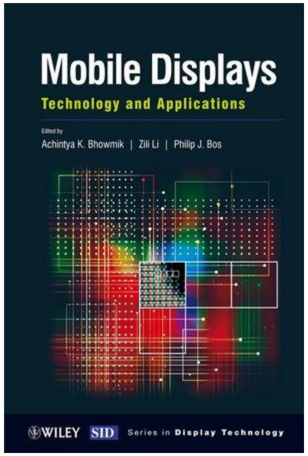
Optics & Displays

CS 294-10: Virtual Reality & Immersive Computing
EECS, UC Berkeley
Fall 2017

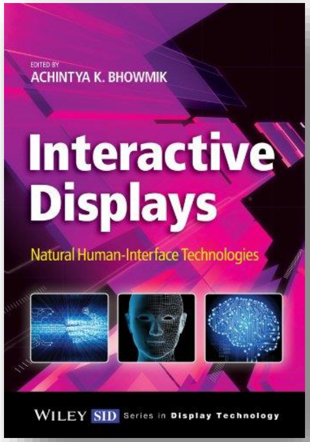
Achin Bhowmik, PhD

CTO & EVP of Engineering
Starkey Hearing Technologies
Berkeley, CA and Eden Prairie, MN

Books (Optional Reading)



Mobile Displays: Technology and Applications,
A. K. Bhowmik, Z. Li, P. J. Bos, Ed., Wiley (2008)
http://www.wiley.com/WileyCDA/WileyTitle/productCd-0470723742.html



Interactive Displays: Natural Human-Interface Technologies,
A. K. Bhowmik, Ed., Wiley (2014)
http://www.wiley.com/WileyCDA/WileyTitle/productCd-1118631374.html

Recall: AR/VR System Components

- Sense
  - Accurate spatio-temporal position tracking and localization (inertial measurement unit, cameras, microphones, …)
- Compute
  - High-performance and power-efficient hardware and software for real-time processing, rendering, and display
- Display
  - Spatial light modulation for immersive 3D visual experience
- Audio
  - 3D immersive sound experience
- Interactions
  - Human inputs and interfaces

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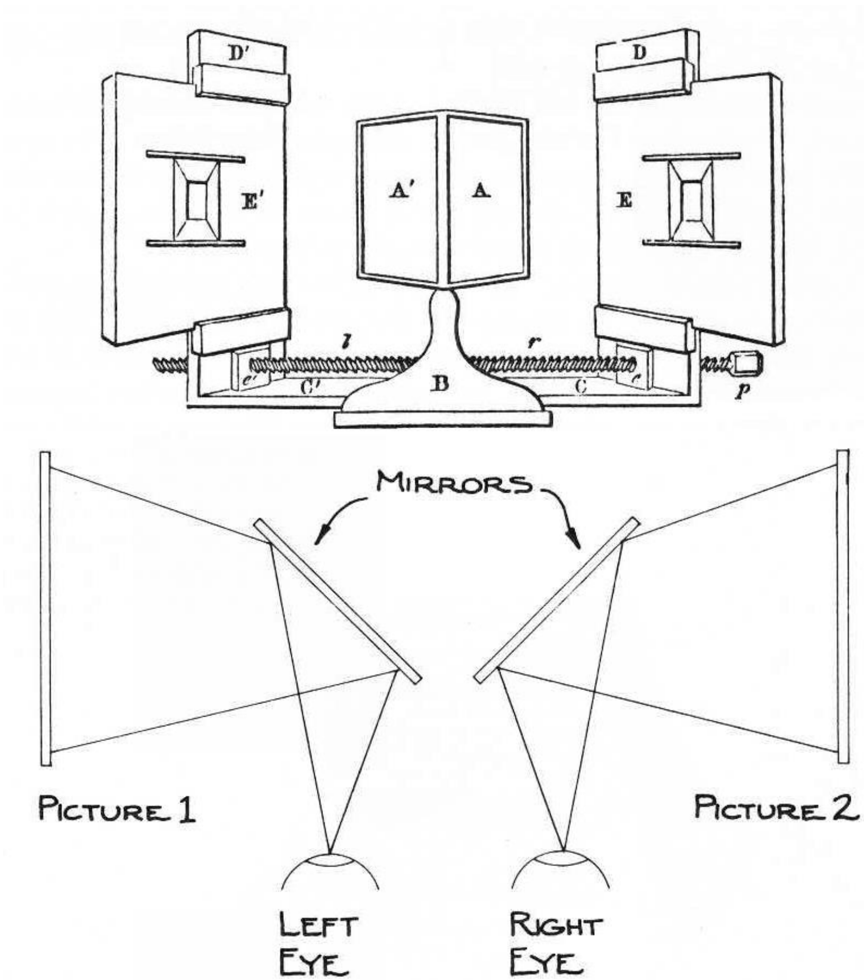
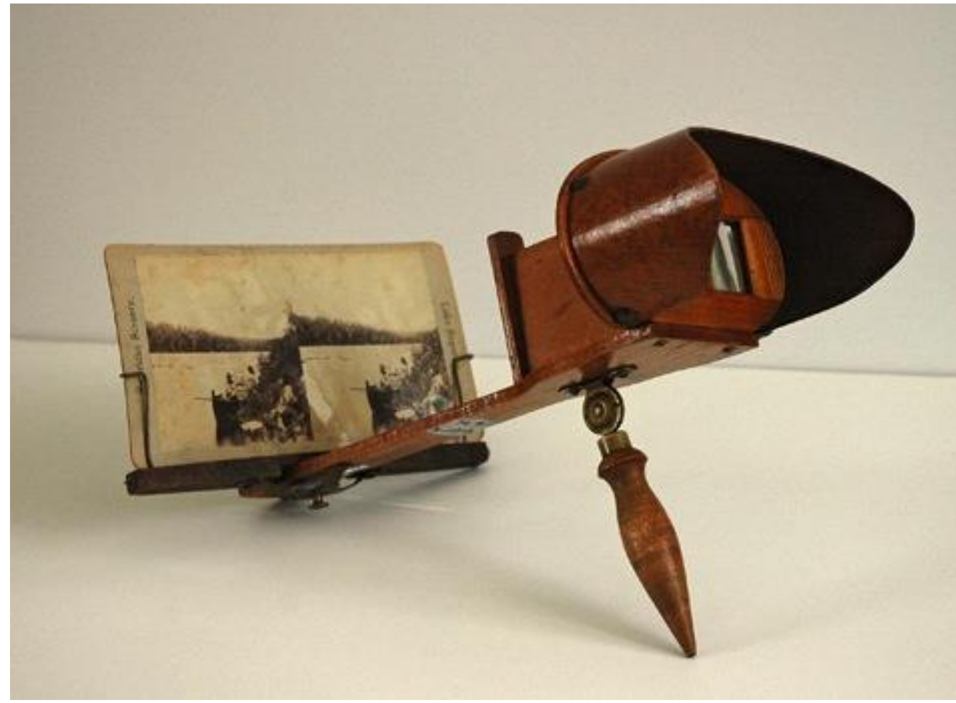
Display: Looking Back in Time…



The Stereoscope, invented by Sir Charles Wheatstone in 1833

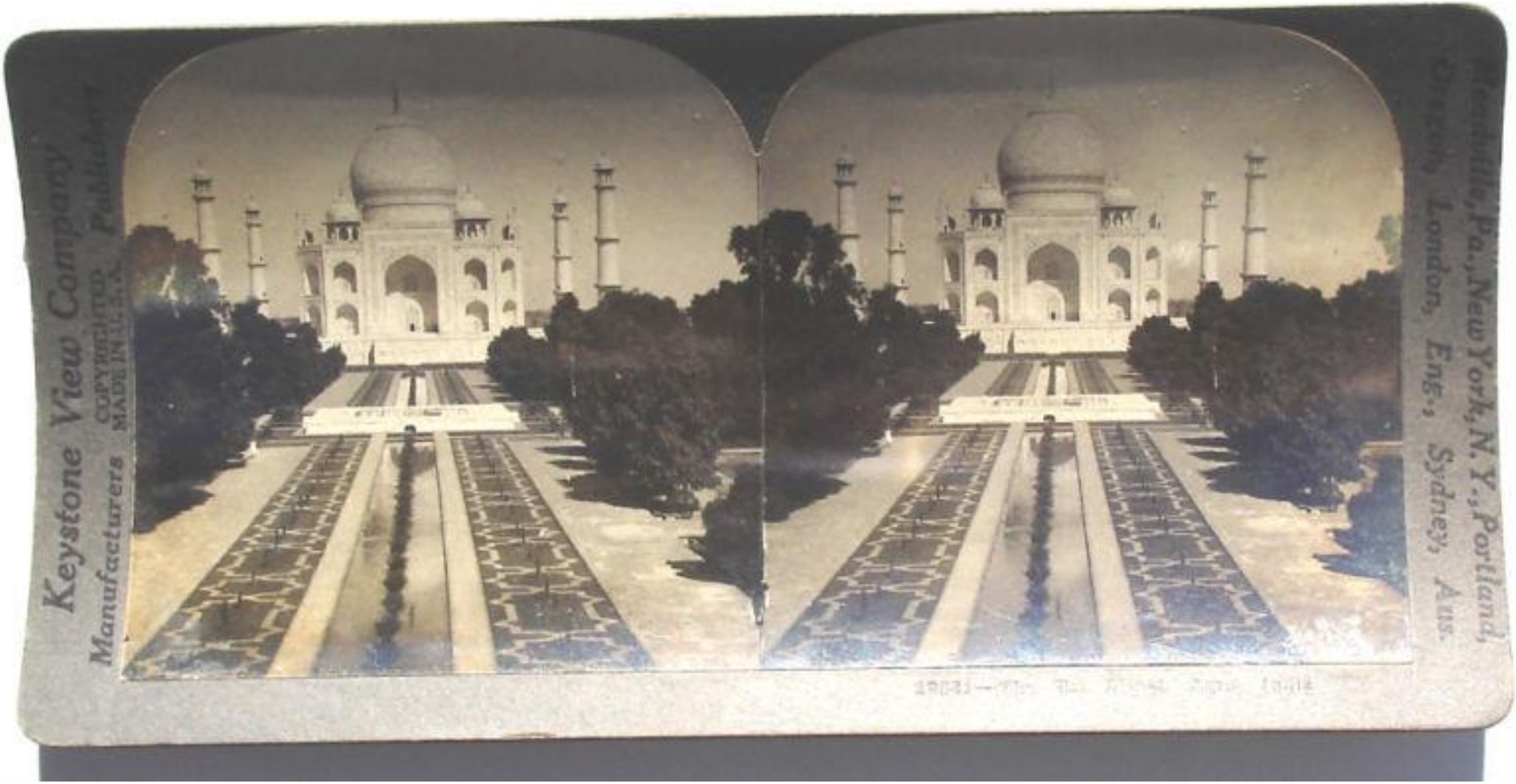


Improved construction by Oliver Wendell Holmes.

Widely popular in late 1800s to early 1900s.

View of Boston, c. 1860

By Soule, John P., 1827-1904, https://commons.wikimedia.org/w/index.php?curid=7456182



Taj Mahal, c. 1909

Modern-Day VR Display Examples

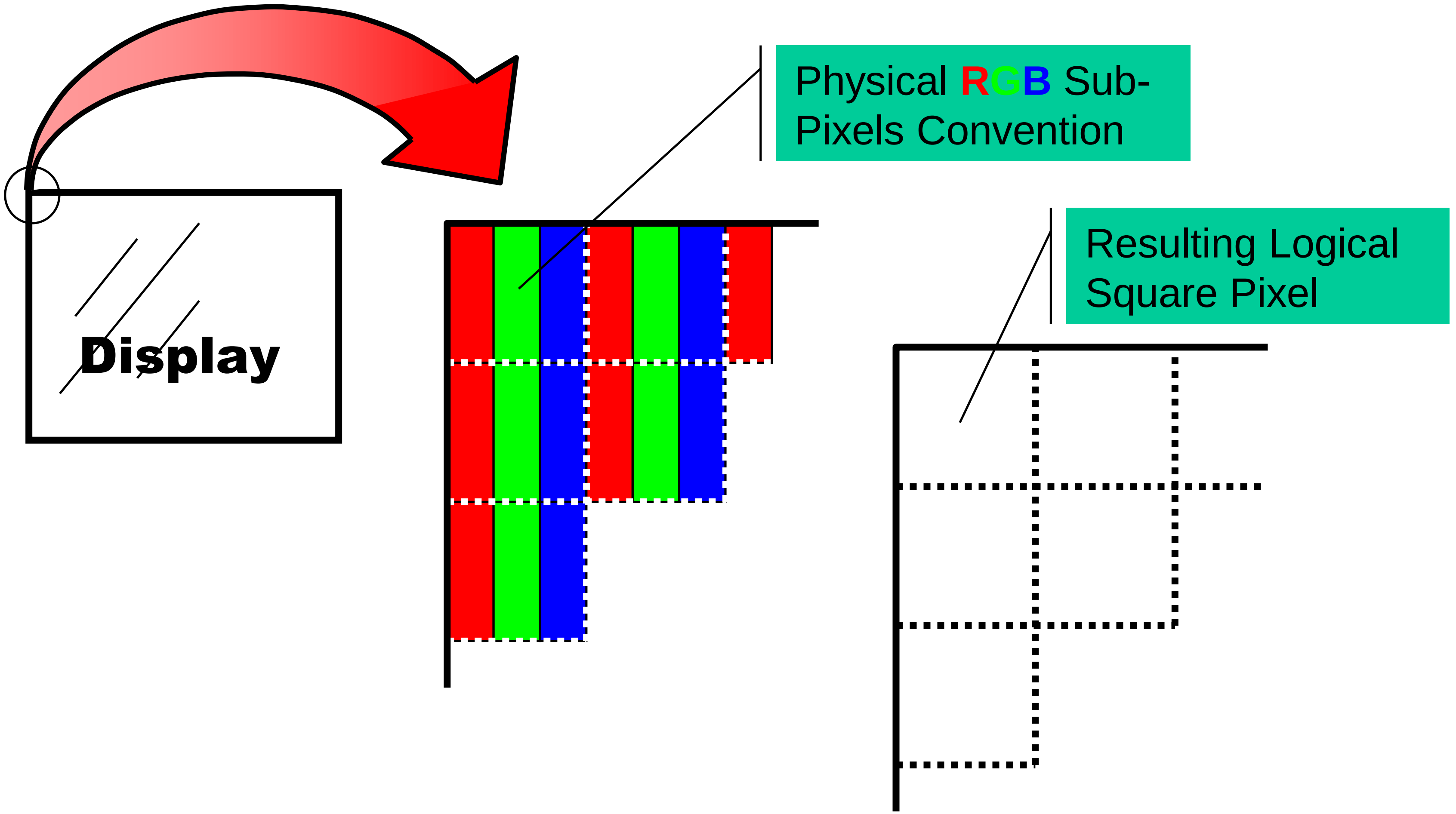
- Oculus Rift and HTC Vive
  - 2160X1200 pixels @461-PPI resolution
  - 90-FPS refresh rate
  - 110° FOV

- Samsung Gear VR (with Galaxy S7)
  - 2560X1440 pixels @577-PPI resolution
  - 60-FPS refresh rate
  - 96° FOV

Key Display Requirements

- Immersive visual experience
  - 3D image display
  - Wide field of view (FOV)
  - High pixel density (resolution) and fill factor
- Low-latency visual perception
  - High frame refresh-rate, global refresh
  - Fast pixel response time, low persistence
- Visual and ergonomic comfort
  - High contrast, brightness, and uniformity
  - Low weight, comfortable design

Pixels



Display
Physical RGB Sub-Pixels Convention
Resulting Logical Square Pixel

Resolution and Field-of-View (FOV)

- For head-mounted display (HMD) applications, pixels-per-degree (PPD) is a more appropriate measure of resolution than pixels-per-inch (PPI) that is typical in describing screen resolution.
- The human-eye has an angular resolution of about 1/60th of a degree at the central vision.
- Each eye has a horizontal field-of-view of ~160° and a vertical field-of-view of ~175°. The two eyes work together for stereoscopic depth perception over ~120° wide and ~135° high FOV.

