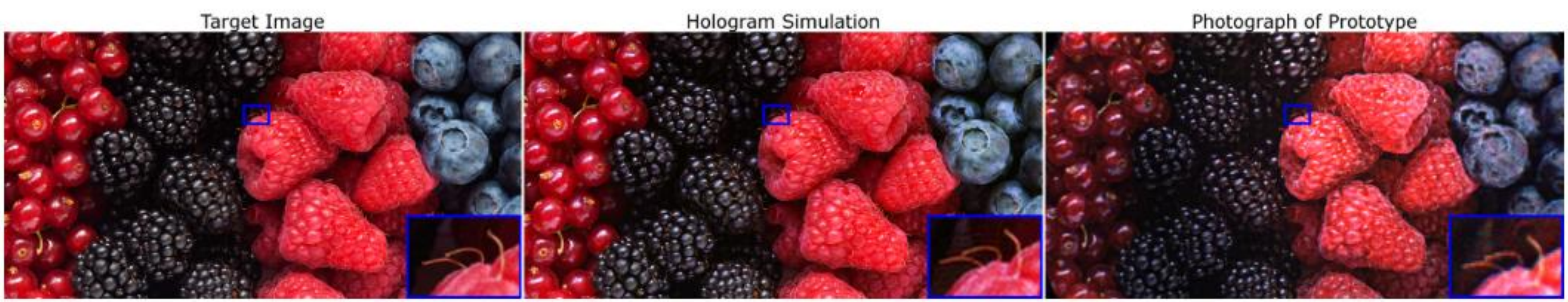
Mathematically, minimum two rays
should be projected inside the pupil
In practice,
3 rays for 1-D
3 x 3 rays for 2-D



