Display Technologies (2D)

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

Latency in VR

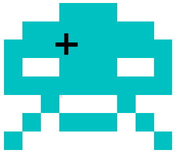
- Sources of latency in VR
  - IMU ~1 ms
  - sensor fusion, data transfer
  - rendering: depends on complexity of scene & GPU – a few ms
  - data transfer again
  - Display
    - 60 Hz = 16.6 ms;
    - 70 Hz = 11.1 ms;
    - 120 Hz = 8.3 ms.
- Target latency
  - Maximum acceptable: 20ms
  - Much smaller (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 than 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

Eye movement - basics

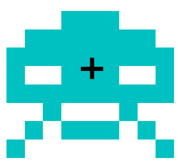
Fixation

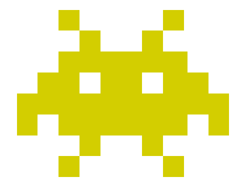


Drift: 0.15-0.8 deg/s

Eye movement - basics

Saccade

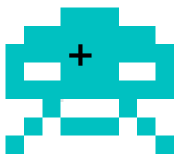




160-300 deg/s

Eye movement - basics

Smooth Pursuit Eye Motion (SPEM)

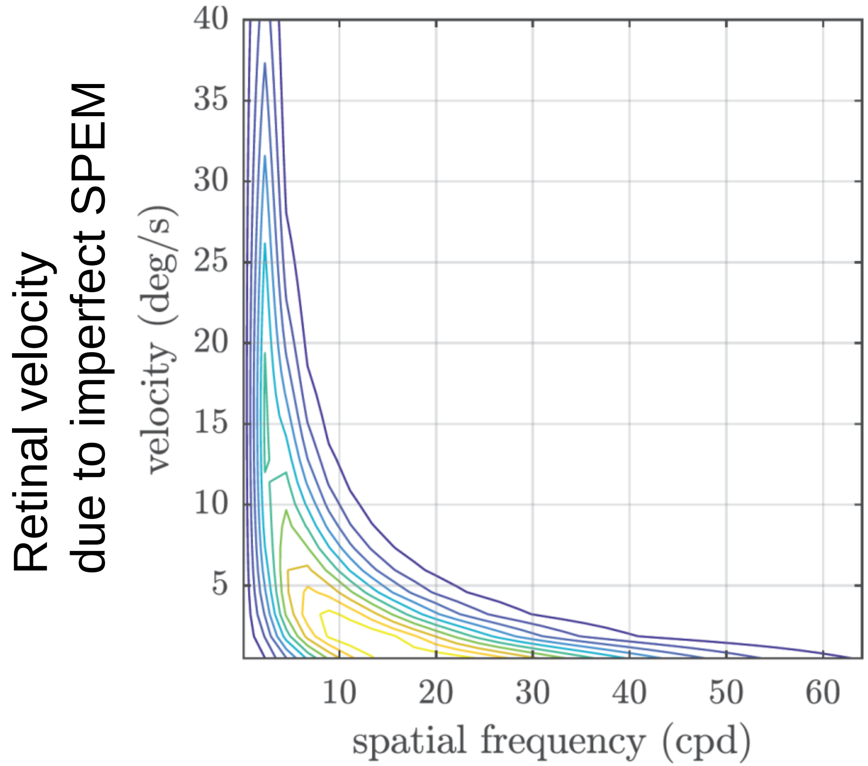


Up to 80 deg/s
The gaze tends to be 5-20% slower than the object

Retinal velocity

- The eye tracks moving objects
  - Smooth Pursuit Eye Motion (SPEM)
  - Stabilizes images on the retina
  - But tracking is not perfect
- Loss of sensitivity mostly caused by imperfect SPEM
  - SPEM worse at high velocities

Spatio-velocity contrast sensitivity



Kelly's model [1979]

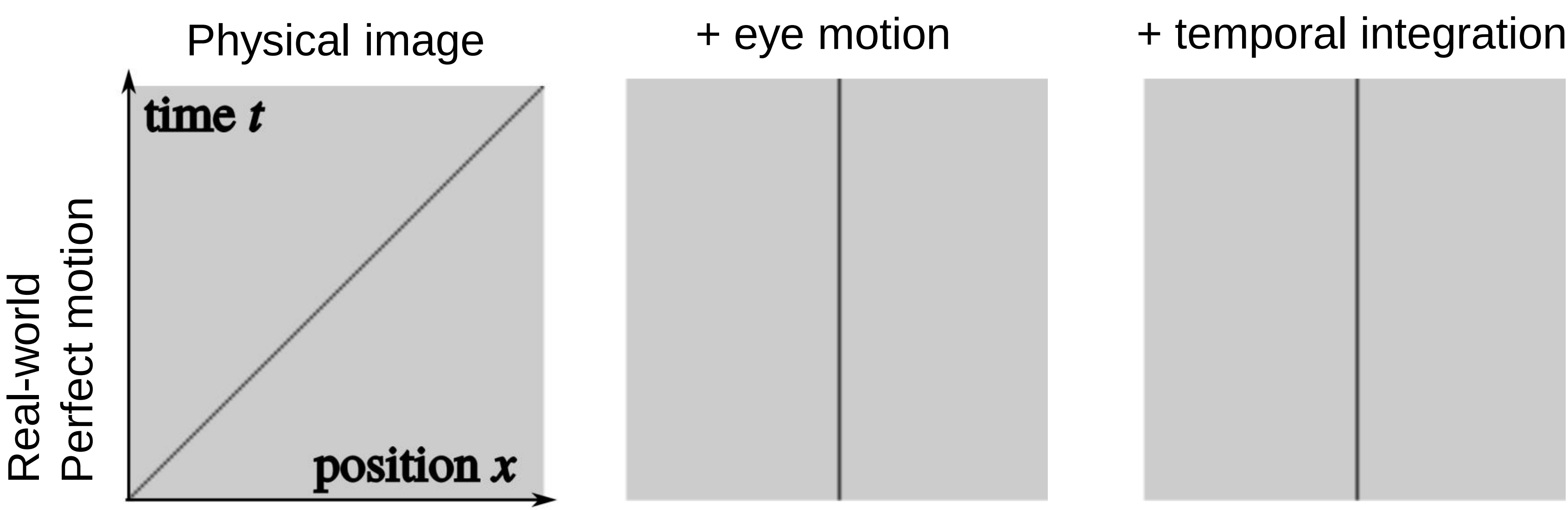
Motion sharpening

- 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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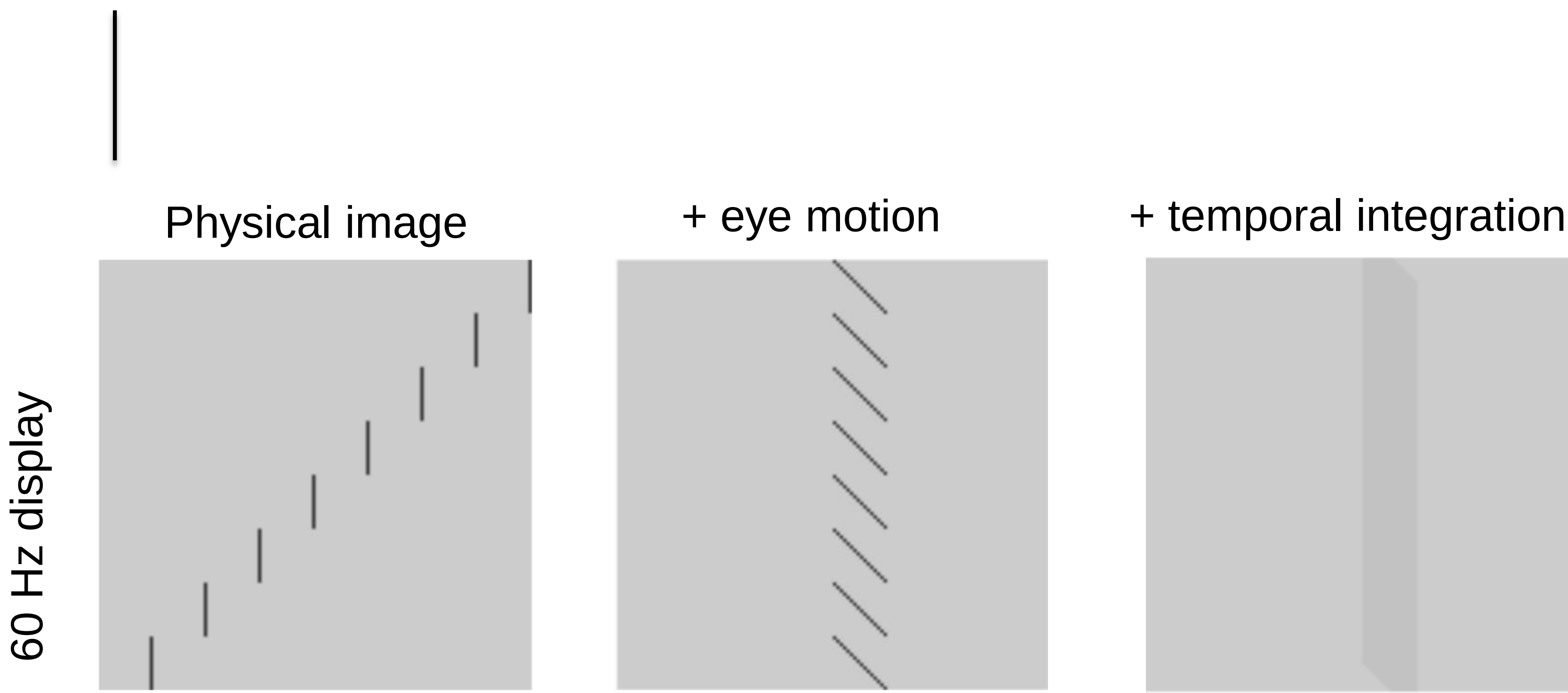