	PPD required	Horizontal FOV (deg)	Equivalent horizontal Kpixels	Vertical FOV (deg)	Equivalent vertical Kpixels	Total Mpixels required
Each eye	60	160	9.6	175	10.5	~100
Stereo vision	60	120	7.2	135	8.1	~60

Ref: http://webvision.med.utah.edu/book/part-xiii-facts-and-figures-concerning-the-human-retina/

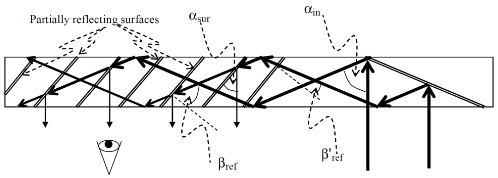
Latencies

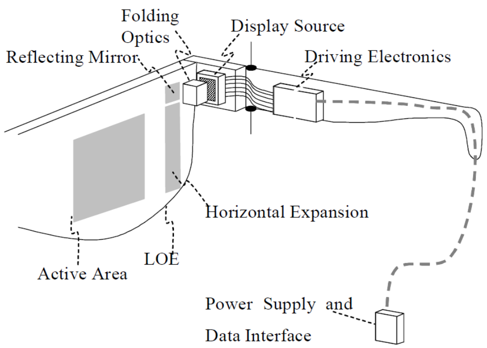
- A key system-level parameter for VR/AR/MR devices is "motion-to-photon latency"
  - Delay between the onset of user-motion to emission of photons from the last pixel of the corresponding image frame
  - It's the sum of the time taken by sensor data acquisition and processing, interfaces, computations, and display updates
  - Desired to be less than 20ms
- Display refresh rate and response time typically dominate the delay time
  - Display refresh rate: 60Hz inadequate, 90Hz prevalent, but desire 120Hz or higher
  - Require low pixel persistence

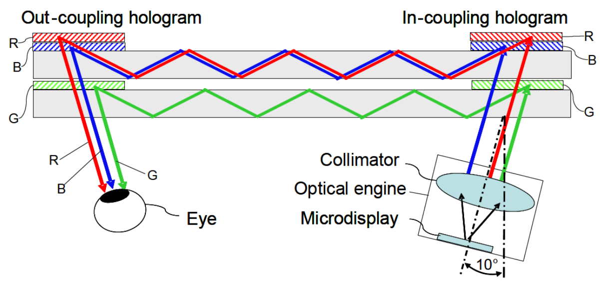
Viewing Optics: Key Considerations

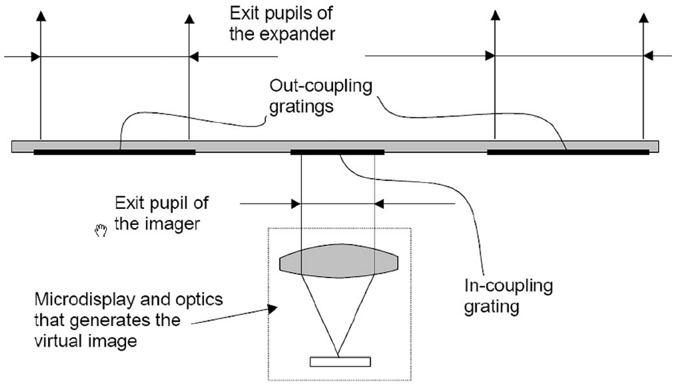
- Eye Box
  - ~12mm X 12mm desired (~4mm pupil + ~6mm eye rotation + ~2mm tolerance for viewing comfort)
- Eye Clearance
  - ~20mm recommended for consumer applications (accommodate prescription glasses)
- Size/Weight/Form-Factor
  - Lighter and stylist consumer designs

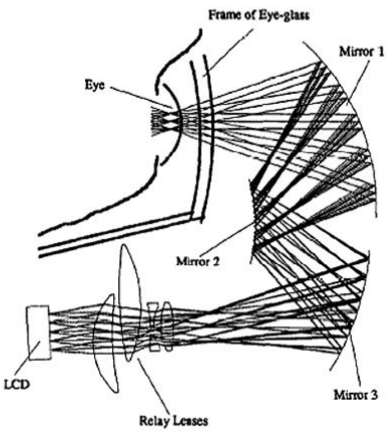
See-Through Displays for AR: Examples
(Details in Backup Slides)

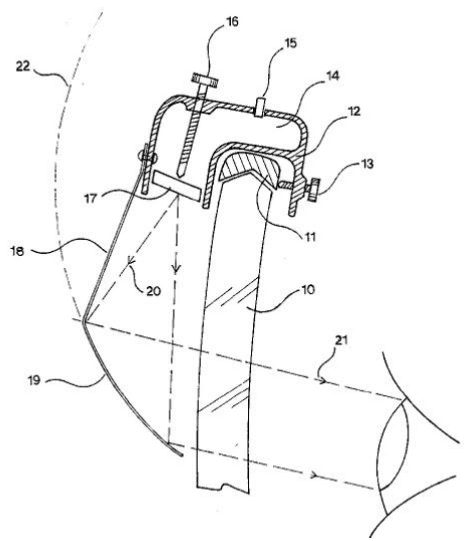


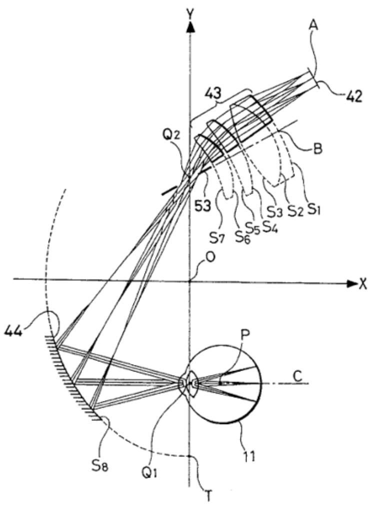


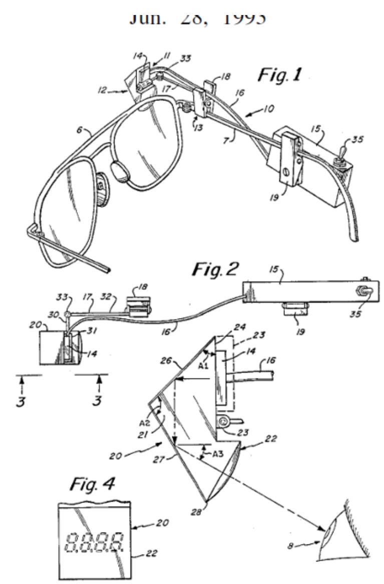






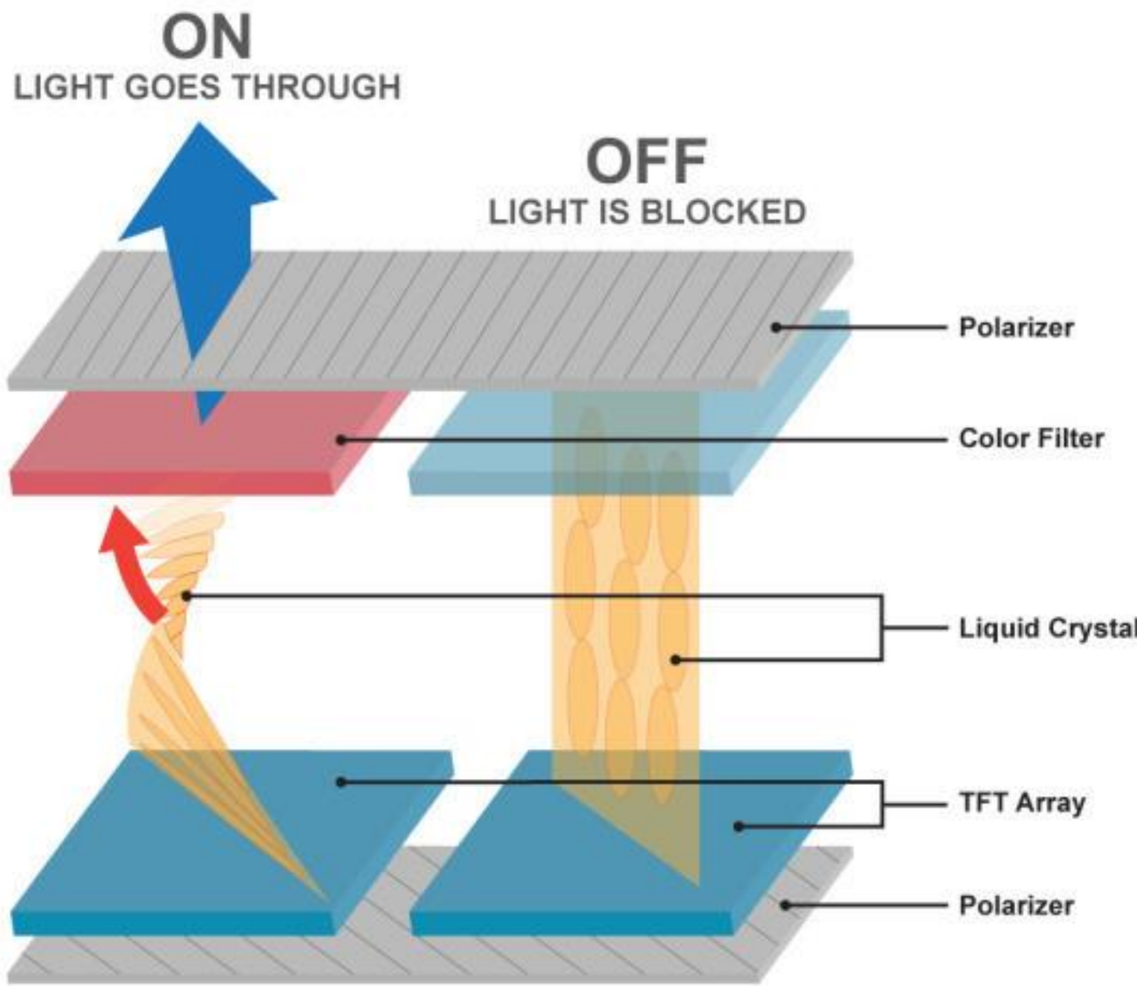




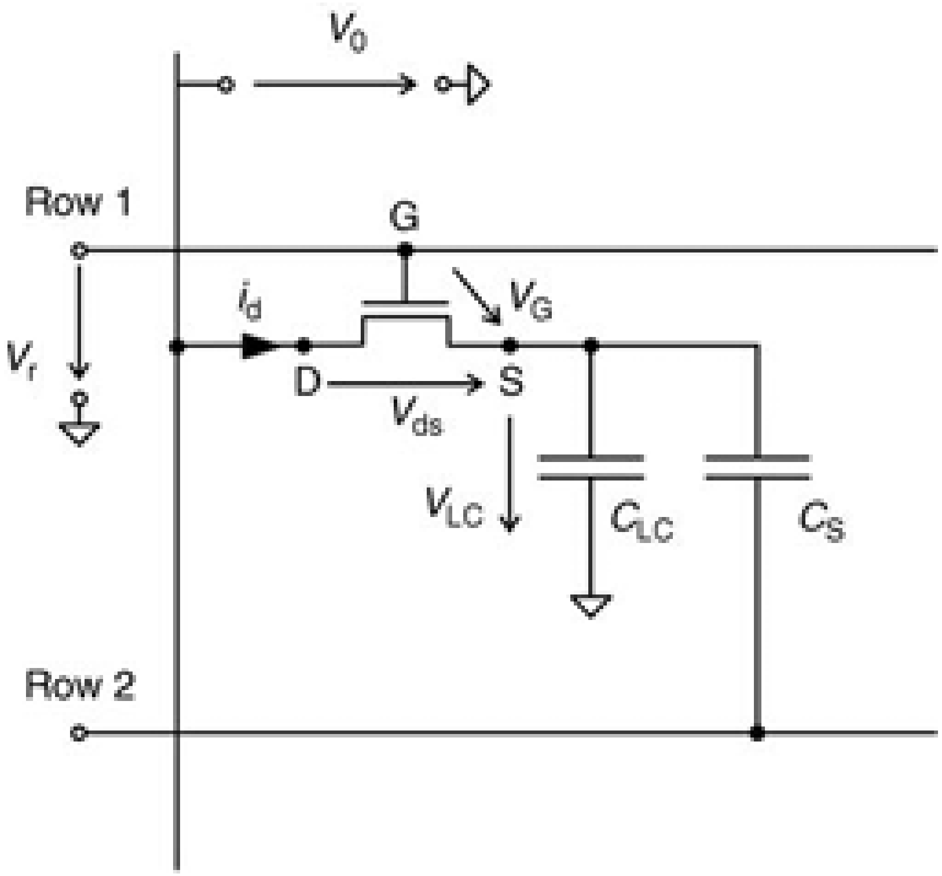


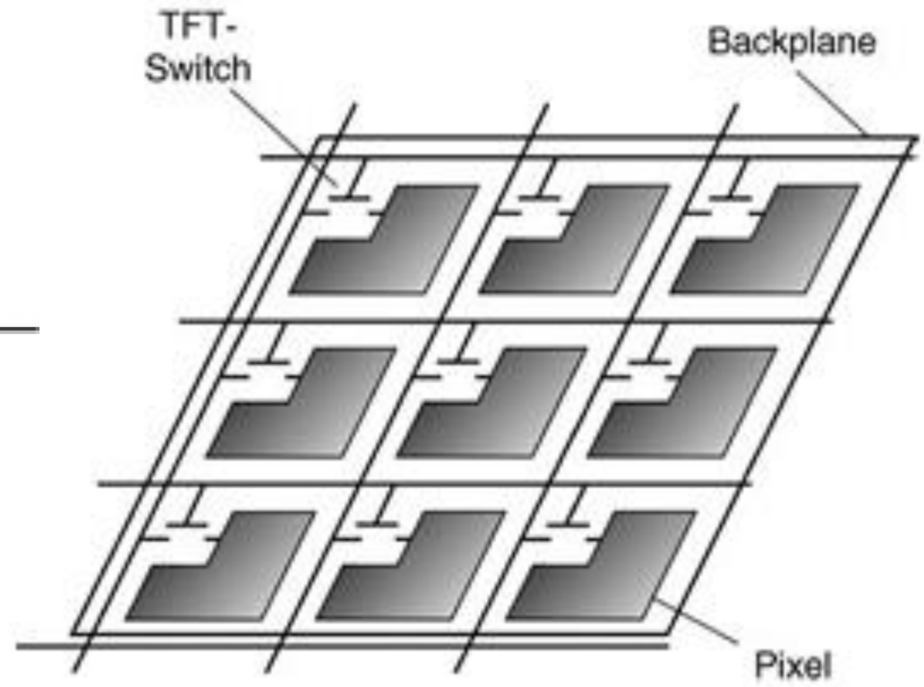
Amitai, Mukawa, Levola, Cakmakci

Spatial Light Modulators: Liquid Crystal Displays (LCD)