Holographic Displays



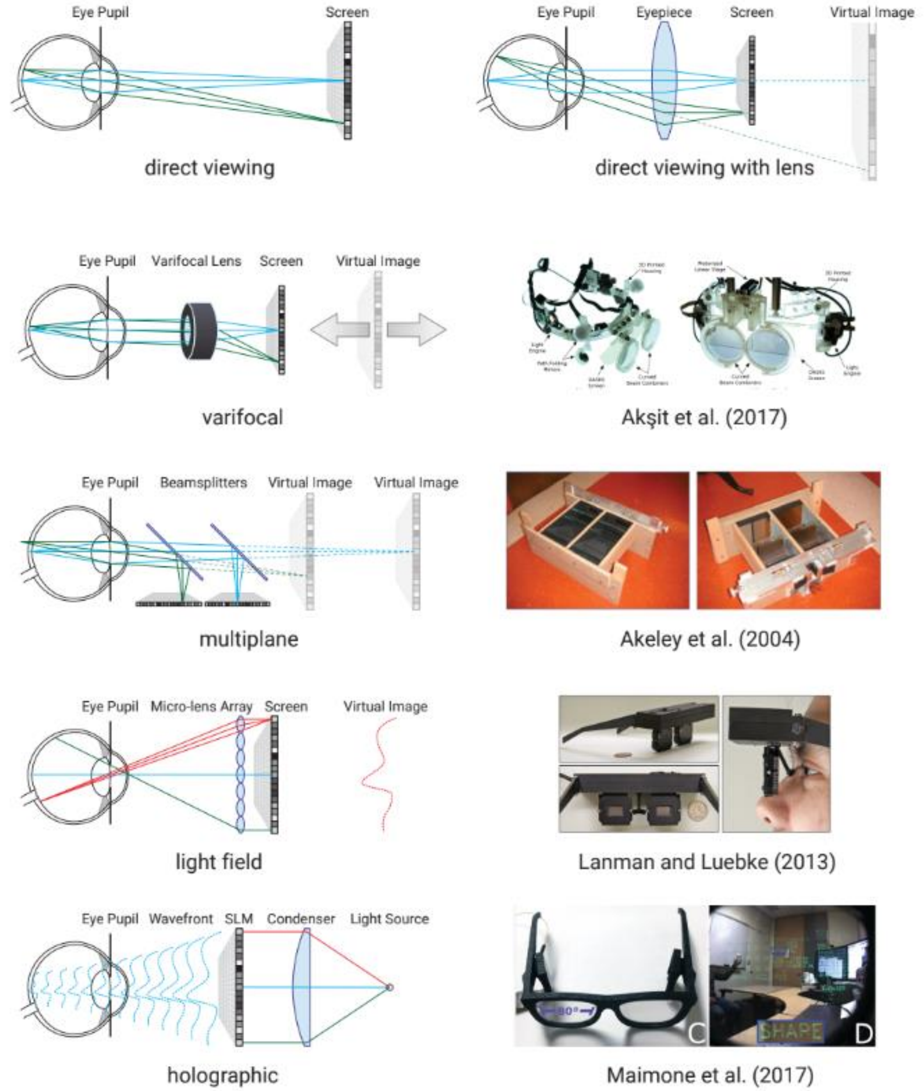




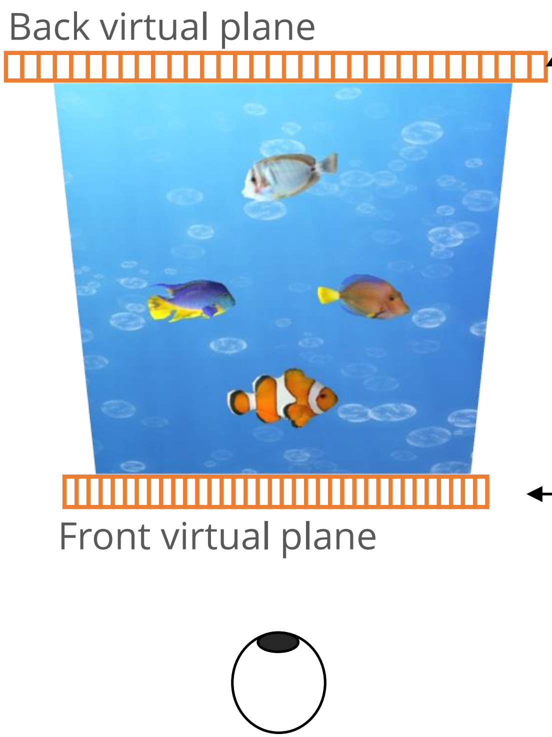
Maimone et al., Siggraph (2017)