Original scene

With hold-type blur

Hold-type blur

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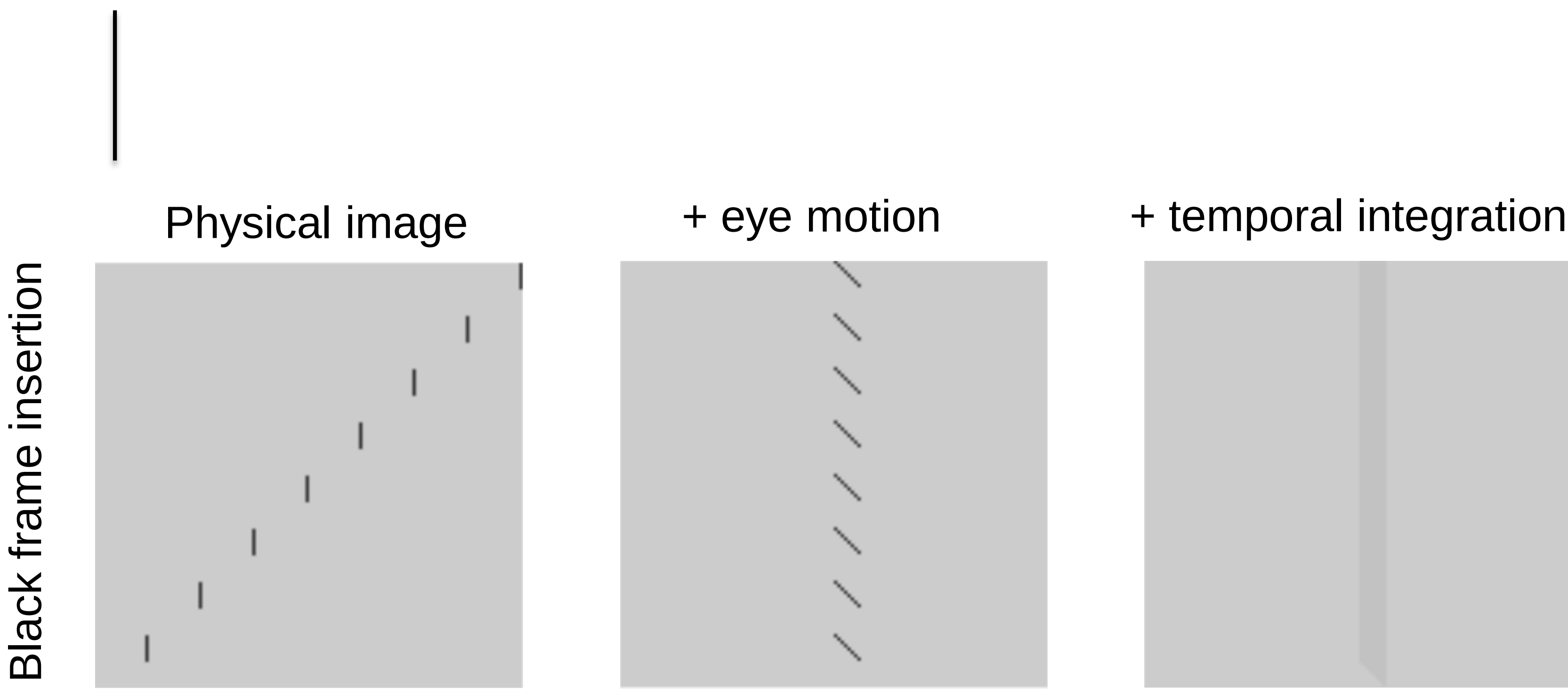
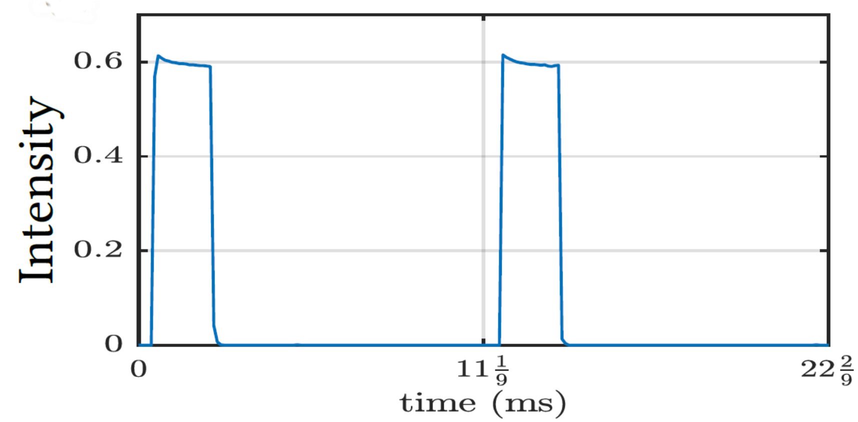


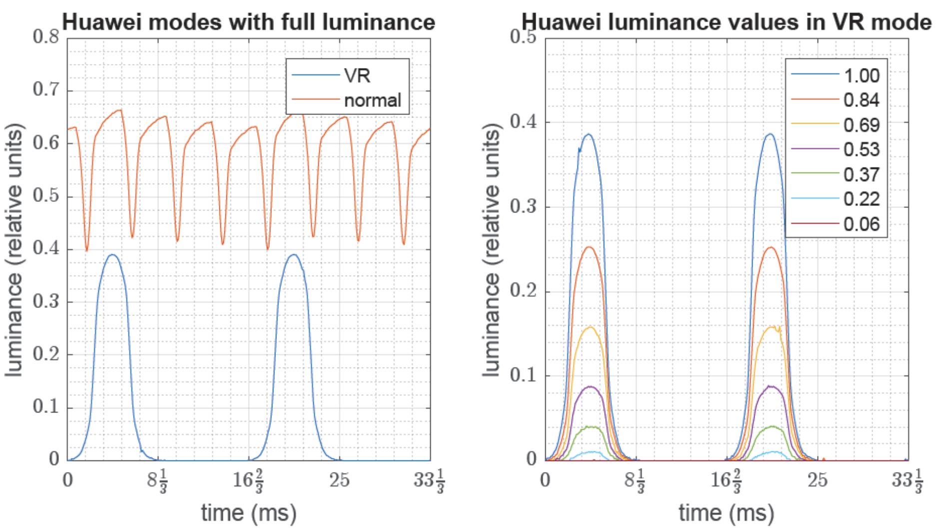
Low persistence displays

- 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

HTC Vive



Mate 9 Pro + DayDream



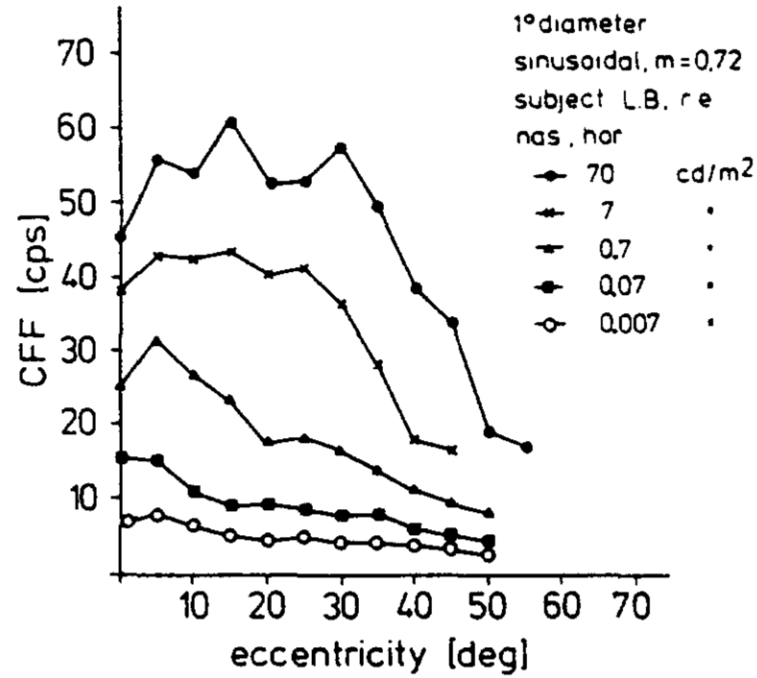
Black frame insertion

- 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
  - Increases with eccentricity
  - and stimulus size
  - It is possible to detect flicker even at 2kHz
    - For saccadic eye motion



[Hartmann et al. 1979]

Overview

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  - 2D spatial light modulators
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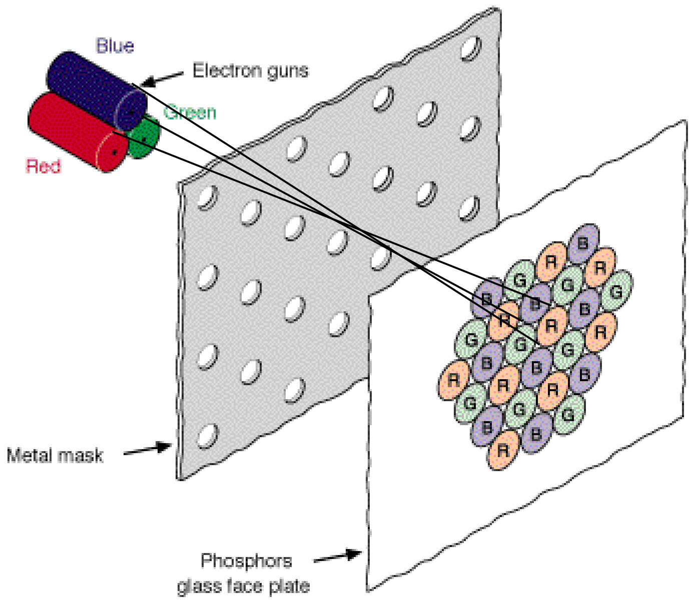
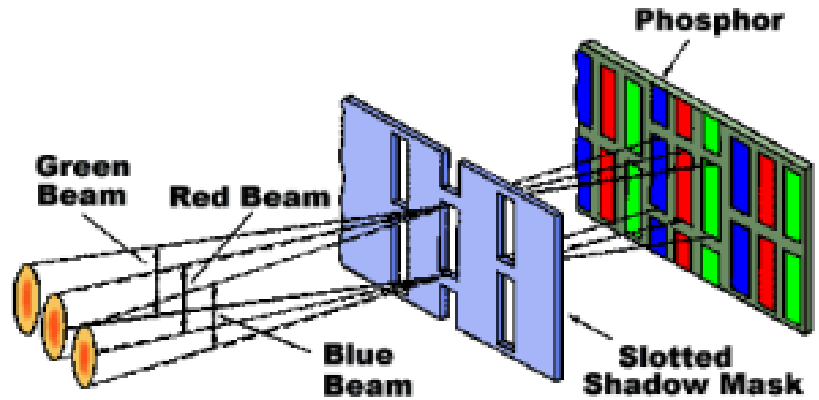
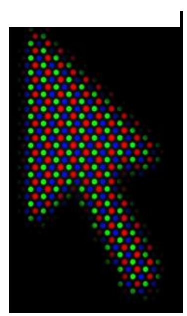
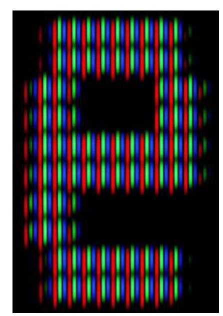
Cathode Ray Tube





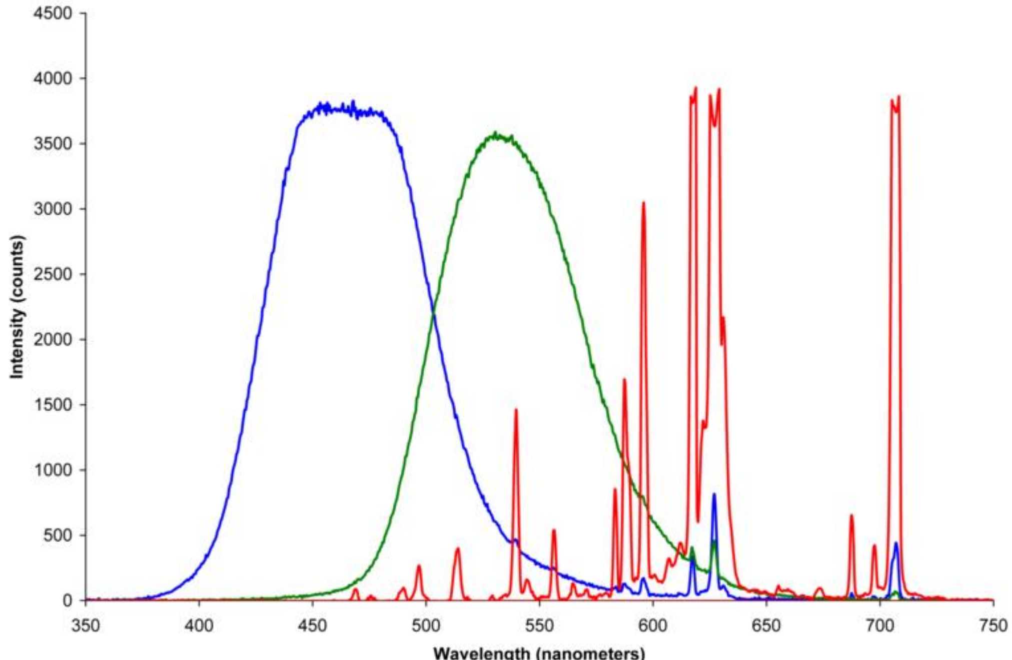




[from wikipedia]