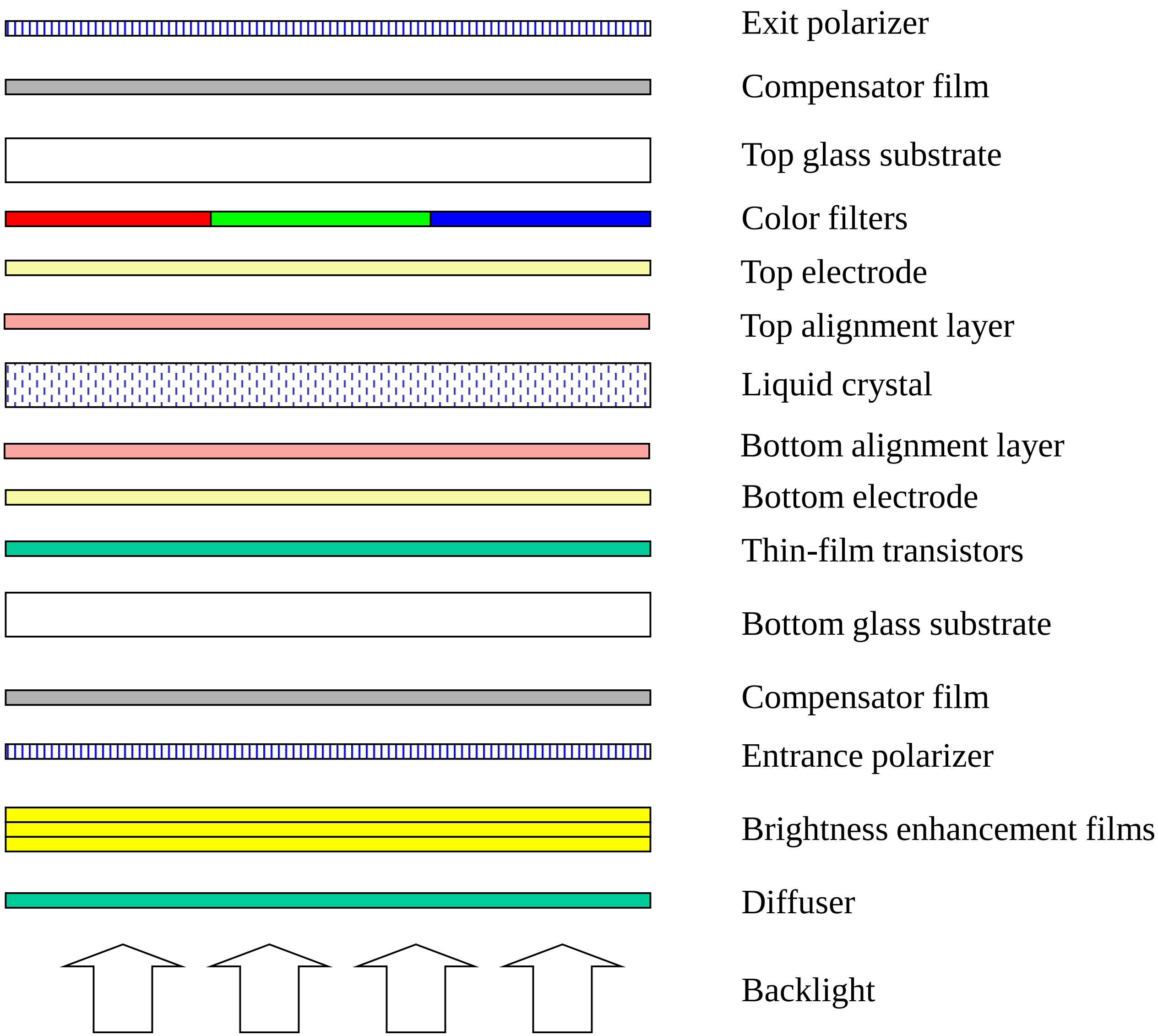

ON
LIGHT GOES THROUGH
OFF
LIGHT IS BLOCKED
Polarizer
Color Filter
Liquid Crystal
TFT Array
Polarizer

LCD Pixel Driving Architecture

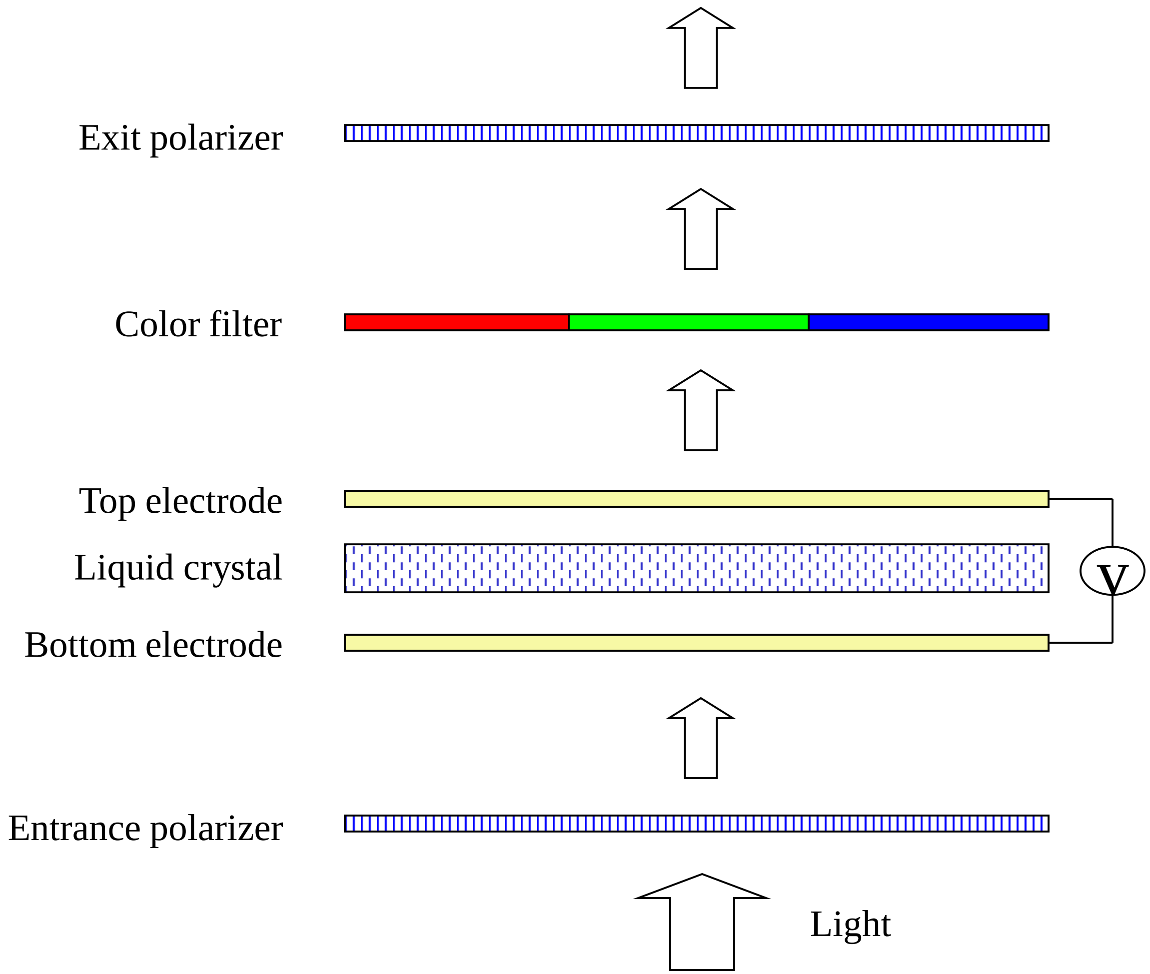




Cross-section of a typical LCD



Let’s just focus on the main elements to understand how LCD works…



The exit polarizer blocks, partially or fully transmits light, depending the polarization.

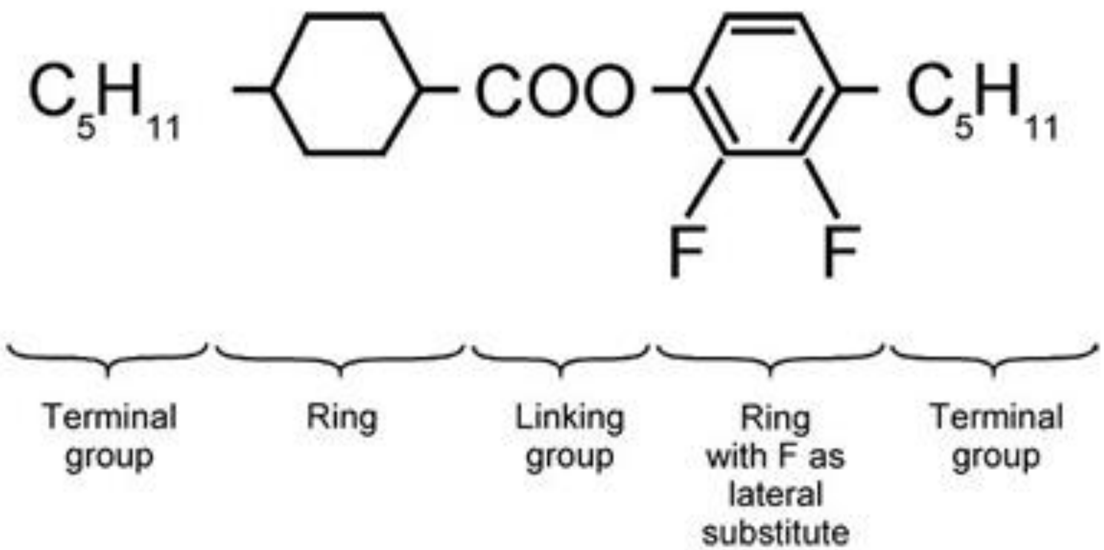
The color filter selectively absorbs undesired wavelength to produce color image.

The birefringent liquid crystal layer alters the polarization, as the electric field changes the effective refractive index.

The entrance polarizer transmits only one polarization of light.

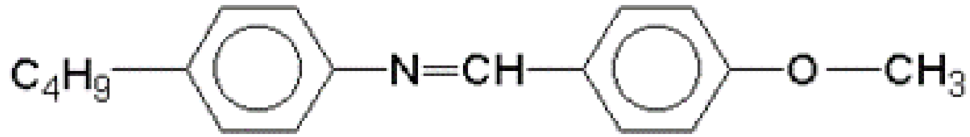
At the “heart” of the LCD: Liquid crystal molecules

An example:

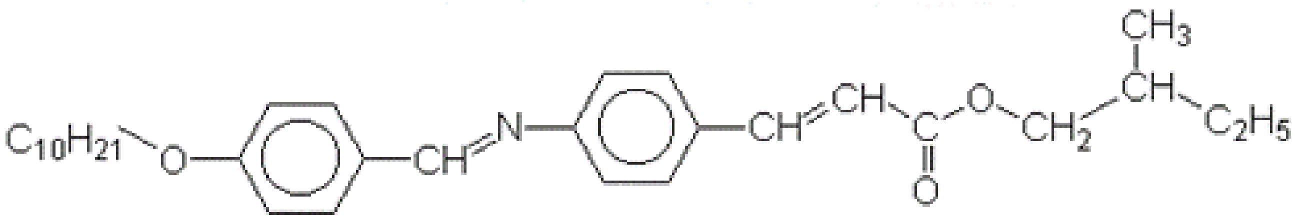


Liquid crystal molecules

Chemist's view:

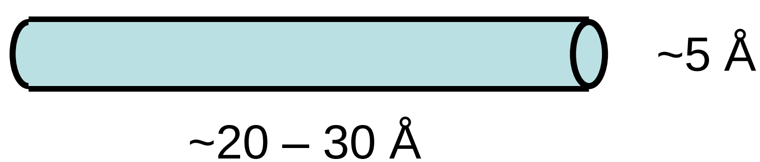


Methoxybenzilidene Butylanaline ("MBBA")

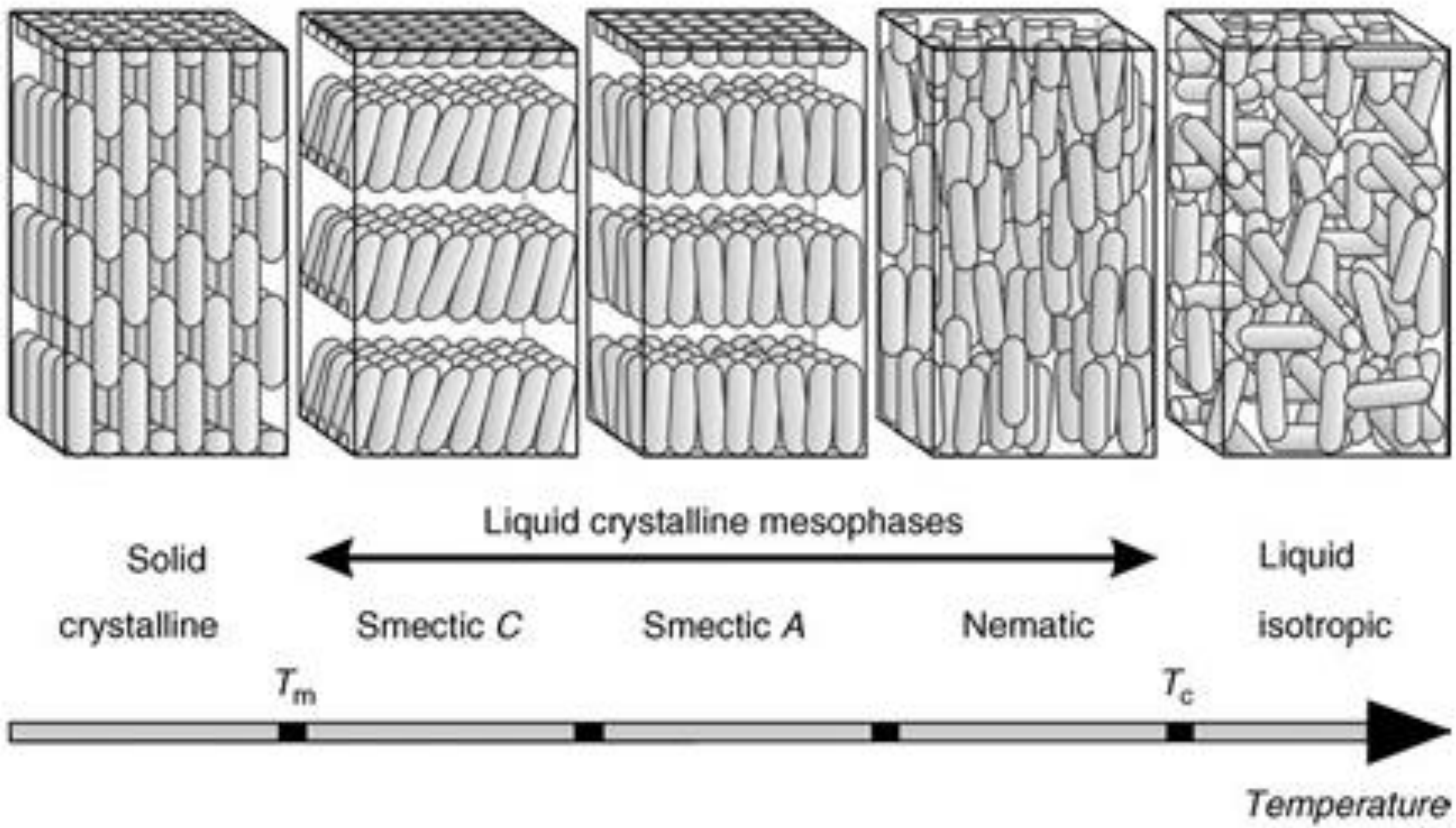


p-decyloxybenzylidene p'-amino 2-methylbutylcinnamate ("DOBAMBC")

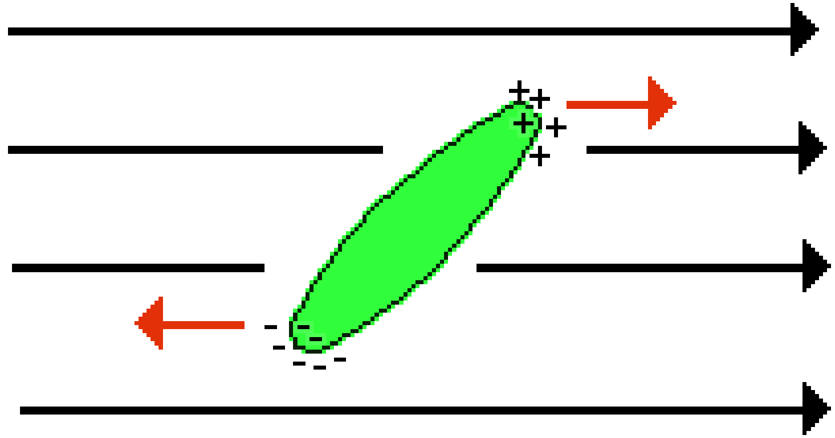
Physicist's view:



This type of liquid crystals are called the "rod-like" molecules, commonly used as the electro-optical material in LCDs.


