Display Technologies

Advanced Graphics and Image Processing

Rafał Mantiuk
Computer Laboratory, University of Cambridge

Overview

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

Latency in VR

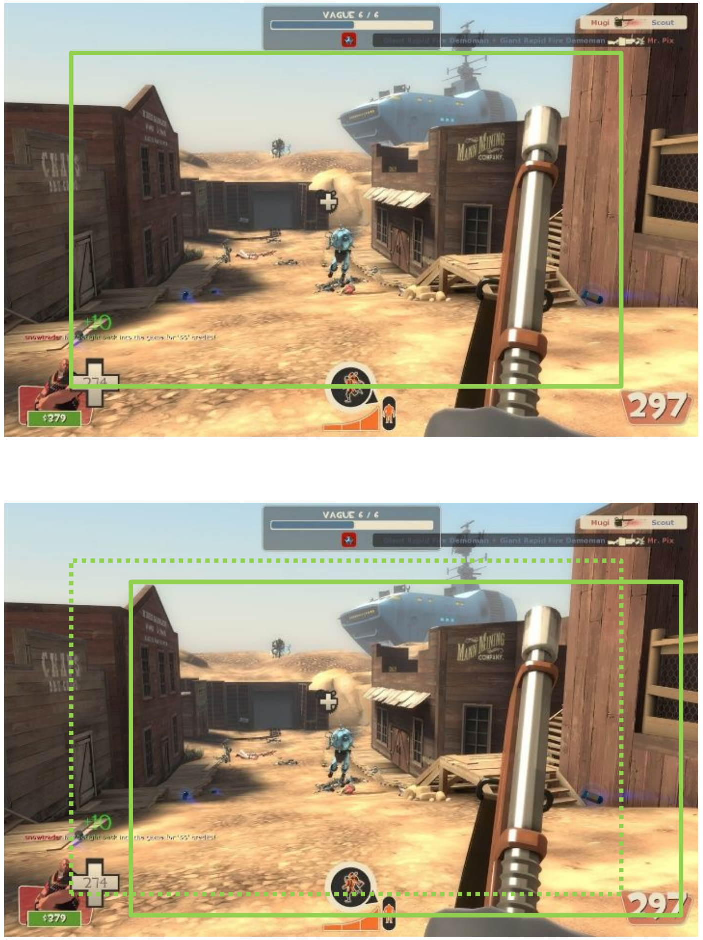
- Sources of latency in VR
  - IMU ~1 ms
    - Inertial Measurement Unit
  - sensor fusion, data transfer
  - rendering: depends on complexity of scene & GPU – a few ms
  - data transfer again
  - Display
    - 60 Hz = 16.6 ms;
    - 70 Hz = 11.1 ms;
    - 120 Hz = 8.3 ms.

- 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

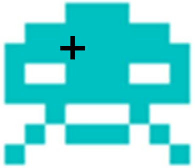
Post-rendering image warp (time warp)

- 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

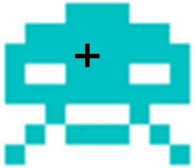
Eye movement - basics

Saccade

160-300 deg/s

Eye movement - basics

Smooth Pursuit Eye Motion (SPEM)

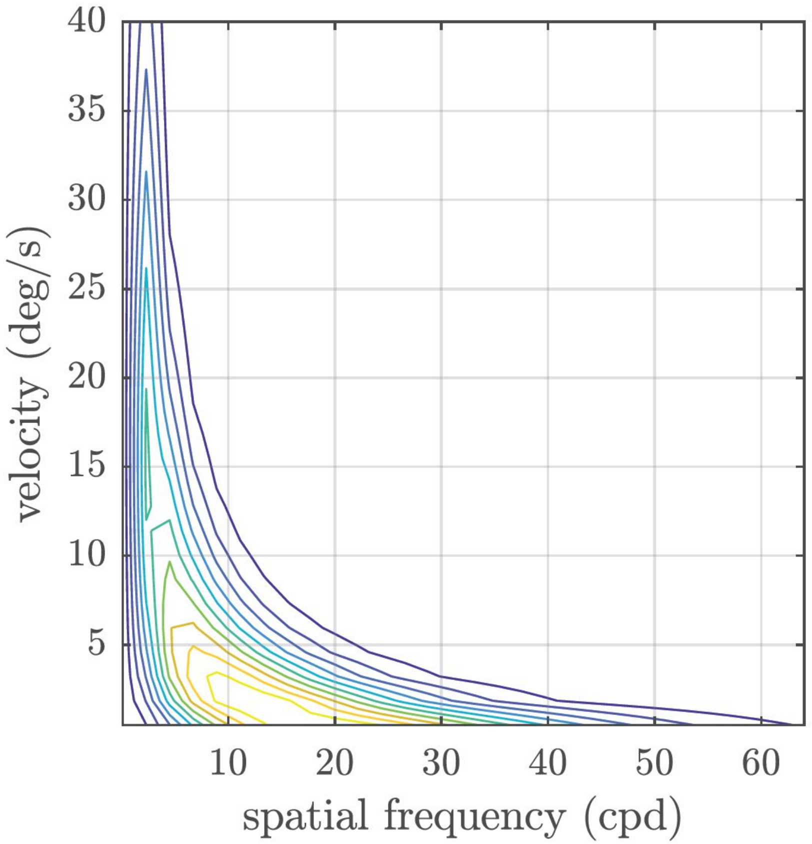


Up to 80 deg/s
The tracking is imperfect
 - especially at higher velocities
 - and for unpredictable motion

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



Retinal velocity due to imperfect SPEM

Kelly's model [1979]

