Display Technologies

Advanced Graphics and Image Processing

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Overview

- Temporal aspects
  - Latency in VR
  - Eye-movement
  - Hold-type blur
- 2D displays
  - 2D spatial light modulators
  - High dynamic range displays
- 3D displays
  - Light field displays
  - Holographic displays

Latency in VR

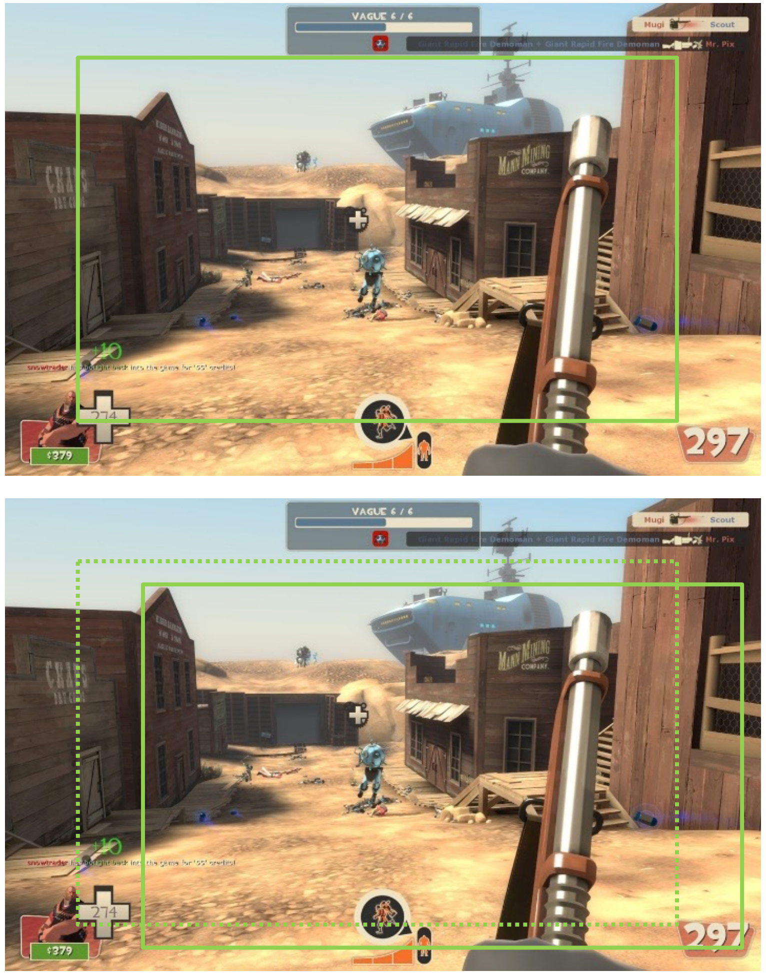
- Sources of latency in VR
  - IMU ~1 ms
    - Inertial Measurement Unit
  - sensor fusion, data transfer
  - rendering: depends on complexity of scene & GPU – a few ms
  - data transfer again
  - Display
    - 60 Hz = 16.6 ms;
    - 70 Hz = 11.1 ms;
    - 120 Hz = 8.3 ms.

- Target latency
  - Maximum acceptable: 20ms
  - Much smaller (5ms) desired for interactive applications

- Example
  - 16 ms (display) + 16 ms (rendering) + 4 ms (orientation tracking) = 36 ms latency total
  - At 60 deg/s head motion, 1Kx1K, 100deg fov display:
    - 19 pixels error
    - Too much

Post-rendering image warp (time warp)

- To minimize end-to-end latency
- The method:
  - get current camera pose
  - render into a larger raster than the screen buffer
  - get new camera pose
  - warp rendered image using the latest pose, send to the display
    - 2D image translation
    - 2D image warp
    - 3D image warp
- Original paper from Mark et al. 1997, also Darsa et al. 1997
  - Meta: Asynchronous Time Warp



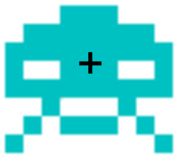
Eye movement - basics

Fixation

Drift: 0.15-0.8 deg/s

Eye movement - basics

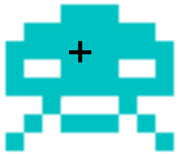
Saccade



160-300 deg/s

Eye movement - basics

Smooth Pursuit Eye Motion (SPEM)

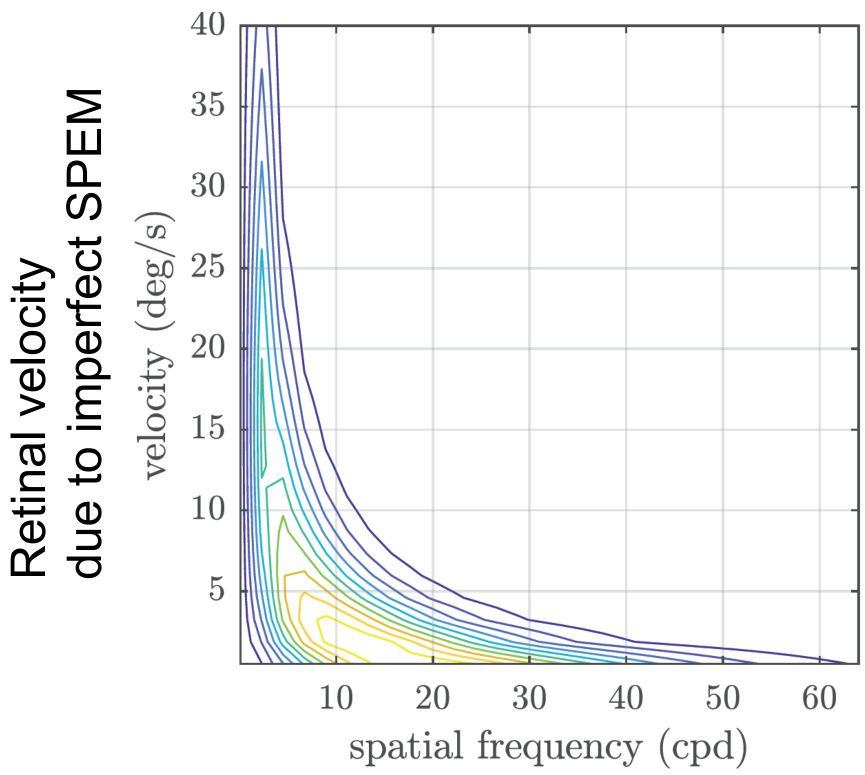


Up to 80 deg/s
The tracking is imperfect
 - especially at higher velocities
 - and for unpredictable motion

Retinal velocity

- The eye tracks moving objects
  - Smooth Pursuit Eye Motion (SPEM) stabilizes images on the retina
  - But SPEM is imperfect
- Loss of sensitivity mostly caused by imperfect SPEM
  - SPEM worse at high velocities

Spatio-velocity contrast sensitivity



Kelly’s model [1979]

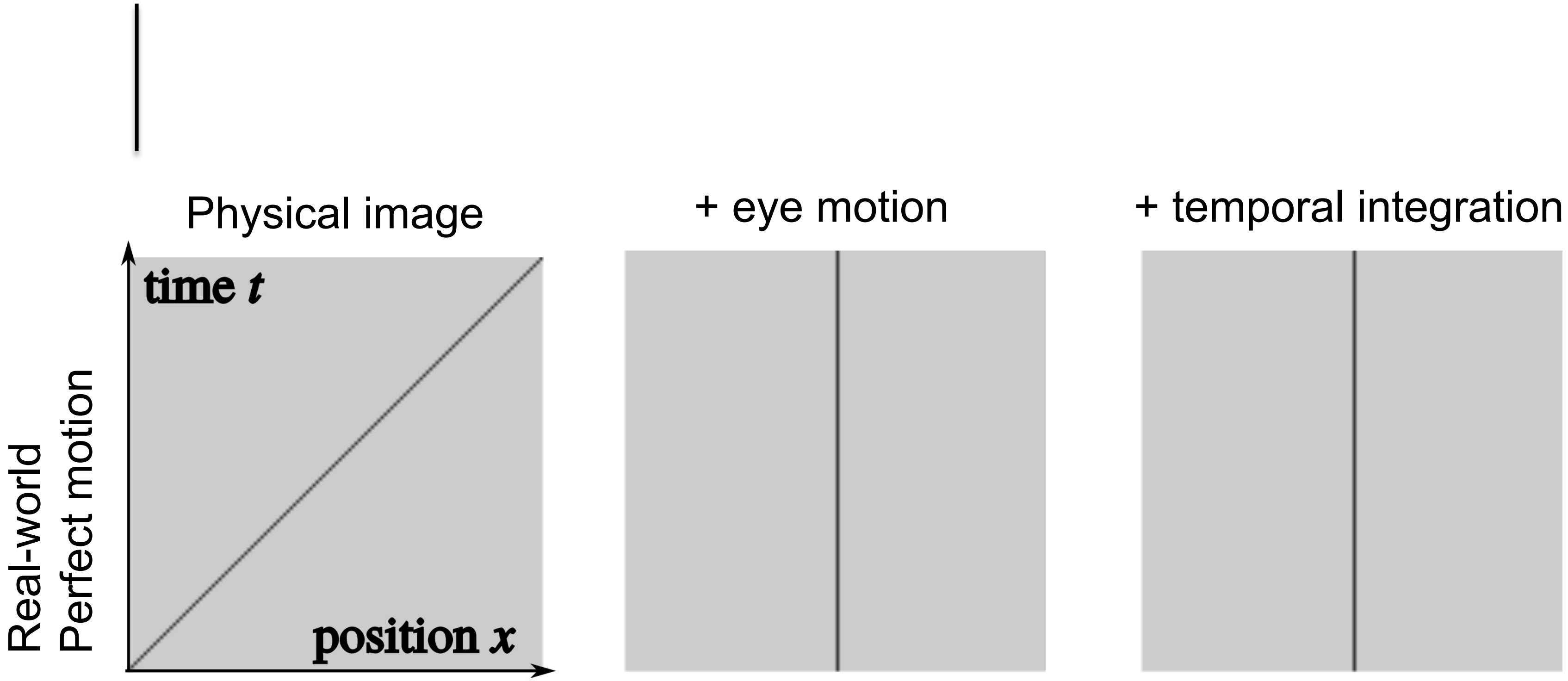
Motion sharpening

- The visual system "sharpens" objects moving at speeds of 6 deg/s or more

  - Potentially a reason why VR appears sharper than it actually is

Hold-type blur

- The eye smoothly follows a moving object
- But the image on the display is "frozen" for 1/60th of a second



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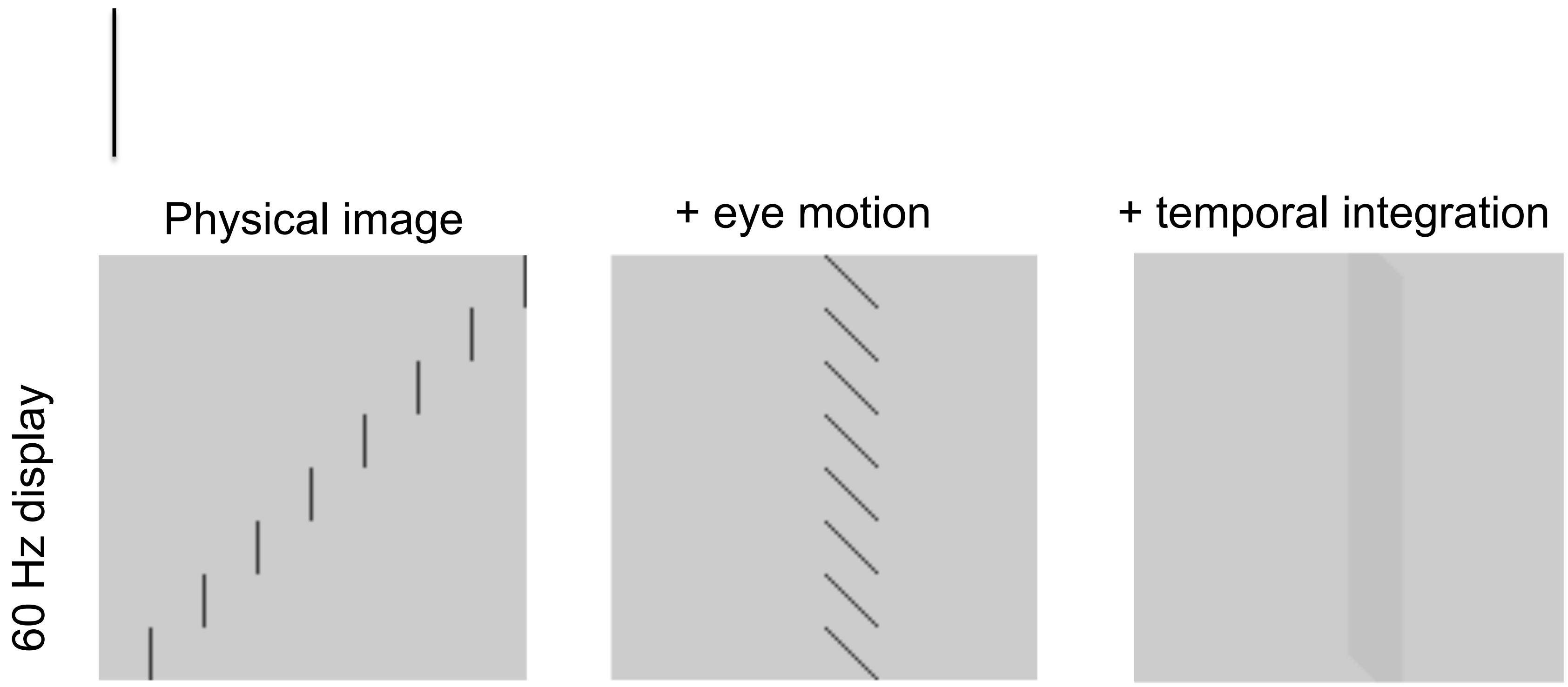