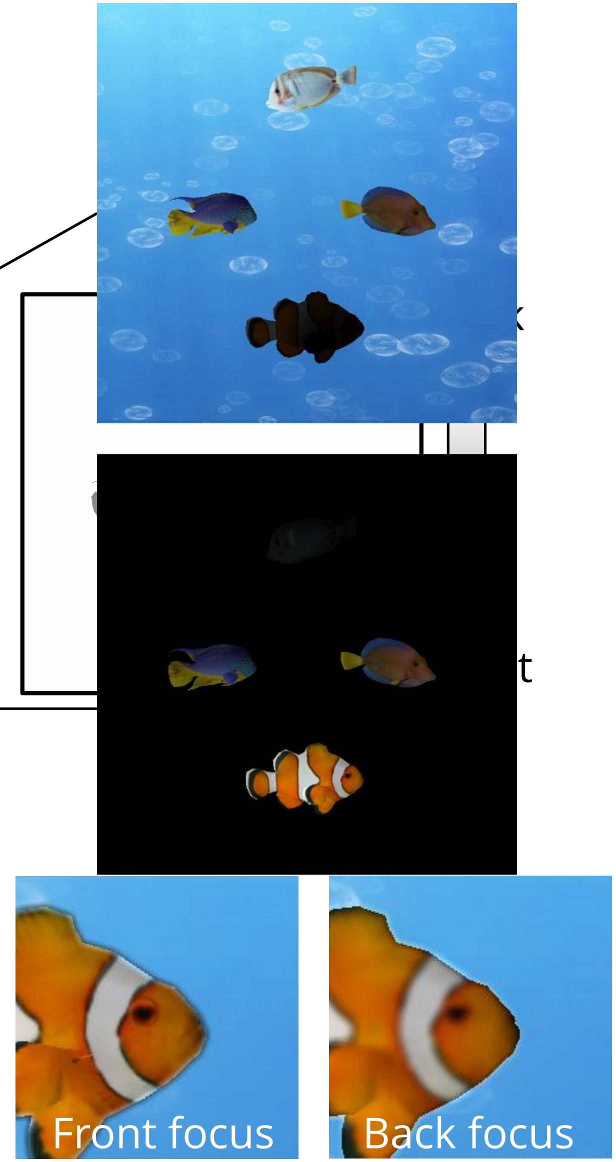
HMD with accommodation cues

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



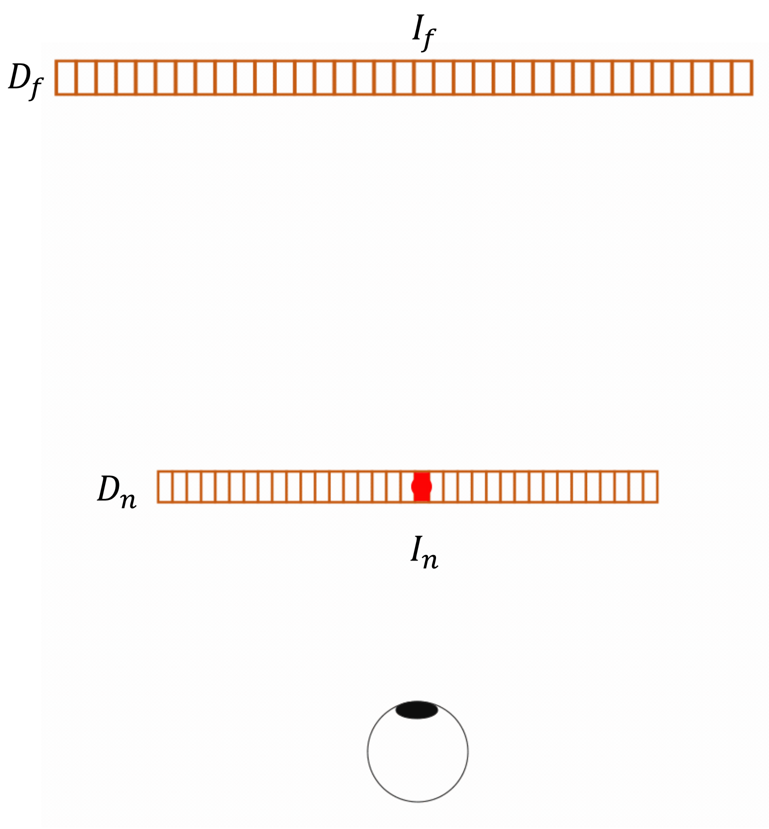
Rendering for multi plane displays
(1) linear Blending Rule





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

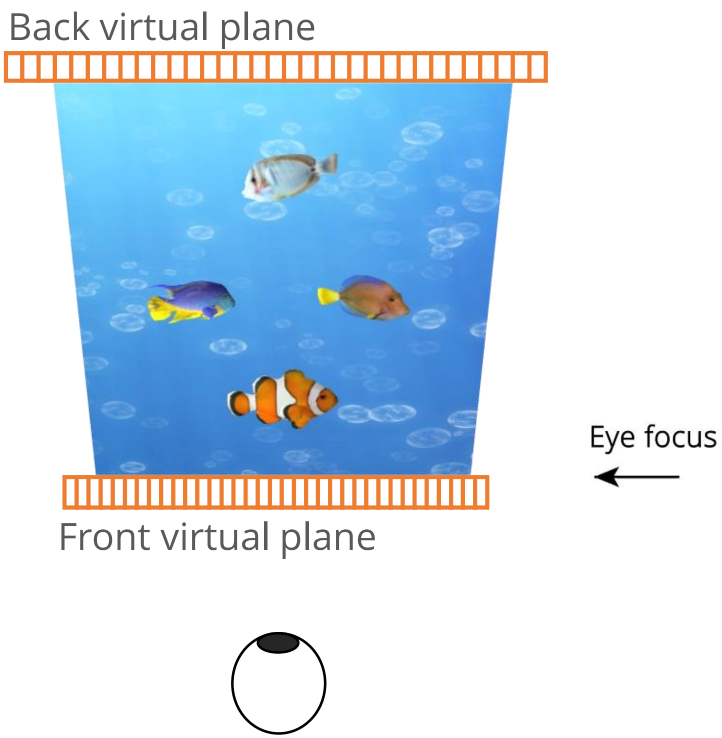
Rendering for multi plane displays
(1) linear Blending Rule



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

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

Rendering for multi plane displays
(2) Retinal Optimization



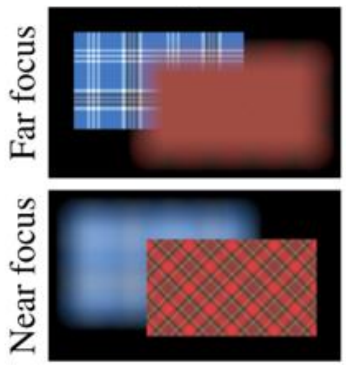
Narain et al (Siggraph 2015)
Mercier et al (Siggraph Asia 2017