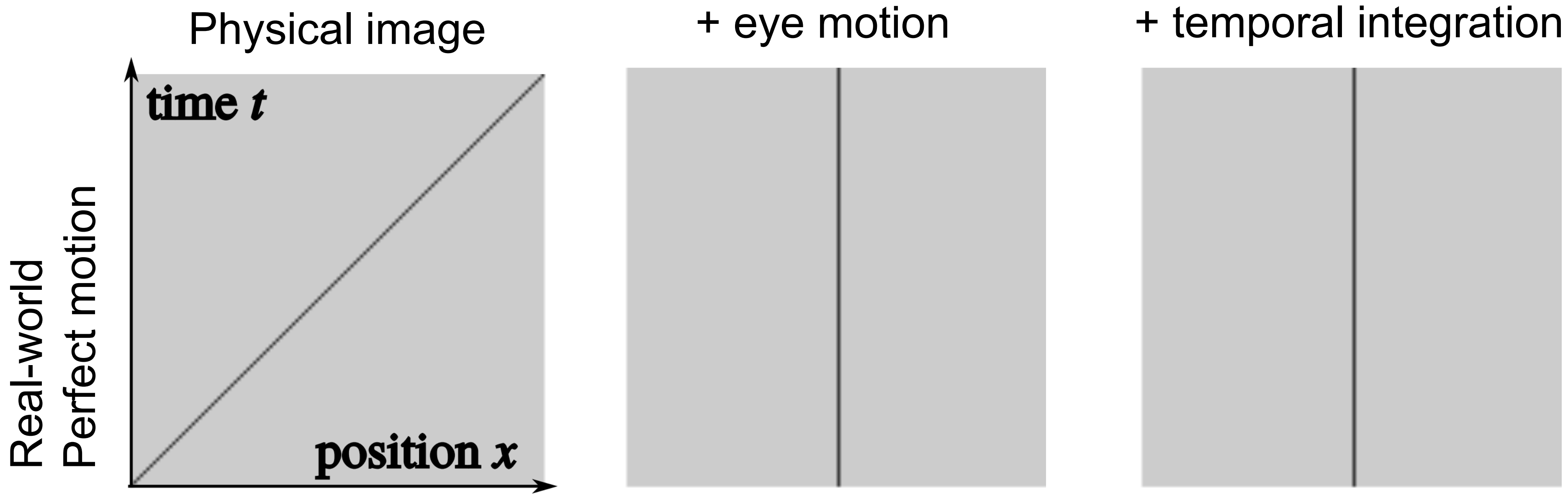
Motion sharpening

- 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

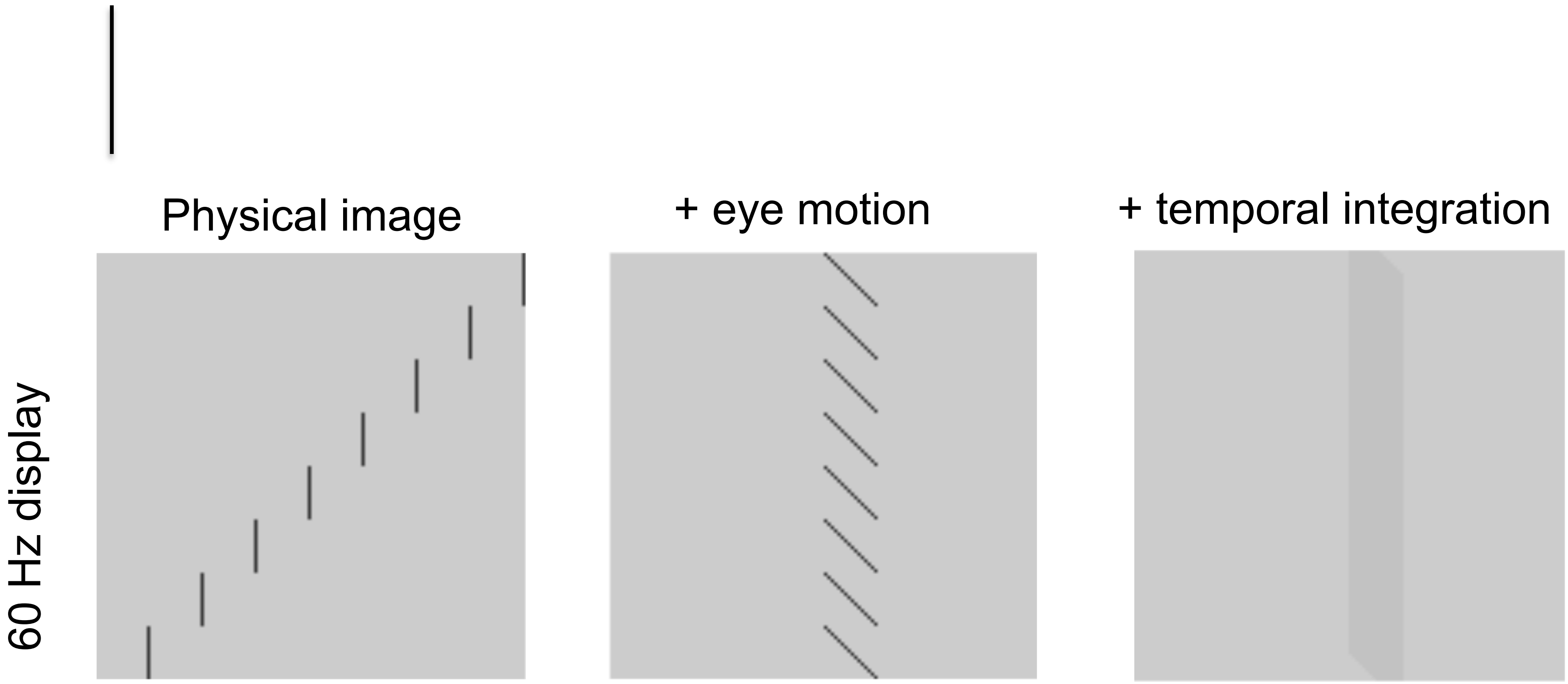

Physical image

+ eye motion

+ temporal integration

Hold-type blur

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

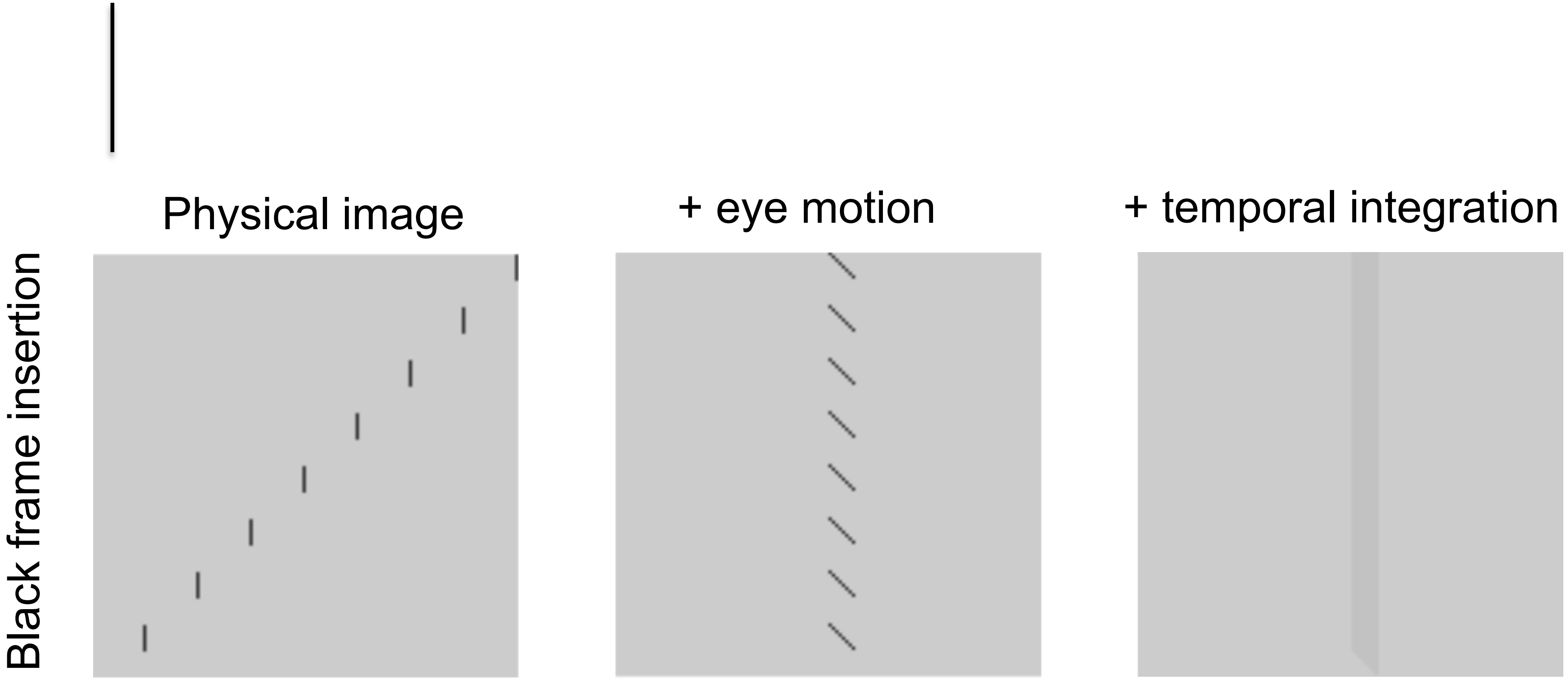


Original scene

With hold-type blur

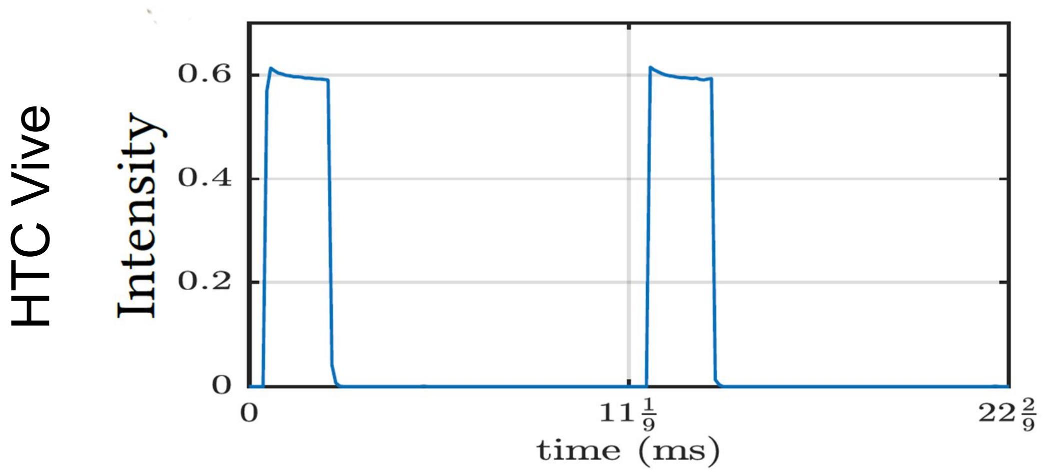
Hold-type blur

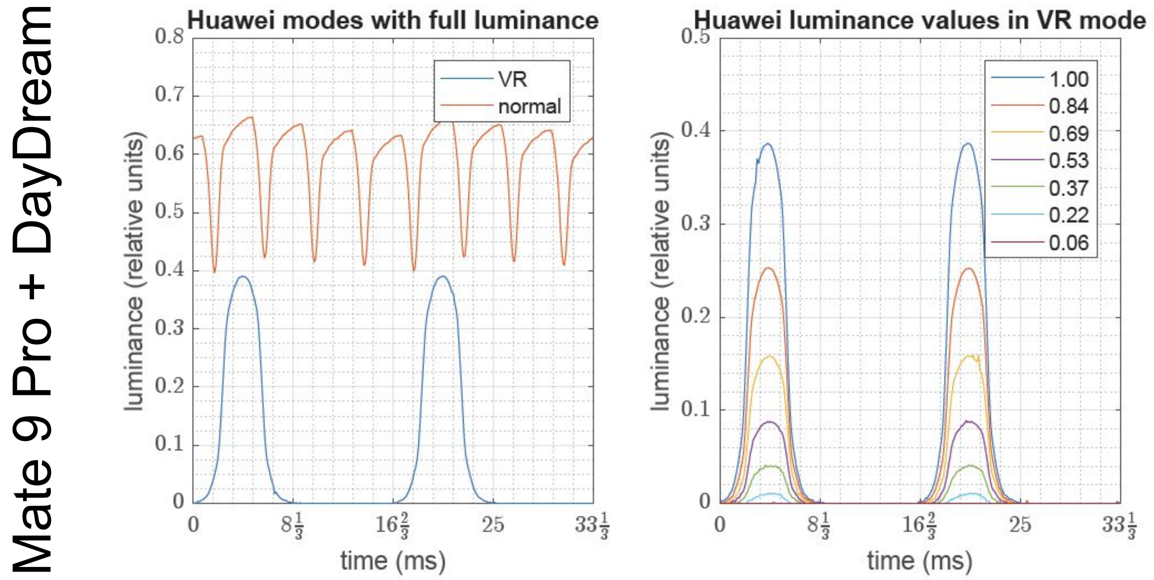
- The eye smoothly follows a moving object
- But the image on the display is "frozen" for 1/60th of a second



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





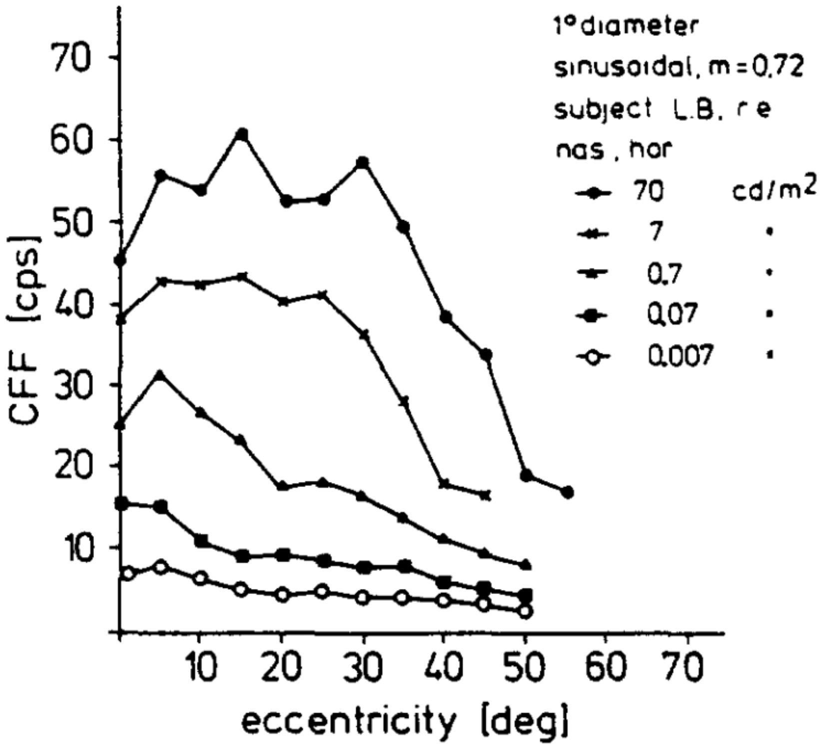
Black frame insertion

- 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

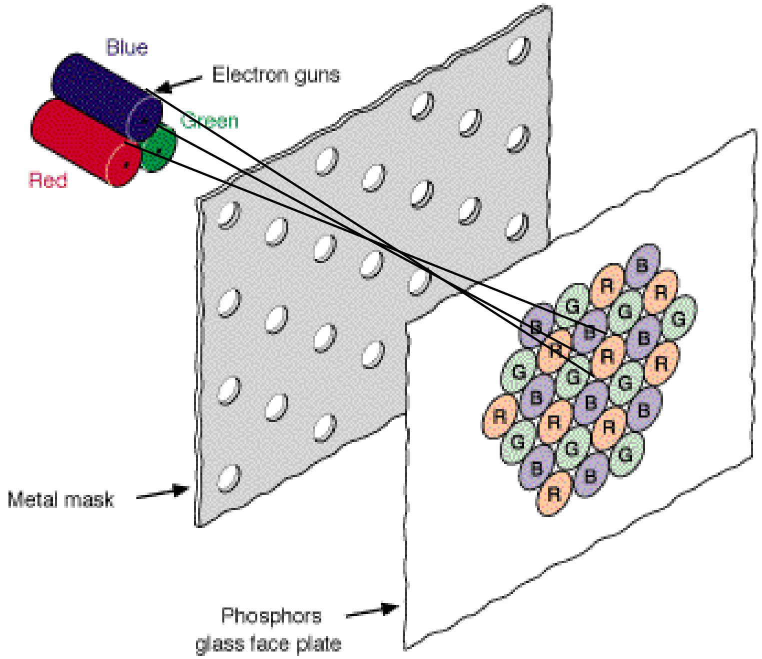


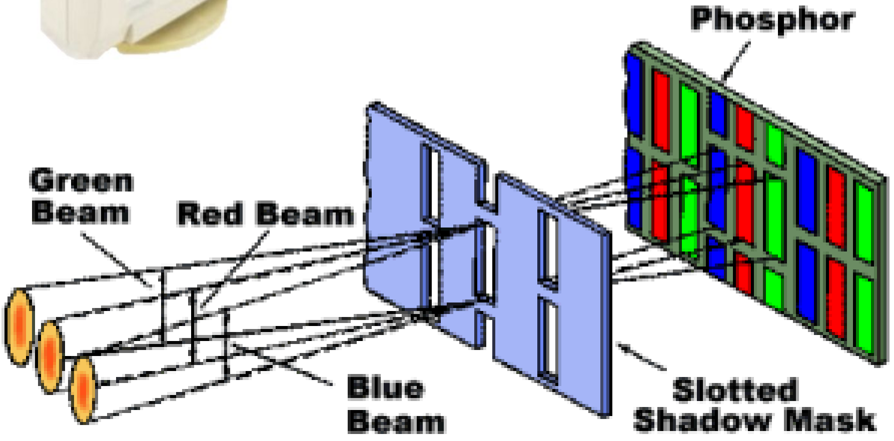
[Hartmann et al. 1979]

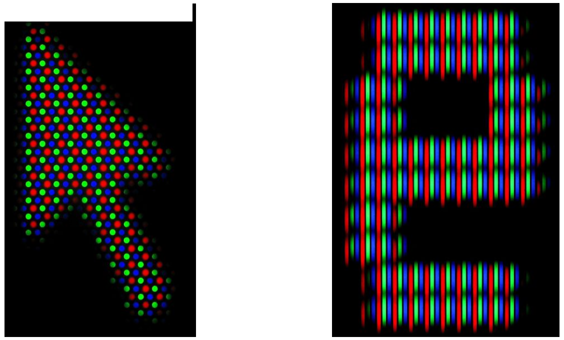
Overview

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

Cathode Ray Tube



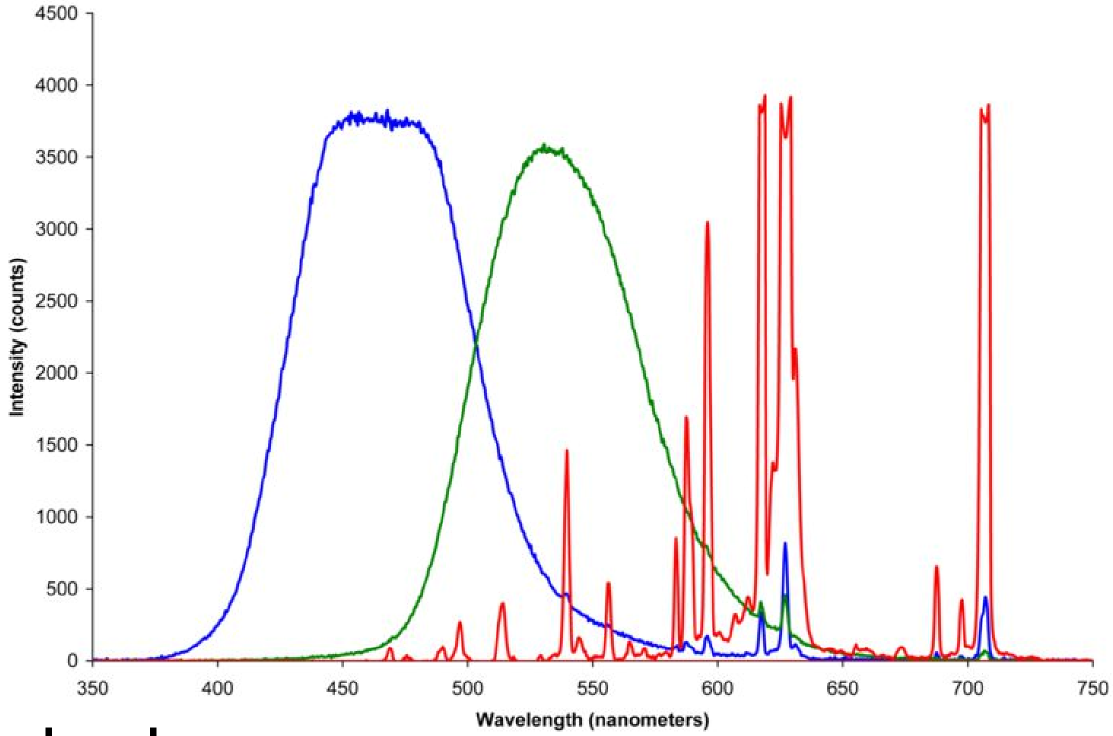




[from wikipedia]