Original scene

With hold-type blur

Hold-type blur

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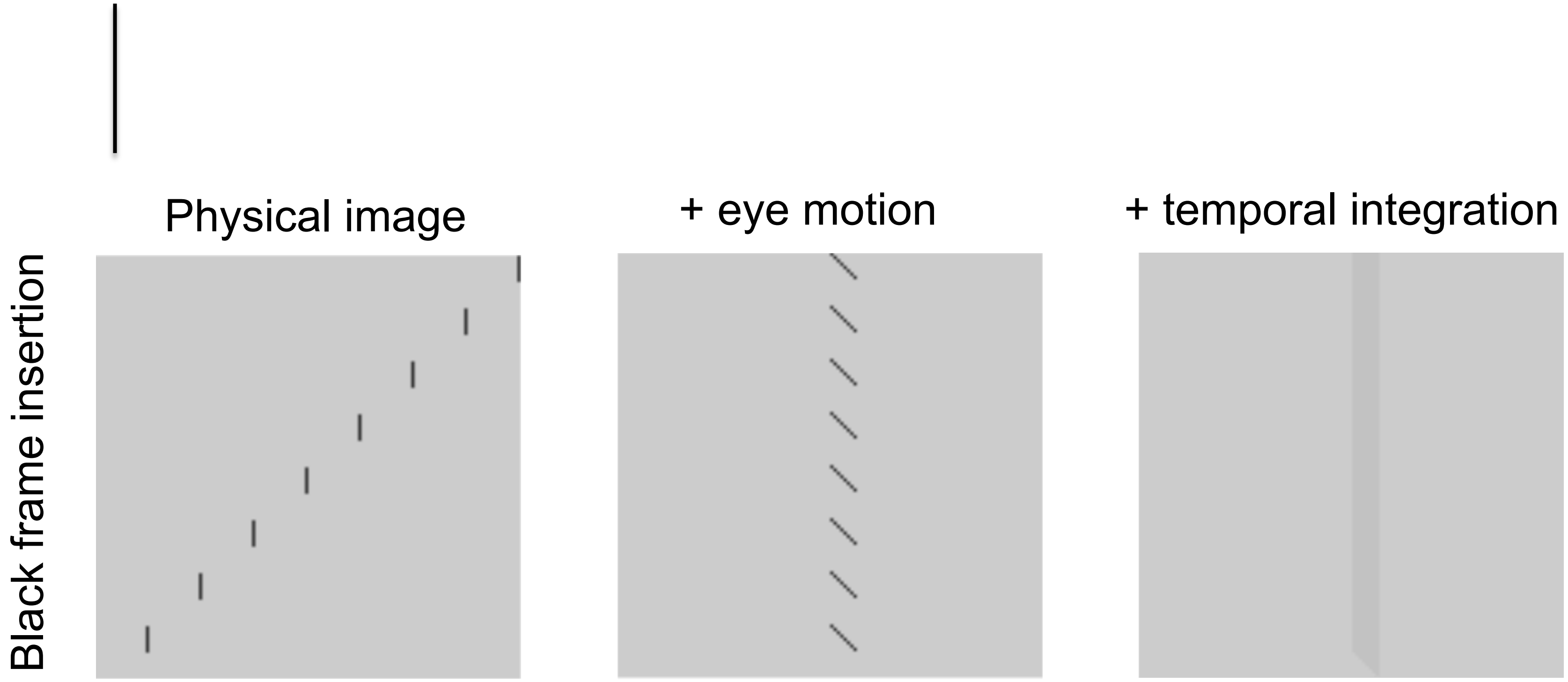
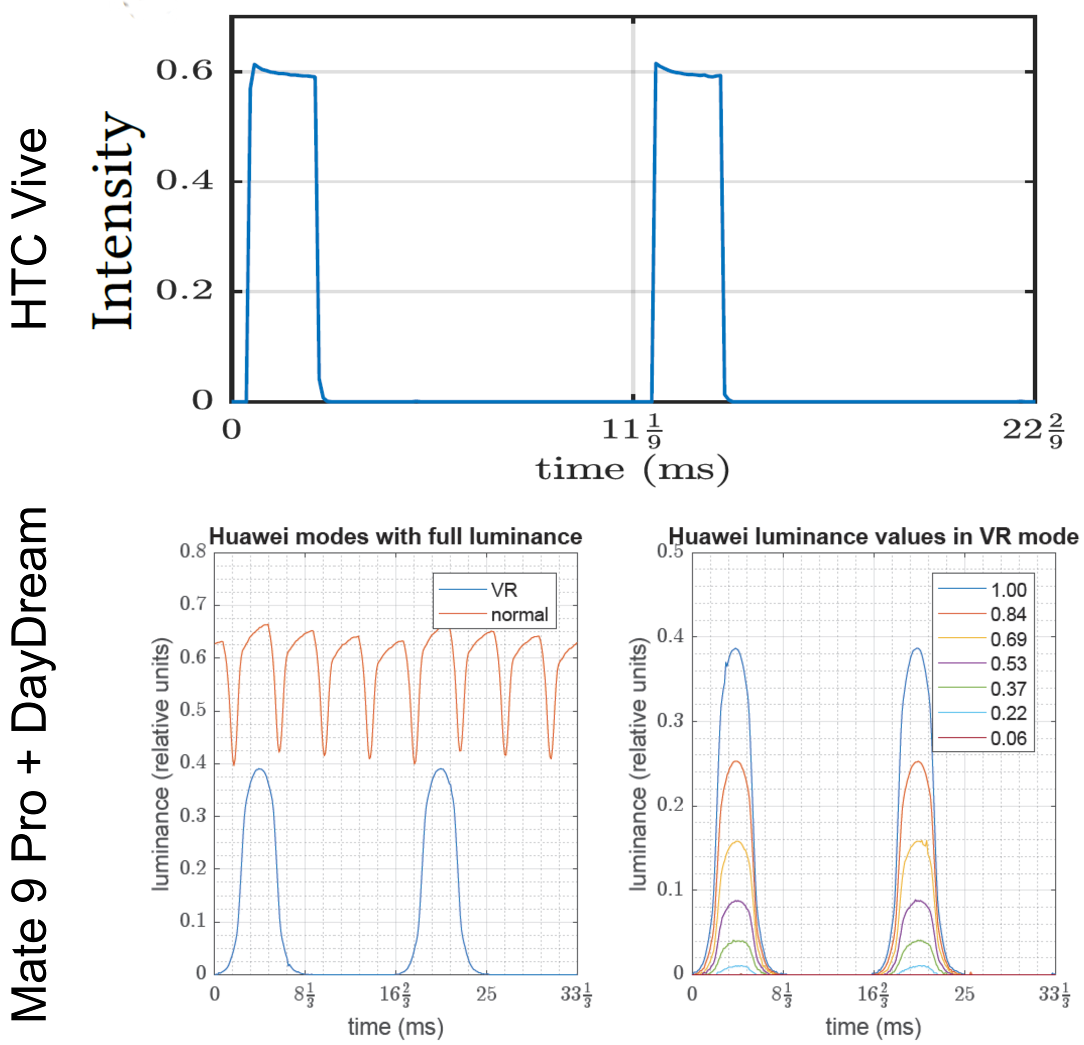
- But the image on the display is "frozen" for 1/60th of a second



Low persistence displays

- Most VR displays flash an image for a fraction of frame duration
- This reduces hold-type blur
- And also reduces the perceived lag of the rendering



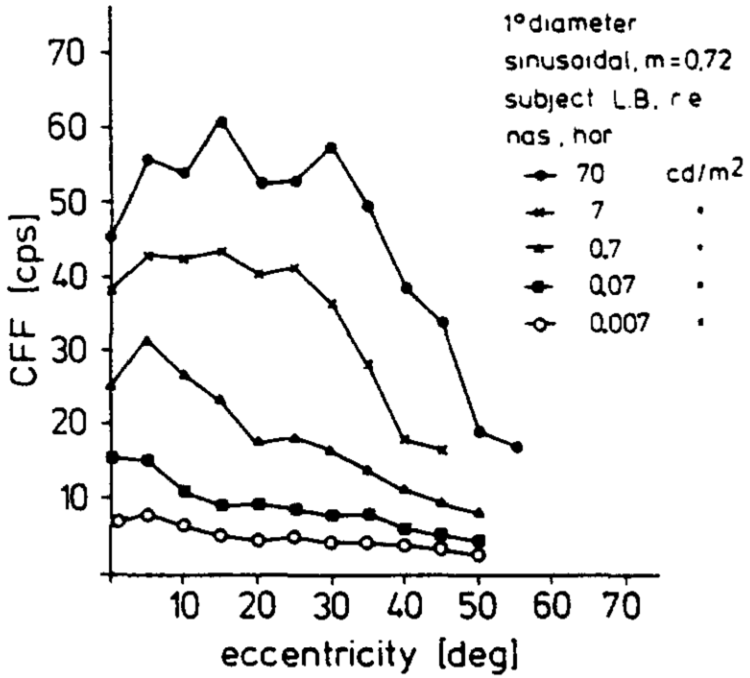
Black frame insertion

- Which invader appears sharper?

- A similar idea to low-persistence displays in VR
- Reduces hold-type blur

Flicker

- Critical Flicker Frequency
  - The lowest frequency at which flickering stimulus appears as a steady field
  - Measured for full-on / off presentation
  - Strongly depends on luminance – big issue for HDR VR headsets
  - Varies with eccentricity and stimulus size
  - It is possible to detect flicker even at 2kHz
    - For saccadic eye motion



[Hartmann et al. 1979]

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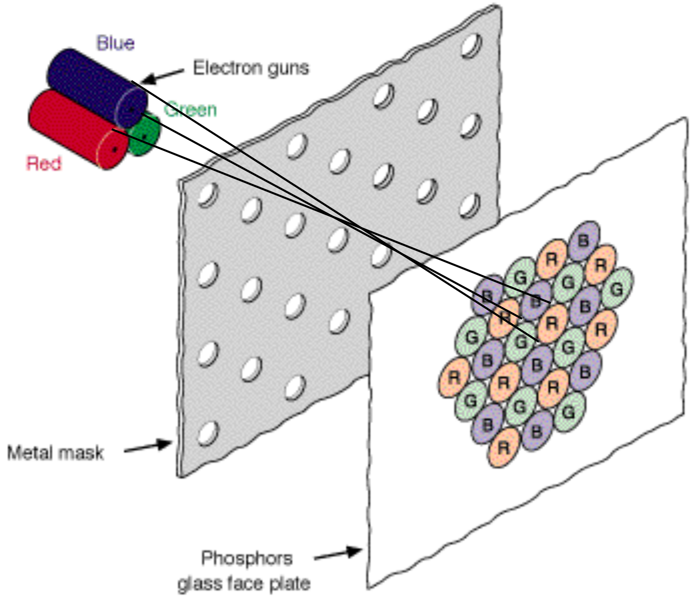
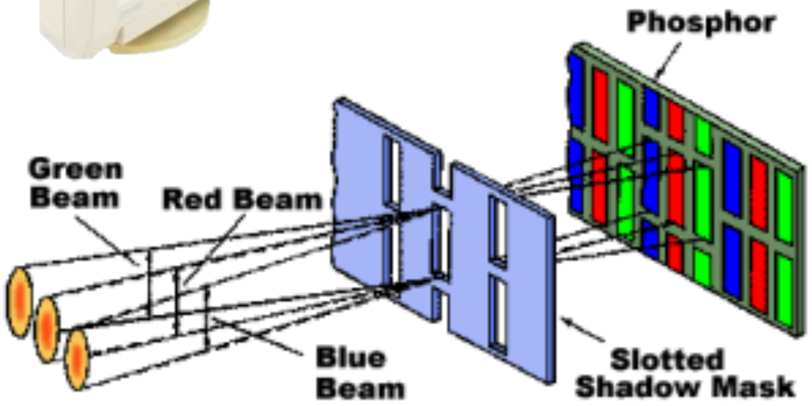
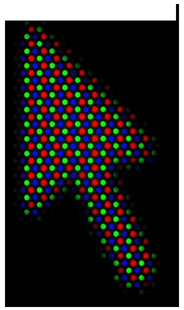
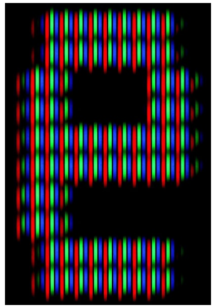
Cathode Ray Tube





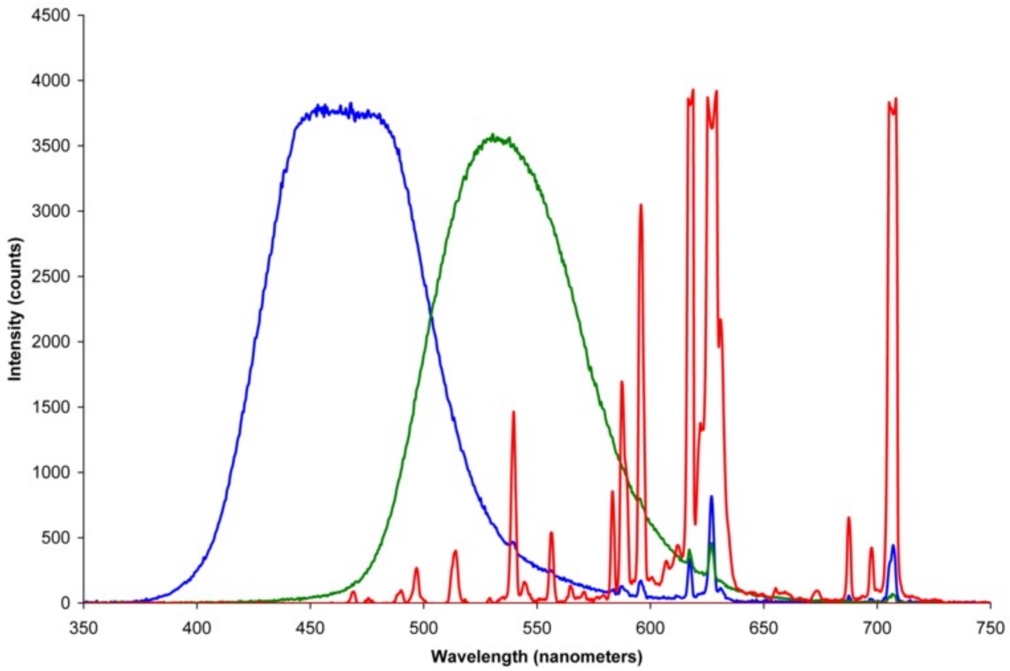




[from wikipedia]