Optimization objective

A focal stack

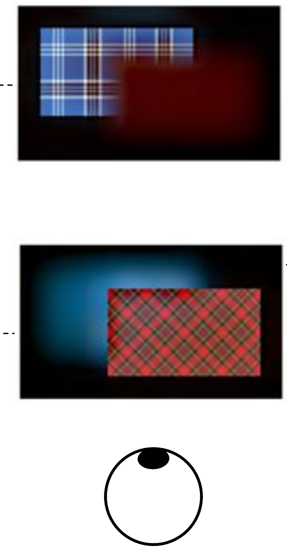
Rendering for multi plane displays
(2) Retinal Optimization

Target 3D scene



R_F

R_N



I_F

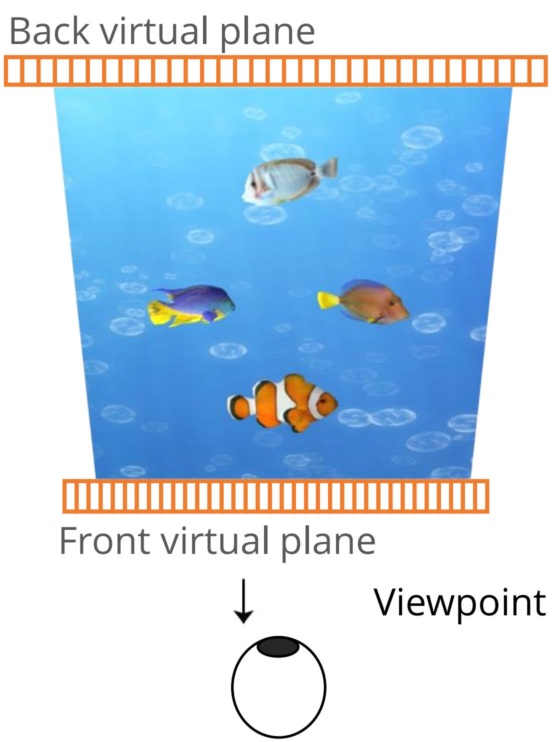
1.4 D ---------- Far virtual plane

I_N

2.0 D ----- Near virtual plane

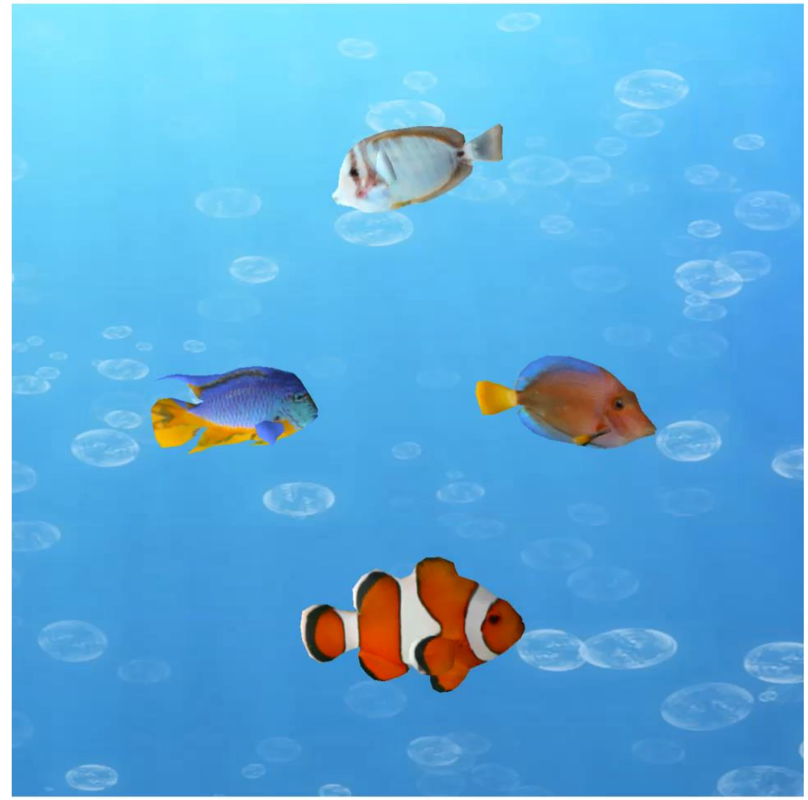
Eye focus	Perceived images
Far plane	$I_F + I_N * Blur_{NF} = R_F$
Near plane	$I_N + I_F * Blur_{FN} = R_N$