Spectral Composition

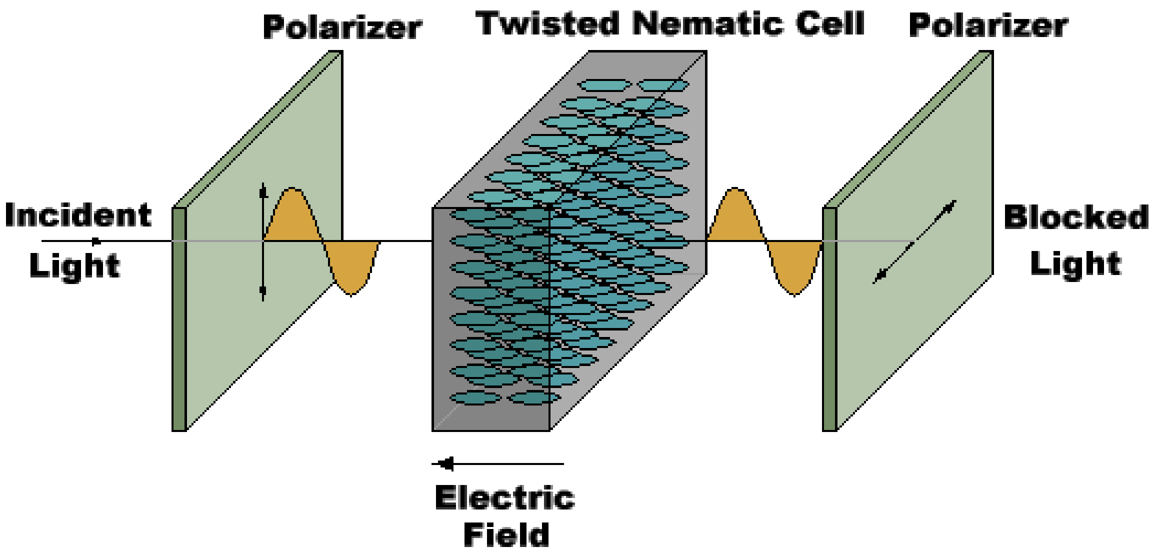
- three different phosphors

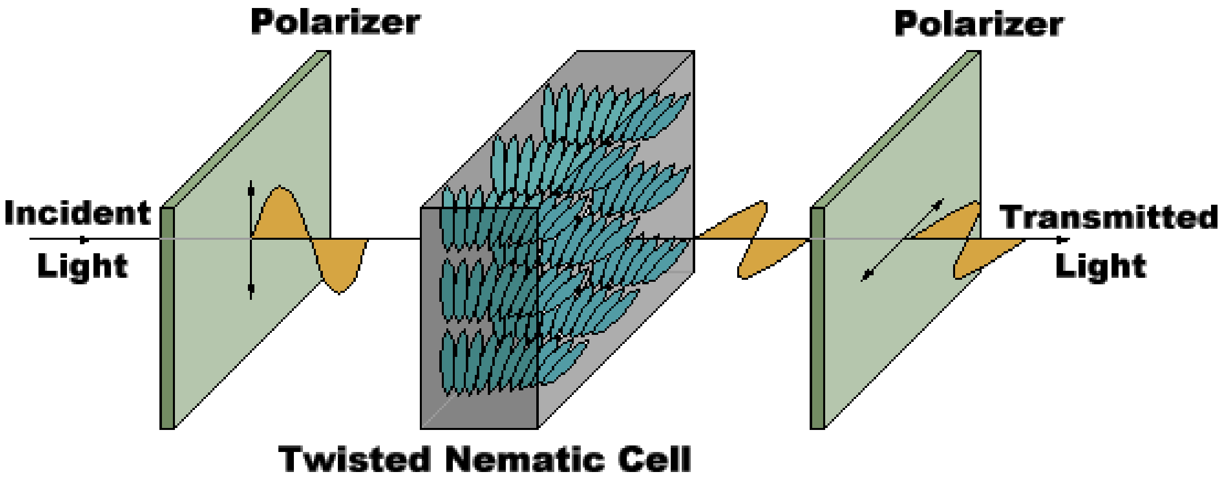


- saturated and natural colors
- inexpensive
- high contrast and brightness

[from wikipedia]

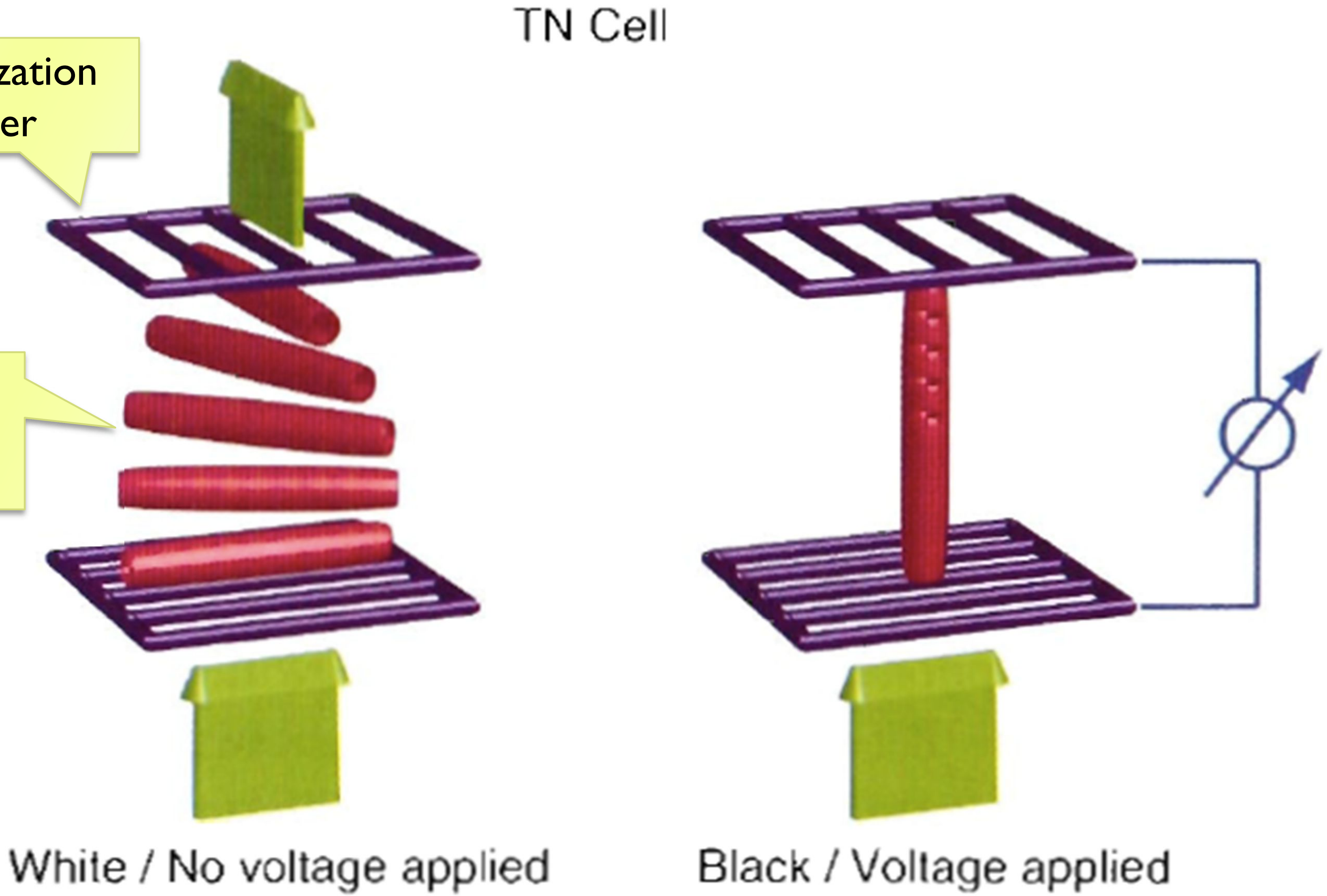
Liquid Chrystal Displays (LCD)





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

Twisted neumatic LC cell



Polarization filter

Liquid crystal (LC)

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

In-plane switching cell (IPS)

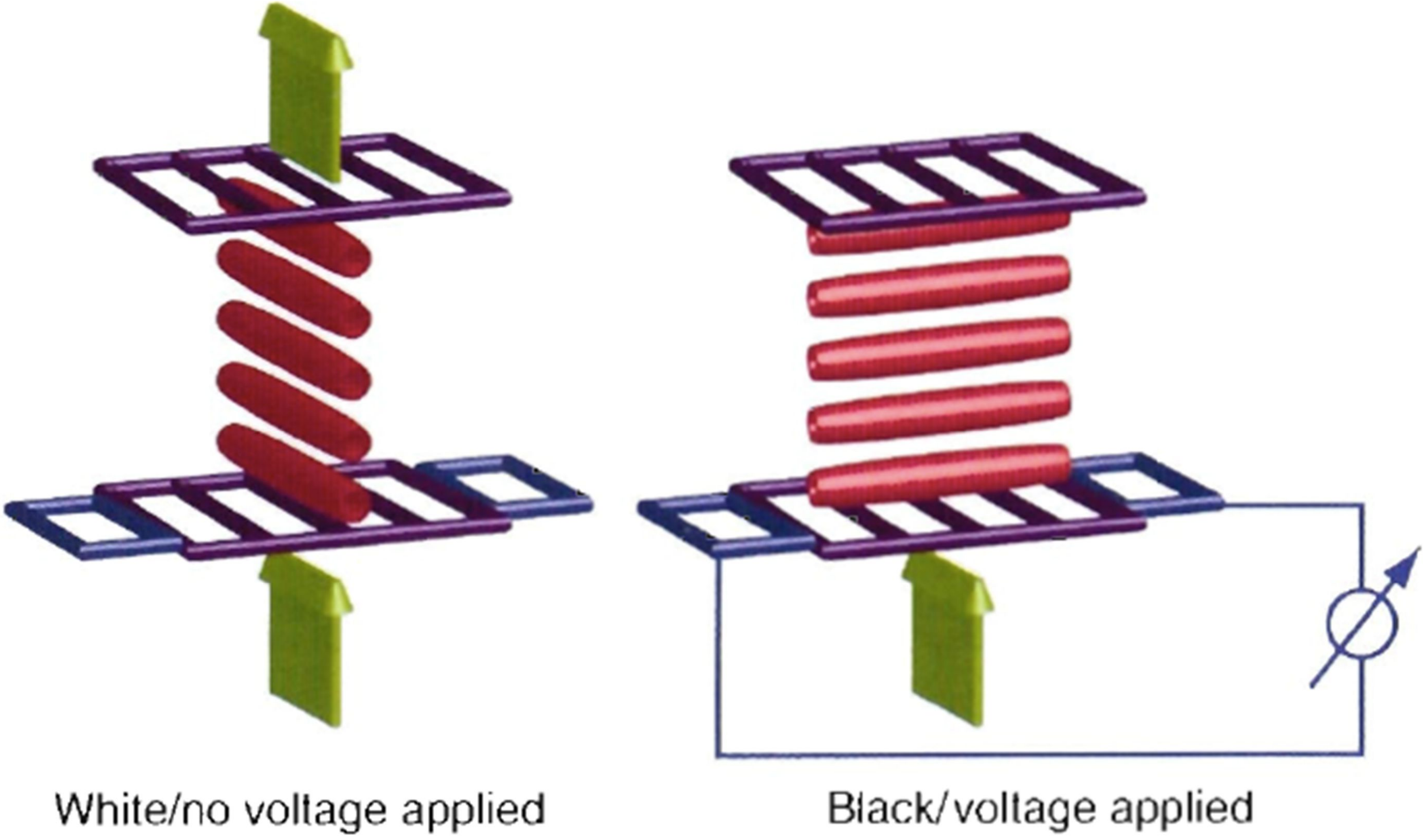
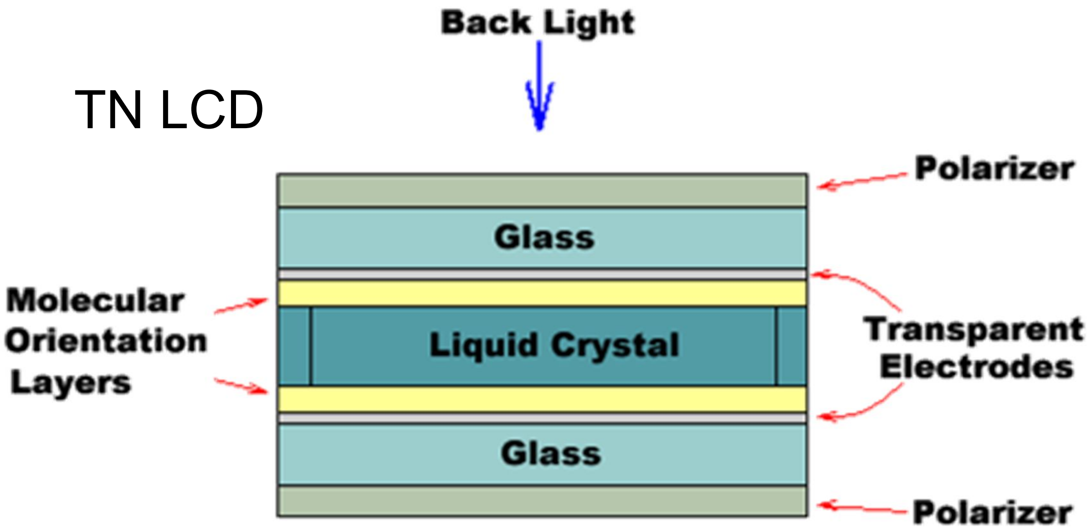
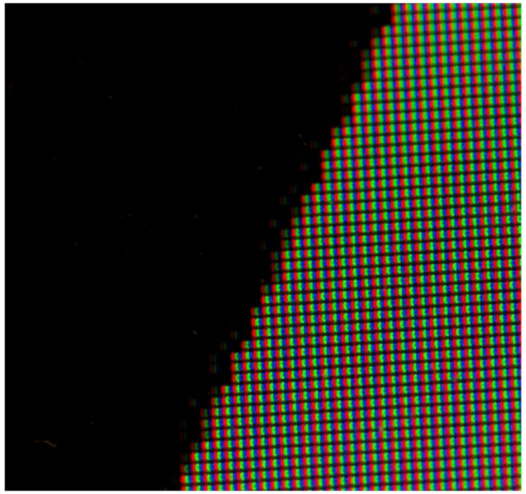


Figure from: High Dynamic Range Imaging by E. Reinhard et al.