Spectral Composition

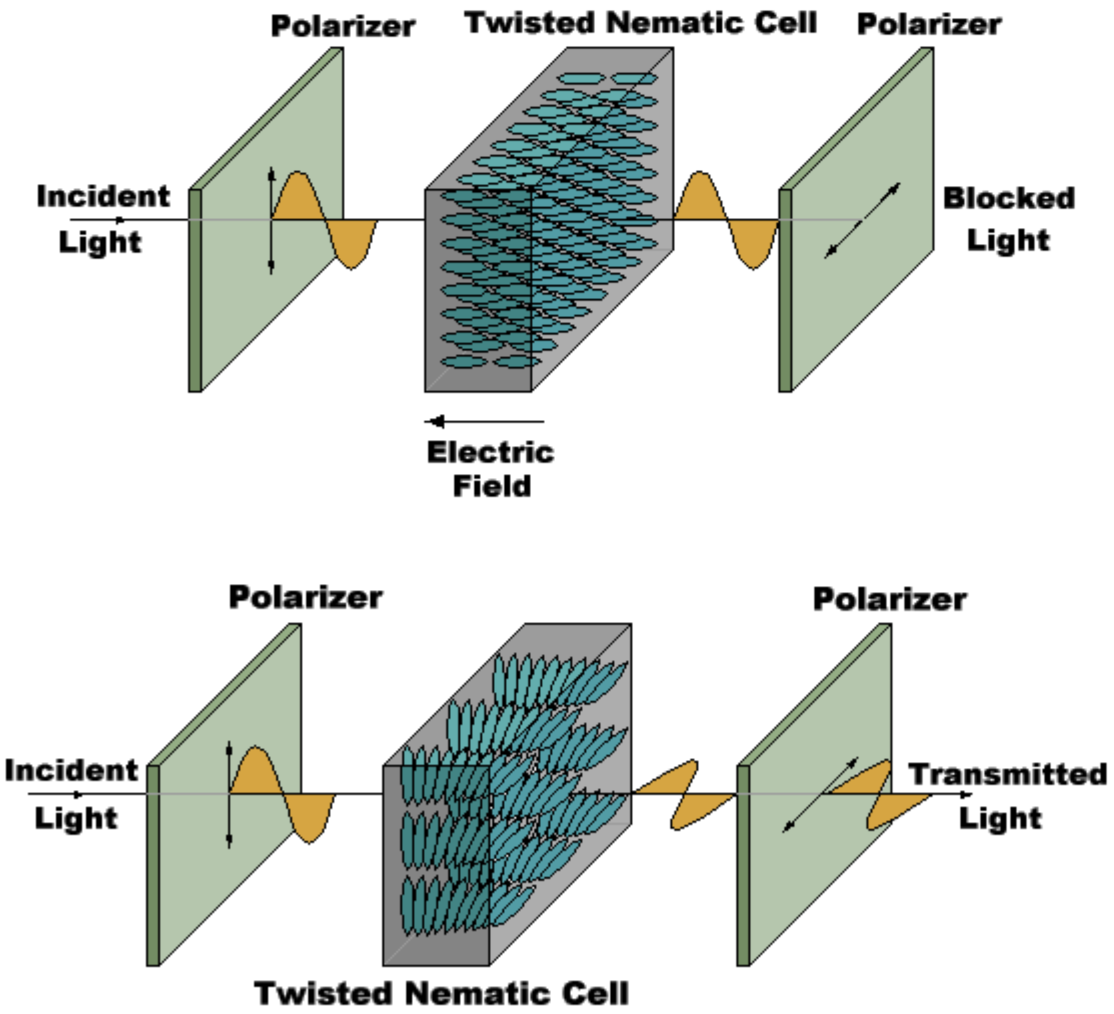
- three different phosphors



- saturated and natural colors
- inexpensive
- high contrast and brightness

[from wikipedia]

Liquid Chrystal Displays (LCD)



From: http://computer.howstuffworks.com/monitor5.htm

Twisted neumatic LC cell

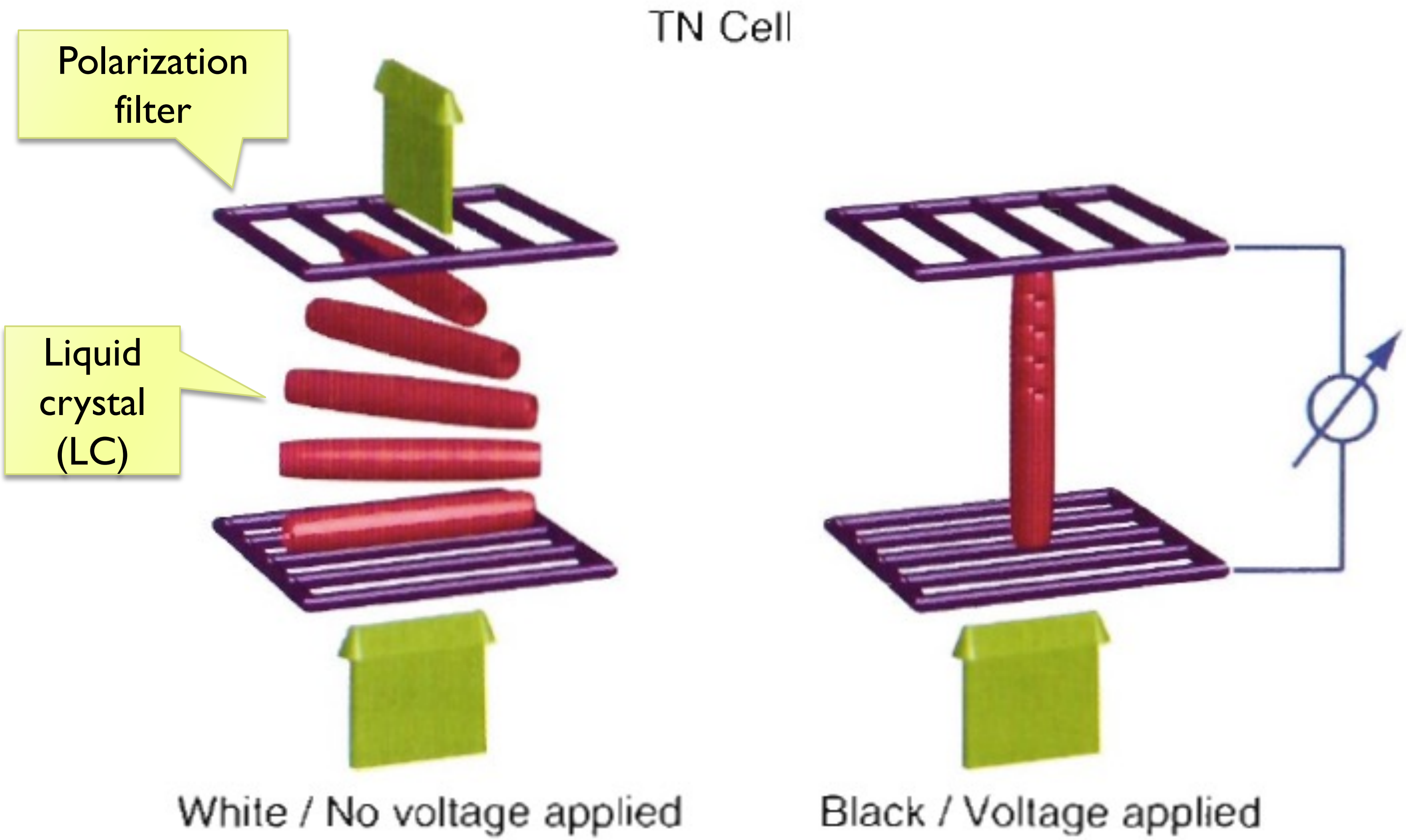


Figure from: High Dynamic Range Imaging by E. Reinhard et al.

In-plane switching cell (IPS)

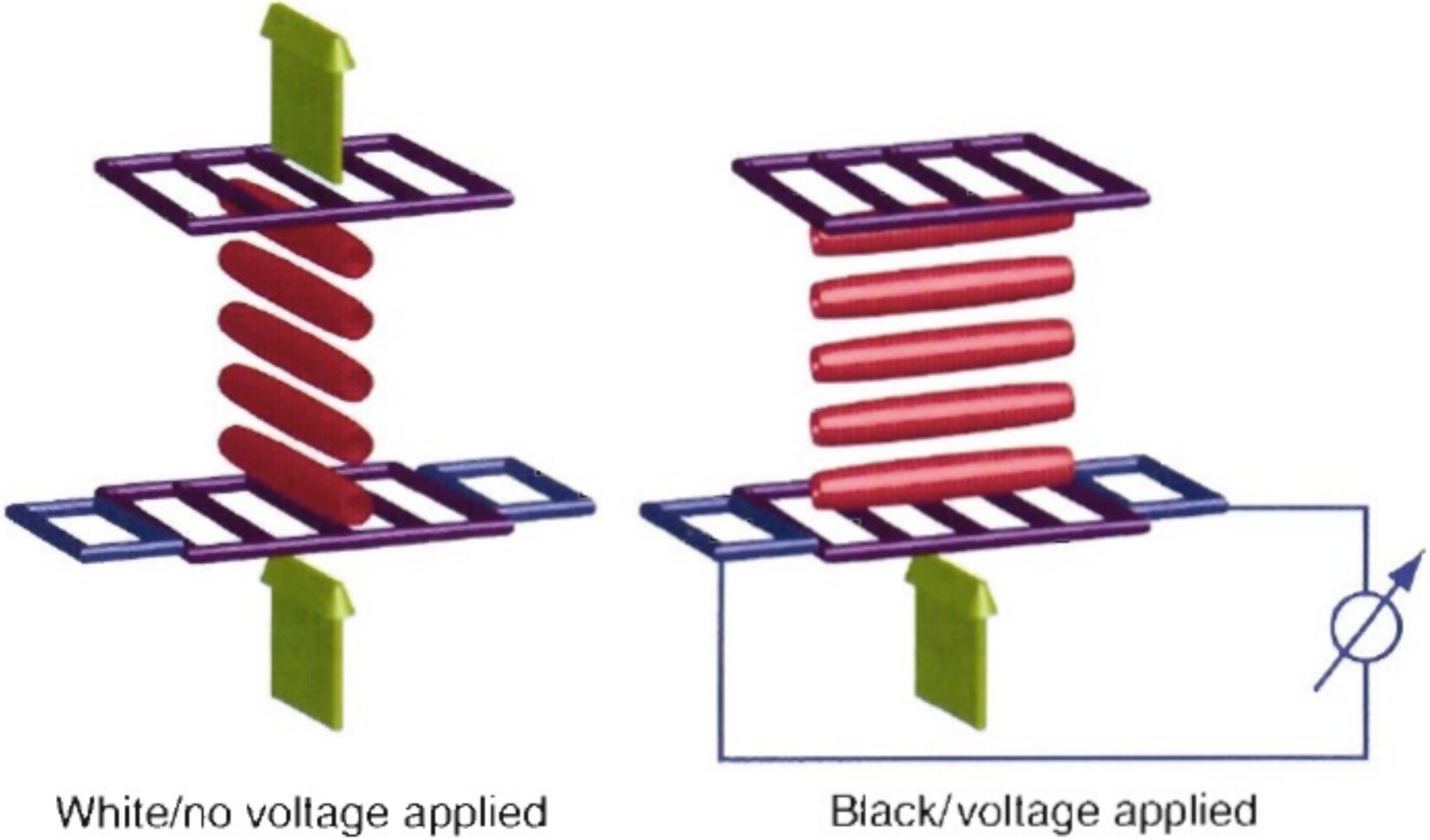
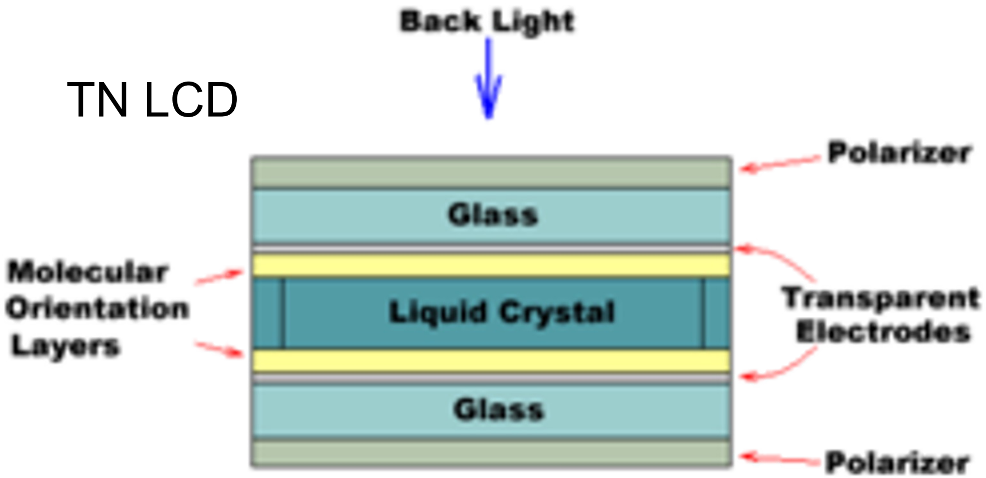
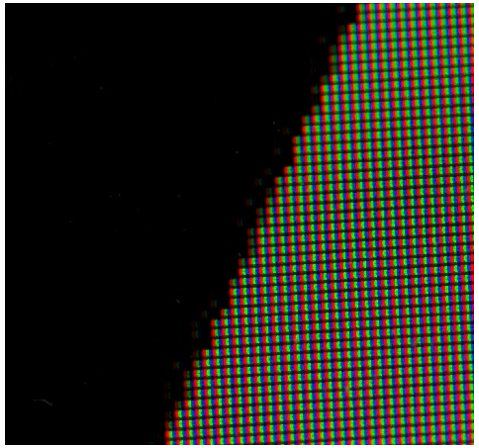


Figure from: High Dynamic Range Imaging by E. Reinhard et al.

LCD

TN LCD



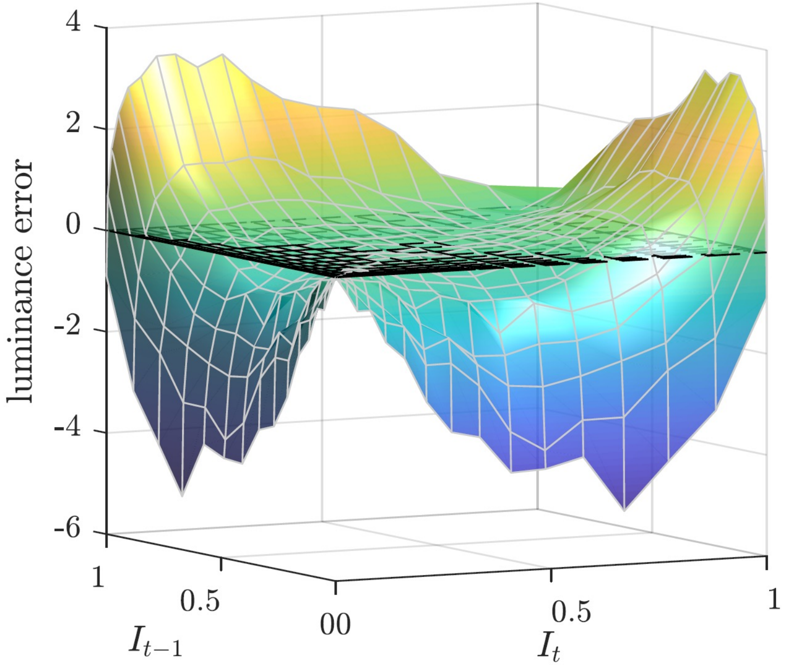


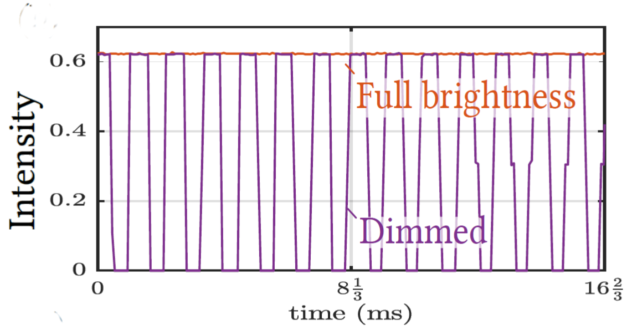
A white slanted edge (photograph)

- color may change with the viewing angle
- contrast up to 3000:1
- higher resolution results in smaller fill-factor
- color LCD transmits only up to 8% (more often close to 4-5%) light when set to full white