Rendering for multi plane displays
(3) Light field synthesis



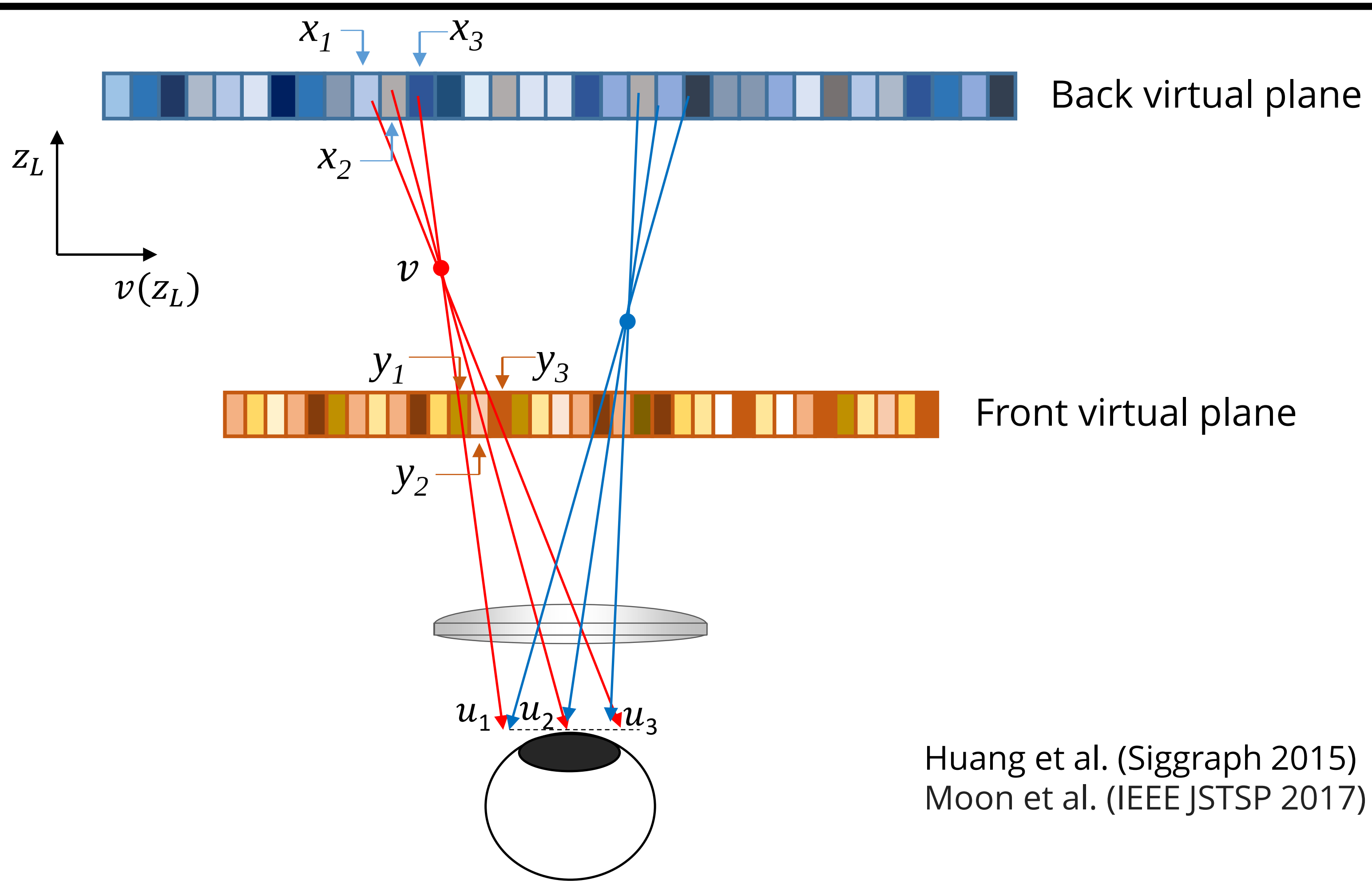
Huang et al. (Siggraph2015)
Moon et al. (IEEE JSTSP 2017)