LCD



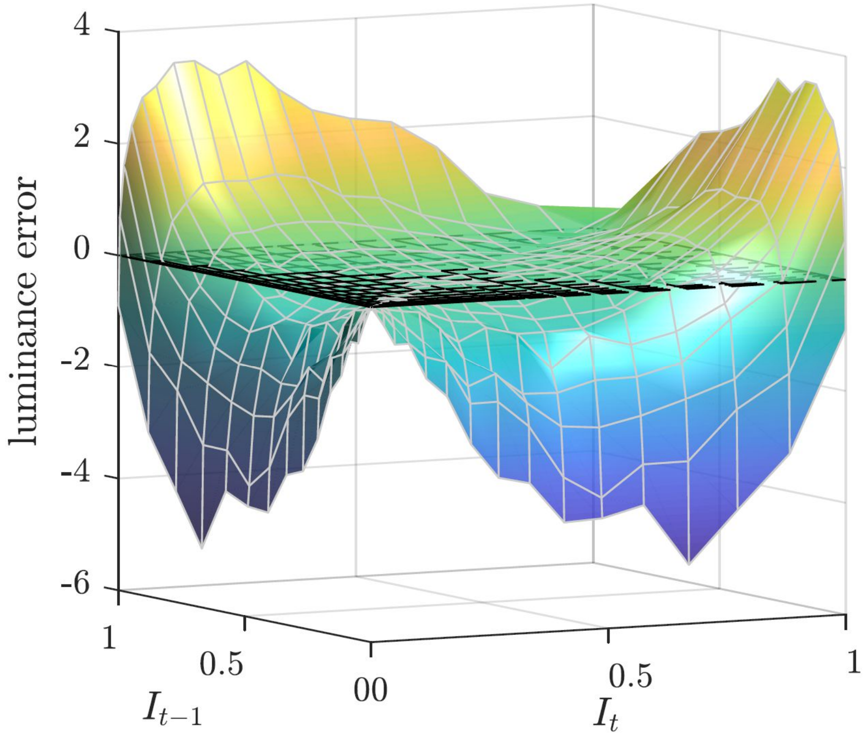


A white slanted edge (photograph)

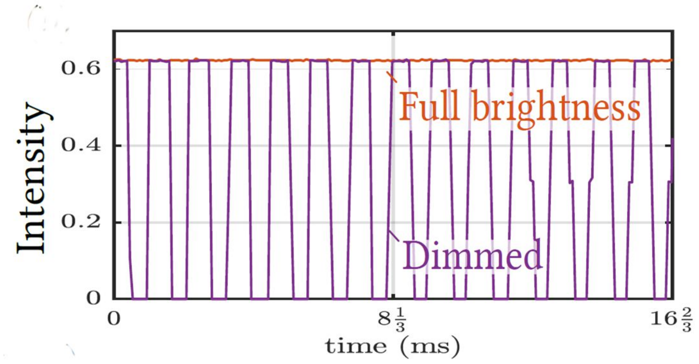
- color may change with the viewing angle
- contrast up to 3000:1
- higher resolution results in smaller fill-factor
- color LCD transmits only up to 8% (more often close to 4-5%) light when set to full white

LCD temporal response

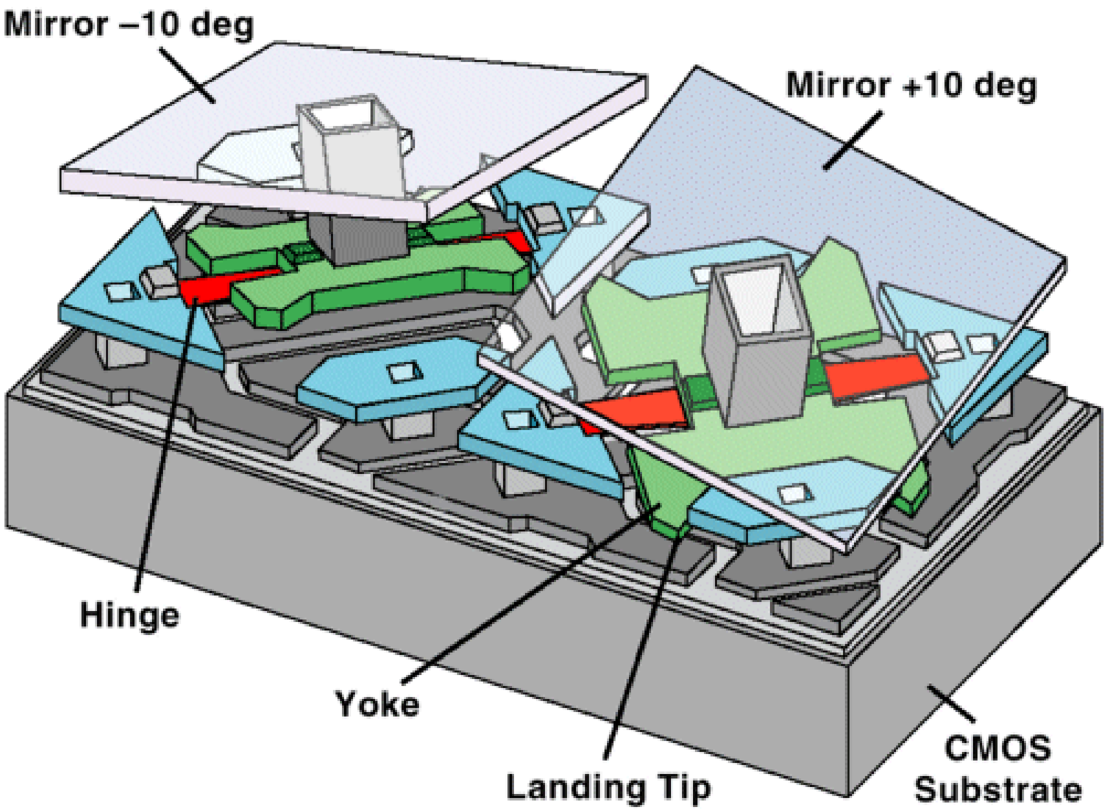
- Experiment on an IPS LCD screen
- We rapidly switched between two intensity levels at 120Hz
- Measured luminance integrated over 1s
- The top plot shows the difference between expected $(\frac{I_{t-1}+I_t}{2})$ and measured luminance



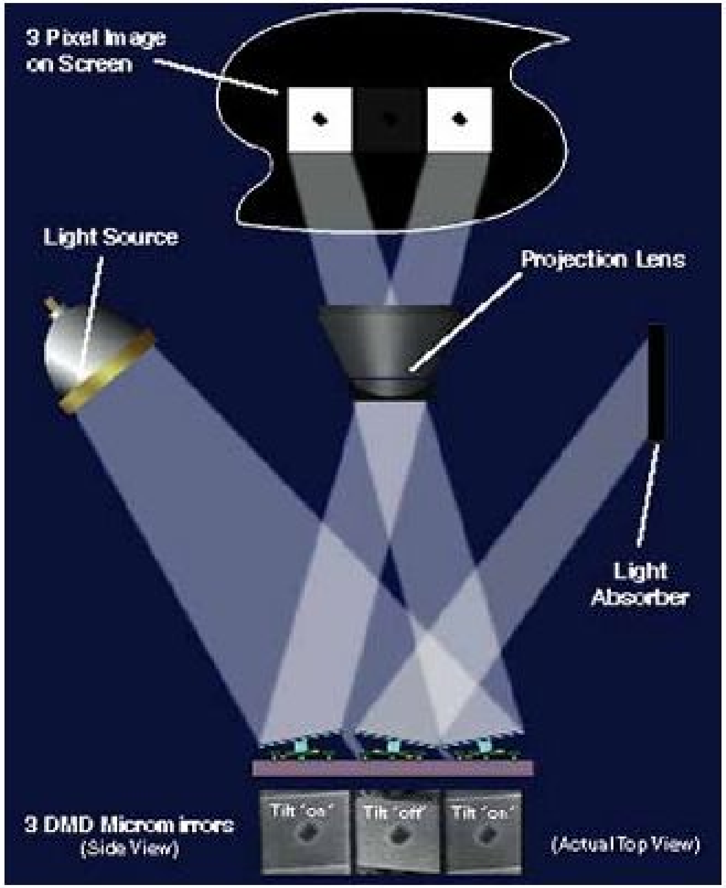
- The bottom plot: intensity measurement for the full brightness and half-brightness display settings
  - Pulse-Width Modulation controls brightness of the backlight



Digital Micromirror Devices (DMDs/DLP)

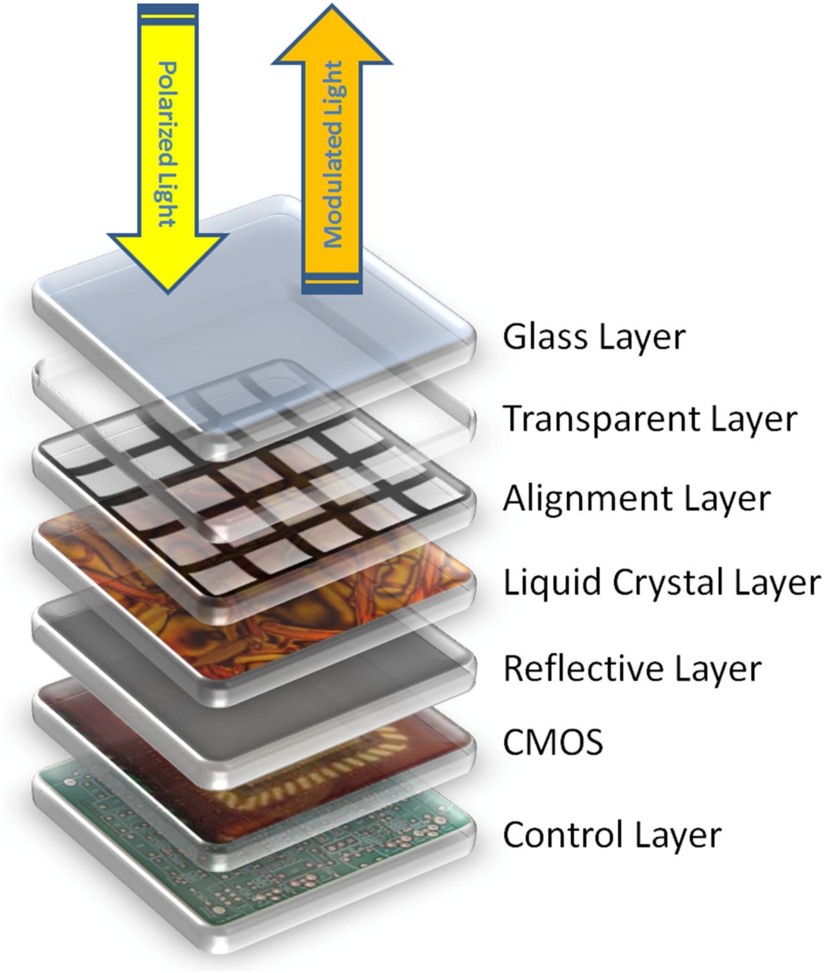


Texas Instruments



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

Liquid Crystal on Silicon (LCoS)