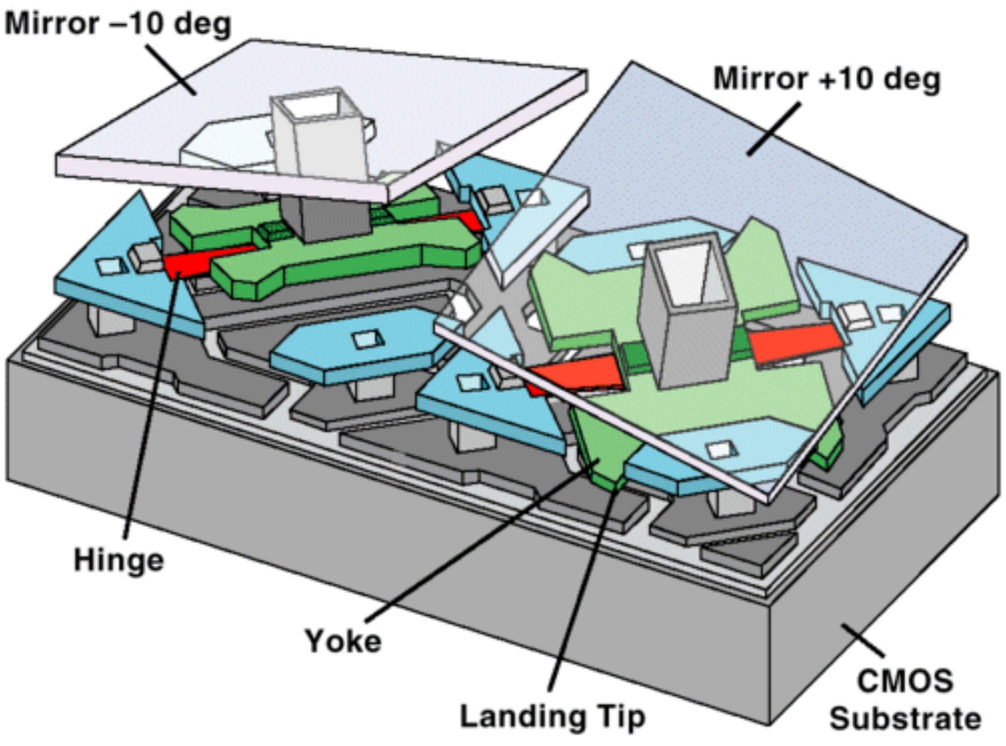
LCD temporal response

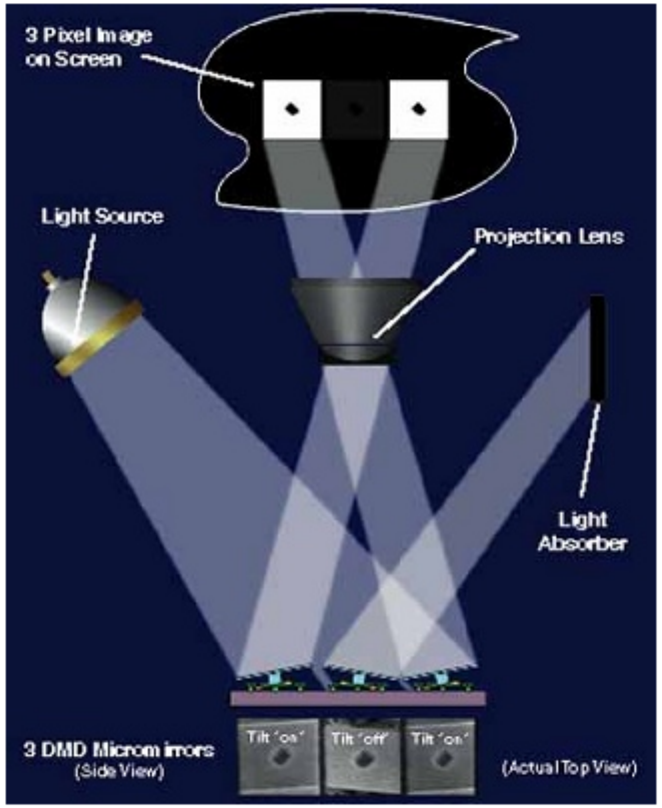
- Experiment on an IPS LCD screen
- We rapidly switched between two intensity levels at 120Hz
- Measured luminance integrated over 1s
- The top plot shows the difference between expected ($\frac{I_{t-1}+I_t}{2}$) and measured luminance
- The bottom plot: intensity measurement for the full brightness and half-brightness display settings
  - Pulse-Width Modulation controls brightness of the backlight





Digital Micromirror Devices (DMDs/DLP)





Texas Instruments

- 2-D array of mirrors
- Truly digital pixels
- Grey levels via Pulse-Width Modulation

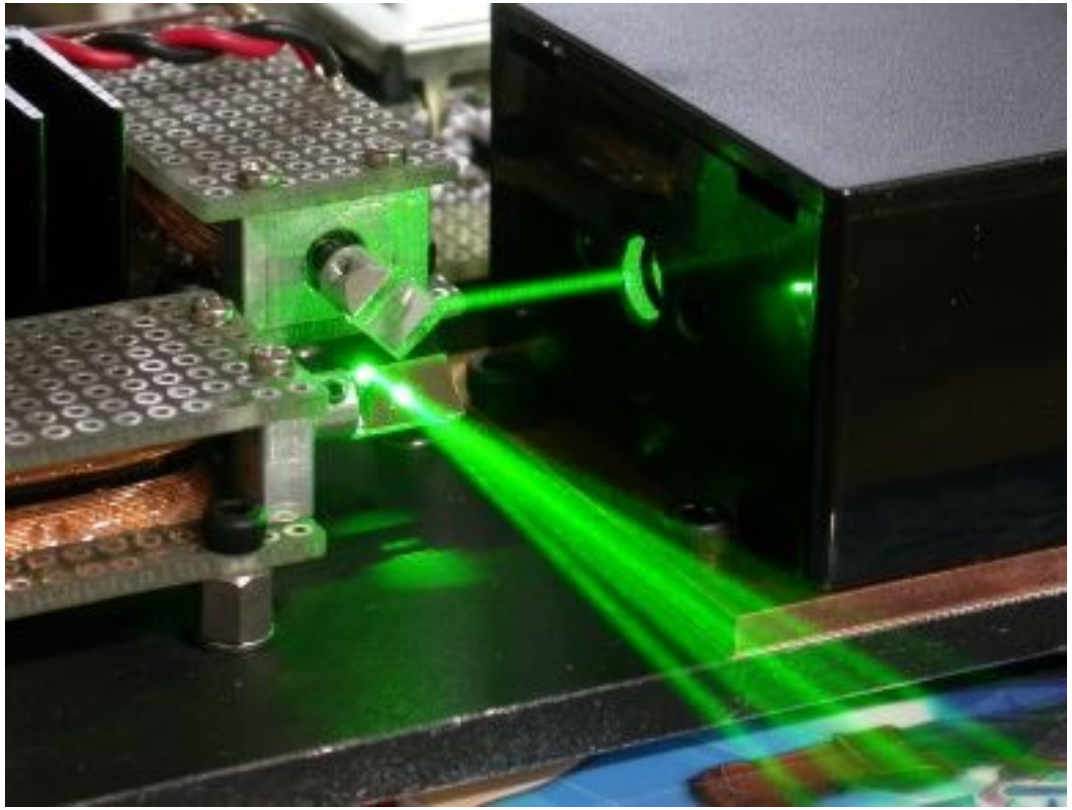
Liquid Crystal on Silicon (LCoS)

- basically a reflective LCD
- standard component in projectors and head mounted displays
- used e.g. in Google Glass

Scanning Laser Projector

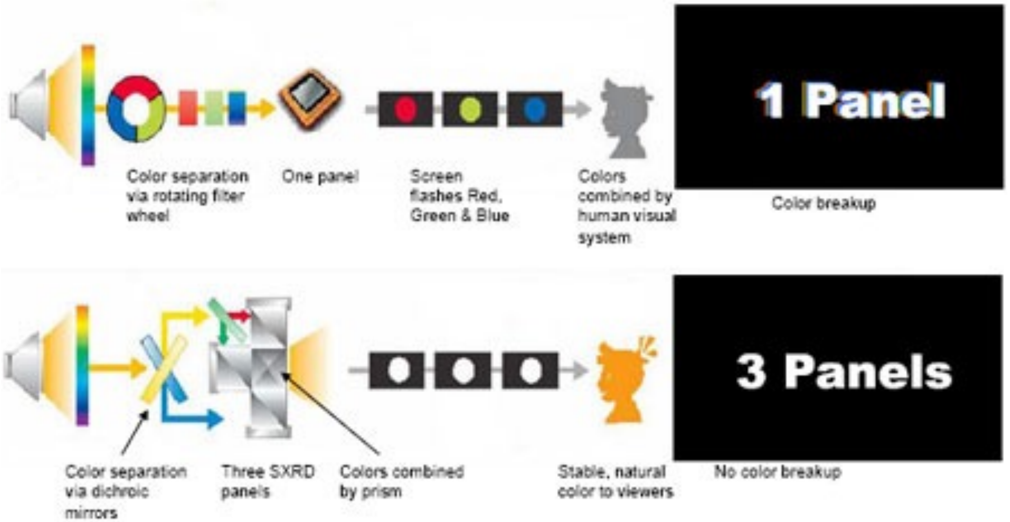
- maximum contrast
- scanning rays

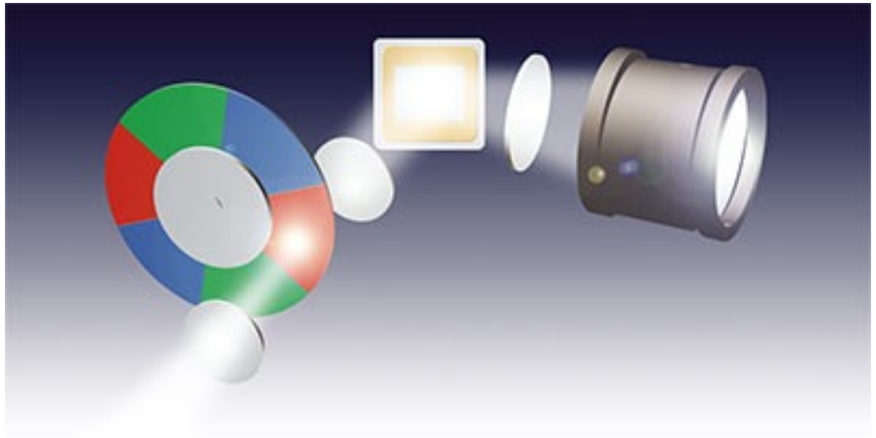
- very high power lasers needed for high brightness



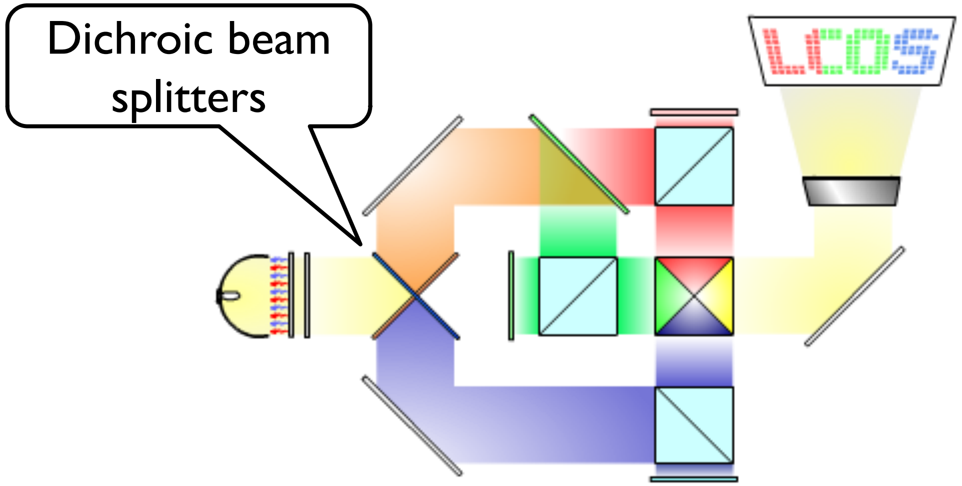
http://elm-chan.org/works/vlp/report_e.html

3-chip vs. Color Wheel Display





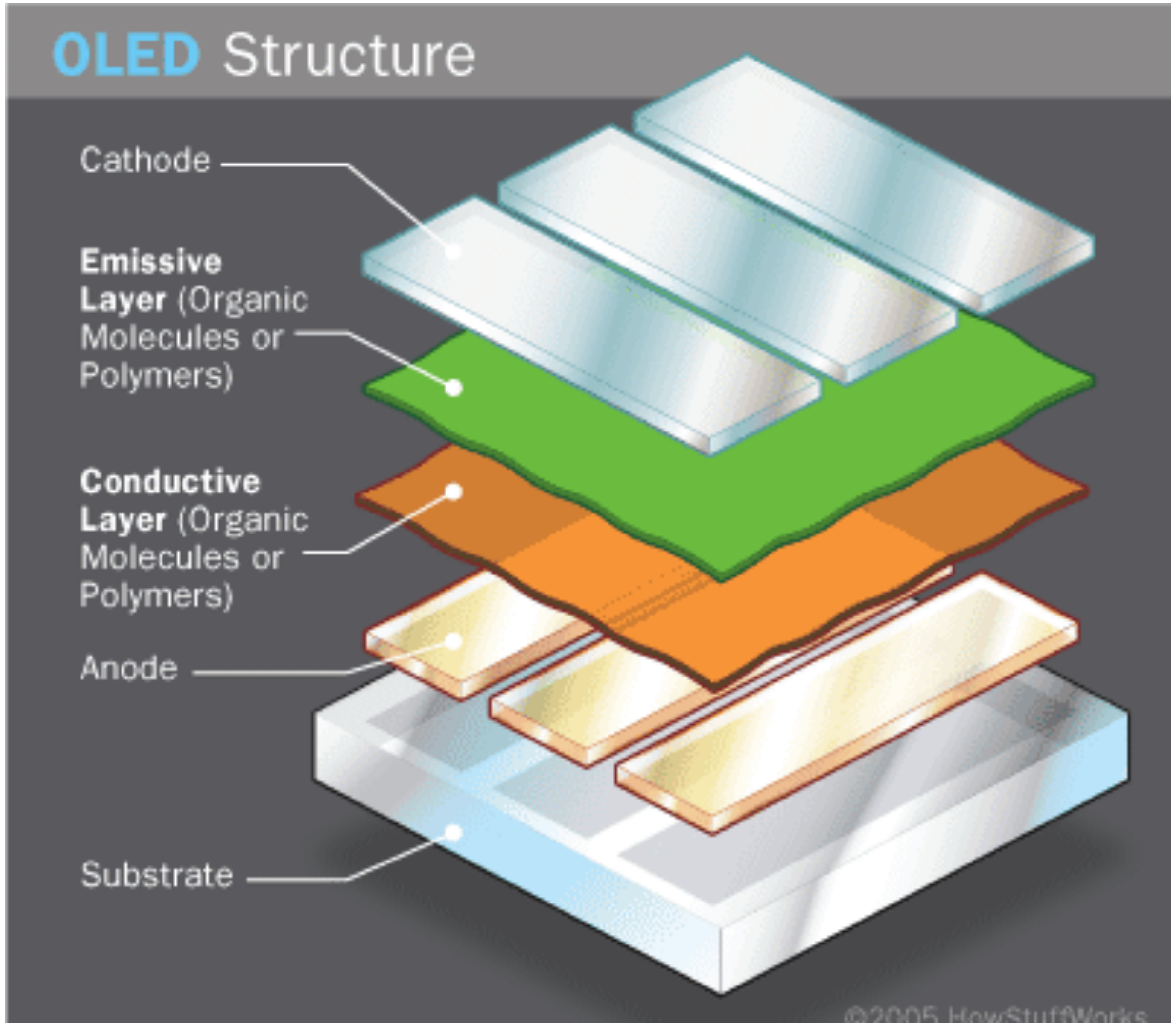
- color wheel
  - cheap
  - time sequenced colors
  - color fringes with motion/video
    - mitigated with advanced colour wheels
- 3-chip
  - complicated setup
  - no color fringes