Spectral Composition

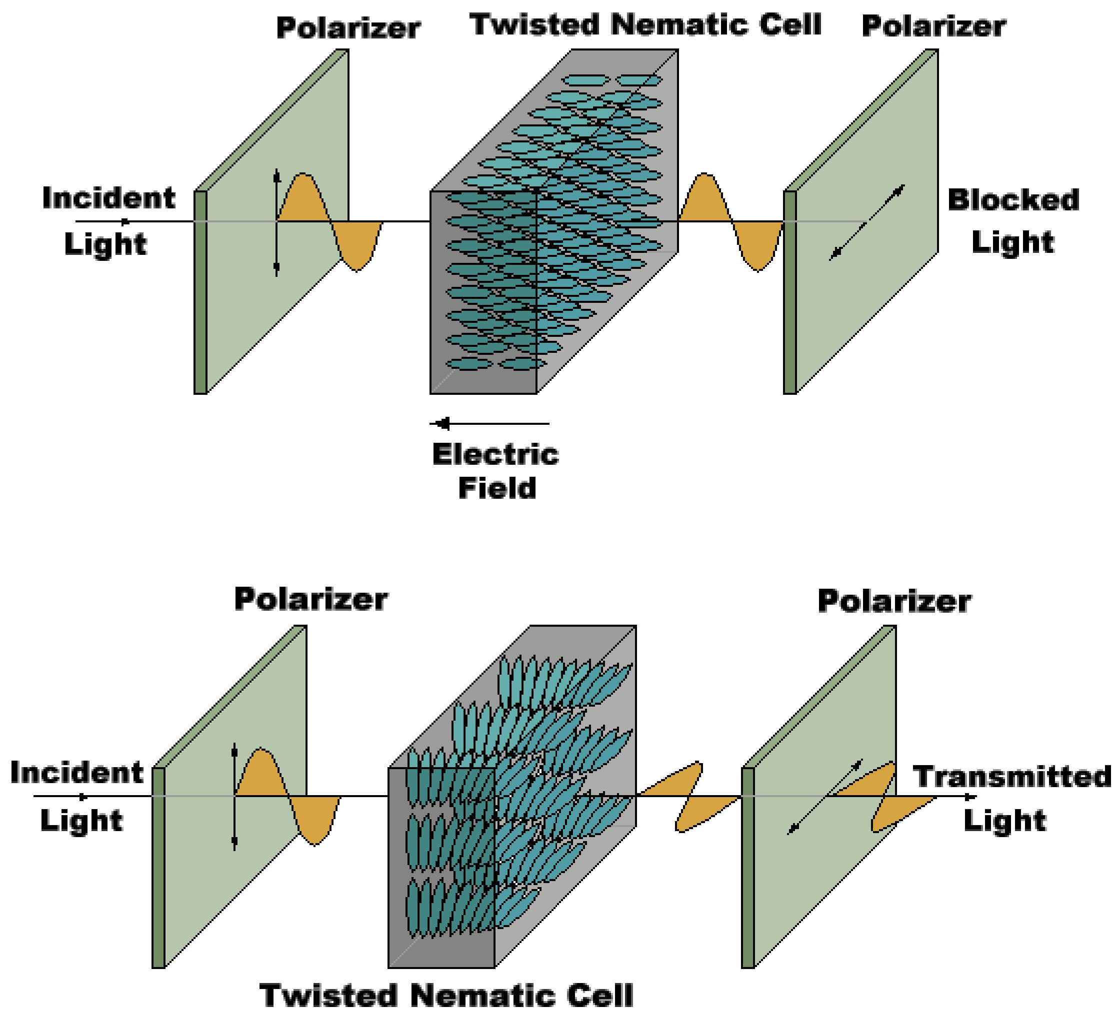
- three different phosphors



- 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

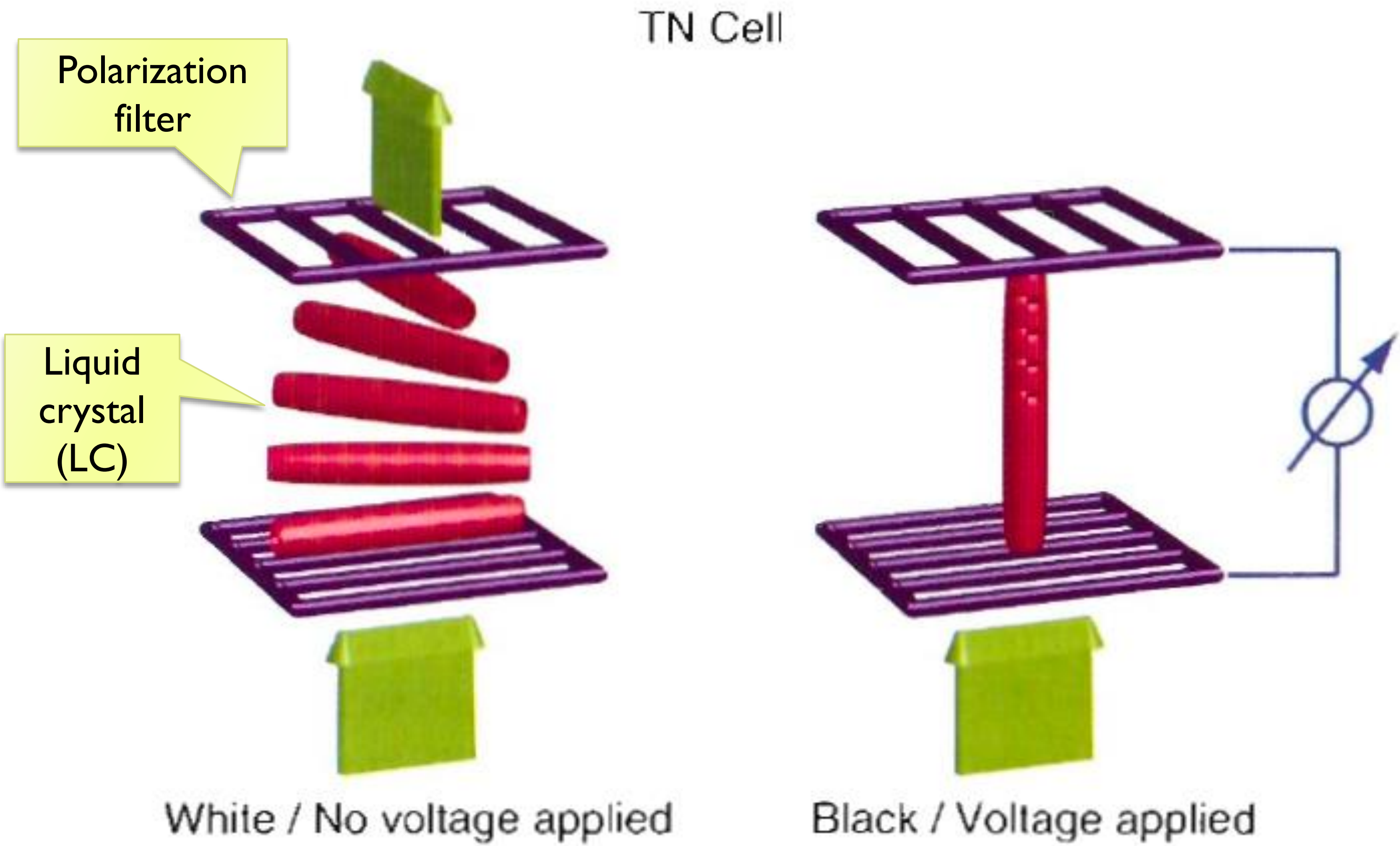


Figure from: High Dynamic Range Imaging by E. Reinhard et al.

In-plane switching cell (IPS)

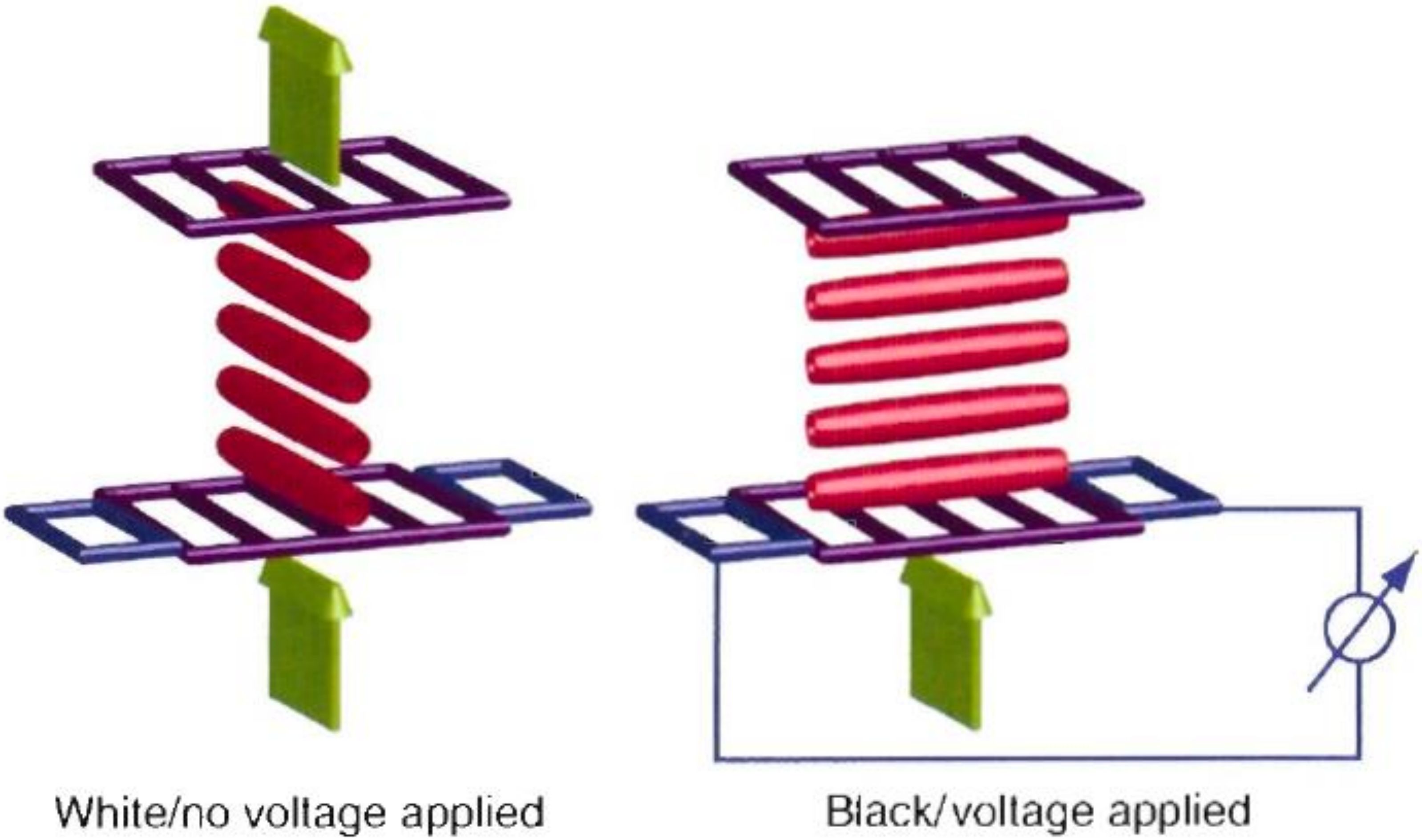
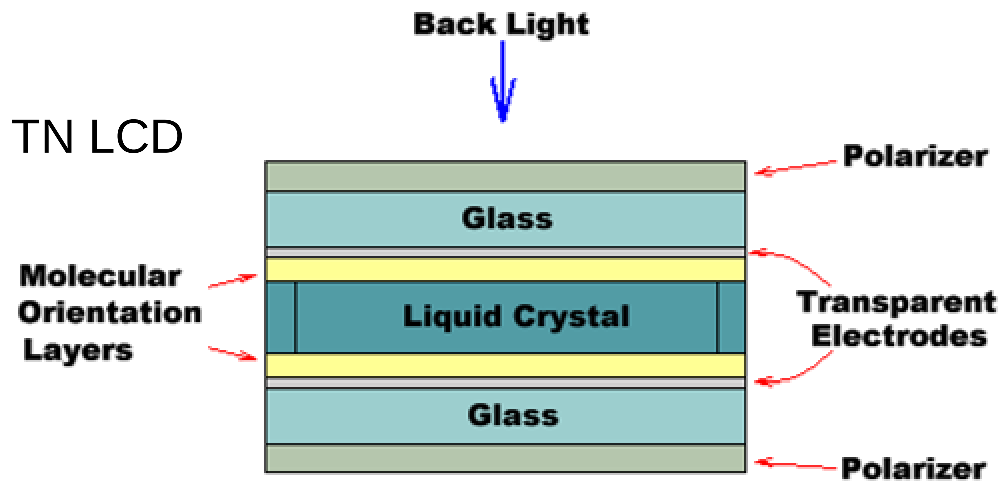