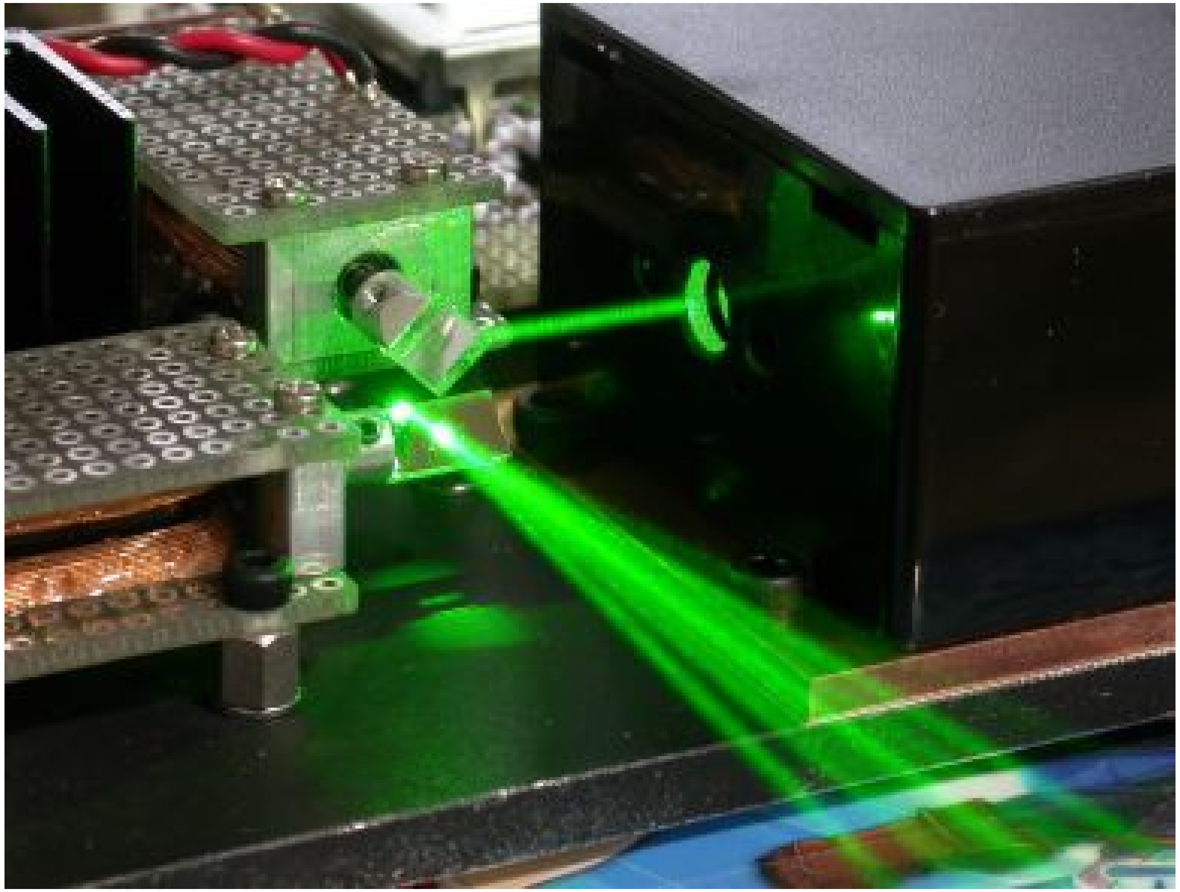


- basically a reflective LCD
- standard component in projectors and head mounted displays
- used e.g. in Google Glass

Scanning Laser Projector

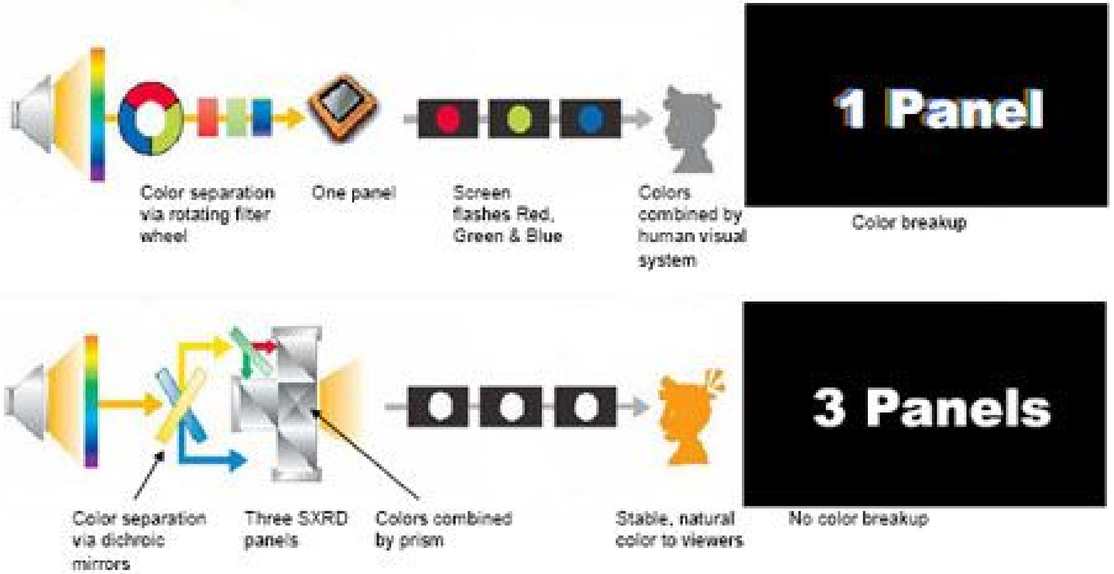
- maximum contrast
- scanning rays

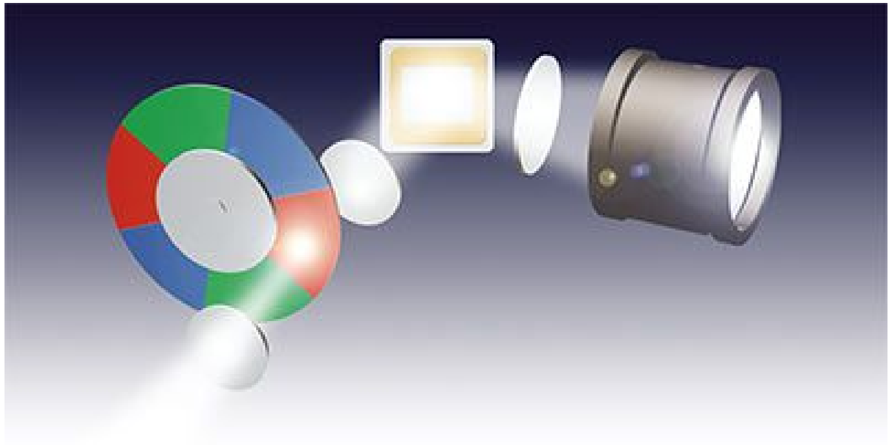
- very high power lasers needed for high brightness



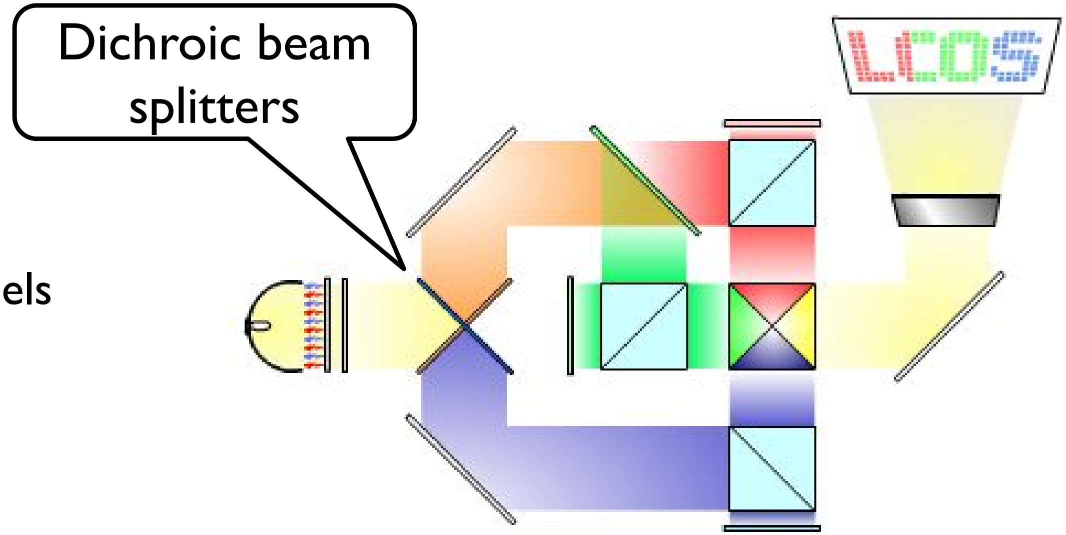
http://elm-chan.org/works/vlp/report_e.html

3-chip vs. Color Wheel Display





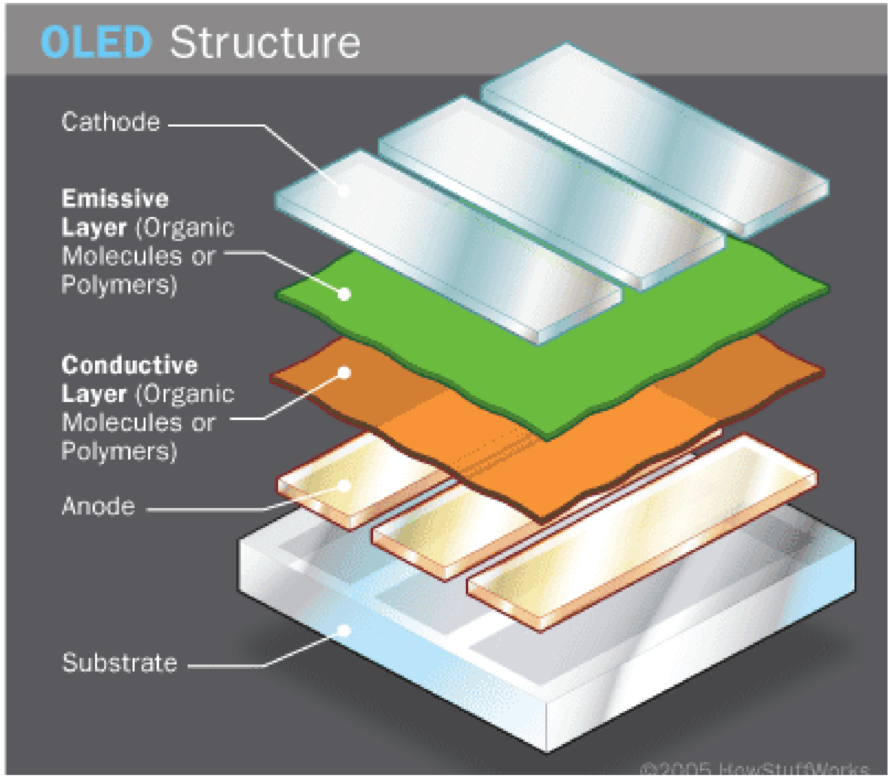
- color wheel
  - cheap
  - time sequenced colors
  - color fringes with motion/video
    - mitigated with advanced colour wheels
- 3-chip
  - complicated setup
  - no color fringes



Dichroic beam splitters

OLED

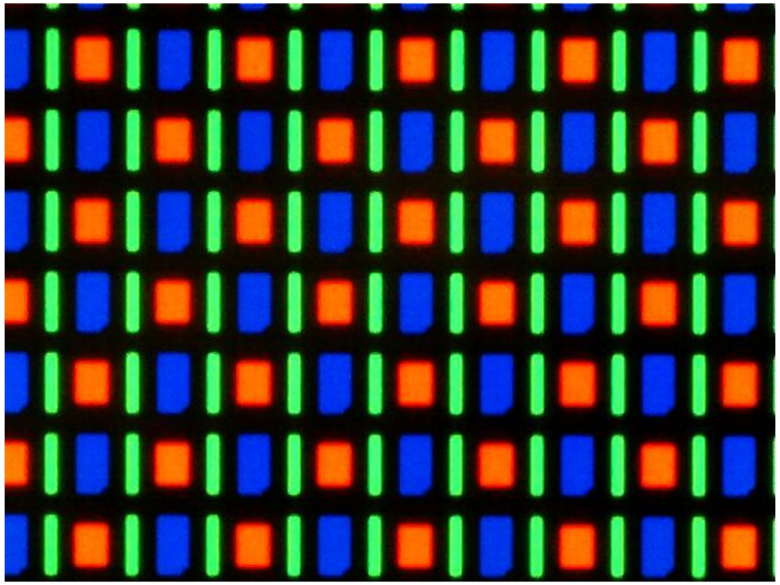
- based on electrophosphorescence
- large viewing angle
- the power consumption varies with the brightness of the image
- fast (< 1 microsec)
- arbitrary sizes



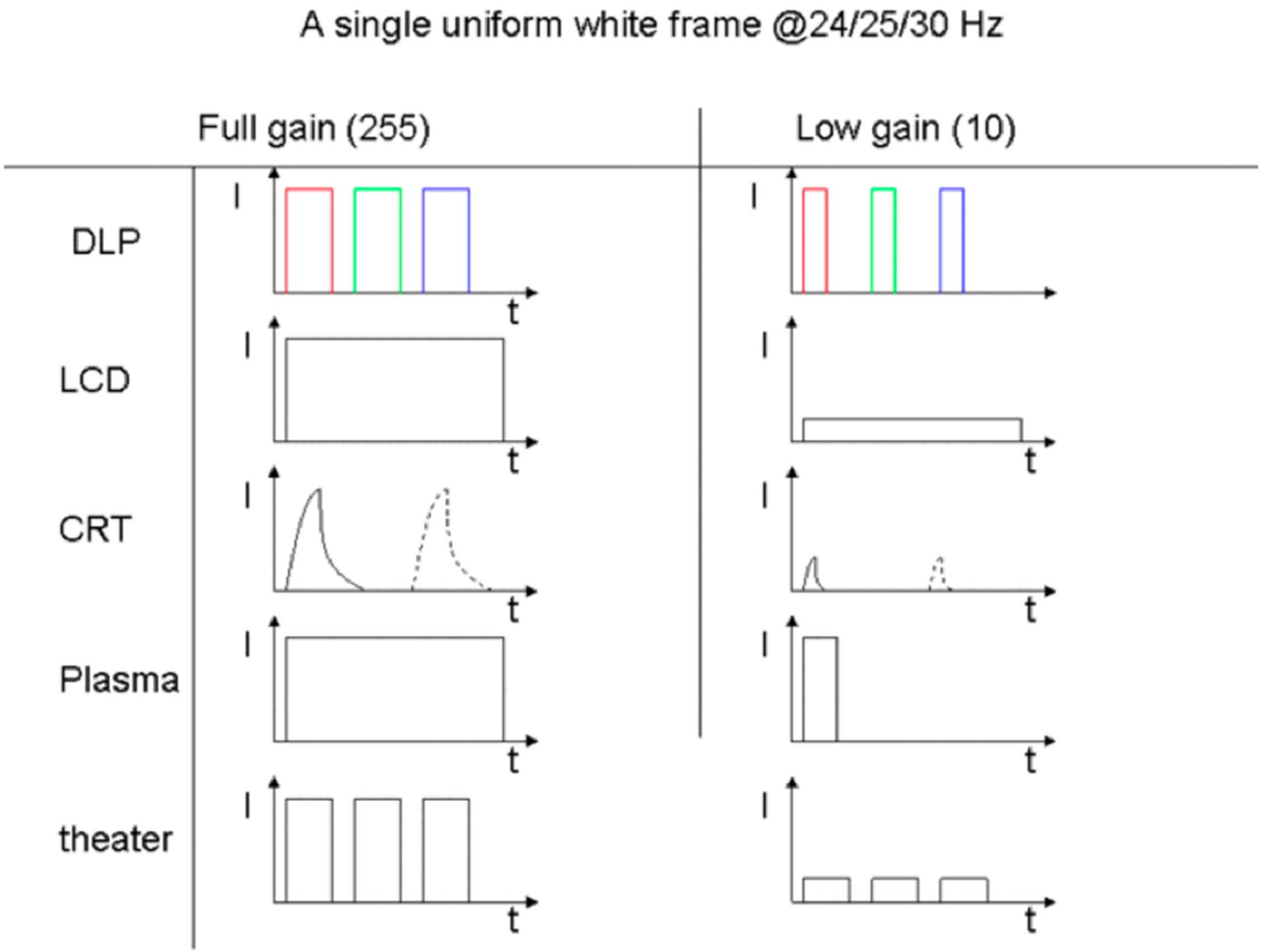
- life-span can be short
  - Worst for blue OLEDs