OLED

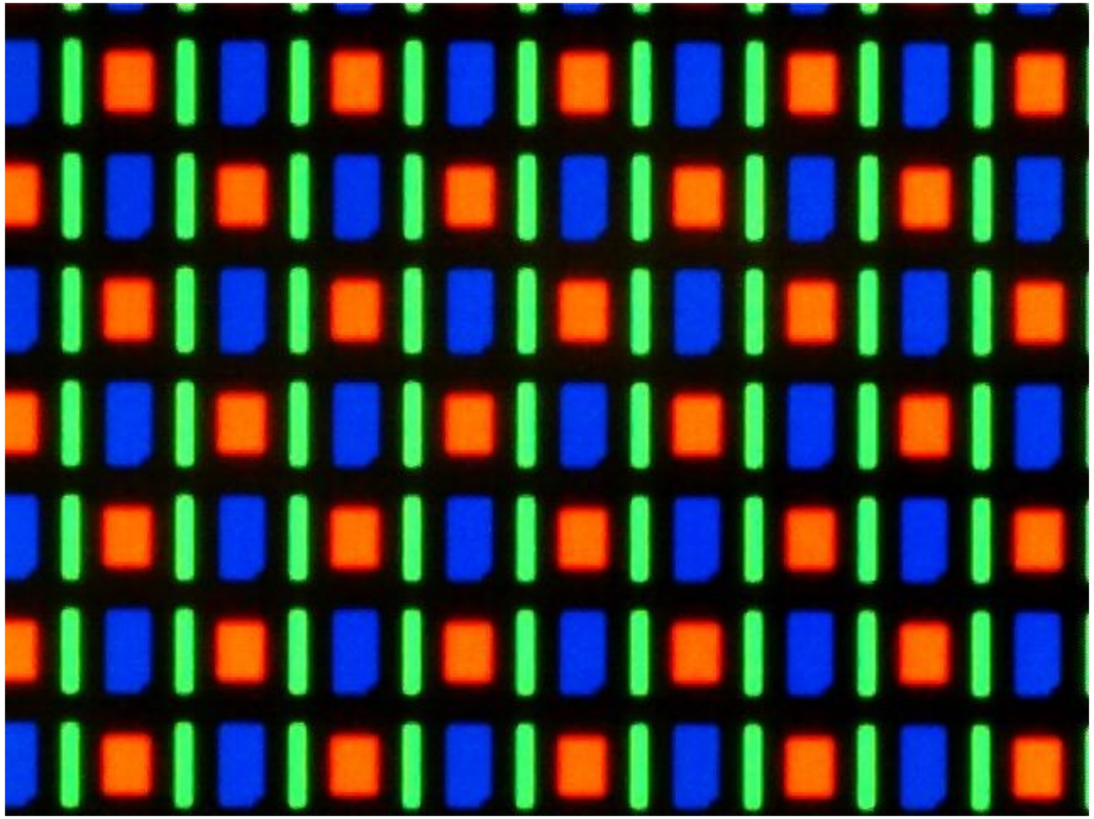
- based on electrophosphorescence
- large viewing angle
- the power consumption varies with the brightness of the image
- fast (< 1 microsec)
- arbitrary sizes

- life-span can be short
  - Worst for blue OLEDs

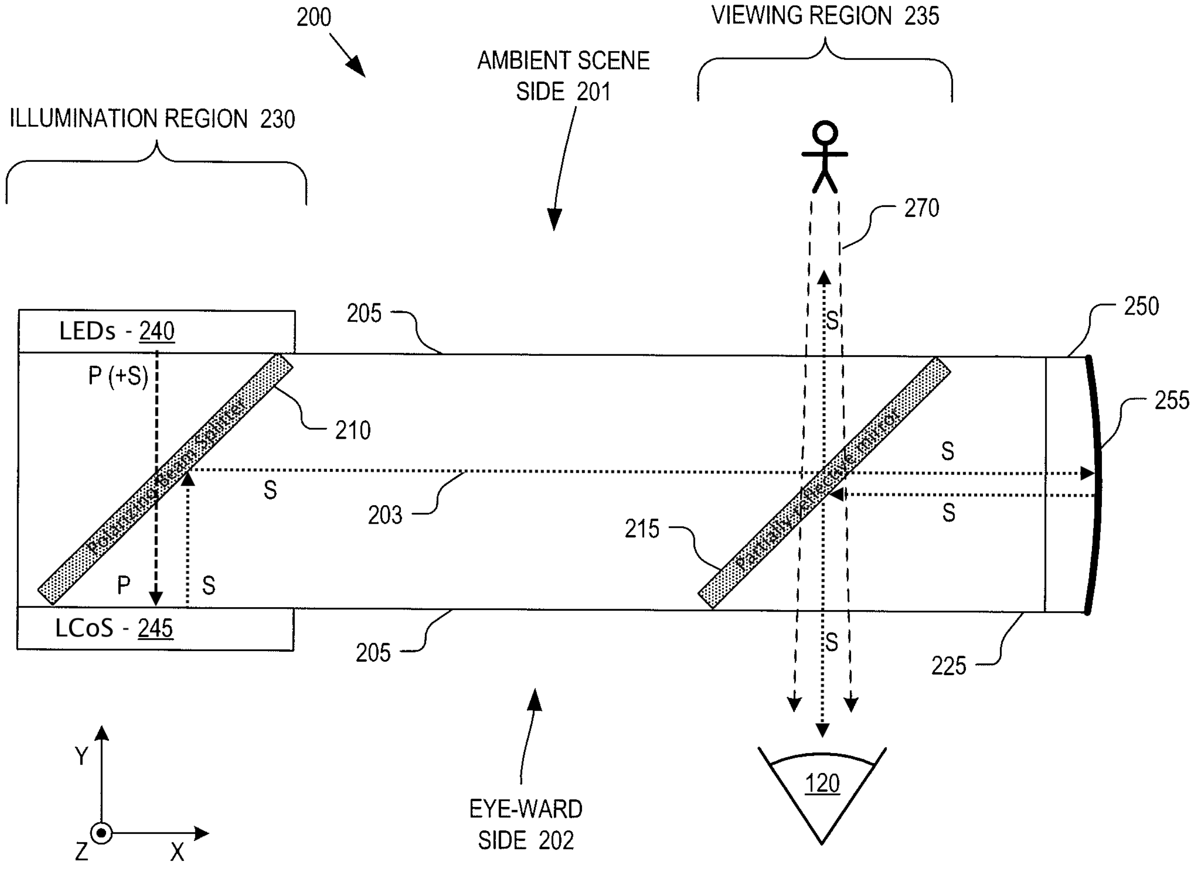


Active matrix OLED

- Commonly used in mobile phones (AMOLED)
- Very good contrast
  - But the screen more affected by glare than LCD
- But limited brightness
  - The brighter is OLED, the shorter is its live-span



Bird-bath optics for near-eye displays



Google Glass

Pros:

- Simple, efficient design

Cons:

- Cannot be scaled up easily

More reading: https://kguttag.com/2017/03/03/near-eye-bird-bath-optics-pros-and-cons-and-immys-different-approach/

Diffractive waveguides

US 2016/0116739

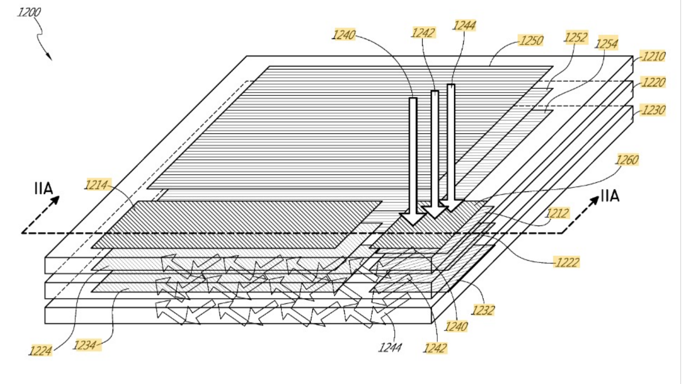
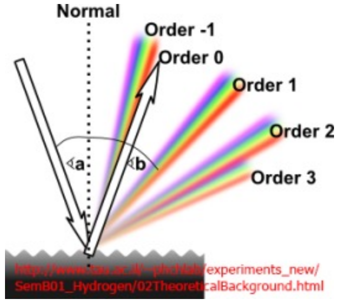
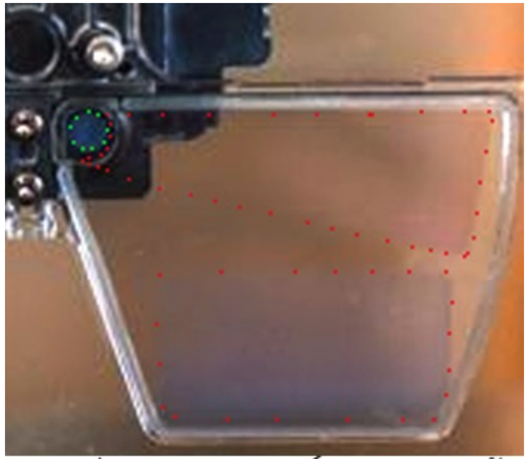
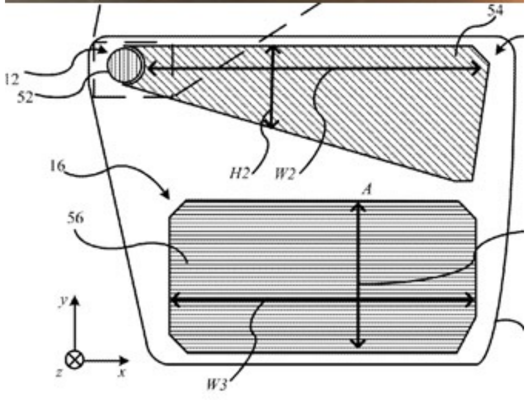


FIG. IIB

Magic Leap

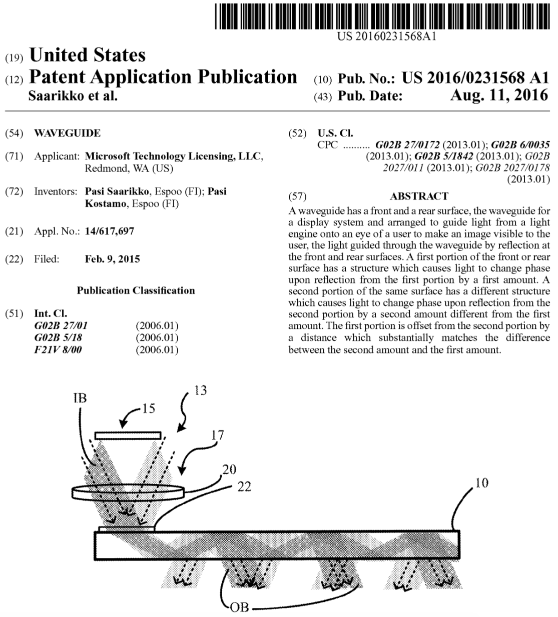






US 2016/0231568

Fig. 3B



US 20160231568A1

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(12) Patent Application Publication
Saarikko et al.

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(43) Pub. Date: Aug. 11, 2016

(54) WAVEGUIDE

(71) Applicant: Microsoft Technology Licensing, LLC, Redmond, WA (US)

(72) Inventors: Pasi Saarikko, Espoo (FI); Pasi Kostamo, Espoo (FI)

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G02B 5/18 (2006.01)
F21V 8/00 (2006.01)

(52) U.S. Cl.
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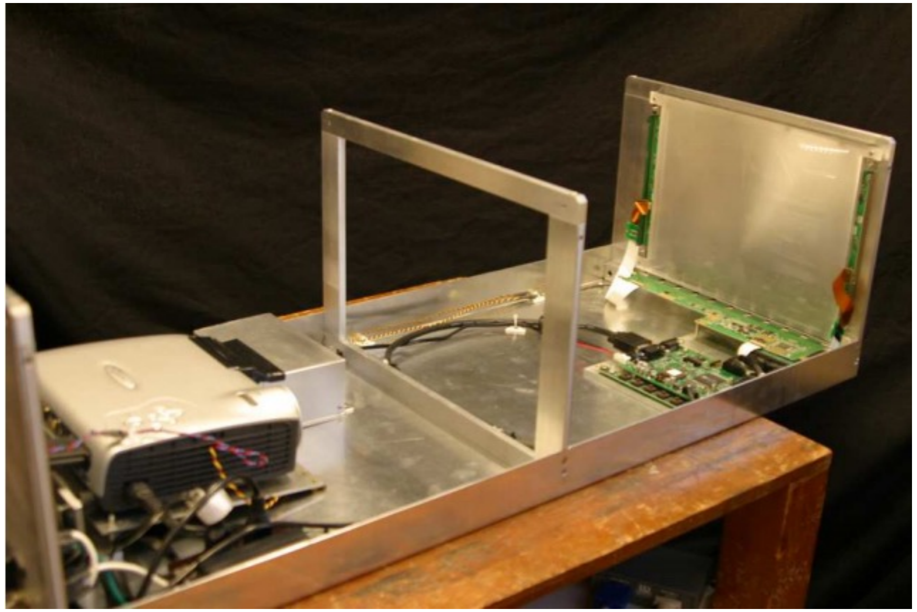
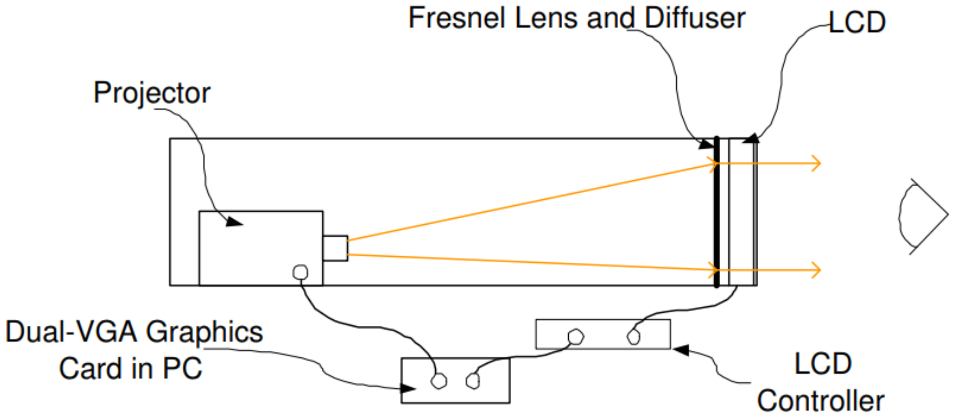
(57) ABSTRACT

A waveguide has a front and a rear surface, the waveguide for a display system and arranged to guide light from a light engine onto an eye of a user to make an image visible to the user, the light guided through the waveguide by reflection at the front and rear surfaces. A first portion of the front or rear surface has a structure which causes light to change phase upon reflection from the first portion by a first amount. A second portion of the same surface has a different structure which causes light to change phase upon reflection from the second portion by a second amount different from the first amount. The first portion is offset from the second portion by a distance which substantially matches the difference between the second amount and the first amount.