Figure from: High Dynamic Range Imaging by E. Reinhard et al.

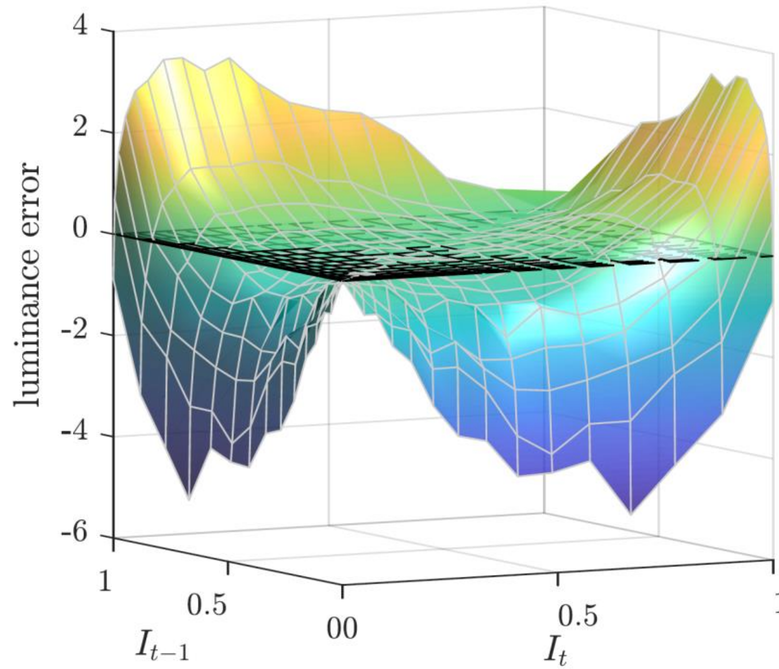
LCD

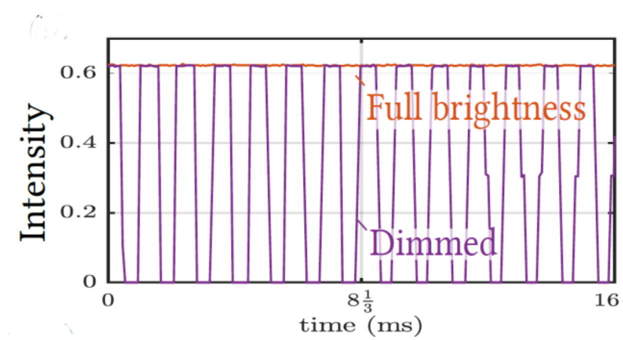


- color may change with the viewing angle
- contrast up to 3000:1
- higher resolution results in smaller fill-factor
- color LCD transmits only up to 8% (more often close to 4-5%) light when set to full white

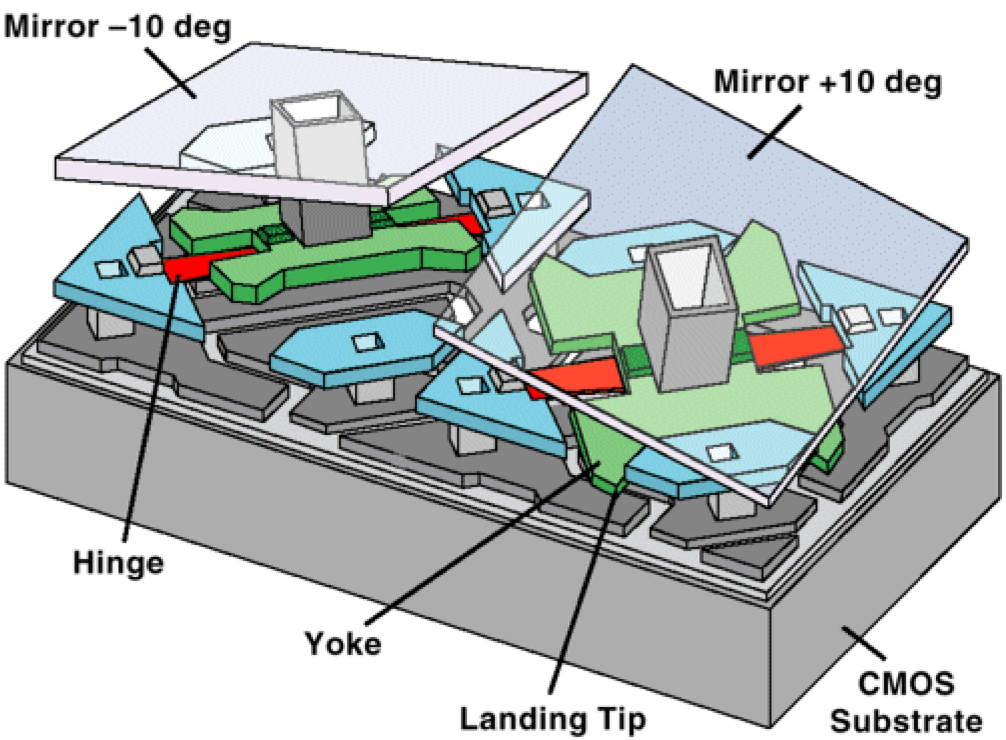
LCD temporal response

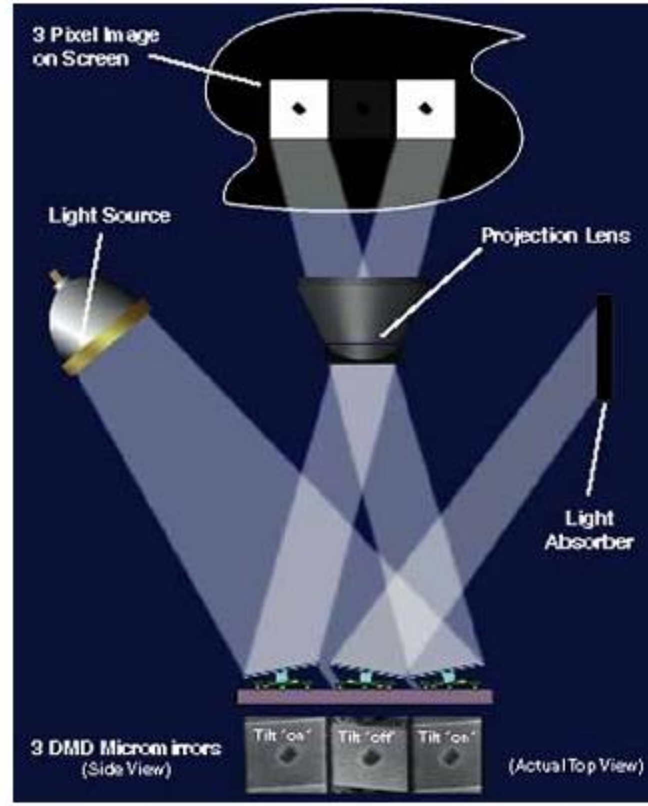
- Experiment on an IPS LCD screen
- We rapidly switched between two intensity levels at 120Hz
- Measured luminance integrated over 1s
- The top plot shows the difference between expected ($\frac{I_{t-1}+I_t}{2}$) and measured luminance
- The bottom plot: intensity measurement for the full brightness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





Digital Micromirror Devices (DMDs/DLP)