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

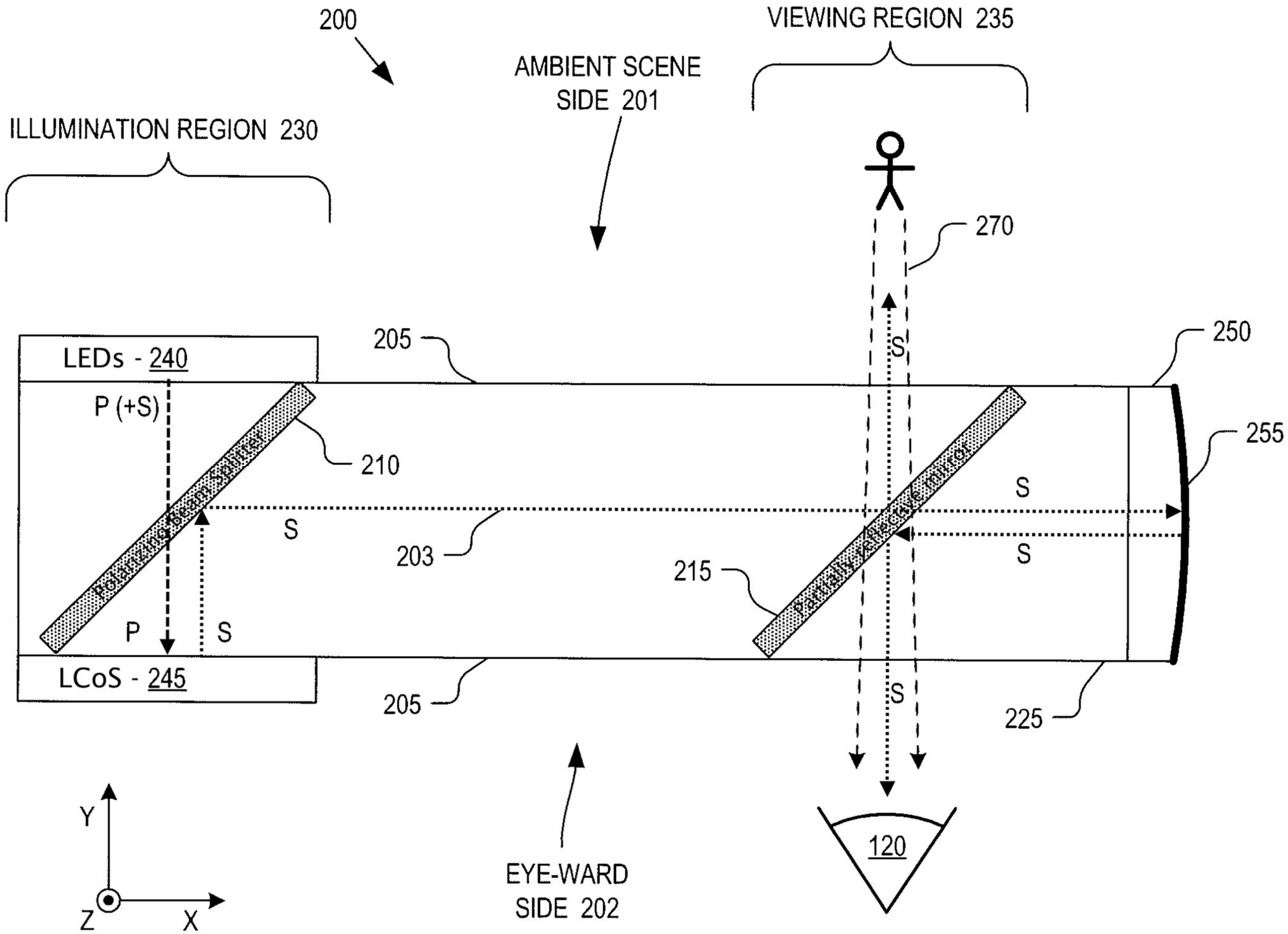


Temporal characteristic



From: http://en.wikipedia.org/wiki/Comparison_of_display_technology

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

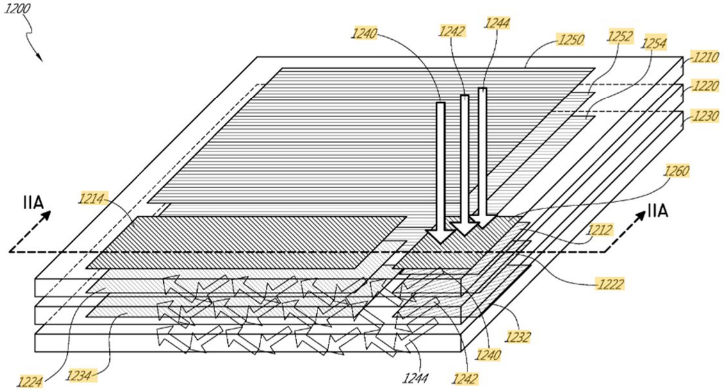
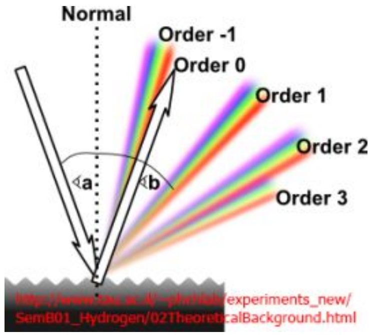
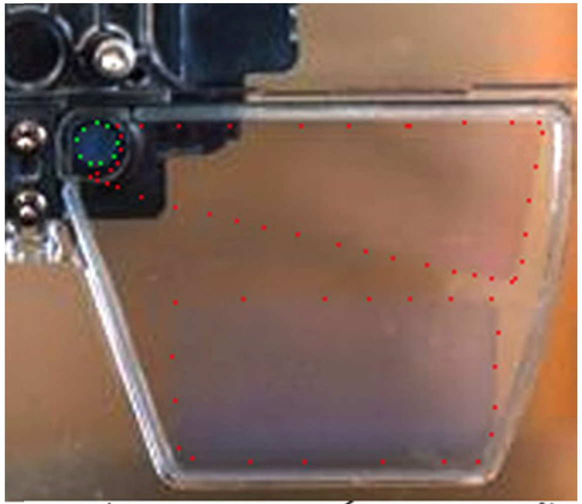


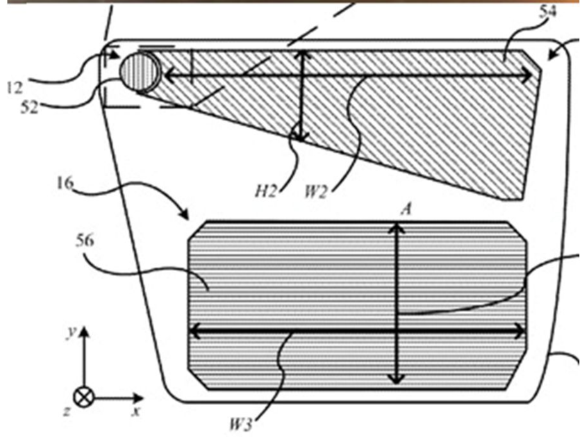
FIG. IIB

Magic Leap



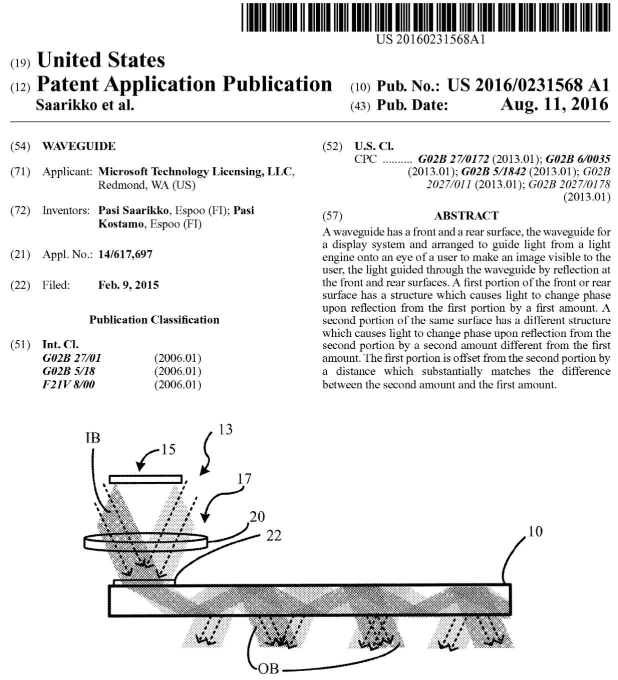
http://www.tau.ac.il/~phchlab/experiments_new/SemB01_Hydrogen/02TheoreticalBackground.html





US 2016/0231568

Fig. 3B



US 20160231568A1

(19) **United States**
(12) **Patent Application Publication**
Saarikko et al.

(10) **Pub. No.: US 2016/0231568 A1**
(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)

(21) Appl. No.: **14/617,697**

(22) Filed: **Feb. 9, 2015**

Publication Classification

(51) **Int. Cl.**

G02B 27/01	(2006.01)
G02B 5/18	(2006.01)
F21V 8/00	(2006.01)

(52) **U.S. Cl.**
CPC ***G02B 27/0172*** (2013.01); ***G02B 6/0035*** (2013.01); ***G02B 5/1842*** (2013.01); *G02B 2027/011* (2013.01); *G02B 2027/0178* (2013.01)

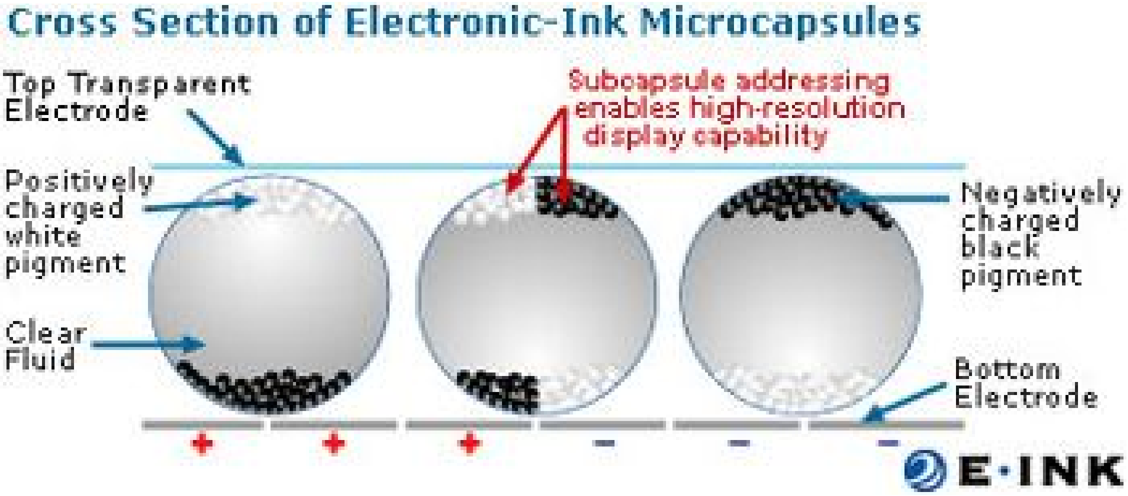
(57) **ABSTRACT**

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.