Microsoft Hololens

Prototype HDR display (2004)

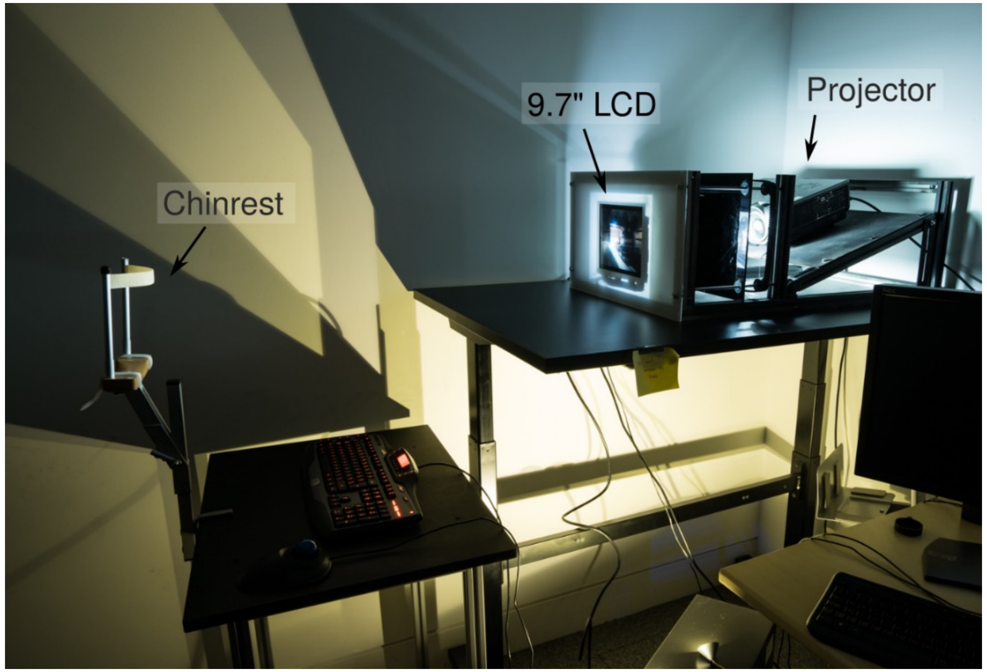


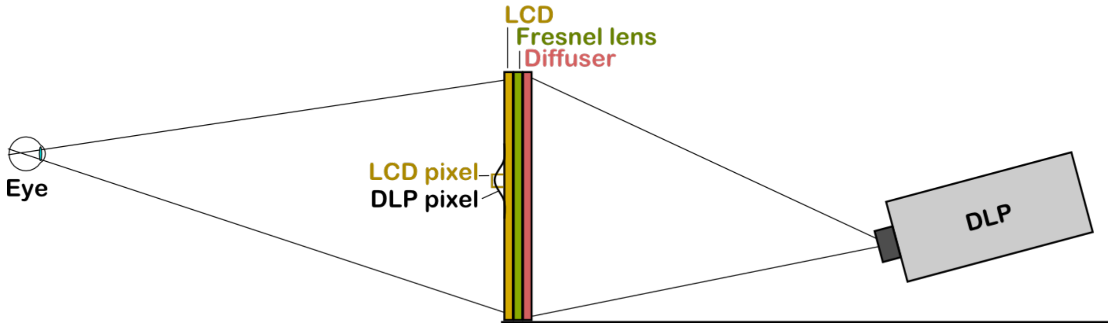


From [Seetzen et al. SIGGRAPH 2004]

Cambridge experimental HDR display

- 35,000 cd/m^2 peak luminance
- 0.01 cd/m^2 black level
- LCD resolution: 2048x1536
- Backlight (DLP) resolution: 1024x768
- Geometric-calibration with a DSLR camera
- Display uniformity compensation
- Bit-depth of DLP and LCD extended to 10 bits using spatio-temporal dithering





Modern HDR displays

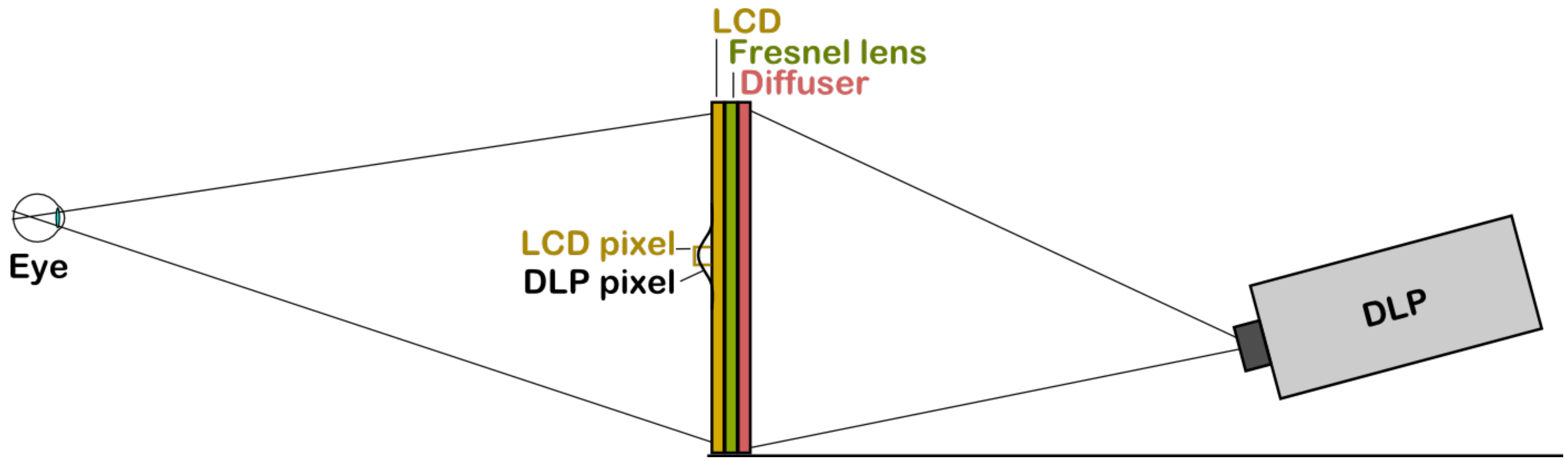
- Modulated LED array
- Conventional LCD
- Image compensation

Low resolution LED Array x High resolution Colour Image = High Dynamic Range Display

HDR Display

- Two spatial modulators
  - 1st modulator contrast 1000:1
  - 2nd modulator contrast 1000:1
  - Combined contrast 1000,000:1
- Idea: Replace constant backlight of LCD panels with an array of LEDs
  - Very few (about 1000) LEDs sufficient
  - Every LED intensity can be set individually
  - Very flat form factor (fits in standard LCD housing)
- Issue:
  - LEDs larger than LCD pixels
  - This limits maximum local contrast

HDR rendering algorithm - high level



Desired image

DLP blur (PSF)

$$\underset{L,D}{\operatorname{argmin}} \left\| I(x,y) - g * D(x,y)L(x,y) \right\|_2$$

DLP image

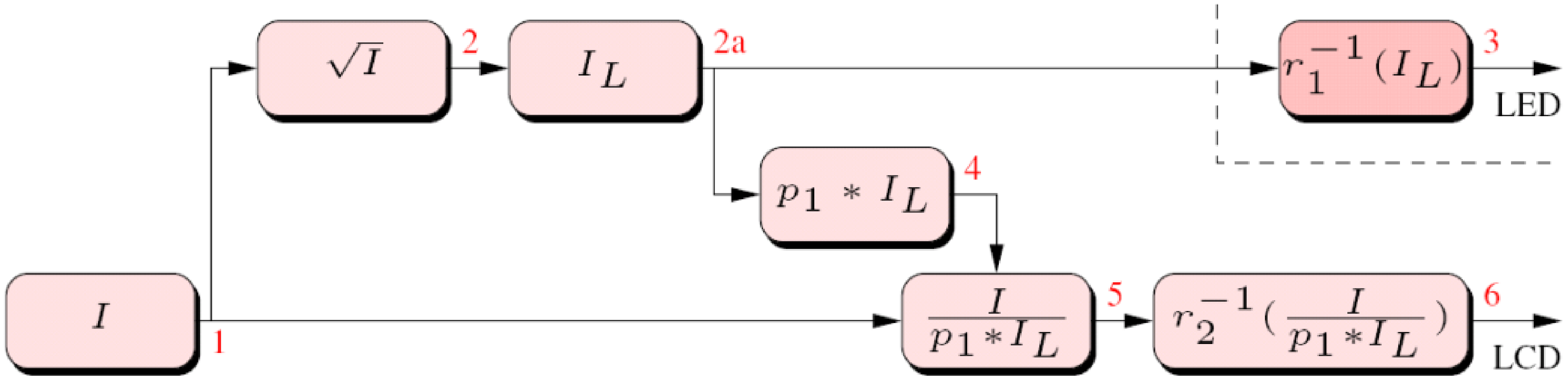
LCD image

Subject to:

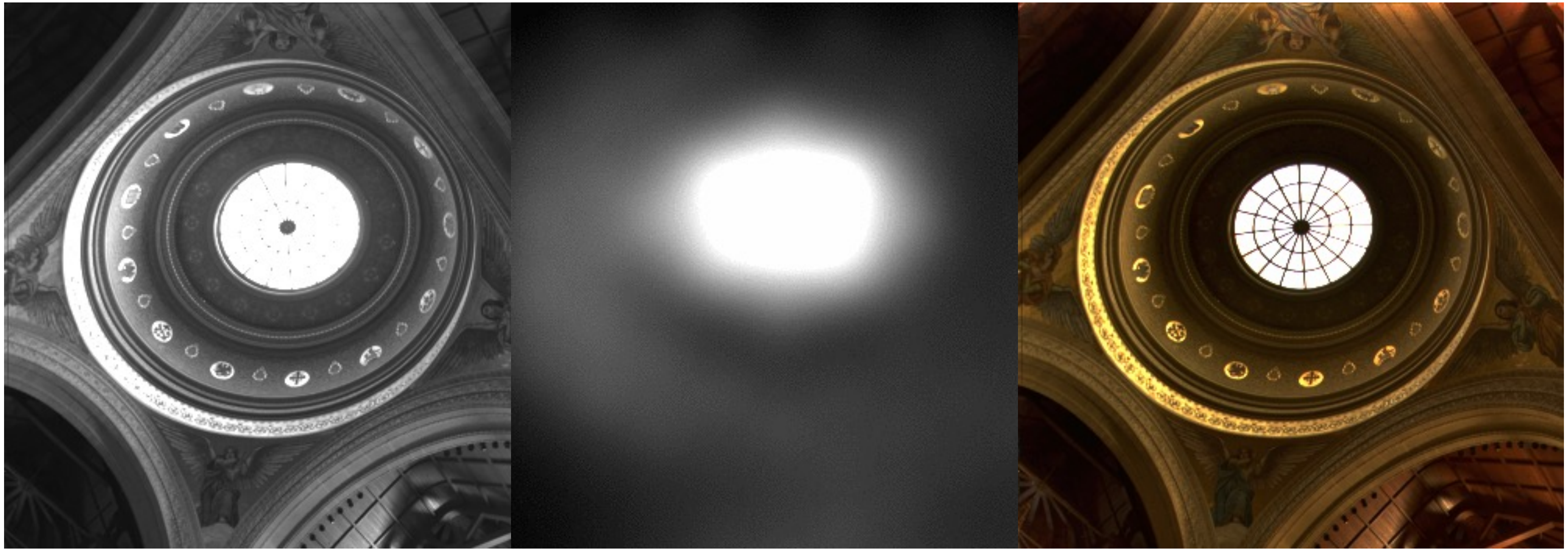
$$\forall (x,y) \quad L_{min} \leq L(x,y) \leq L_{max}$$

$$\forall (x,y) \quad D_{min} \leq D(x,y) \leq D_{max}$$

Simplified HDR rendering algorithm



Rendering Algorithm



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‘Auto’stereoscopic 3D Displays

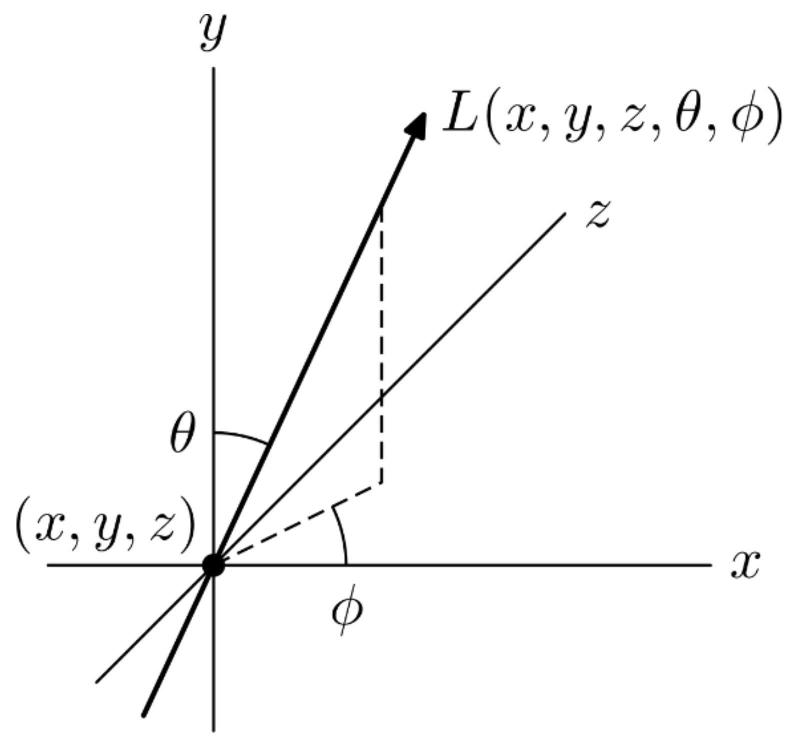
Autostereoscopy is any method of displaying stereoscopic images (adding binocular perception of 3D depth) without the use of special headgear, glasses, something that affects vision, or anything for eyes on the part of the viewer. Because headgear is not required, it is also called "**glasses-free 3D**" or "**glassesless 3D**". (from Wikipedia)

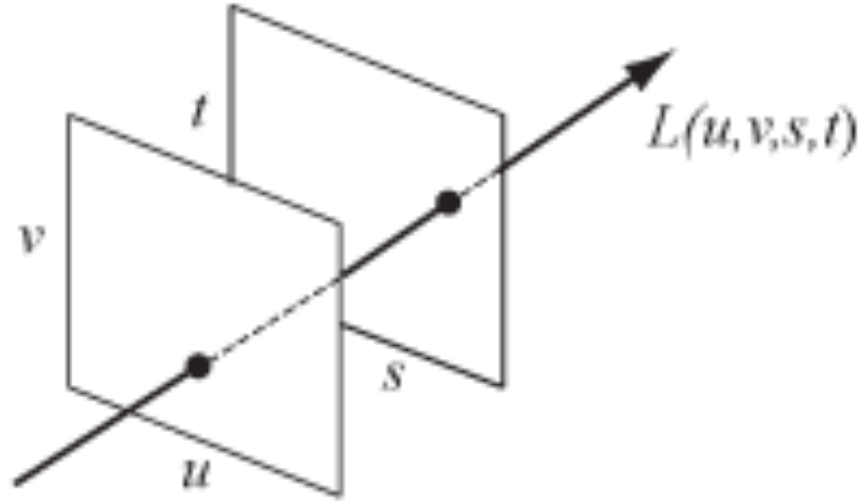
How to deliver?