Liquid crystalline mesophases
Solid
crystalline
Smectic C
Smectic A
Nematic
Liquid
isotropic
T_m
T_c
Temperature

Effect of electric field on Liquid Crystal molecules



Electric field direction

The torque experienced by rod-like liquid crystal molecules due to the electric dipole-field interaction aligns them along the direction of the electric field.

The disc-like molecules align perpendicular to the electric field.

A brief look at the history of LCD

Good references:

“*The history of liquid-crystal displays*”, by H. Kawamoto, Proceedings of the IEEE, Vol. 90, No. 4, pp 460 – 500, 2002.

“*Liquid gold: the story of liquid crystal displays and the creation of an industry*”, by J. Castellano, World Scientific, 2005.

Discovery of the "Liquid Crystal"

Friedrich Reinitzer, an Austrian botanist, first observed liquid crystals in 1888, when he discovered that cholesteryl benzoate exhibits a mesophase between solid state and liquid state.

Otto Lehmann, in 1889, discovered that the mesophase exhibited a double refraction effect like a crystal, and named it "fliessende krystalle" or the "liquid crystal".

Friedrich Reinitzer
(1857 – 1927)

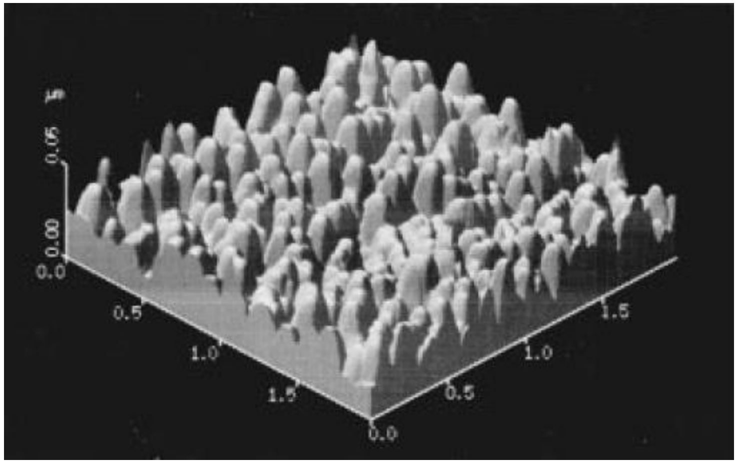
Otto Lehmann
(1855 – 1922)

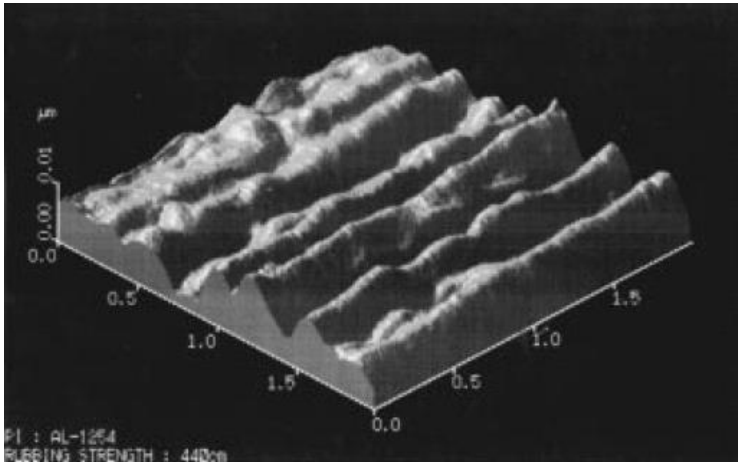
Aligning liquid crystal molecules

Construction of a liquid crystal device requires aligning the molecules in specific directions in between the substrates, thus inventing the processes to accomplish this was a major step.

The method widely used throughout the industry is to coat polyimide on the ITO covering the glass and then rub with cotton cloth.

The origin of this rubbing technique goes back to 1928, due to **H. Zocher**.



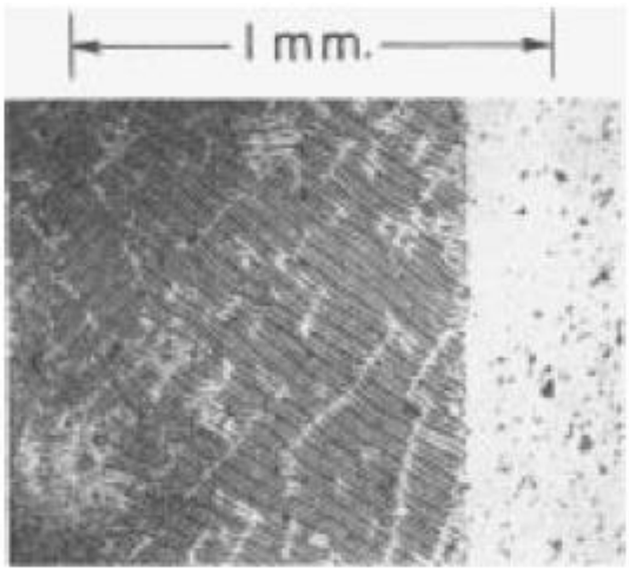


AFM micrographic picture of polyimide surface before and after rubbing, from a 1992 study by T. Uchida *et al.*

Birth of the LCD

Vsevolod Freedericksz, in 1931, discovered periodic hydrodynamic domains in liquid crystals subjected to electric fields. **Richard Williams** of RCA, in 1962, discovered the “Williams domains”. These effects demonstrated the feasibility of liquid crystals as electro-optical elements for display devices.

George Heilmeier of RCA, in 1964, invented the LCD, by discovering the “guest-host mode” and “dynamic scattering mode” and demonstrating devices.



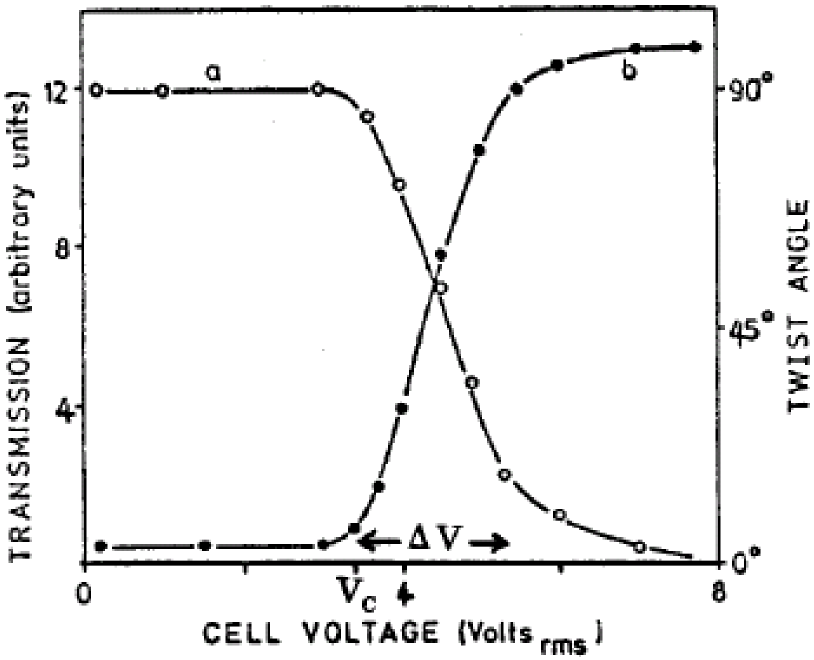
The “Williams domains” published in 1963

Heilmeier with a DSM display in 1968

Discovery of the Twisted Nematic (TN) mode

Wolfgang Helfrich with **Martin Schadt**, in 1970, demonstrated the TN mode, the most prominent liquid crystal mechanism for decades to come, thereby arguably establishing the basis of the modern LCD industry. The early idea of TN structure is traced back to **Charles Mauguin** in 1911.

Helfrich in 1976



Results from the historic 1971 paper by Helfrich and Schadt

The first commercial devices

In 1973, Sharp announced and subsequently introduced the Elsi Mate EL-805 pocket calculator, the first commercial liquid crystal device. In 1975, Sharp developed the Magic Mirror Clock. Both were based on DSM.

Seiko, in 1973, introduced the first digital liquid-crystal watch, using TN mode.

The first liquid-crystal pocket calculator based on DSM

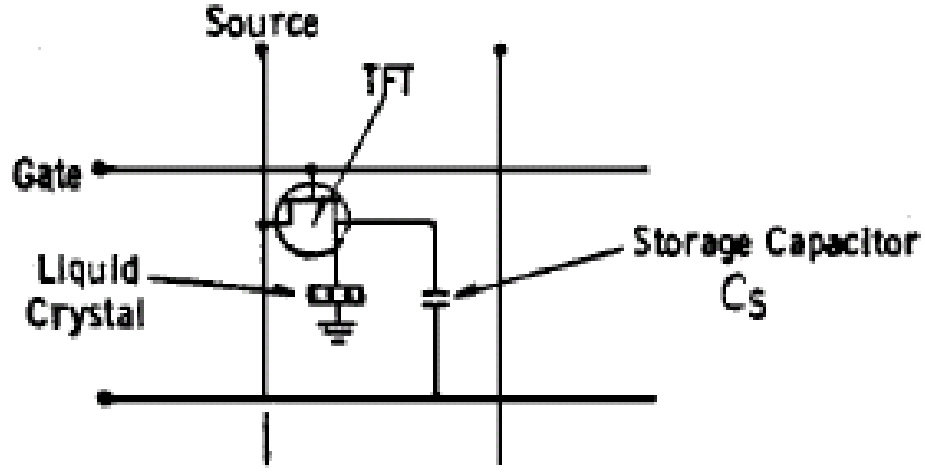
The Magic Mirror Clock, based on DSM

The first TN product: 06LC digital watch

Concept of the Active-Matrix Drive

In 1971, **Bernard Lechner** *et al.* proposed the idea of using an array of Thin-Film Transistors (TFTs) to control cells operating in DSM.

As shown in the figure below, they even conceived the idea of an external storage capacitor! This pixel driving configuration is still in use in modern LCDs.

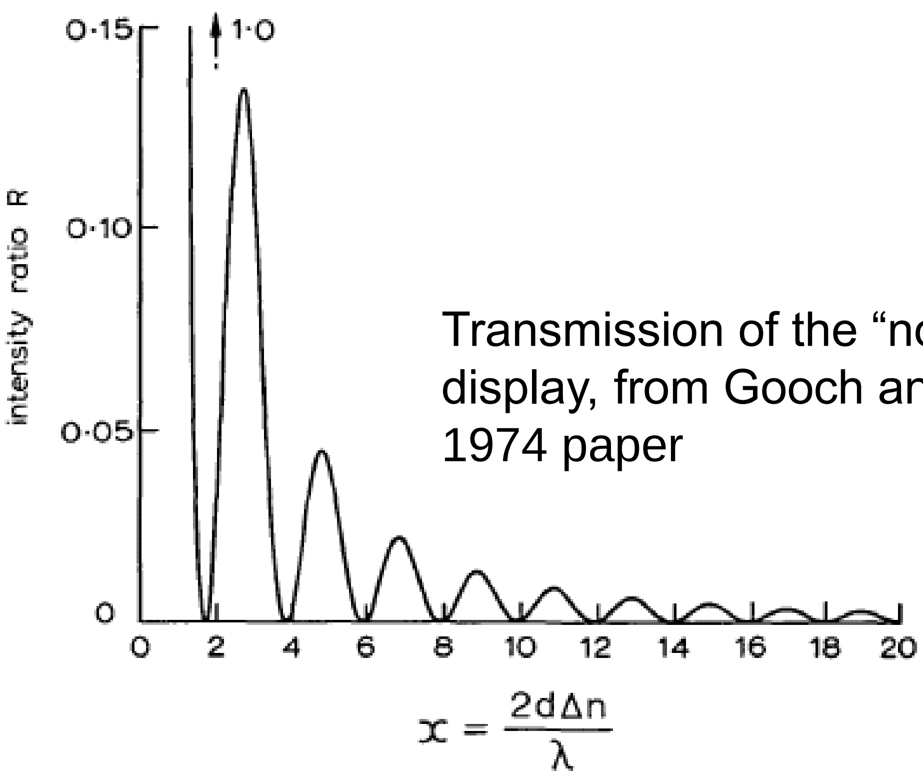


AM circuit with external storage capacitor proposed by Lechner *et al.*

Optics of LCD

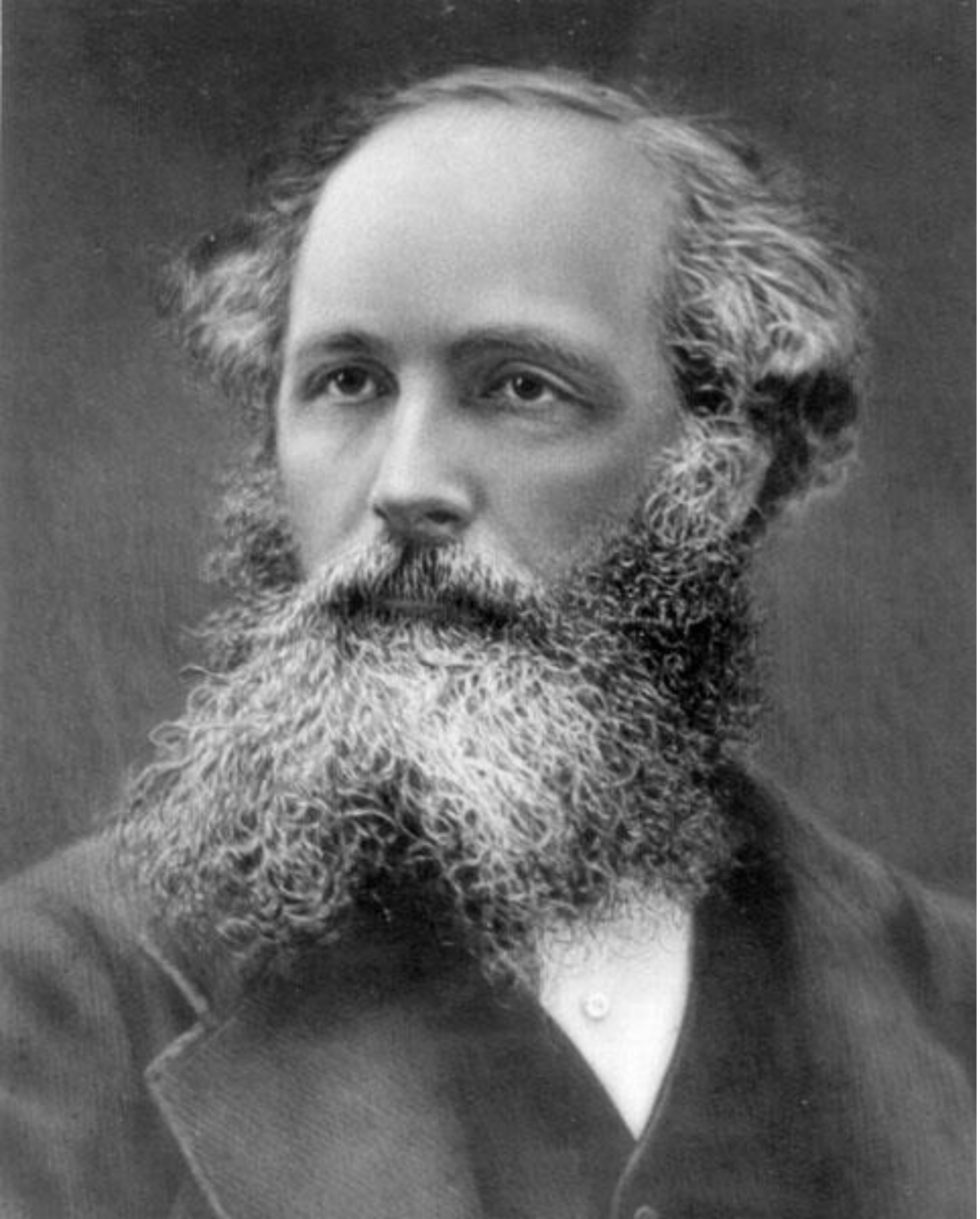
C. H. Gooch and **H. A. Tarry**, in 1974, derived the famous optical transmission equations for the TN mode liquid crystal display.