Optimization objective



Light field

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

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

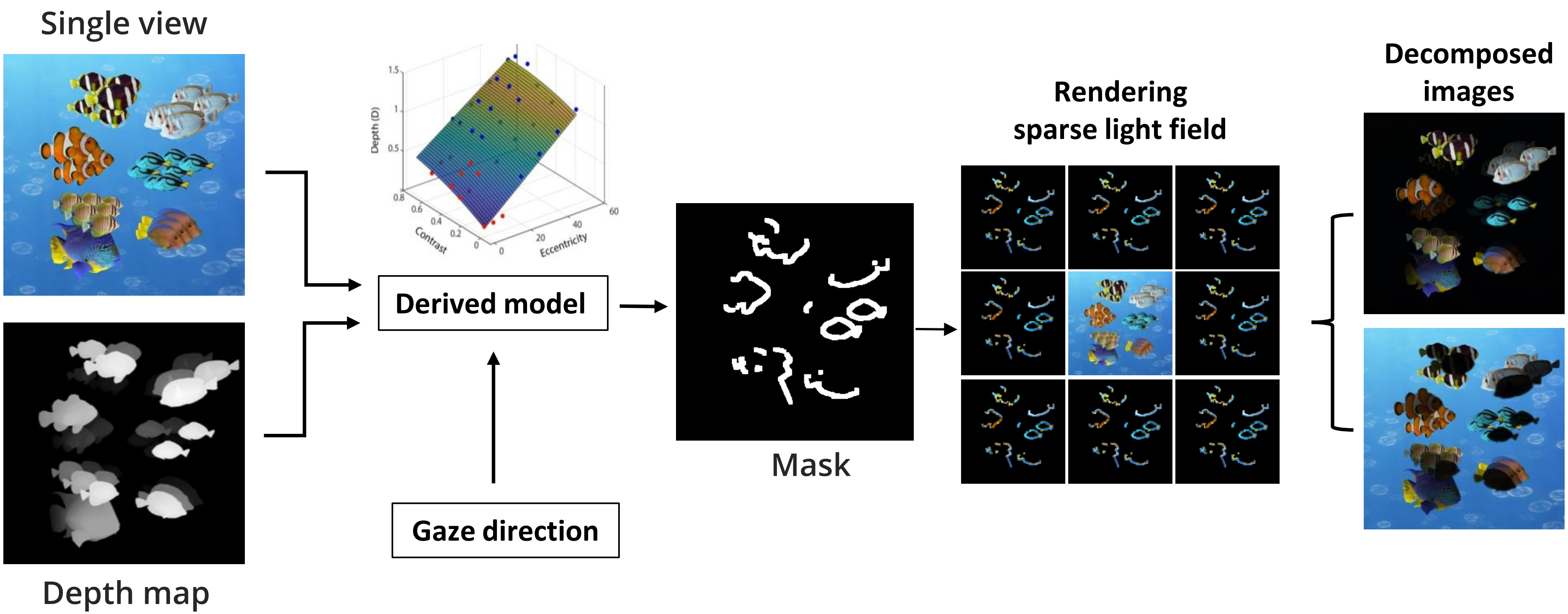
$L(v,u_3) = x_1 + y_3$

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

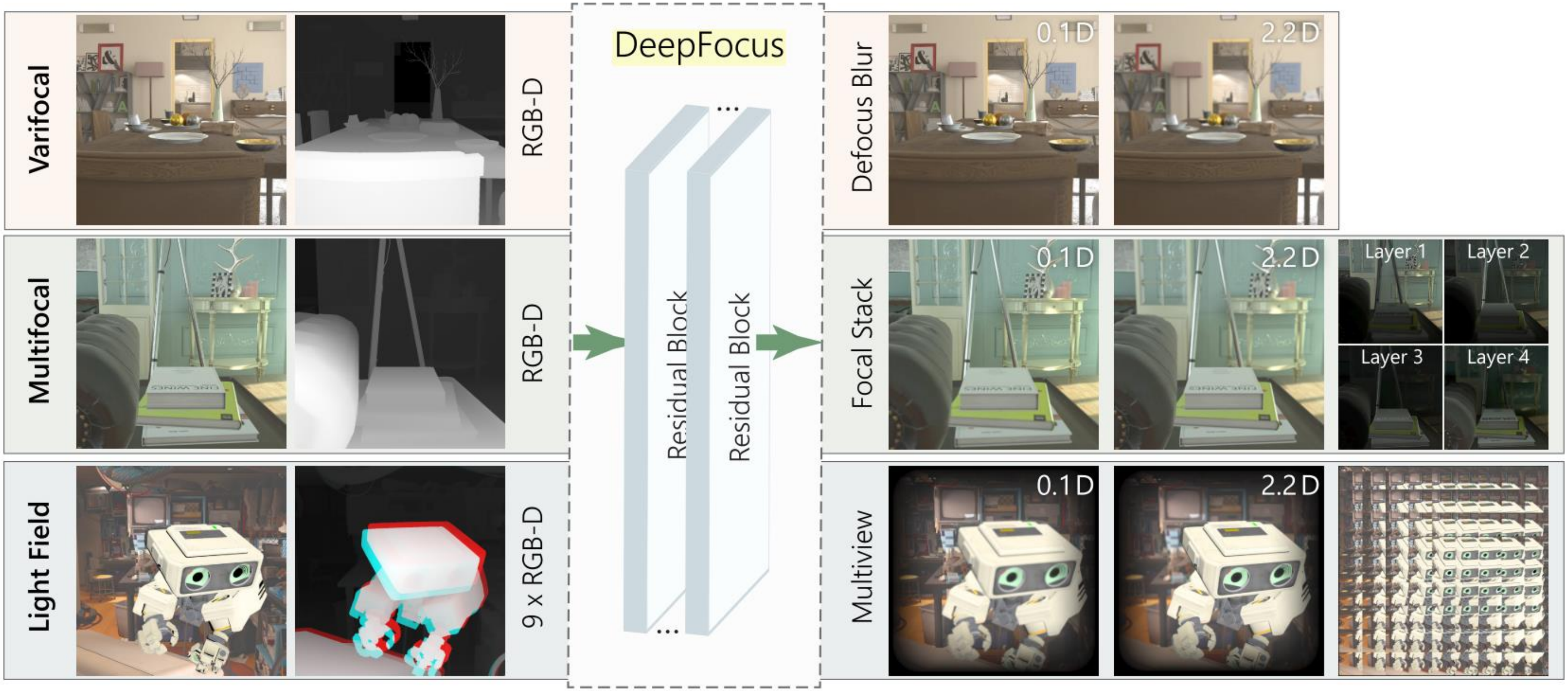
[1] Akeley et al, Siggraph (2014)