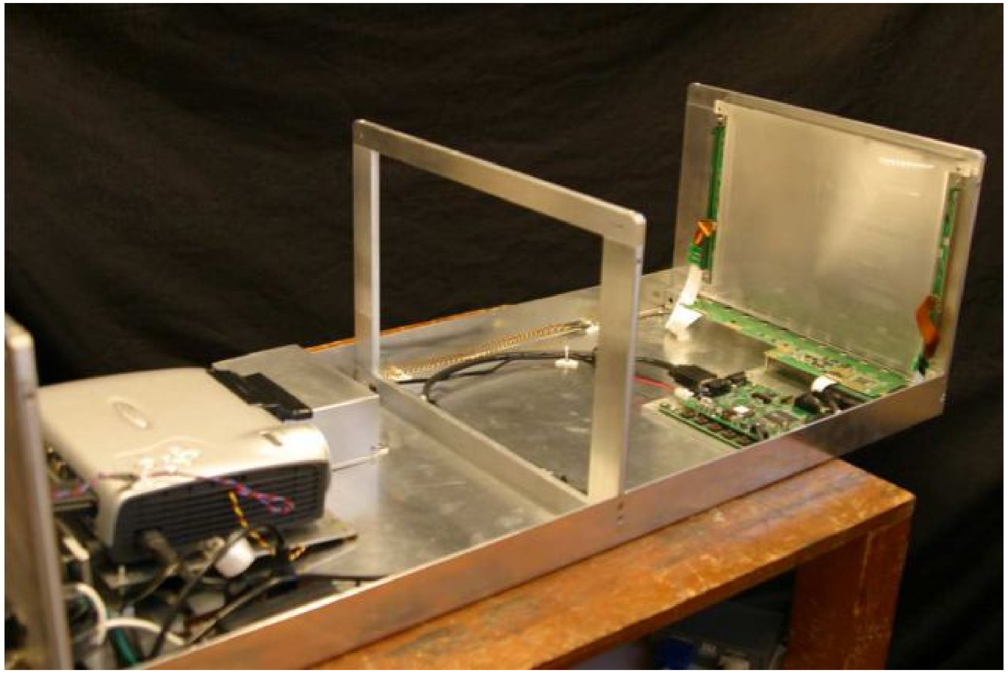
Microsoft Hololens

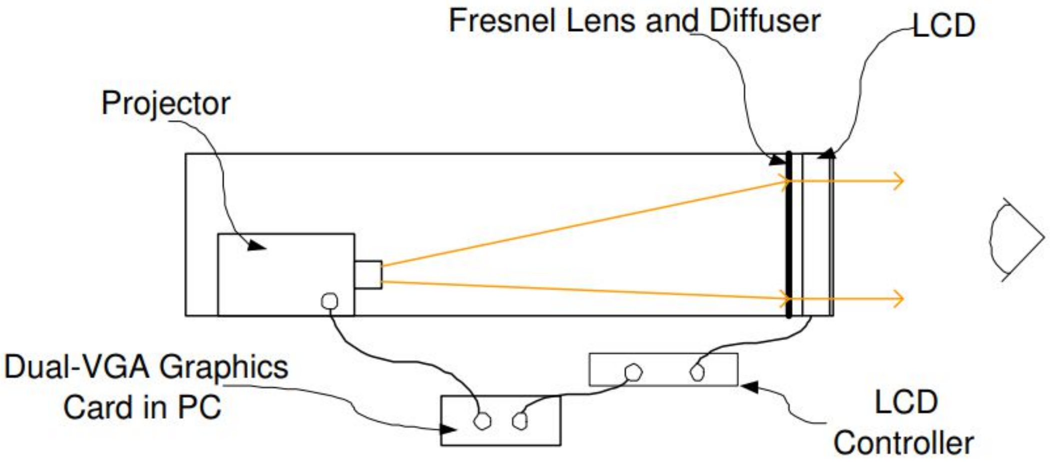
Electronic Paper

www.eink.com



Prototype HDR display (2004)

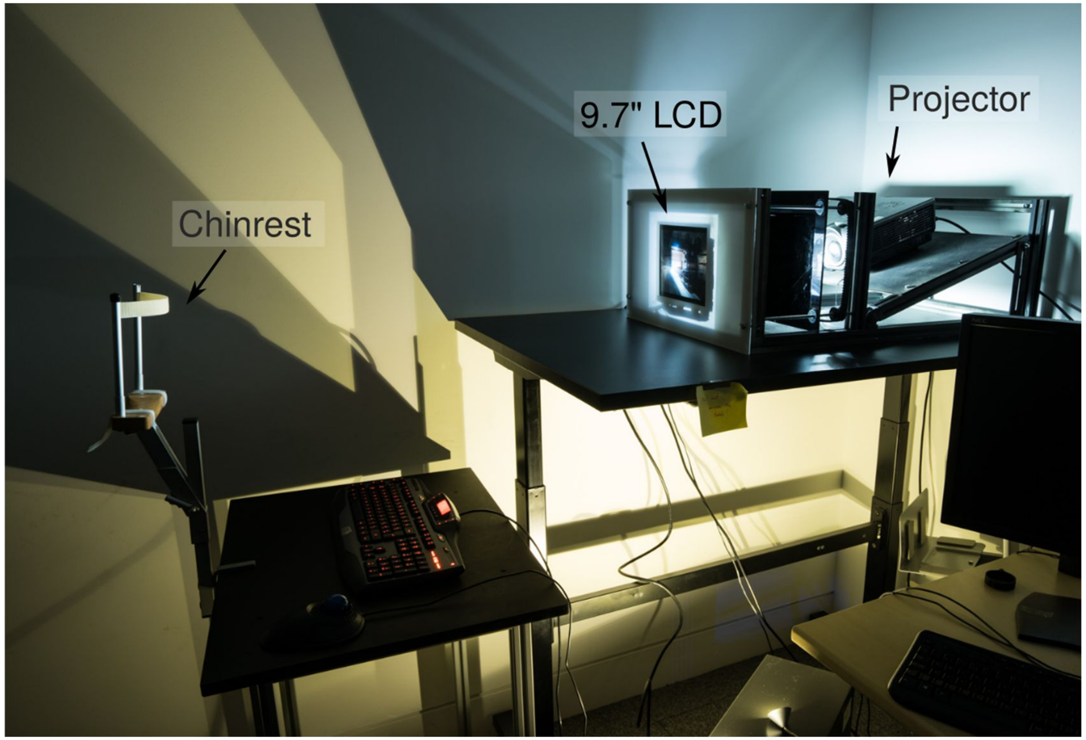


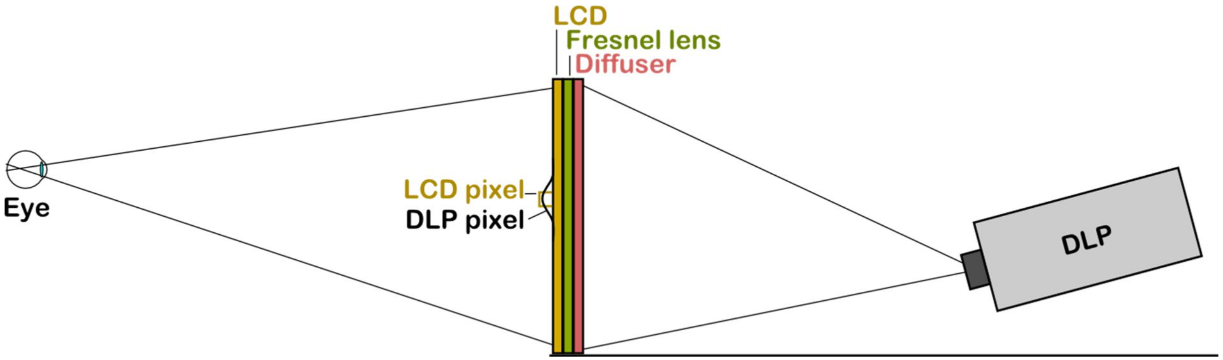


From [Seetzen et al. SIGGRAPH 2004]

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

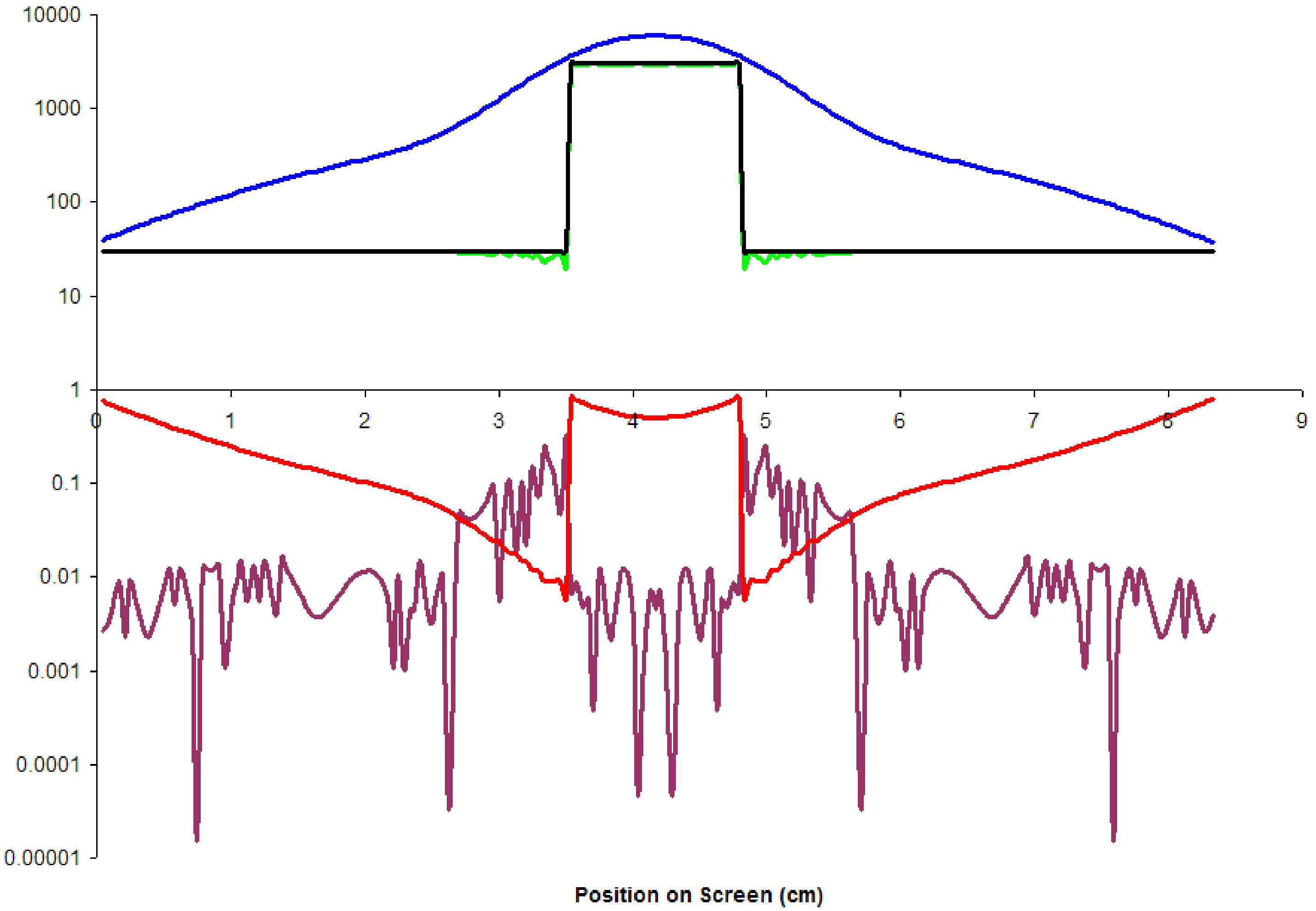
- Modulated LED array
- Conventional LCD
- Image compensation

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

Veiling Luminance



Receive Image

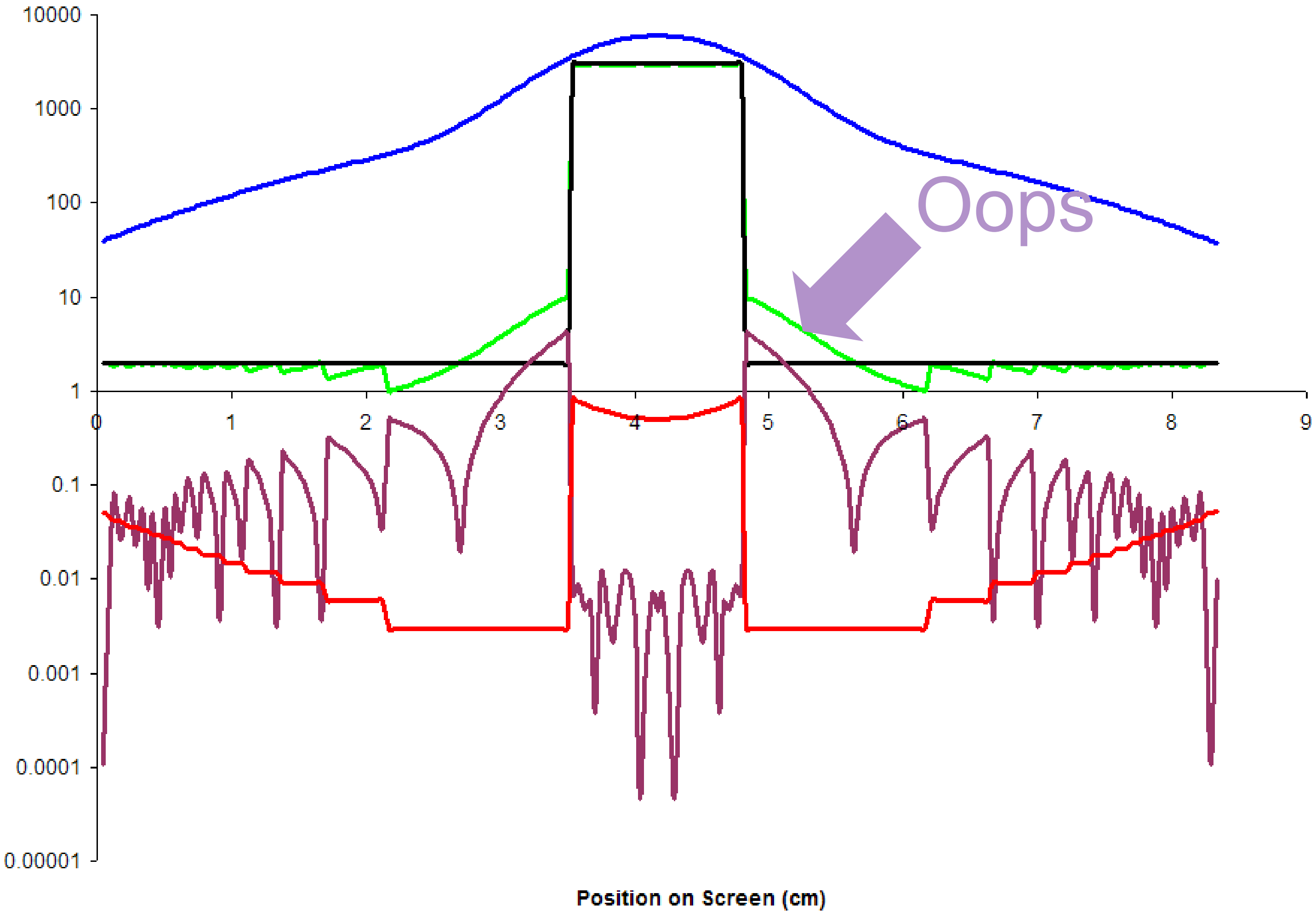
Drive LED

Divide Image by LED light field to obtain LCD values

Output Luminance is the product of LED light field and LCD transmission

(modest error)