We will look into it later in this class.



Transmission of the “normally black” TN display, from Gooch and Tarry’s historic 1974 paper

Optics of LCD



JAMES CLERK MAXWELL
1831-1879

“One scientific epoch ended and another began with James Clerk Maxwell”

- Albert Einstein

The equations of optics are Maxwell's equations

$$\vec{\nabla} \cdot \vec{E} = \rho / \varepsilon \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{B} = \mu\varepsilon \frac{\partial \vec{E}}{\partial t}$$

$$\Rightarrow \boxed{\vec{\nabla}^2 E - \mu\varepsilon \frac{\partial^2 E}{\partial t^2} = 0}$$

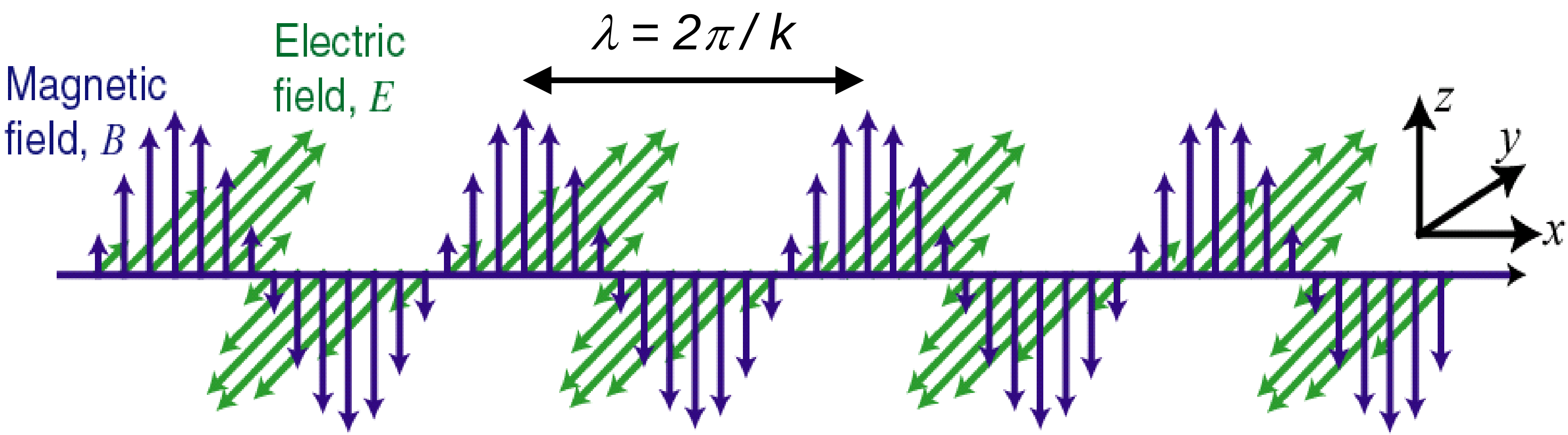
"Wave" equation

where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, ρ is the charge density, ε is the permittivity, and μ is the permeability of the medium.

An Electromagnetic Wave

The electric and magnetic fields are **in phase**.

snapshot of the wave at one time

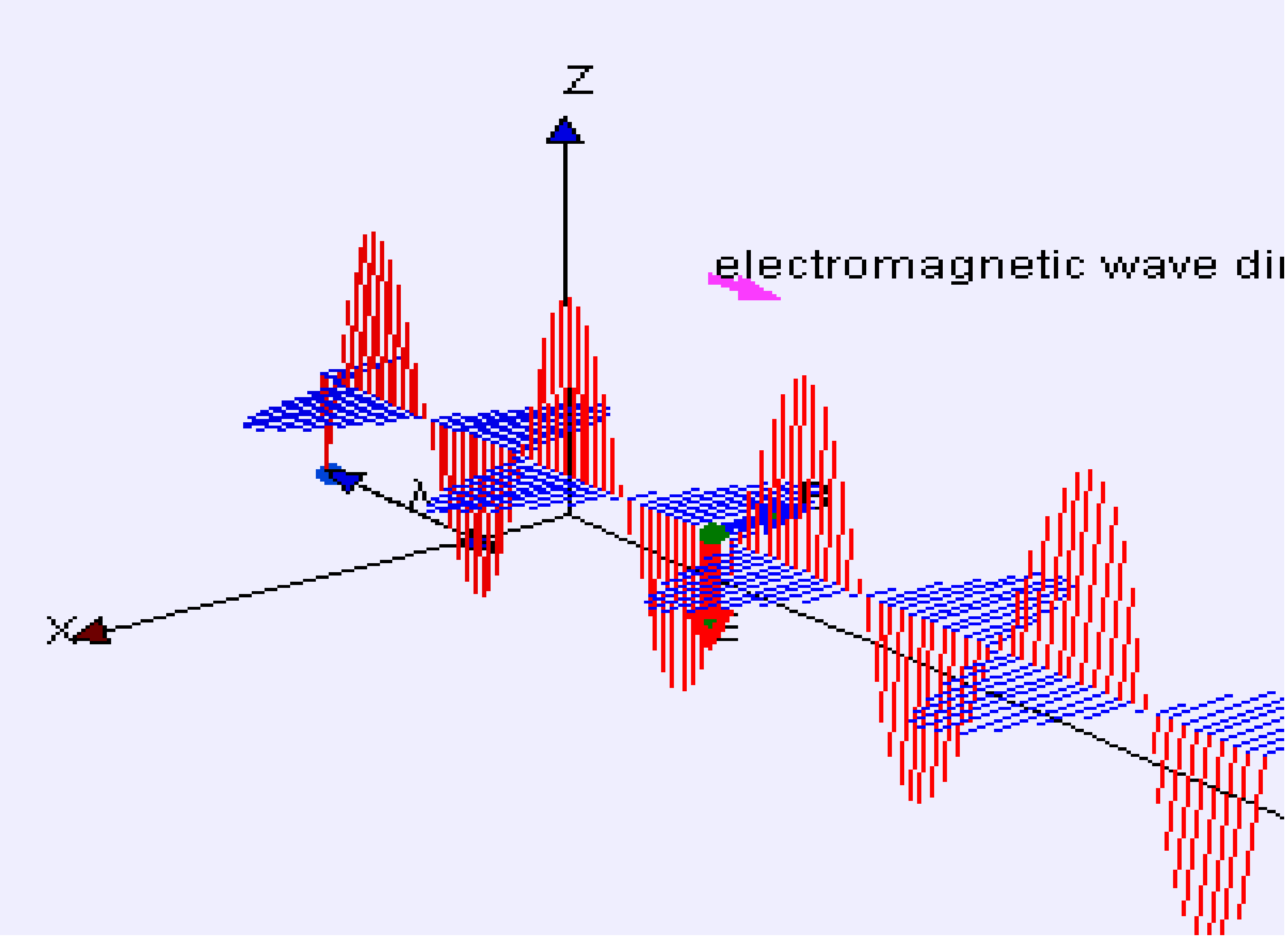


$$\underset{\sim}{E}(x,t) = \underset{\sim}{E}_0 \exp i(kx - \omega t)$$

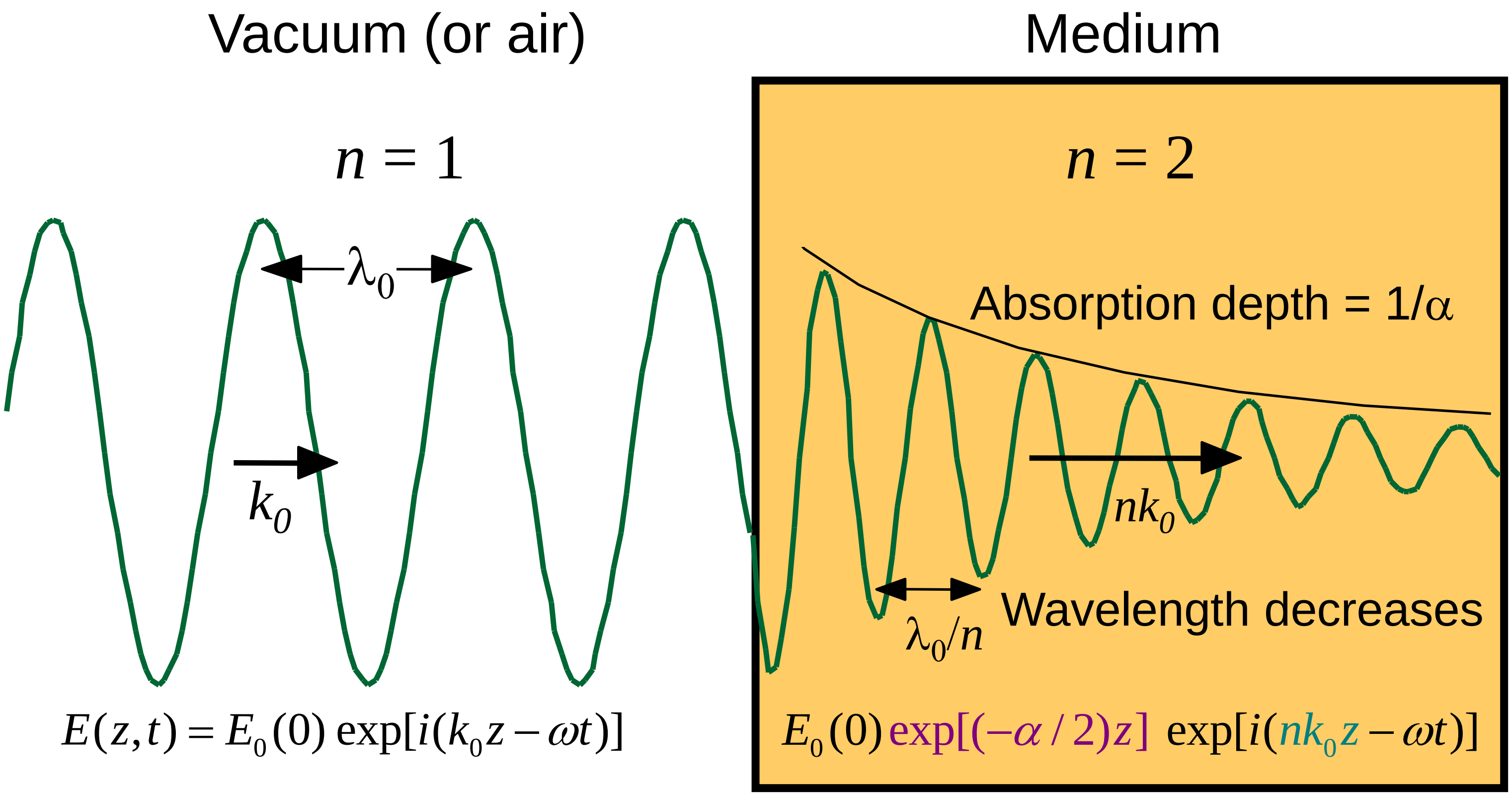
The electric field, the magnetic field, and the k-vector are all perpendicular:

$$\vec{E} \times \vec{B} \propto \vec{k}$$

An Electromagnetic Wave



A Light Wave Entering a Medium



n = refractive index; α = absorption coefficient

Typically, the speed of light, the wavelength, and the amplitude decrease, but the frequency, ω, doesn't change.

Absorption Coefficient and the Irradiance

The irradiance is proportional to the (average) square of the field.

$$I = E \cdot E^*$$

Since $E(z) \propto \exp(-\alpha z/2)$, the irradiance is then:

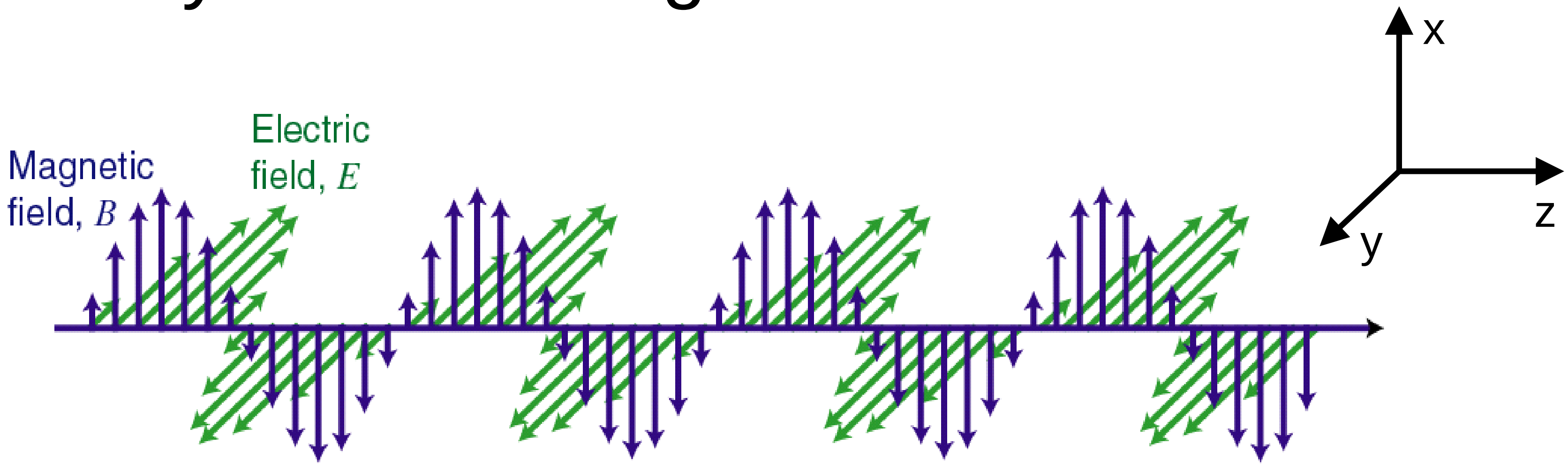
$$\boxed{I(z) \;=\; I(0)\exp(-\alpha\, z)}$$

where $I(0)$ is the irradiance at $z = 0$, and $I(z)$ is the irradiance at z.

Thus, due to absorption, a beam's irradiance exponentially decreases as it propagates through a medium.