[2] Narain et al (Siggraph 2015)
[3] Mercier et al, Siggraph Asia (2017)
[4] Moon et al, IEEE JSTSP (2017)

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



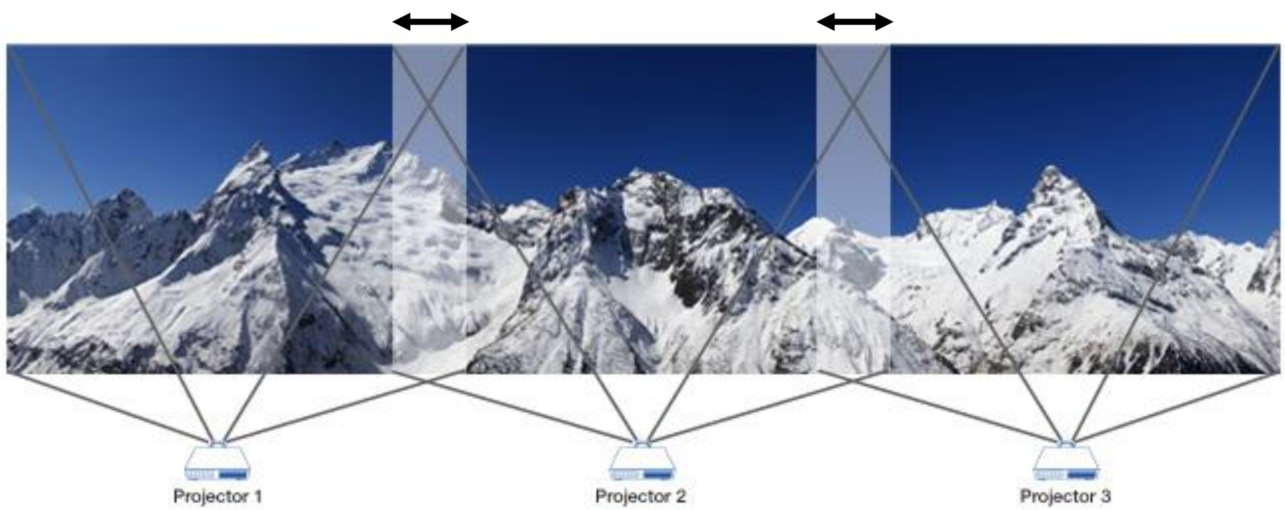
XIAO ET AL, 2018. DeepFocus : Learned Image Synthesis for Accommodation-Supporting Displays. *Siggraph Asia*