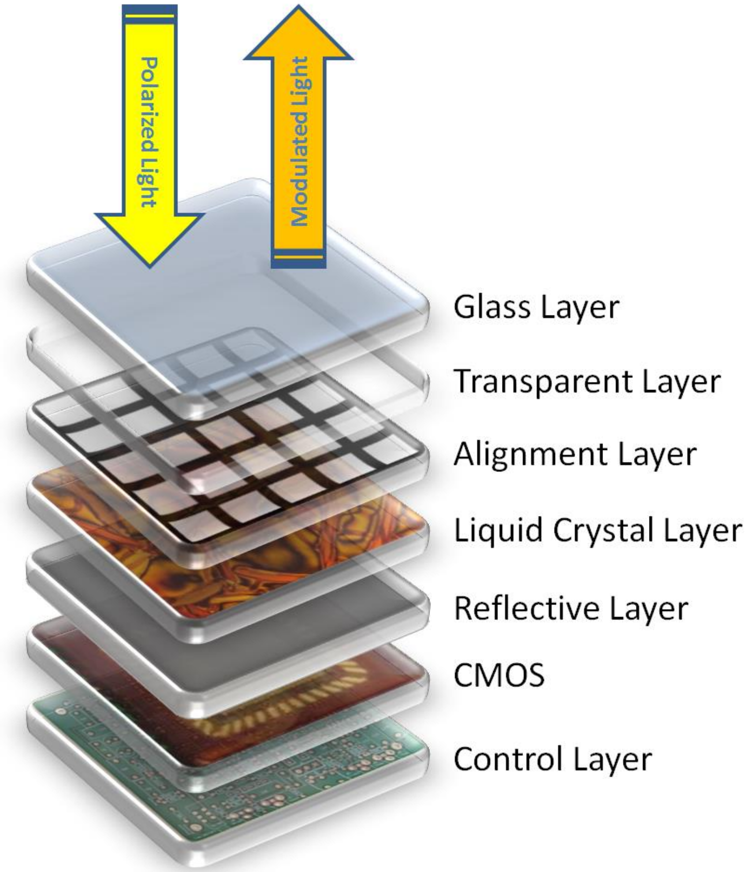




Texas Instruments

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

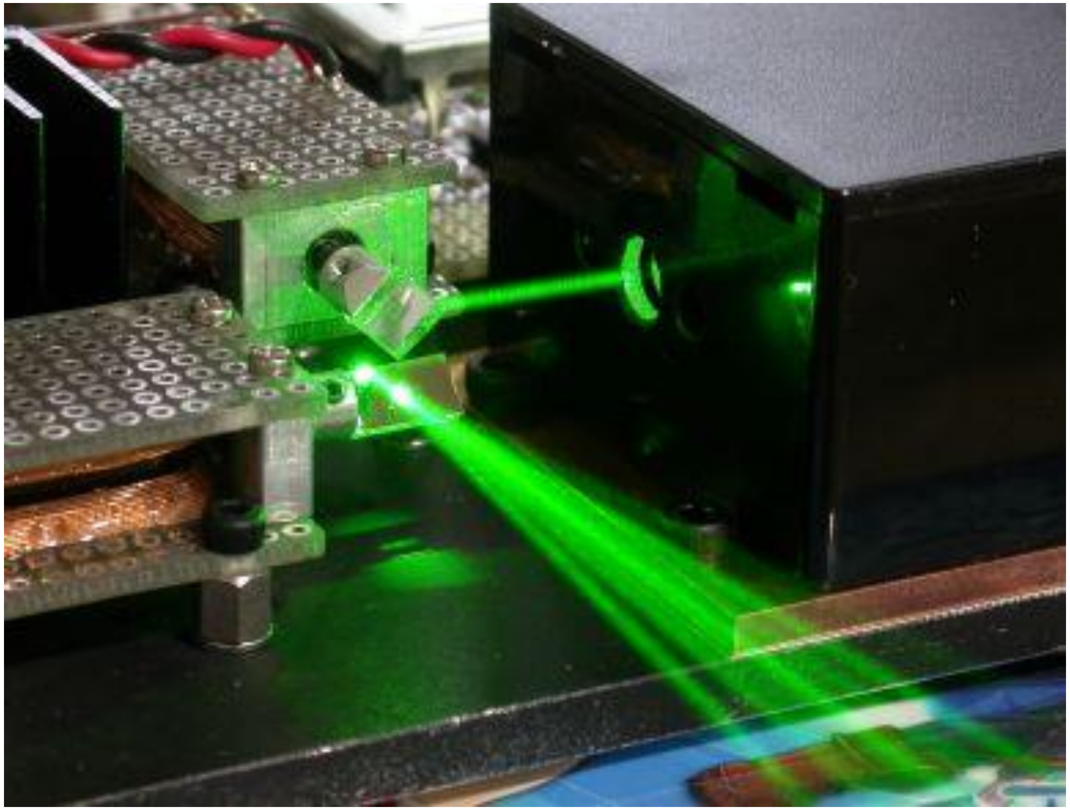
Liquid Crystal on Silicon (LCoS)



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

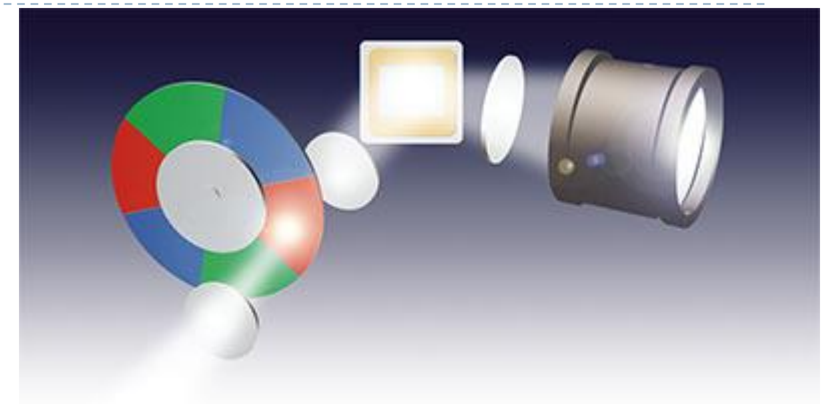
Scanning Laser Projector

- maximum contrast
- scanning rays
- very high power lasers needed for high brightness

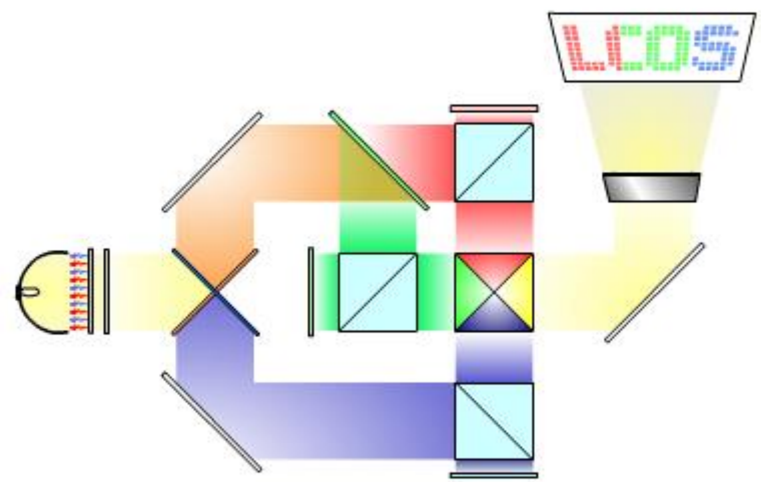


http://elm-chan.org/works/vlp/report_e.html

3-chip vs. Color Wheel Display



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

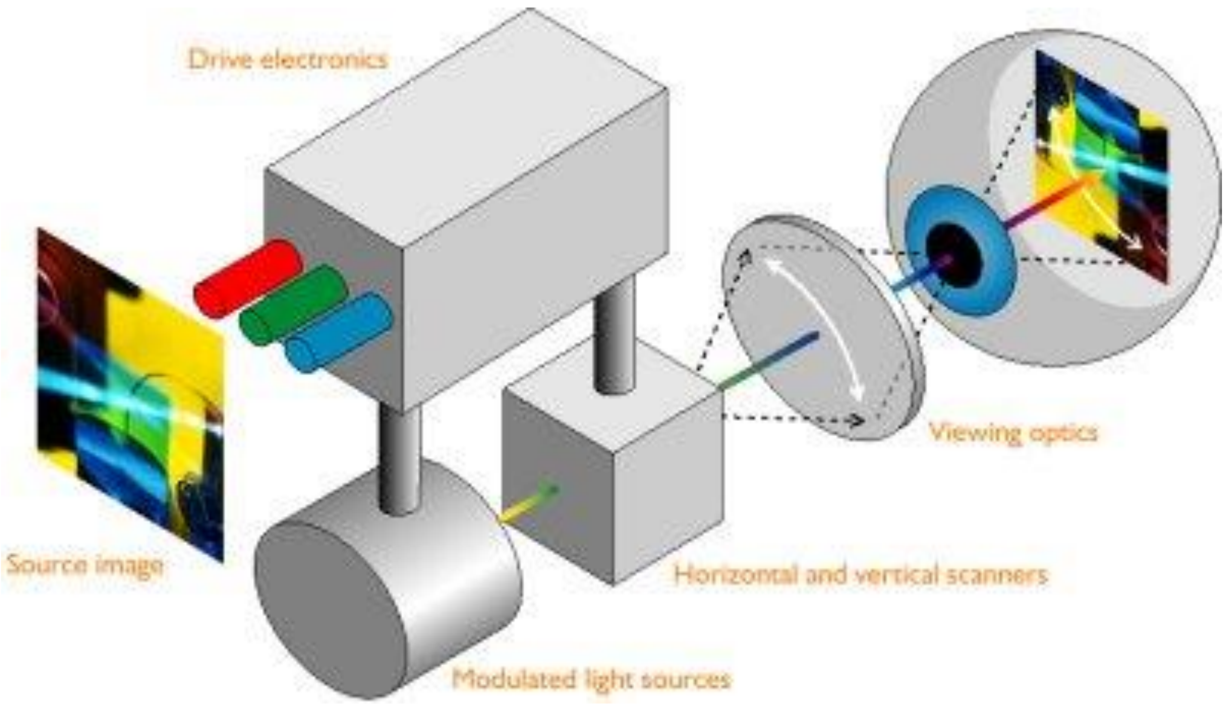


AiRScouter

Virtual Retinal Display

- projection onto the retina
- challenge – small viewing box

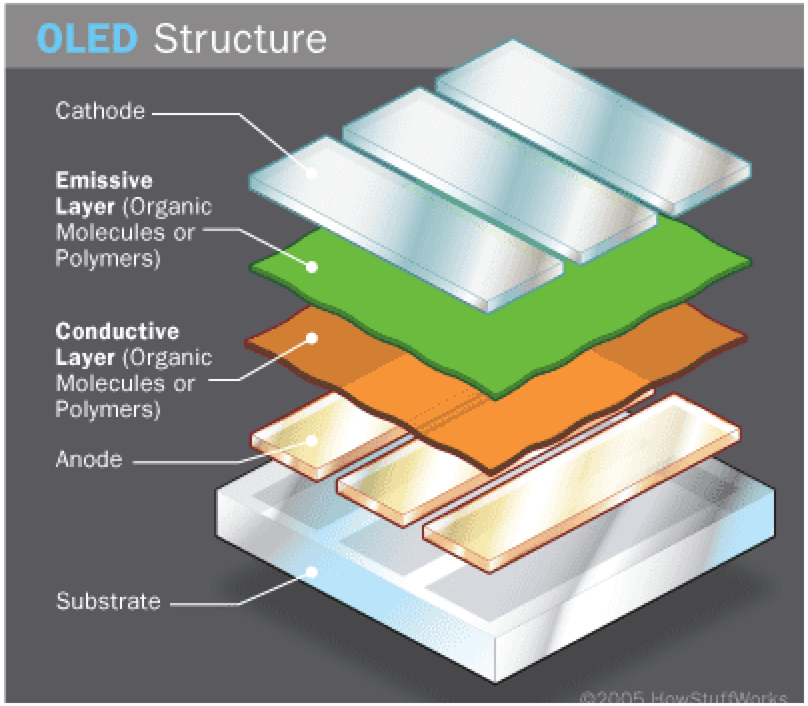

From: http://www.engadget.com/2010/09/17/brothers-airscouter-floats-a-16-inch-display-onto-your-eye-bisc/