Polarization of Light

Linearly Polarized Light

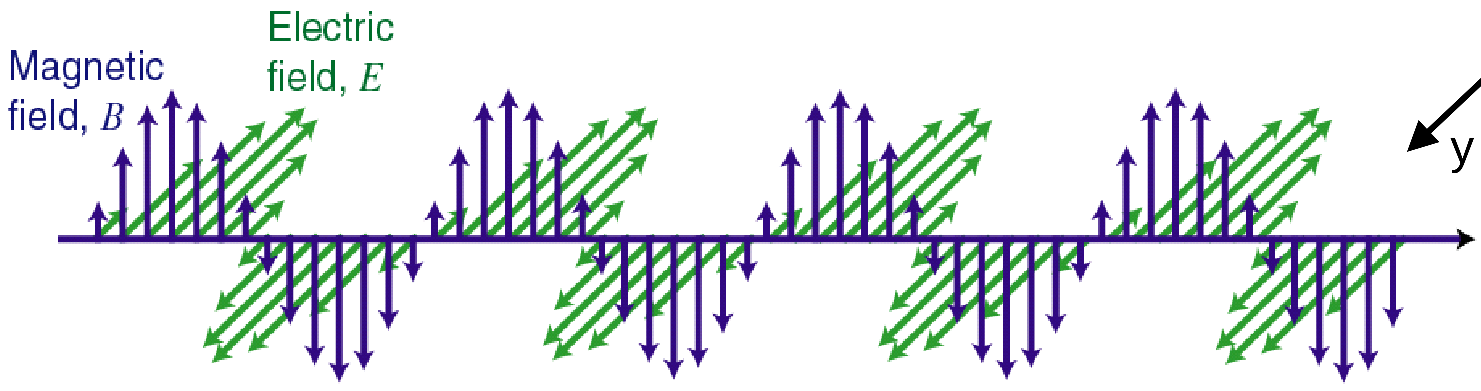


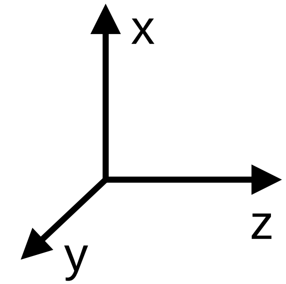
The light wave shown above has its Electric field vector oscillating purely along one axis (y-axis)

The oscillating Electric field vector of this light wave lies in one single plane (yz-plane)

This wave is “linearly polarized” along y-axis

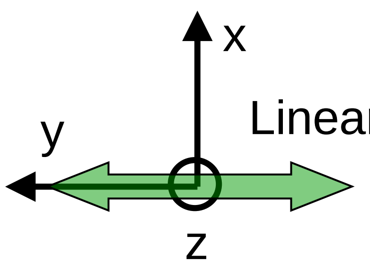
Visualizing Polarization





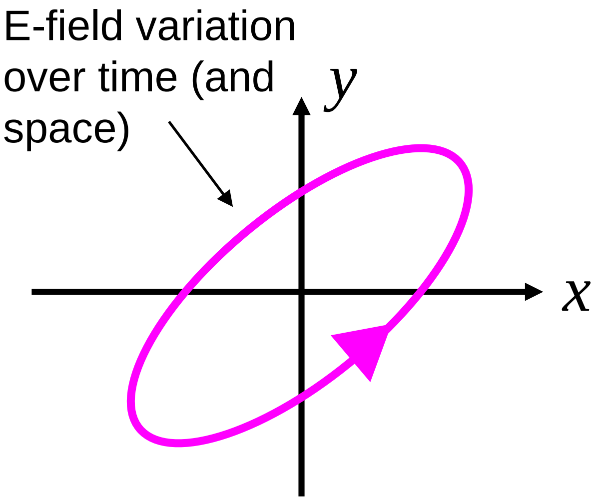
"Look into" the wave as if it is propagating towards you, trace the tip of the E-field vector

In the case of the wave shown above



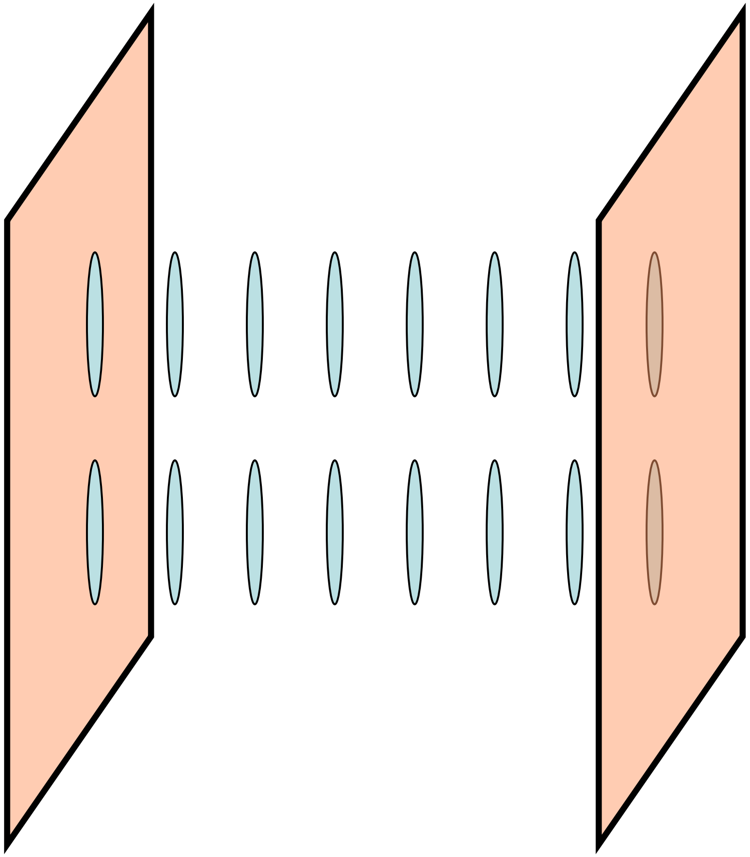
Linearly polarized along y-axis

Unequal arbitrary-relative-phase components yield "elliptical polarization"

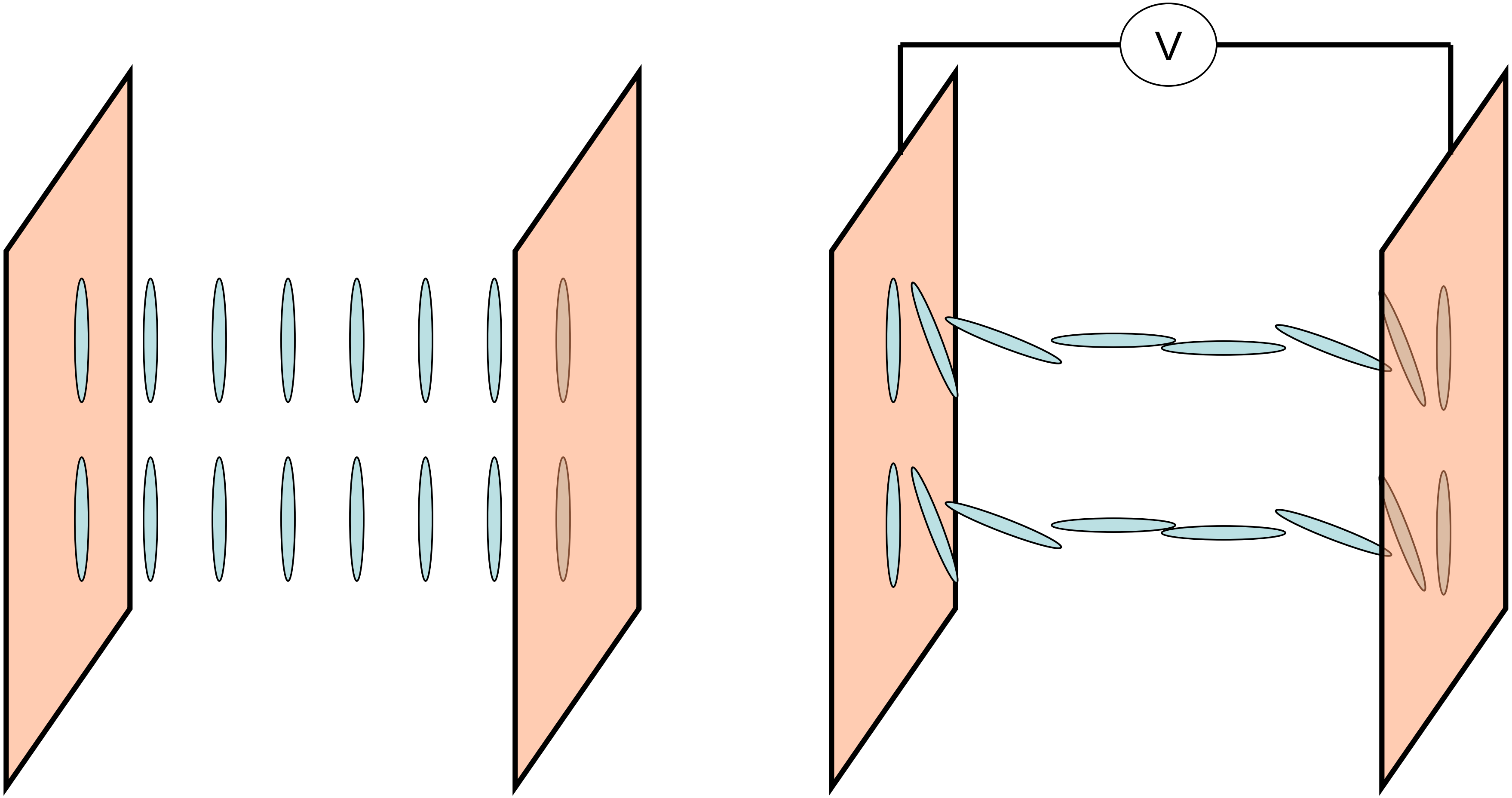


Elliptical polarization is the general case of polarized light

Homogenous LC cell:
Substrates rubbed along the same axis



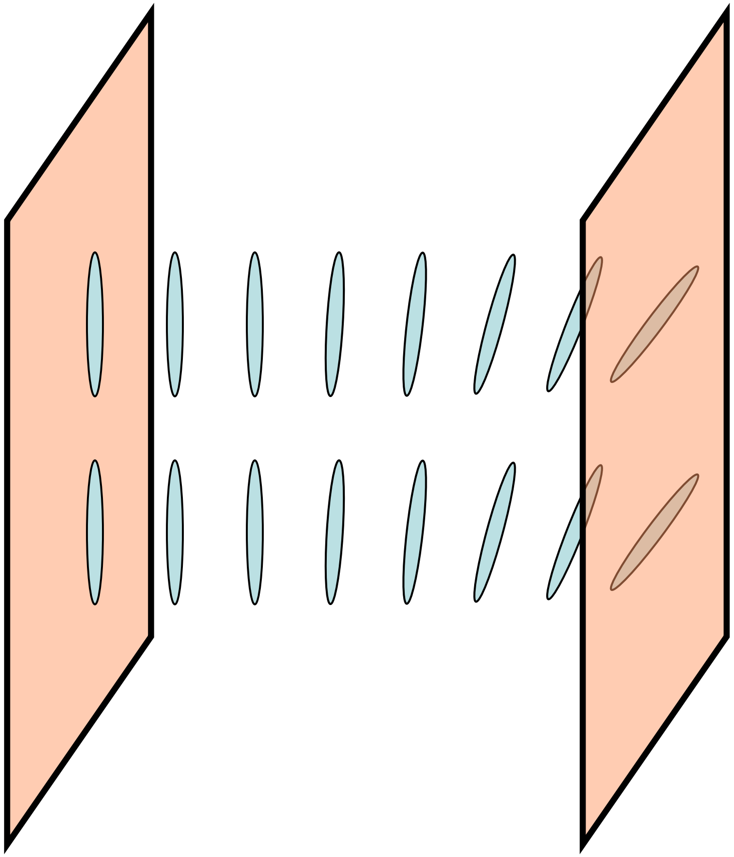
Homogenous cell: effect of electric field



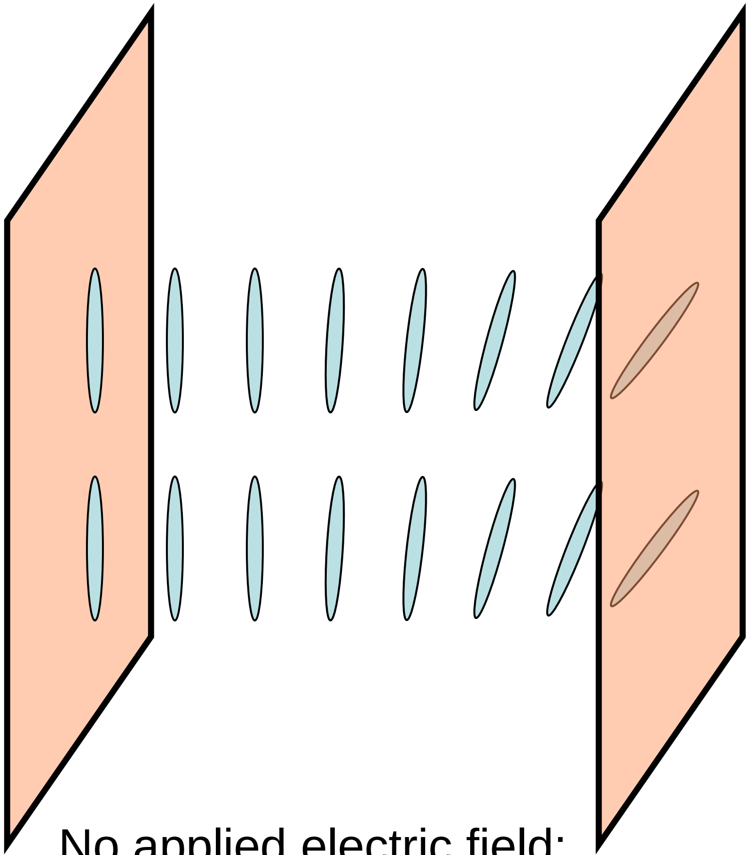
No applied electric field

High electric field

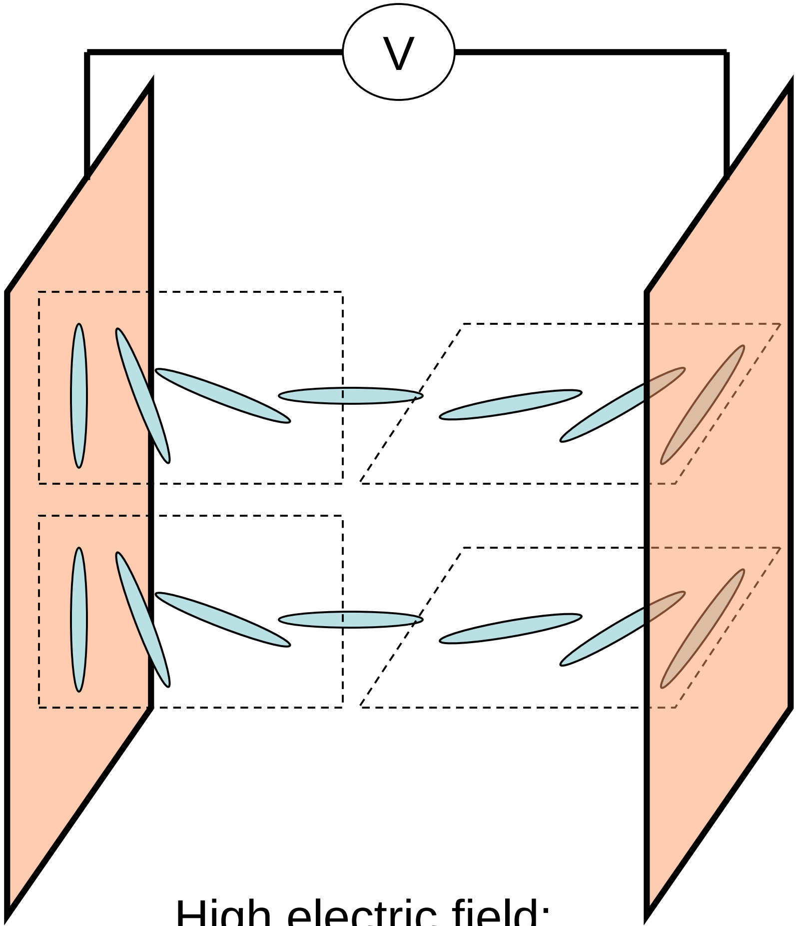
Twisted LC cell:
Substrates rubbed in the perpendicular directions