Outline

- Binocular 3D displays
  - Color Anaglyph
  - Polarization
  - Active Shutter Glasses
  - Head-Mounted Displays
- Autostereoscopic (Glass-free 3D) Displays
  - Parallax Barriers
  - Integral Imaging
  - Multi-layer displays
  - Holographic displays
- Head-Mounted Displays with accommodation cues
- Multi-projector displays
- HDR displays

Multi-projector Displays

- **Mainly used to provide a wide panoramic display**
- **Edge blending, color/contrast/brightness matching between overlapping regions is an issue (the transition must be seamless)**
- **The display surface may be curved**



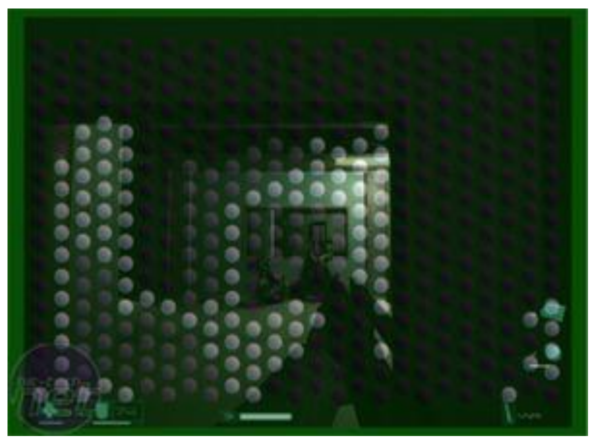
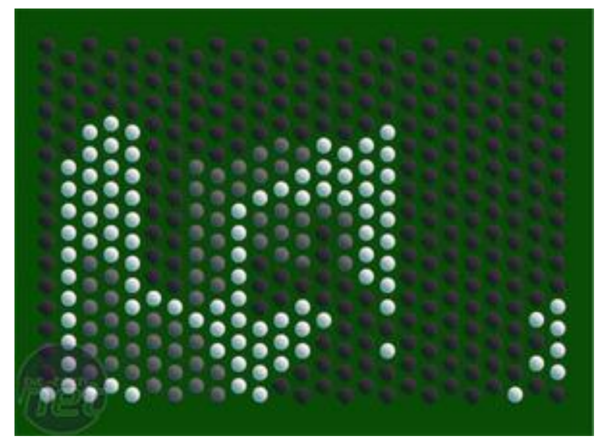
Images adapted from http://www.matrox.com

Multi-projector Displays

Video adapted from https://www.youtube.com/watch?v=dOY2lREuwjU

HDR Displays

- **Instead of using a single constant backlight source, an array of LEDs is used**
- **The LEDs may be individually adjusted for different brightness levels**

Images adapted from http://www.bit-tech.net/hardware/2005/10/04/brightside_hdr_edr/6

HDR Displays

- **Comparison of LDR display (left) with Brightside HDR display (right)**

Images adapted from http://www.bit-tech.net/hardware/2005/10/04/brightside_hdr_edr/8

HDR Displays

- **Comparison of LDR display (left) with Brightside HDR display (right)**

Images adapted from http://www.bit-tech.net/hardware/2005/10/04/brightside_hdr_edr/8

HDR Displays

- **Comparison of LDR display (left) with Brightside HDR display (right)**

Images adapted from http://www.bit-tech.net/hardware/2005/10/04/brightside_hdr_edr/8

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- **Cholewiak et al, “ChromaBlur: Rendering Chromatic Eye Aberration Improves Accommodation and Realism in HMDs”. ACM Transactions on Graphics, (2017)**
- **Yu et al*, “*A Perception-driven Hybrid Decomposition for Multi-layer Accommodative Displays” IEEE Transactions on Visualization and Computer Graphics (2019)**

Acknowledgements

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