Google – project Glass

OLED

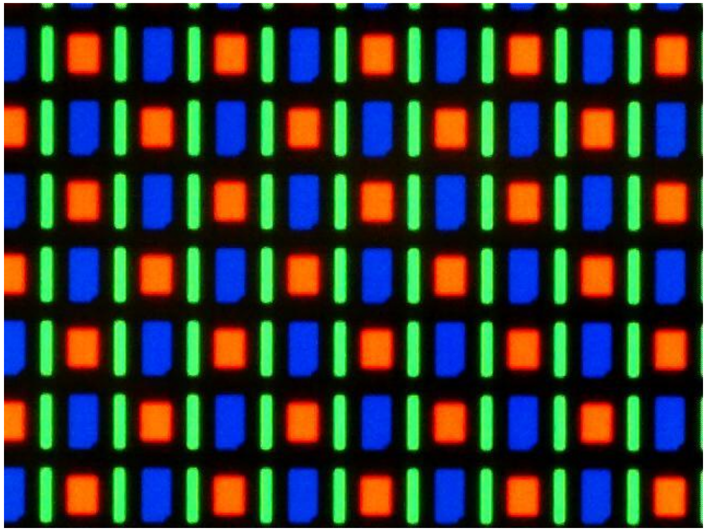
- based on electrophosphorescence
- large viewing angle
- the power consumption varies with the brightness of the image
- fast (< 1 microsec)
- arbitrary sizes



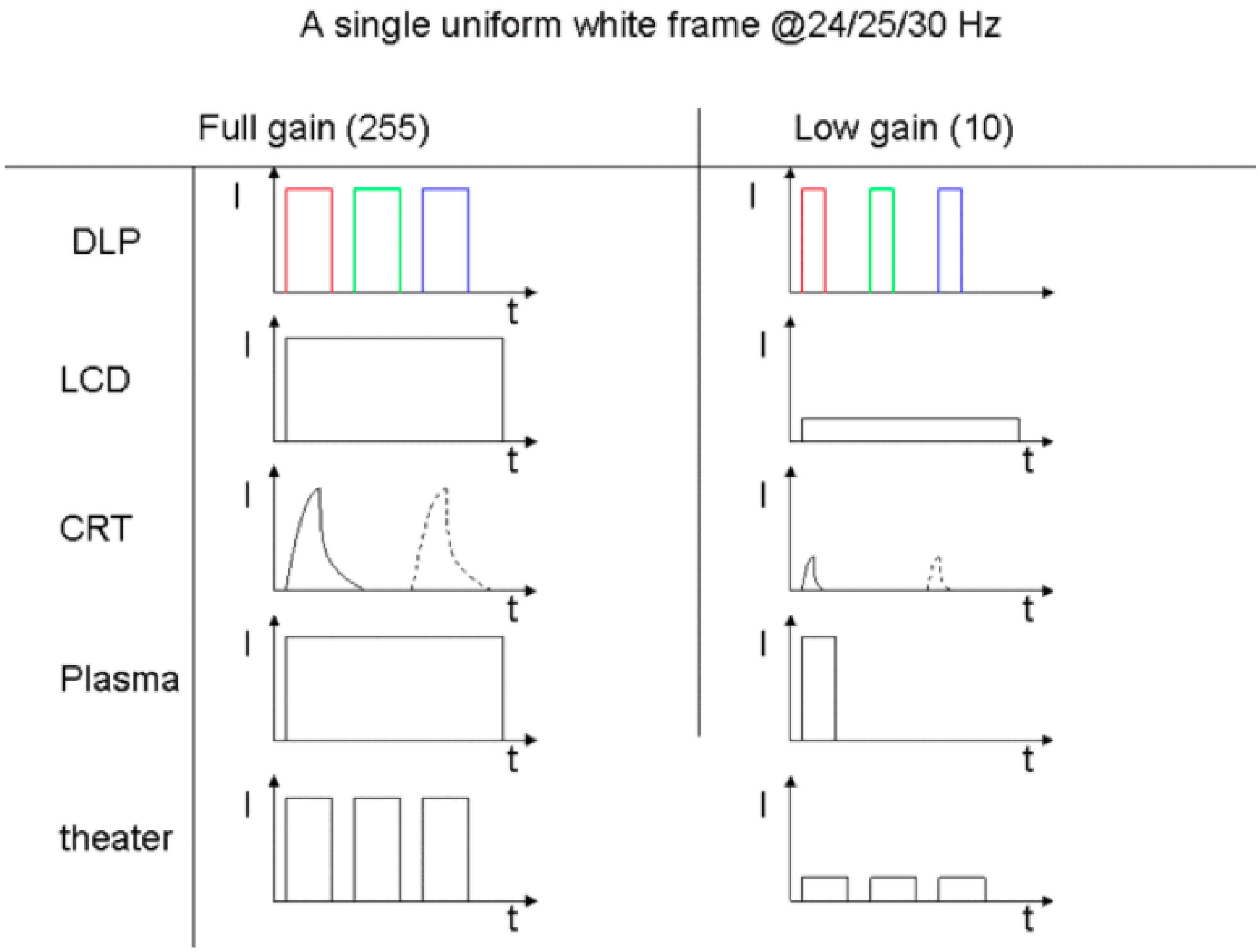
- life-span can be short
  - Worst for blue OLEDs

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



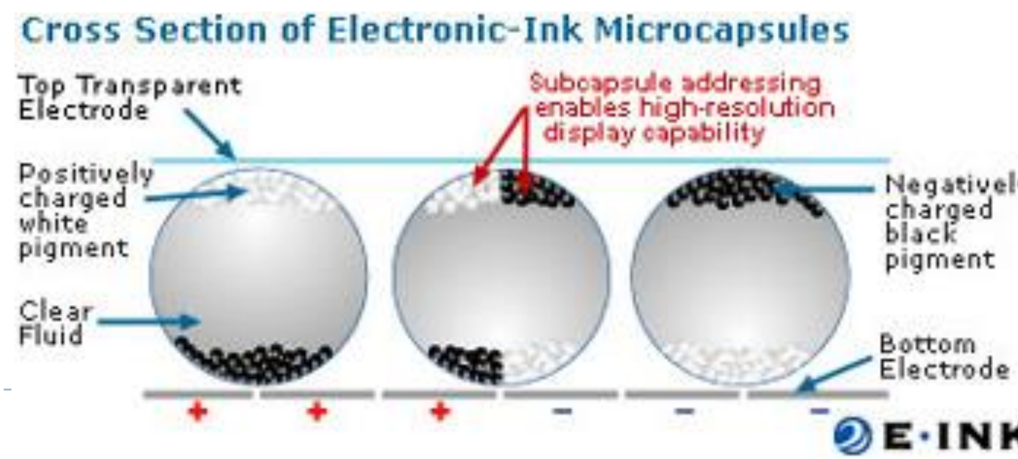
Temporal characteristic



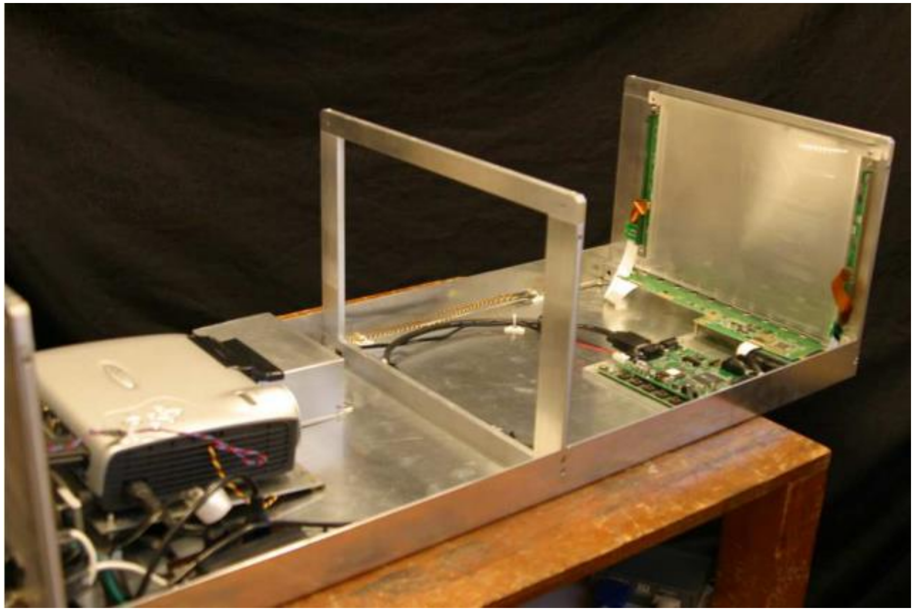
From: http://en.wikipedia.org/wiki/Comparison_of_display_technology

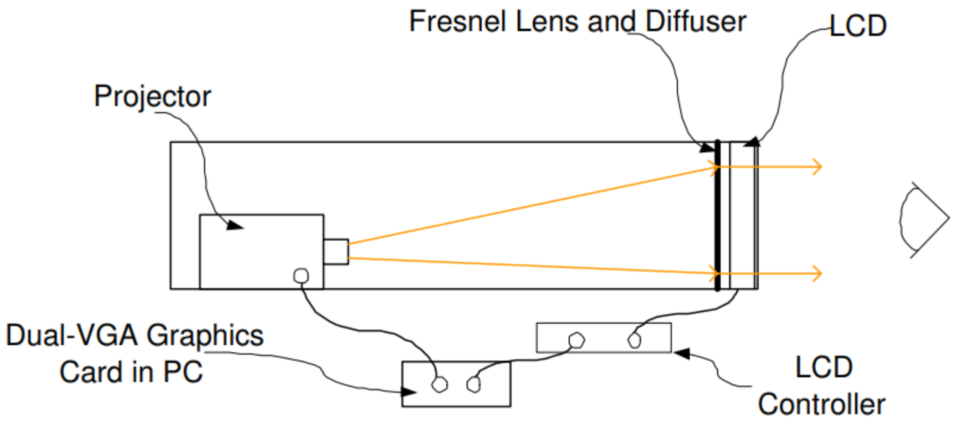
Electronic Paper

www.eink.com



Prototype HDR display (2004)