Twisted cell: effect of electric field

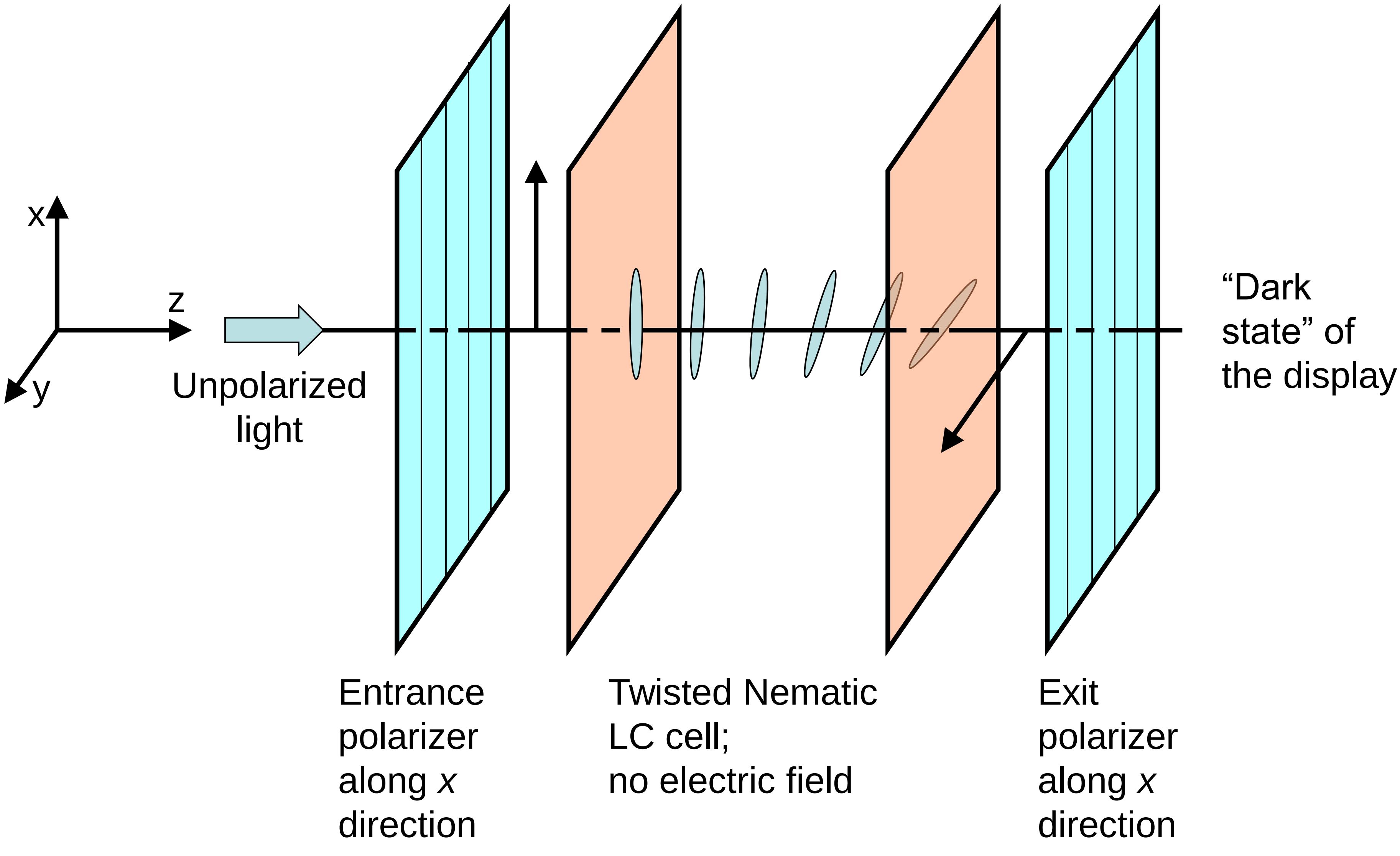


No applied electric field:
Molecules are uniformly twisted

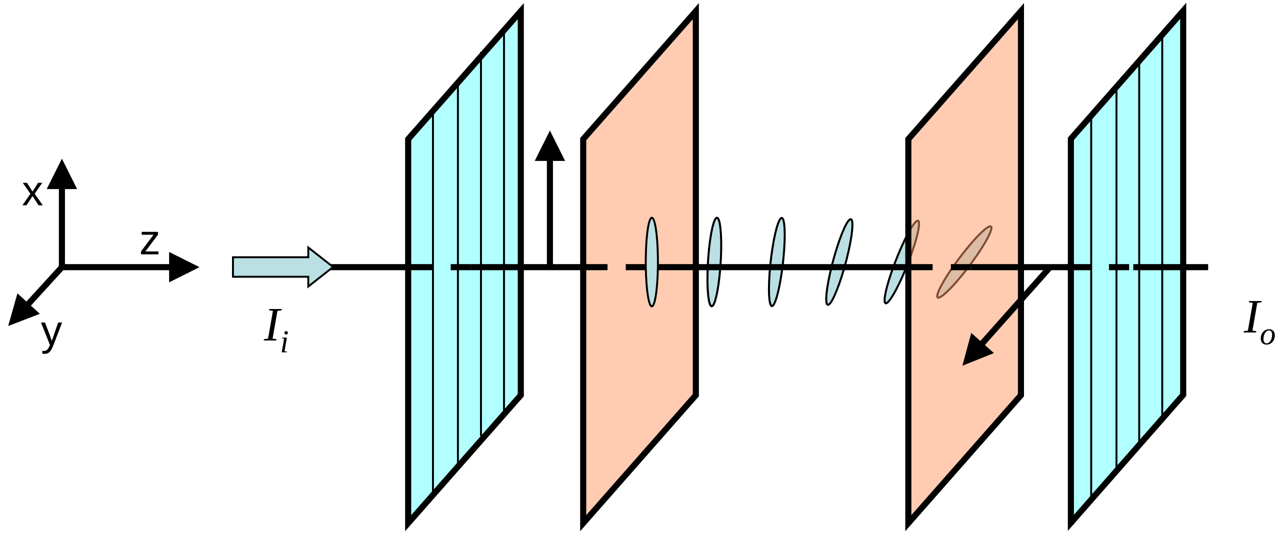


High electric field:
Molecules are untwisted

The “normally-black” 90º TN display



Light transmission equation for the "normally-black" 90º TN display

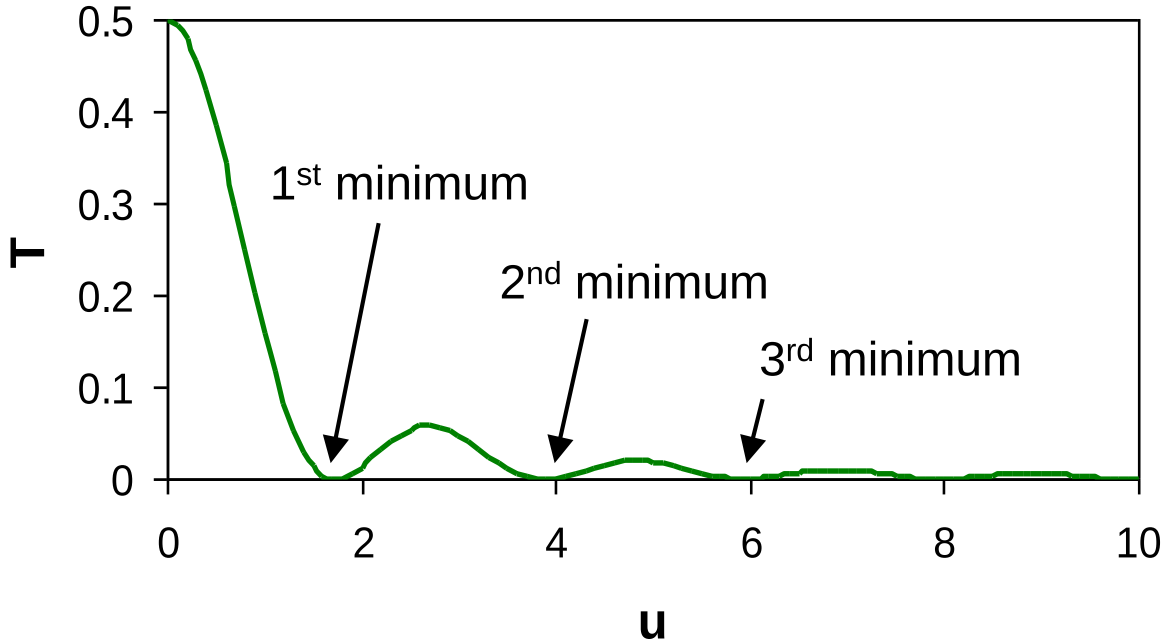


The transmittance, ratio of output to input light intensity, is given by:

$$T = \frac{I_0}{I_i} = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+u^2}\right)}{2\left(1+u^2\right)}$$

Where, $$u = \frac{2\left(n_e - n_0\right)l}{\lambda}$$

So, is the “normally-black” 90º TN display really always black?



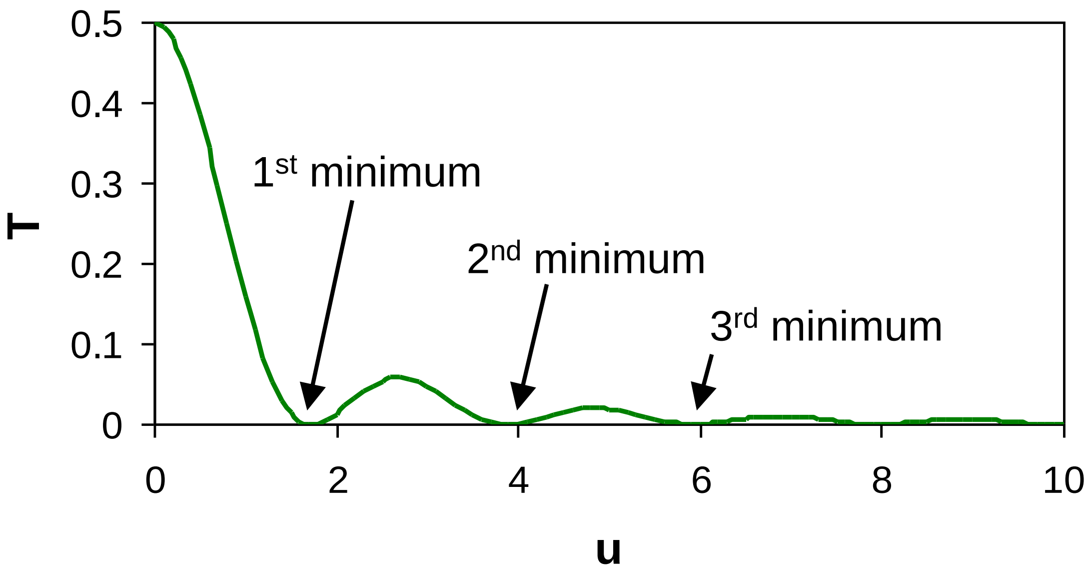
$$T = \frac{I_0}{I_i} = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+u^2}\right)}{2\left(1+u^2\right)}$$

$$u = \frac{2\left(n_e - n_0\right)l}{\lambda}$$

The transmittance is zero only for specific values of u, leading to the various minima conditions.

However, the transmittance is generally very small when u becomes large.

Maximizing Contrast



$$T = \frac{I_0}{I_i} = \frac{\sin^2\left(\frac{\pi}{2}\sqrt{1+u^2}\right)}{2\left(1+u^2\right)}$$

$$u = \frac{2\left(n_e - n_0\right)l}{\lambda}$$

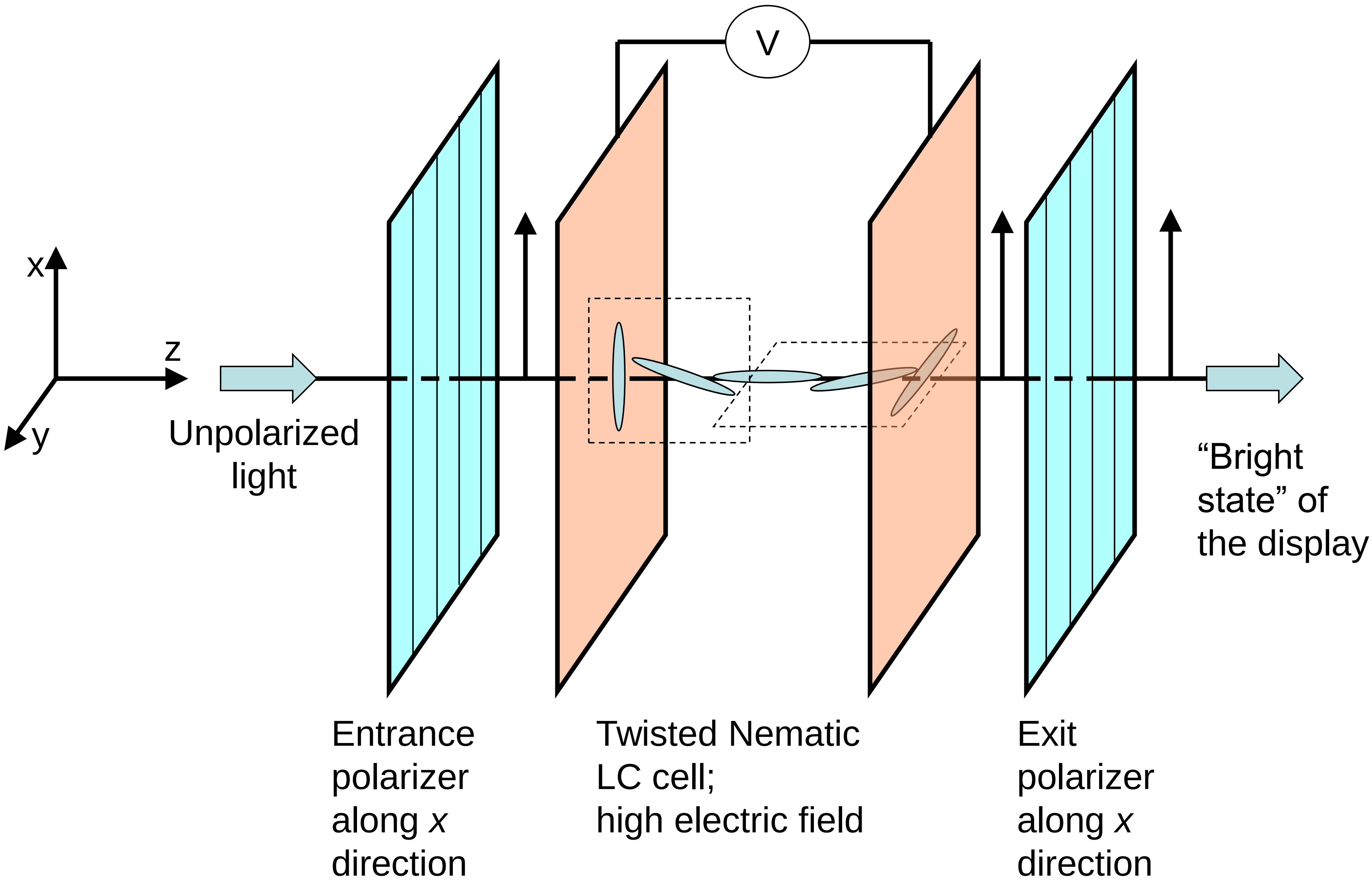
The transmission is zero (minimized), when the argument of sin in the numerator is an integral multiple of π.

$$\frac{\pi}{2}\sqrt{1+u^2} = m\pi \quad \Rightarrow \quad u = \sqrt{4m^2 - 1}$$ where m is an integer.