Control the direction of light!

Light field

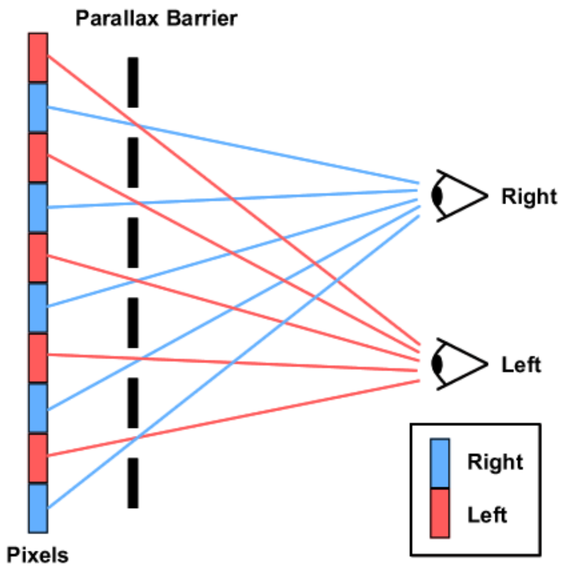
- Light field expression
  - Origin coordinate: 3D + Angle: 2D: 5D
  - If the intensity is preserved, it can be represented as 4D.

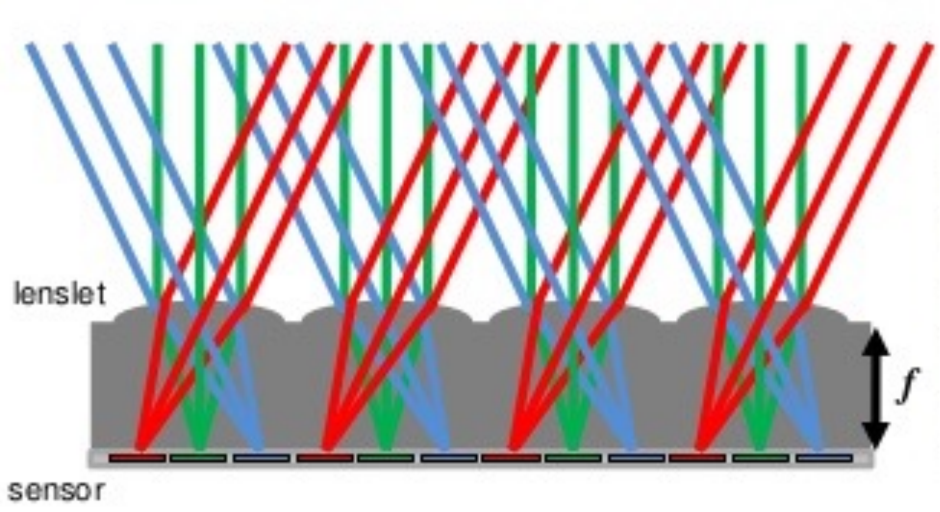




Light field displays

- Conventional Light Field Displays

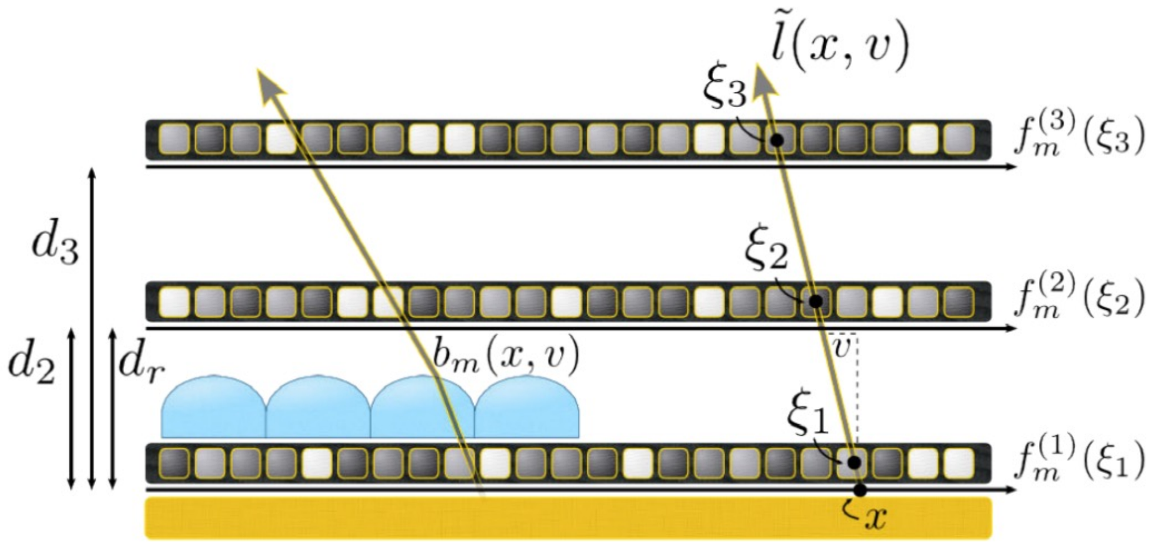




- Effective resolution = Display resolution / # of views
  - e.g. Display: 1920 (H) / 4 (horizontal views) = 480 res

Light field displays

- Compressive Light Field Displays



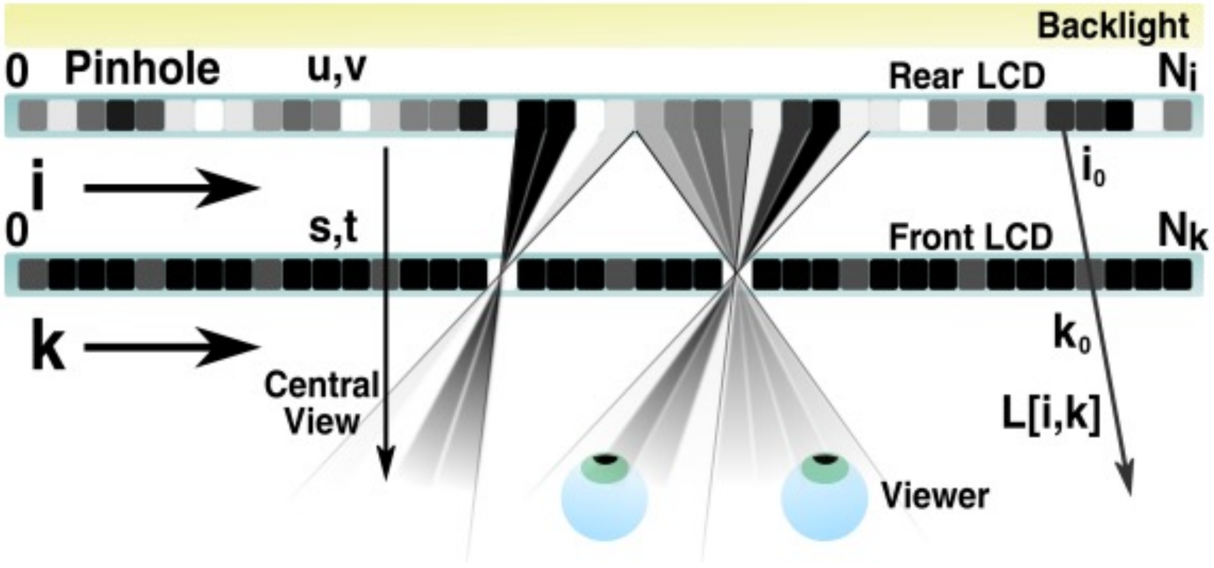
- 4D information is compressed: (# of layers) x 2D
- Get the 'optimal' pattern by solving a least-square problem.

$$\underset{f}{\operatorname{argmin}} \left\| L(x,y,\theta,\phi) - \sum_k \mathrm{P}_k(f_k(x,y)) \right\|_2$$

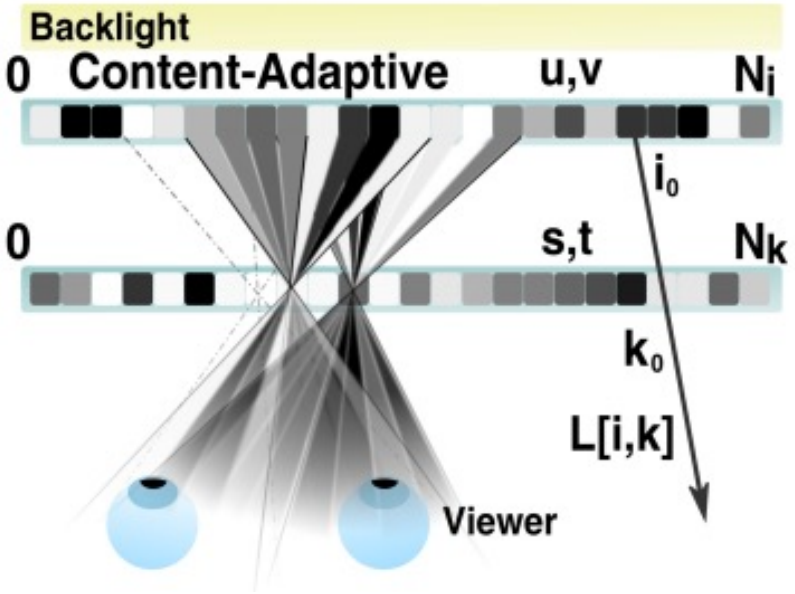
P_k: Projection operation of layer k
f_k: Image of layer k
$L(x,y,\theta,\phi)$: GT light field

G. Wetzstein, et al. *ACM Transactions on Graphics (TOG)*. 31(4), 2012.

- Content-adaptive parallax barriers (2010)



Passive parallax barrier
(Conventional)

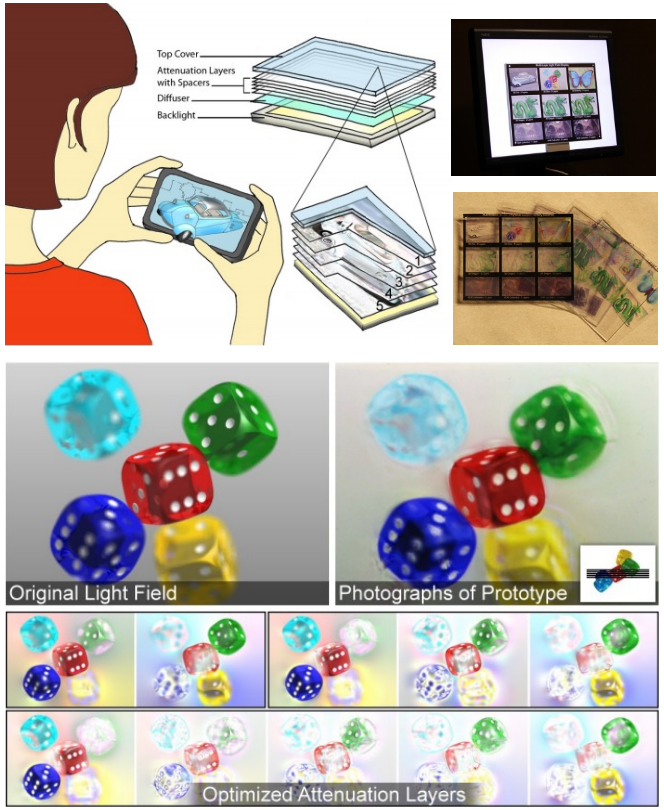


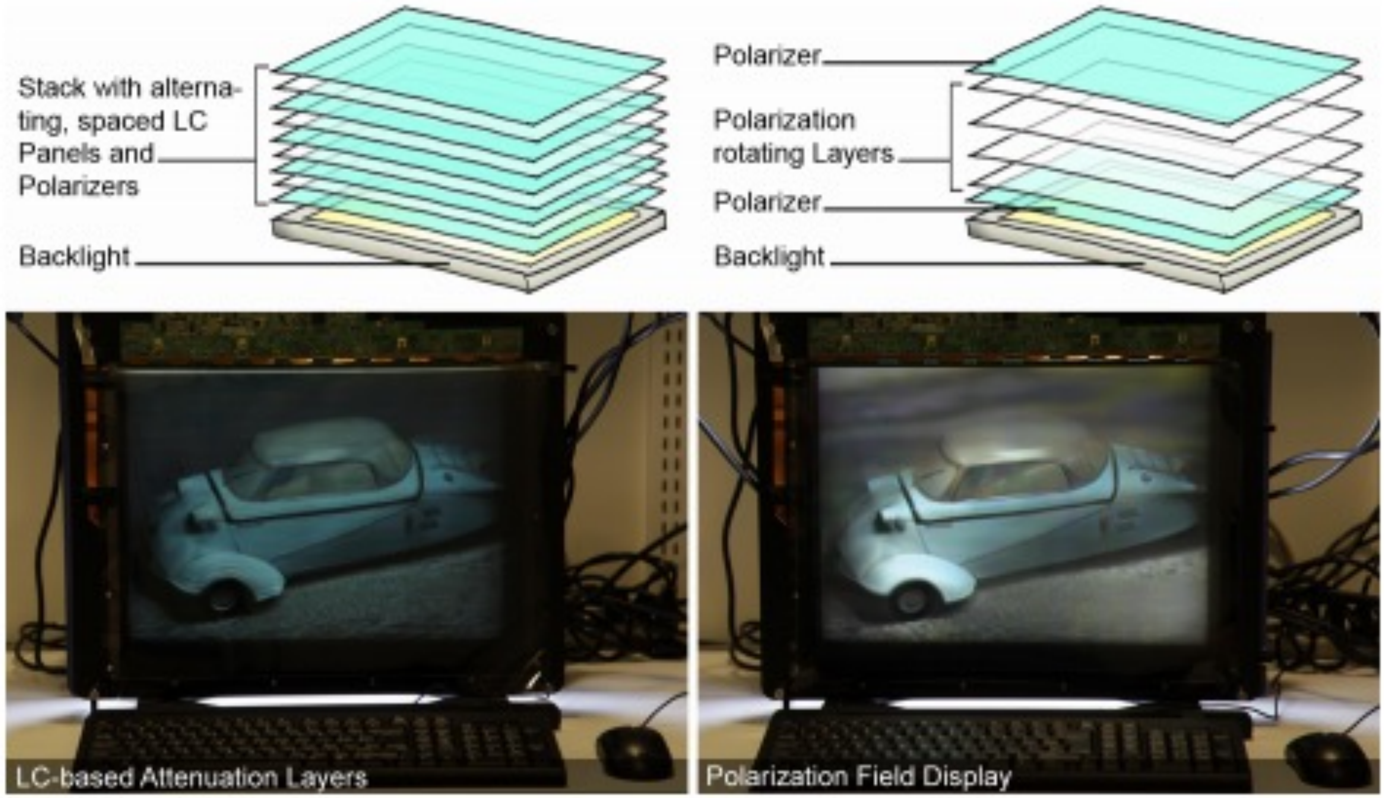
Active (Content-adaptive)
parallax barrier

D. Lanman, et al. *ACM Transactions on Graphics (TOG)*. 29(6), 2010.

Light field displays - research

- Volumetric attenuators / Polarization fields (2011)



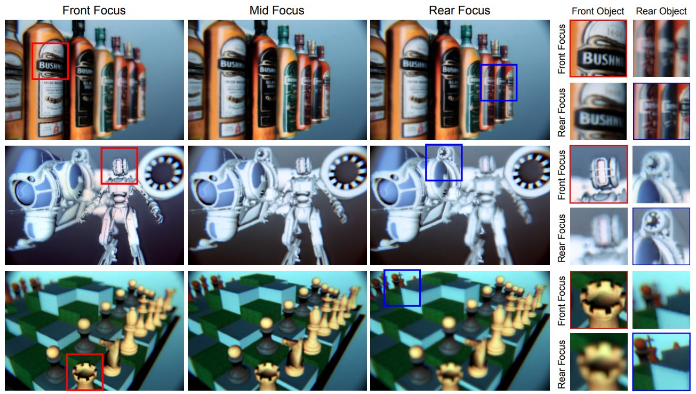


G. Wetzstein, et al. ACM Transactions on Graphics (ToG). 30(4), 2011.
D. Lanman, et al. ACM Transactions on Graphics (ToG). 30(6), 2011.