Veiling Luminance



Receive Image

Drive LED

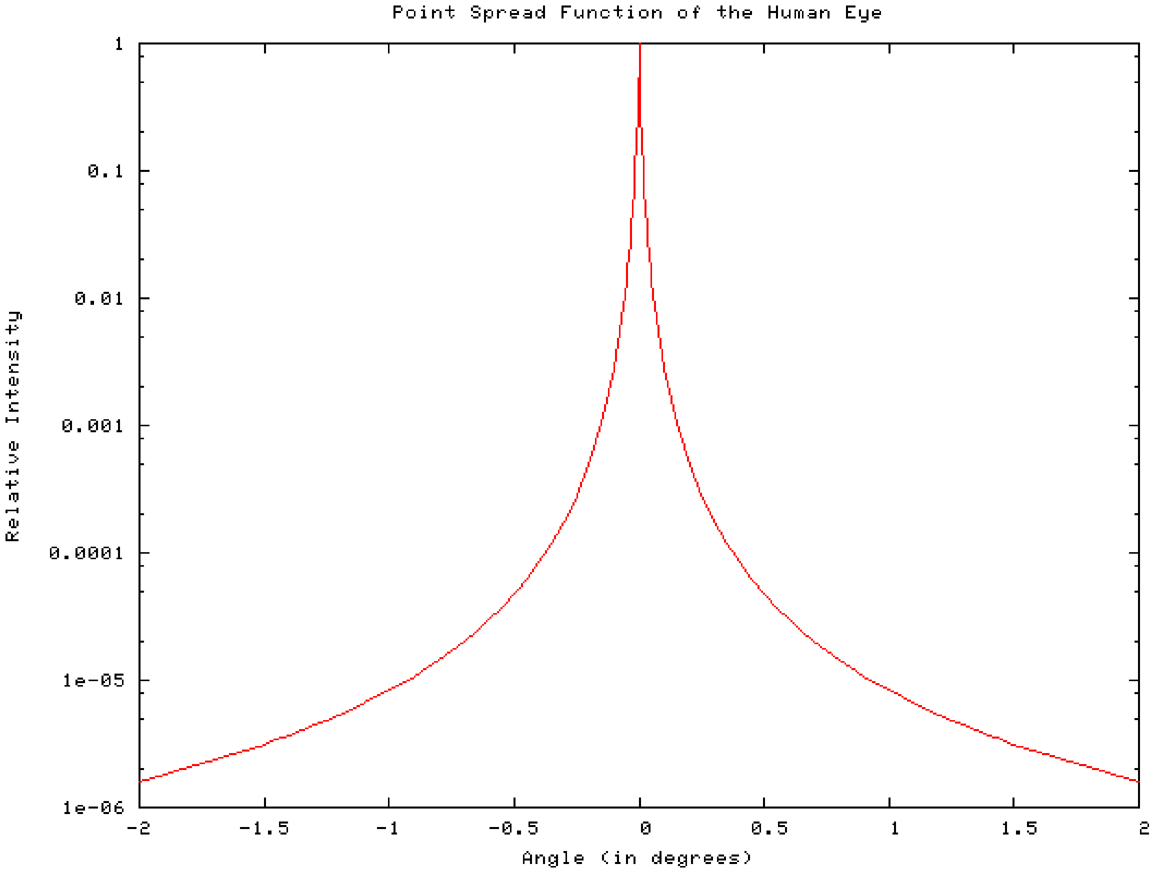
Divide Image by LED light field to obtain LCD values

Output Luminance is the product of LED light field and LCD transmission

(Problematic error)

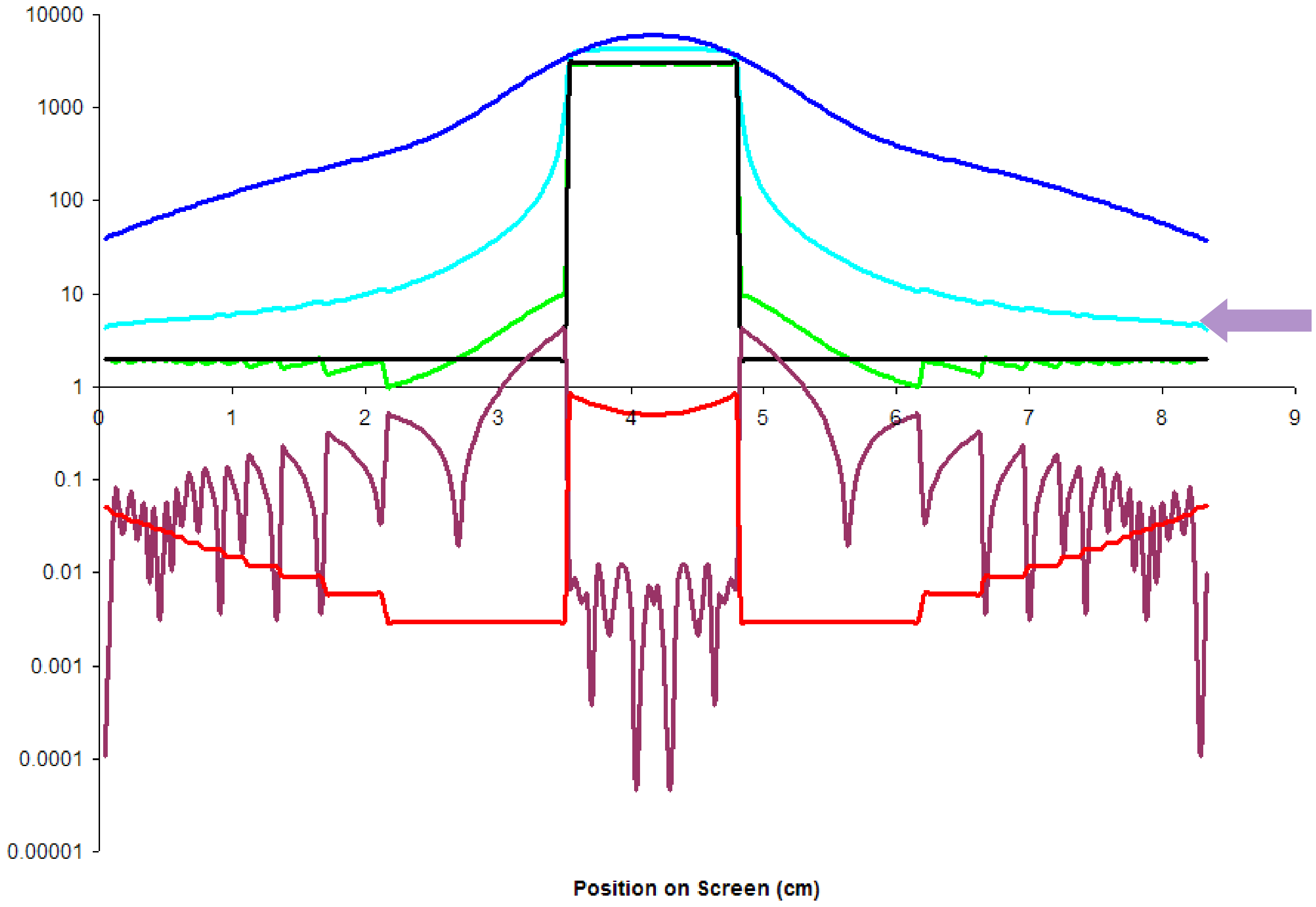
Veiling Luminance

- Maximum perceivable contrast
  - Globally very high (5-6 orders of magnitude)
    - That is why we create these displays!
  - Locally can be low: 150:1
- Point-spread function of human eye
  - Refer to „HDR and tone mapping" lecture
  - Consequence: high contrast edges cannot be perceived at full contrast



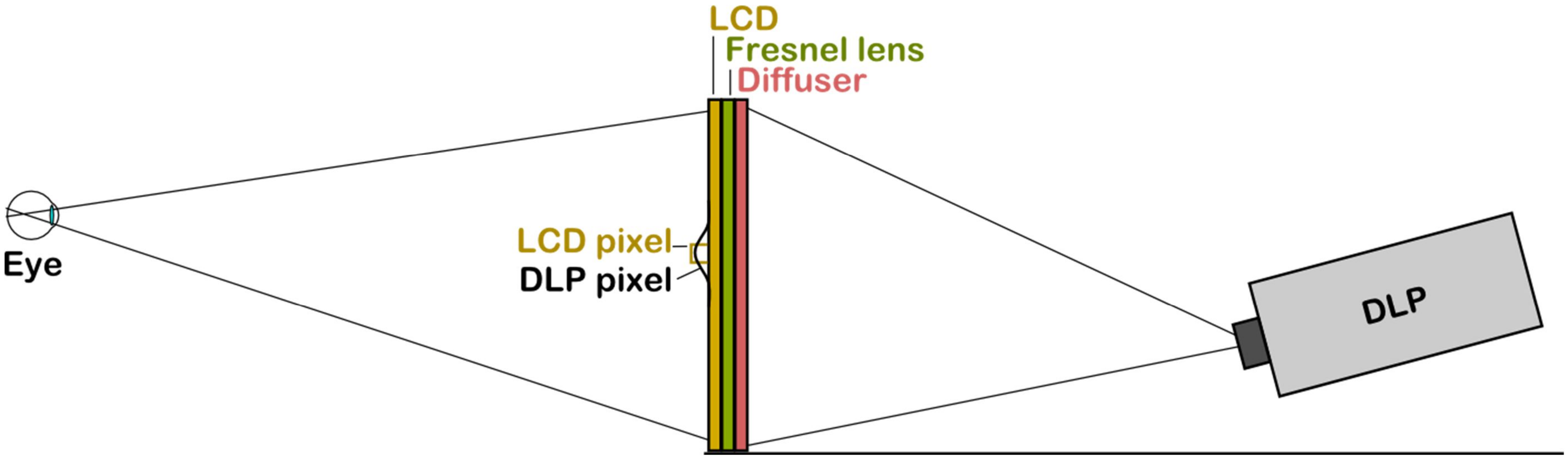
Veiling Glare (Camera)

Veiling Luminance



Veiling Luminance masks imperfection

HDR rendering algorithm - high level



Desired image

DLP blur (PSF)

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

DLP image

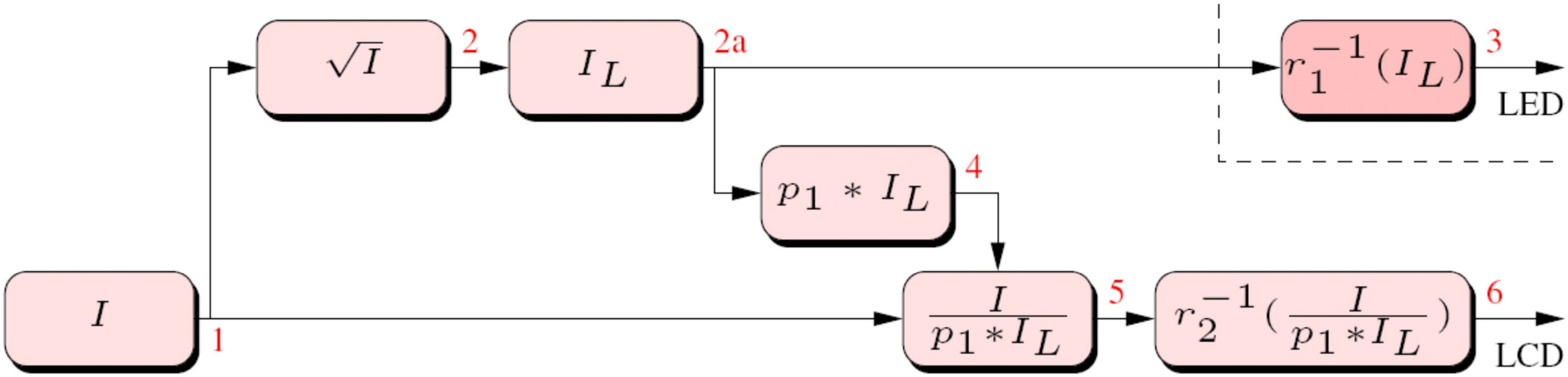
LCD image

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

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/