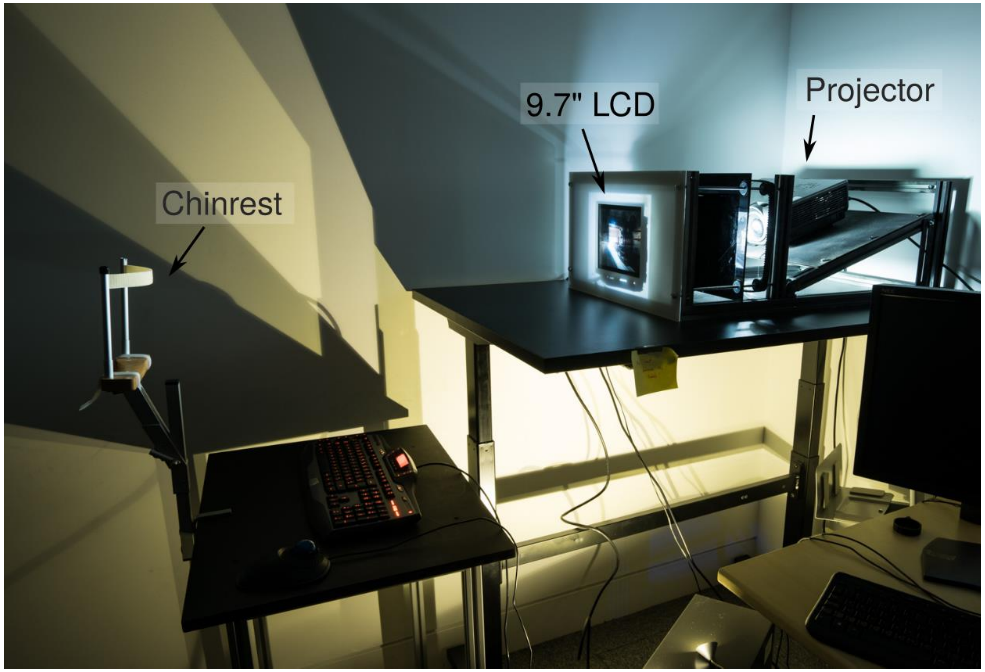


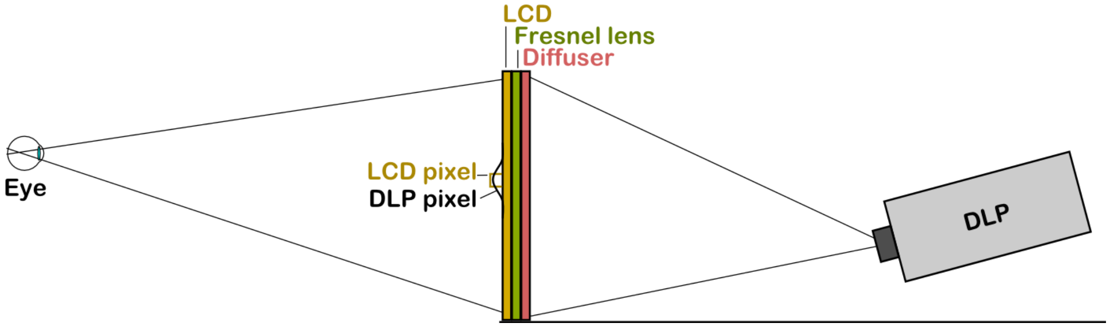


From [Seetzen et al. SIGGRAPH 2004]

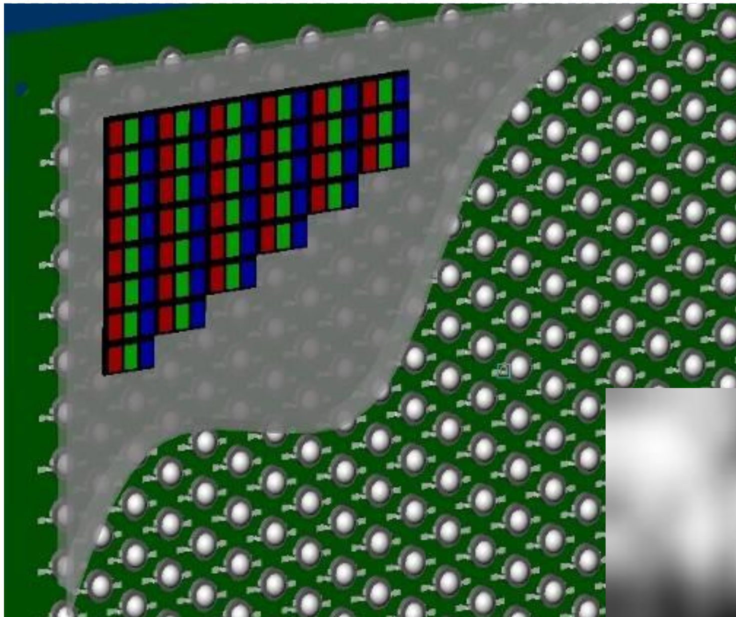
Cambridge experimental HDR display

- 15,000 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



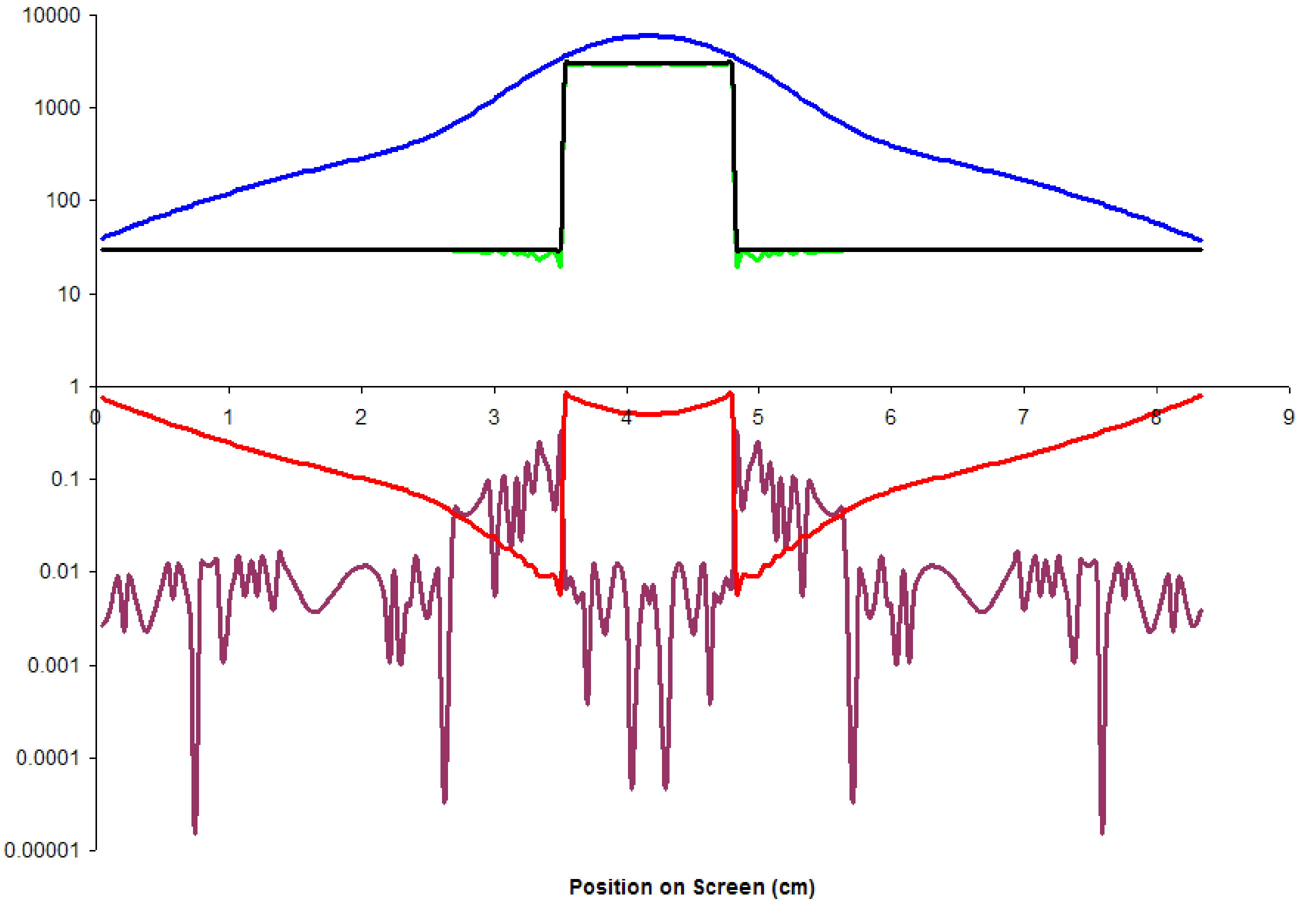
- Modulated LED array
- Conventional LCD
- Image compensation

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 w/ 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