Brighter, why?

Light field displays - research

- Light field stereoscope (2015)



- Optimization : Attenuation-based, Target : view image
- Components : 2 LCDs
- Application : HMD with Focus cues

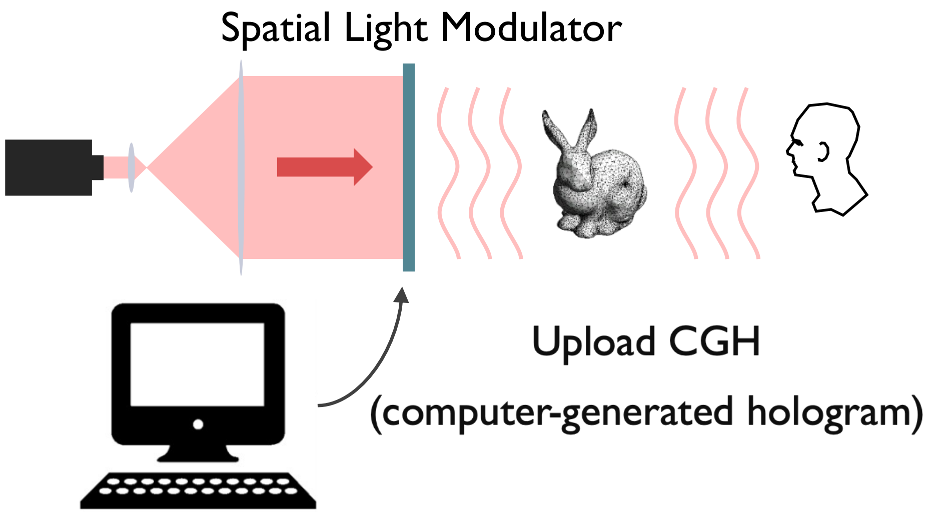
F. Huang, et al. ACM Transactions on Graphics (ToG). 34(4), 2015.

Holographic displays

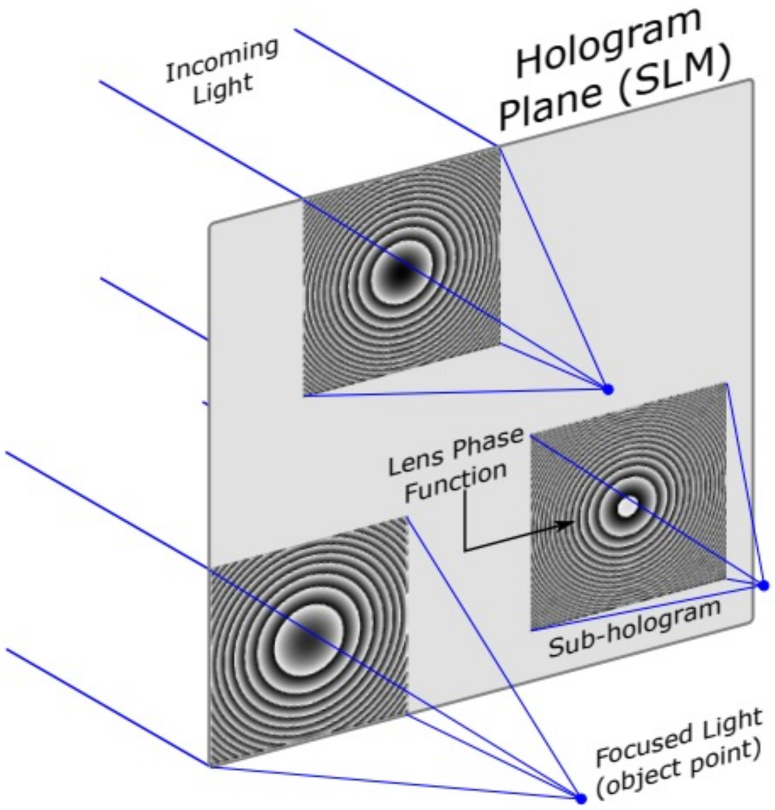
- Analog hologram vs. Dynamic hologram

Analog hologram

Dynamic hologram



Holographic displays - principle

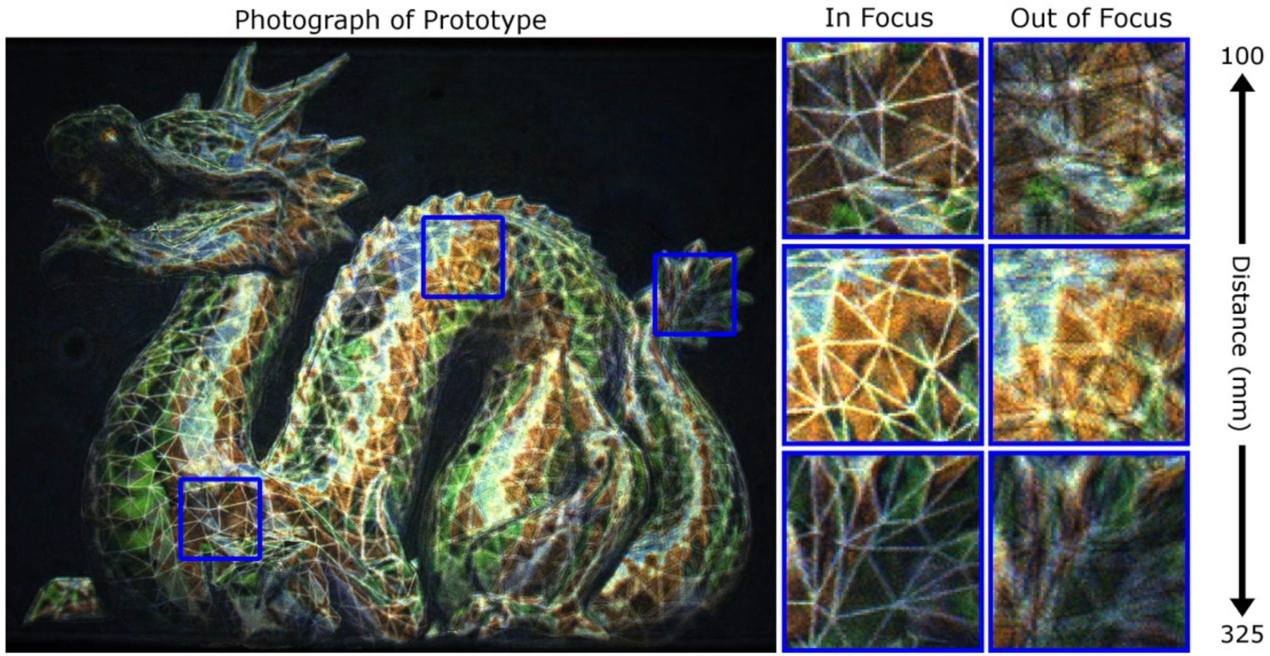


Phase of coherent light (laser) is modulated with LC in spatially-variant manner.

- Per-pixel modulation of depth.

Holographic displays - research

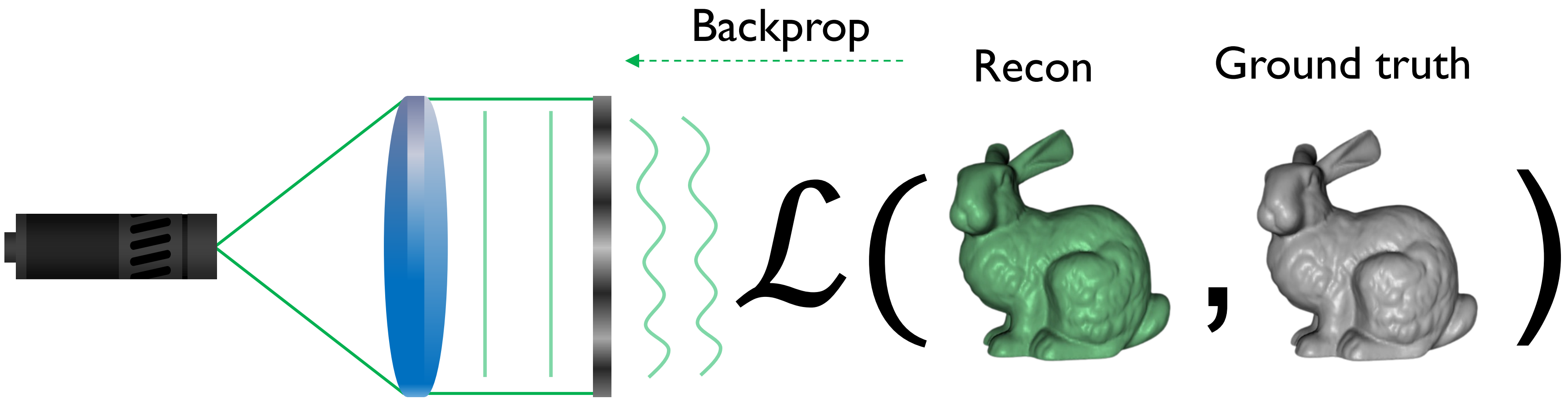
- Eyeglass-form factor holographic display



A. Maimone, A. Georgiou, & J. S. Kollin, ACM Transactions on Graphics (TOG), *36*(4), 2017.

Holographic displays - research

- Differentiable holography

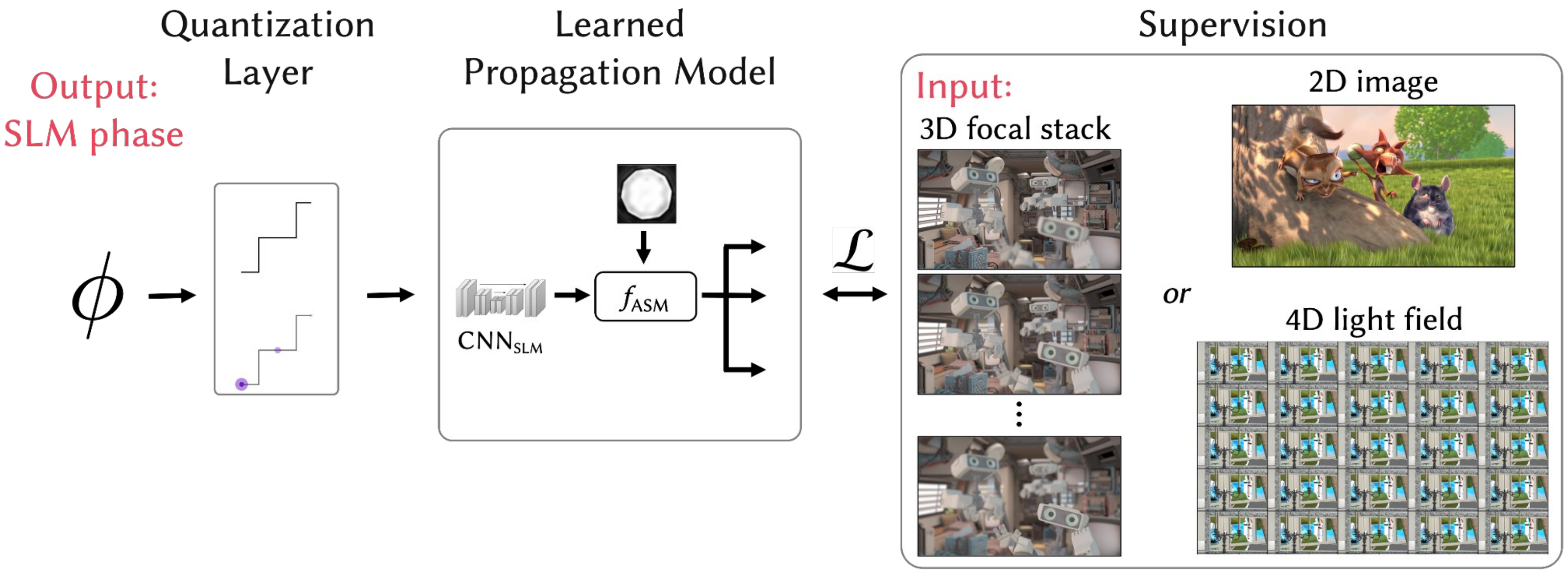


Computer-generated hologram optimization with differentiable pipeline (PyTorch autodiff)

Y. Peng et al., ACM Transactions on Graphics (TOG) 39(6), 2020.

Holographic displays - research

- Light field holography – rendering



Generalized CGH rendering framework w/ various volumetric representations

S. Choi et al., ACM SIGGRAPH Proceeding, 2022.

Holographic displays - research

- Light field holography – perceptual evaluation

3D: (x, y, z)

4D: (x, y, θ, ϕ)

Perceptual assessments with modern 4D holography

D. Kim et al., ACM Transactions on Graphics (TOG) 43(4), 2024.

References

- HAINICH, R.R. AND BIMBER, O. 2011. *Displays: Fundamentals and Applications*. CRC Press.
- SEETZEN, H., HEIDRICH, W., STUERZLINGER, W., ET AL. 2004. High dynamic range display systems. *ACM Transactions on Graphics 23*, 3, 760.
- Visual motion test for high-frame-rate monitors:
  - https://www.testufo.com/