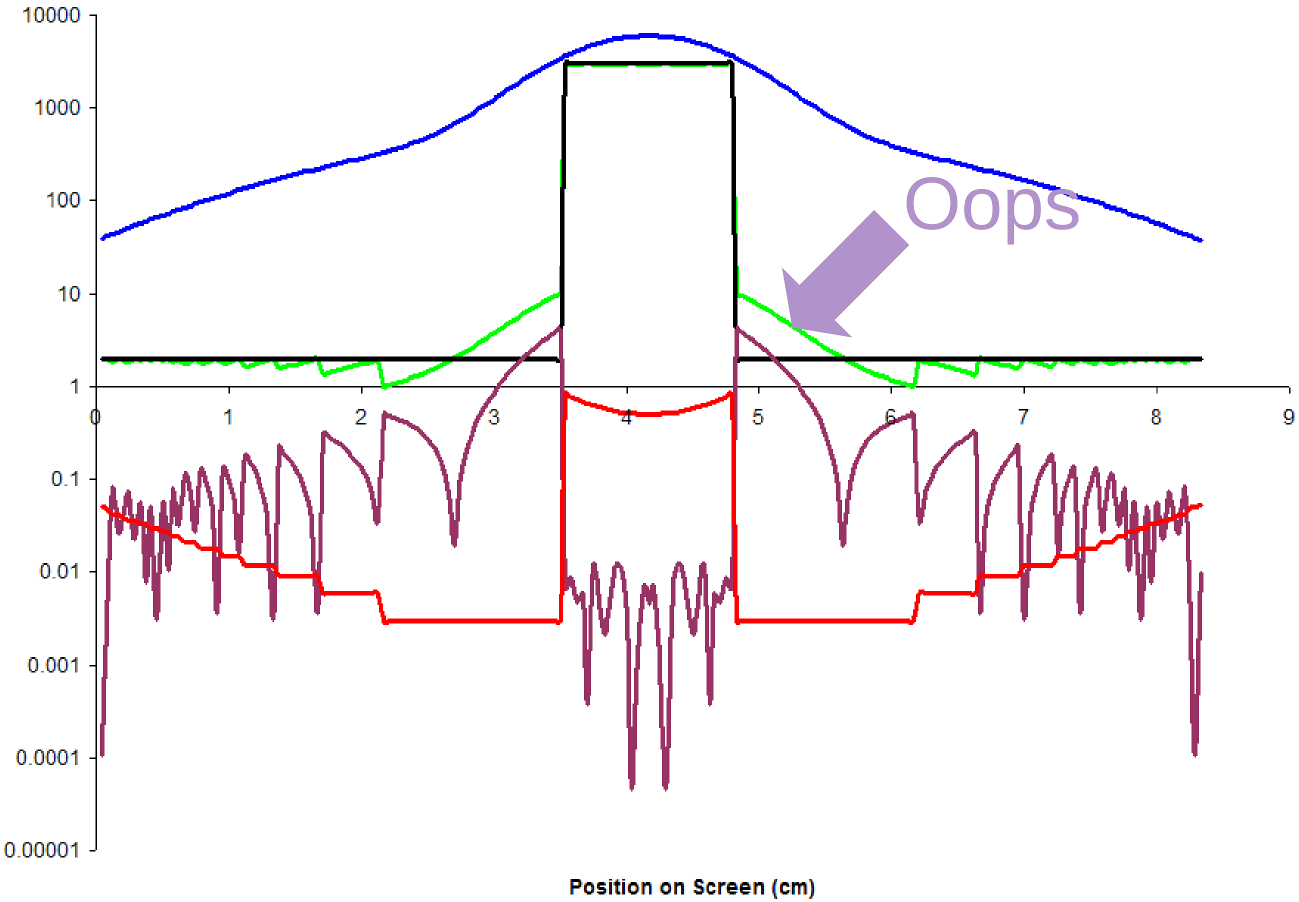
Receive Image

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

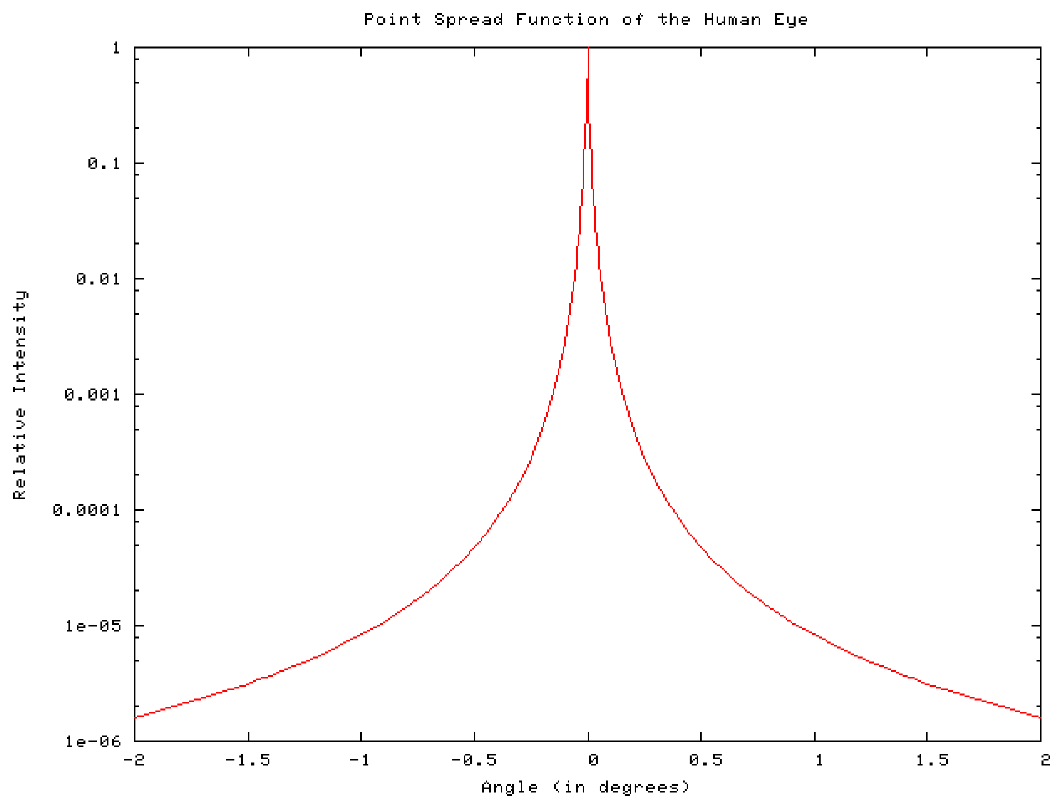
Drive LED

Divide Image by LED light field to obtain LCD values

Output Luminance is the product of LED light field and LCD transmission (Problematic error)

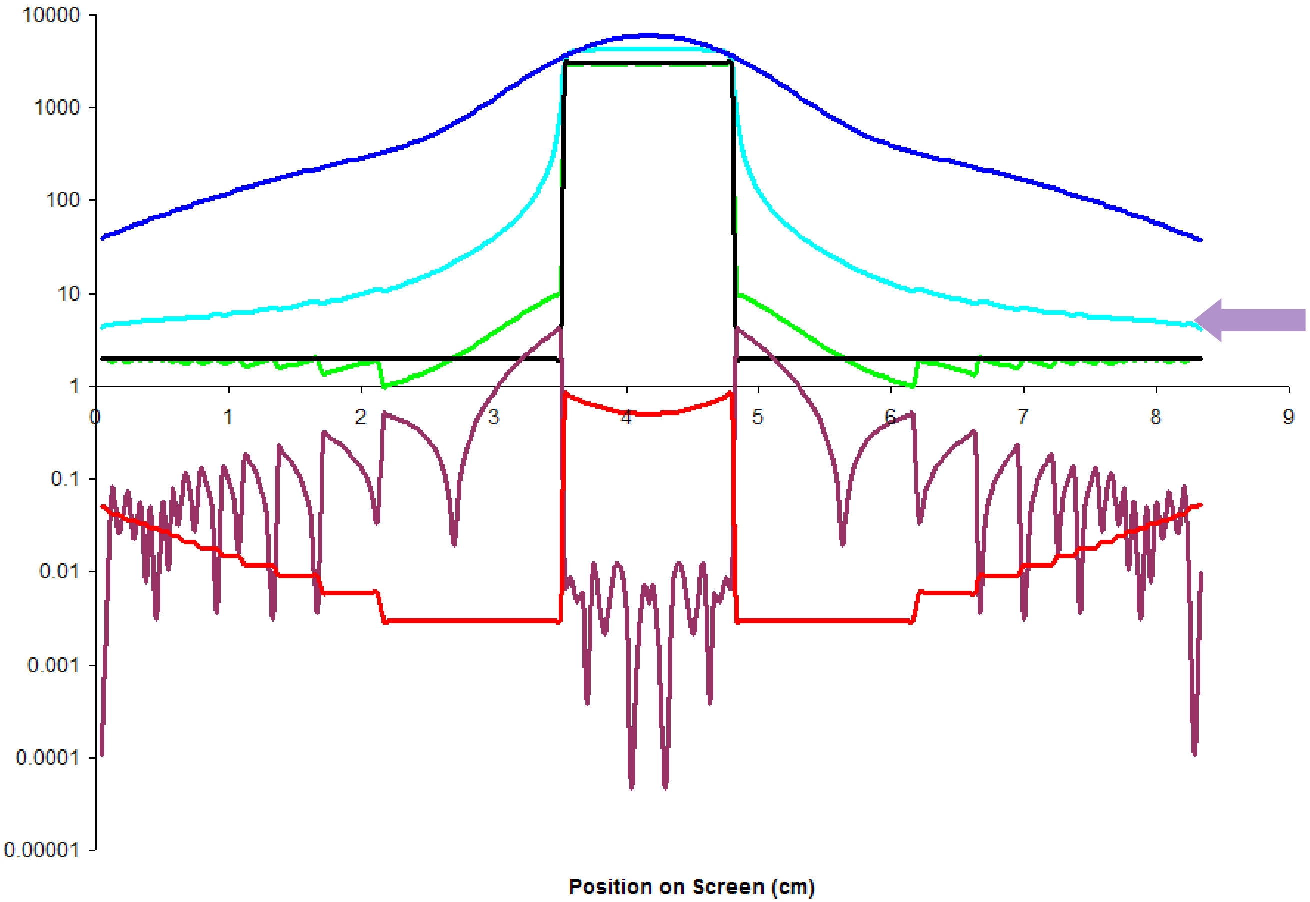
Veiling Luminance

- 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



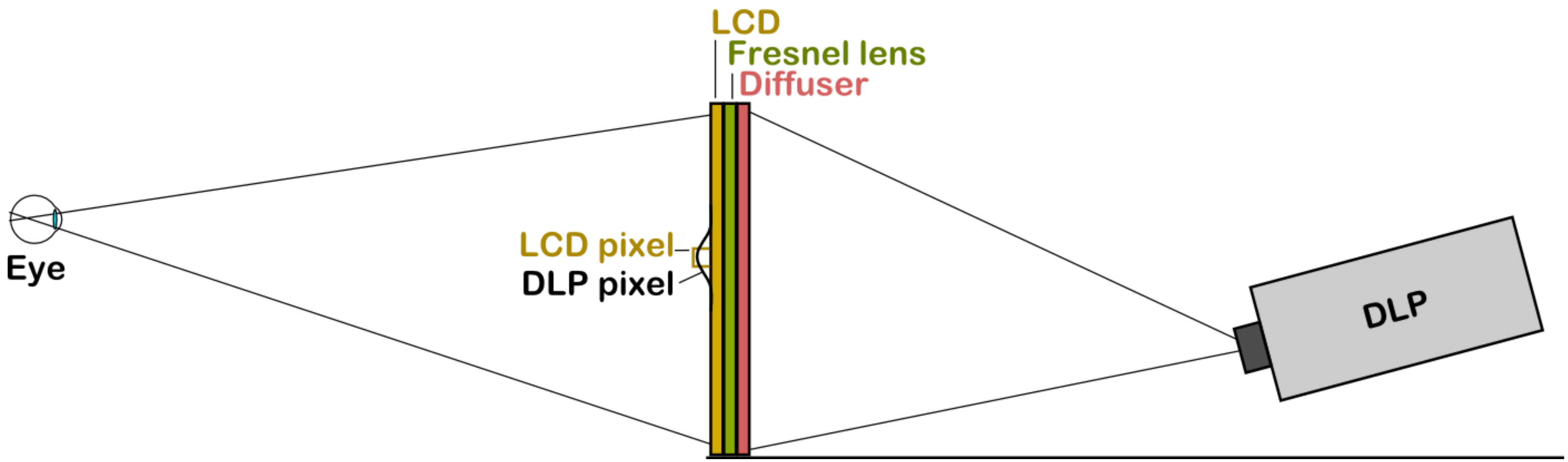
Veiling Glare (Camera)

Veiling Luminance



Veiling Luminance masks imperfection

HDR rendering algorithm - high level



Desired image

DLP blur (PSF)

$$\arg\min_{L,D} ||I - g\, D \circ L||_2$$

DLP image

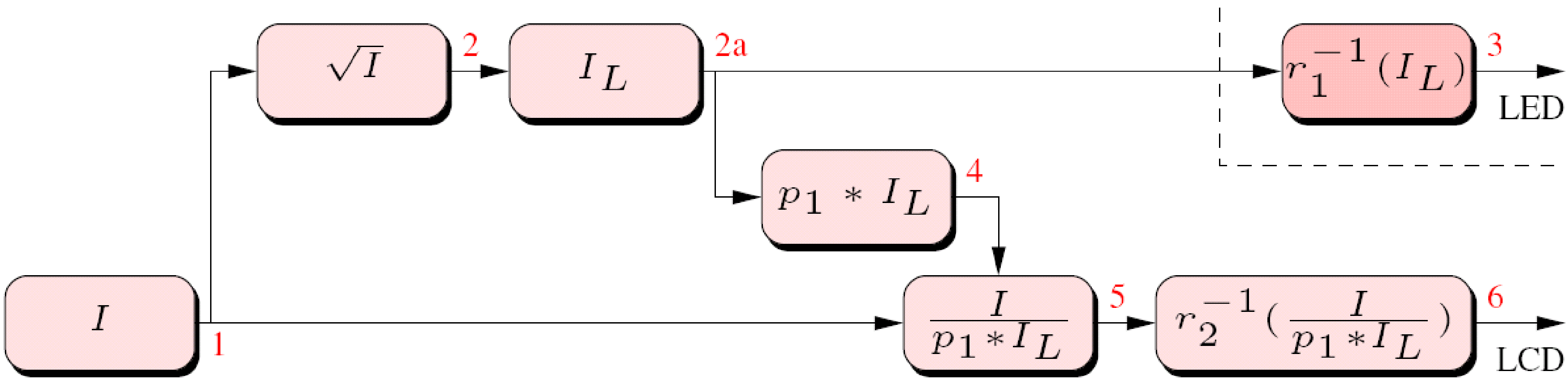
LCD image

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/