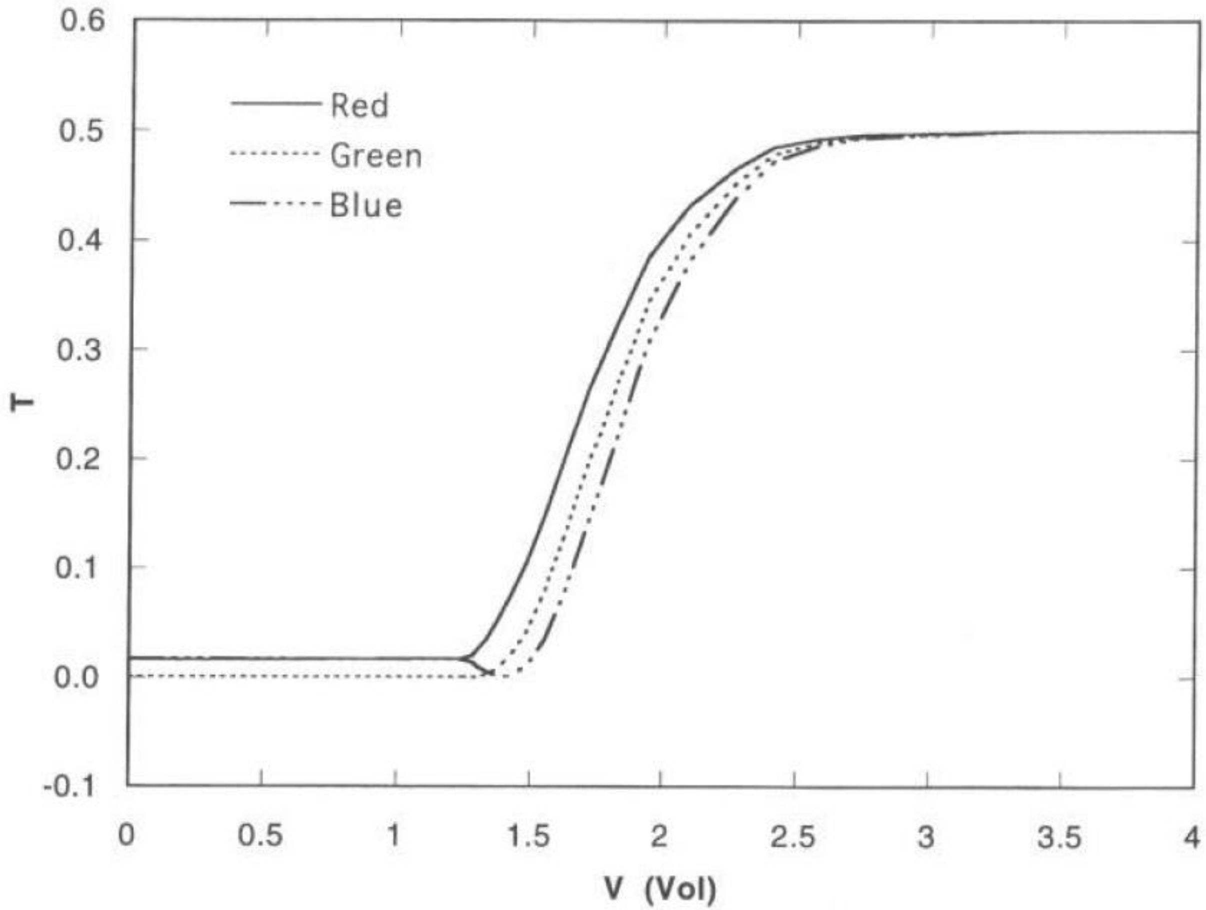
This corresponds to $u = \sqrt{3}, \sqrt{15}, \sqrt{35}$ for the first, second, and third minimum conditions.

The cell is typically optimally designed for green light (e.g., λ = 550nm)

The 90º TN display with high electric field

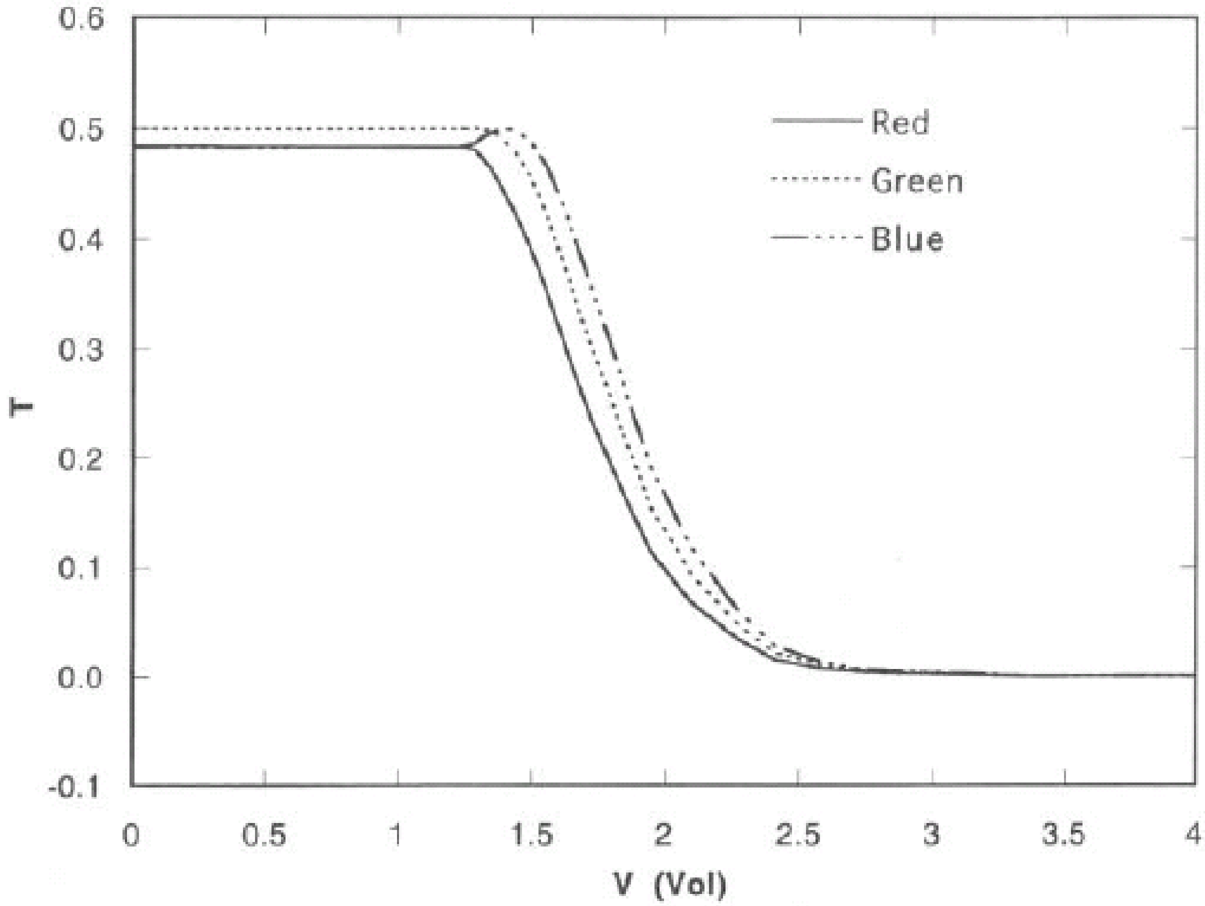


Transmission of Normally-Black mode



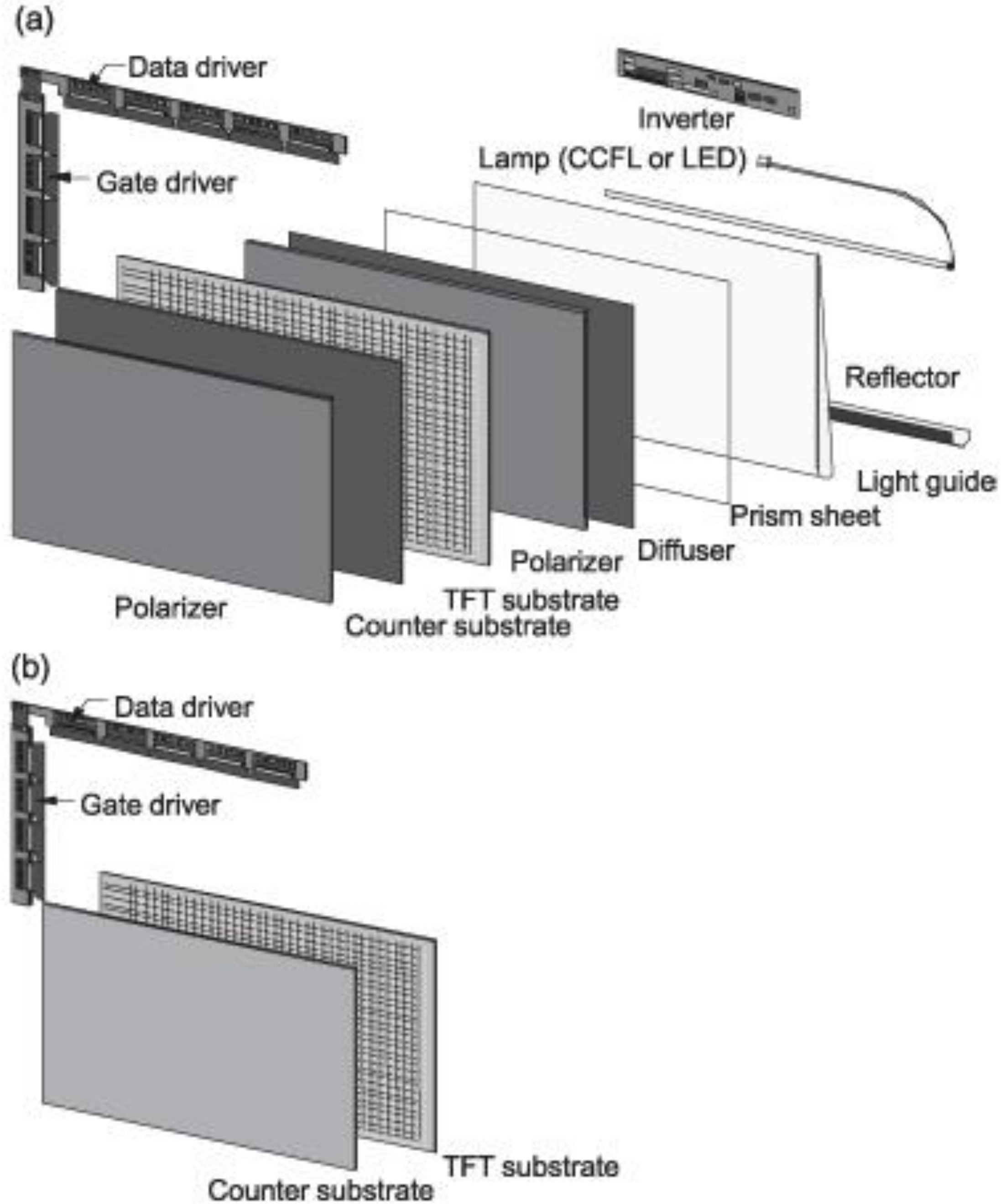
Consider Δnd = 0.48 μm, which corresponds to the 1st minimum of a normally black TN display at field-OFF state for green light at λ = 550nm.

Transmission of Normally-White mode

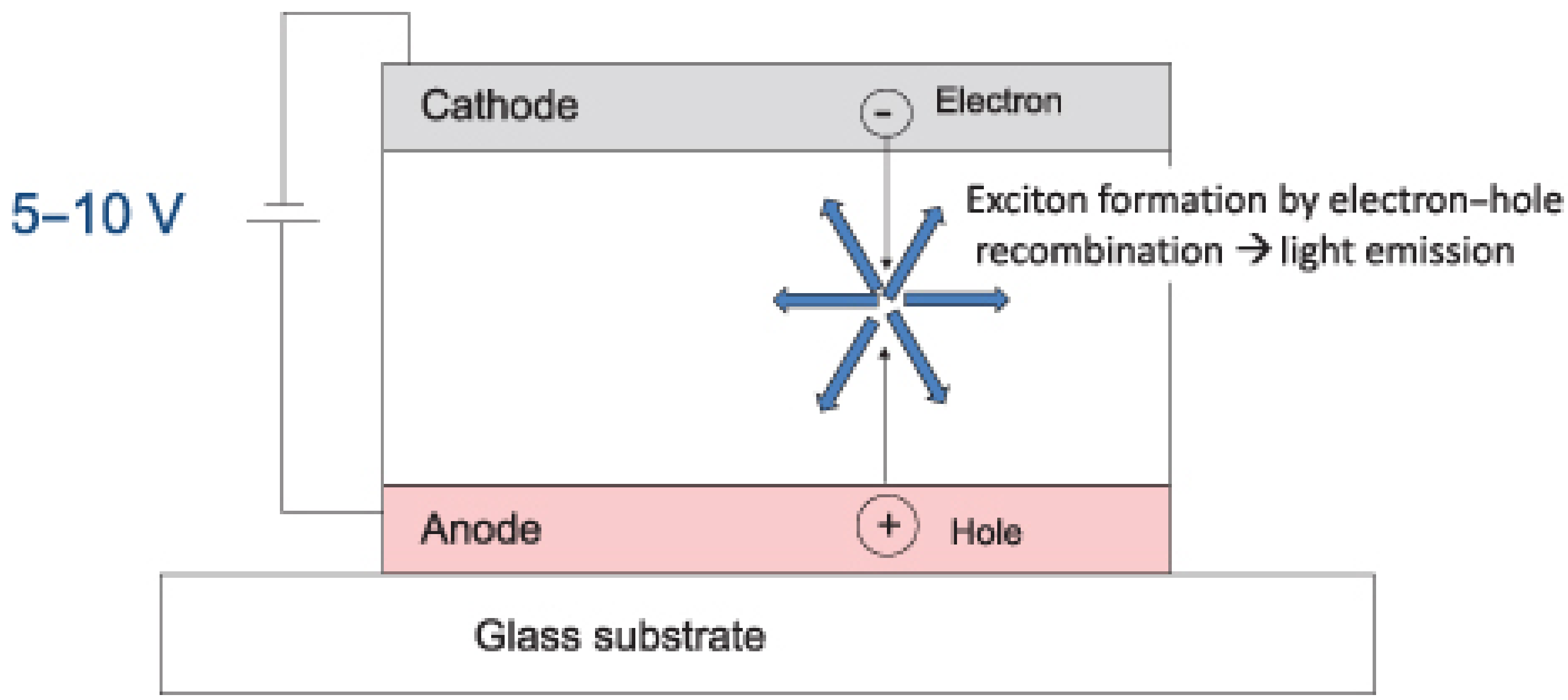


Spatial Light Modulators:
Organic Light Emitting Diode (OLED)

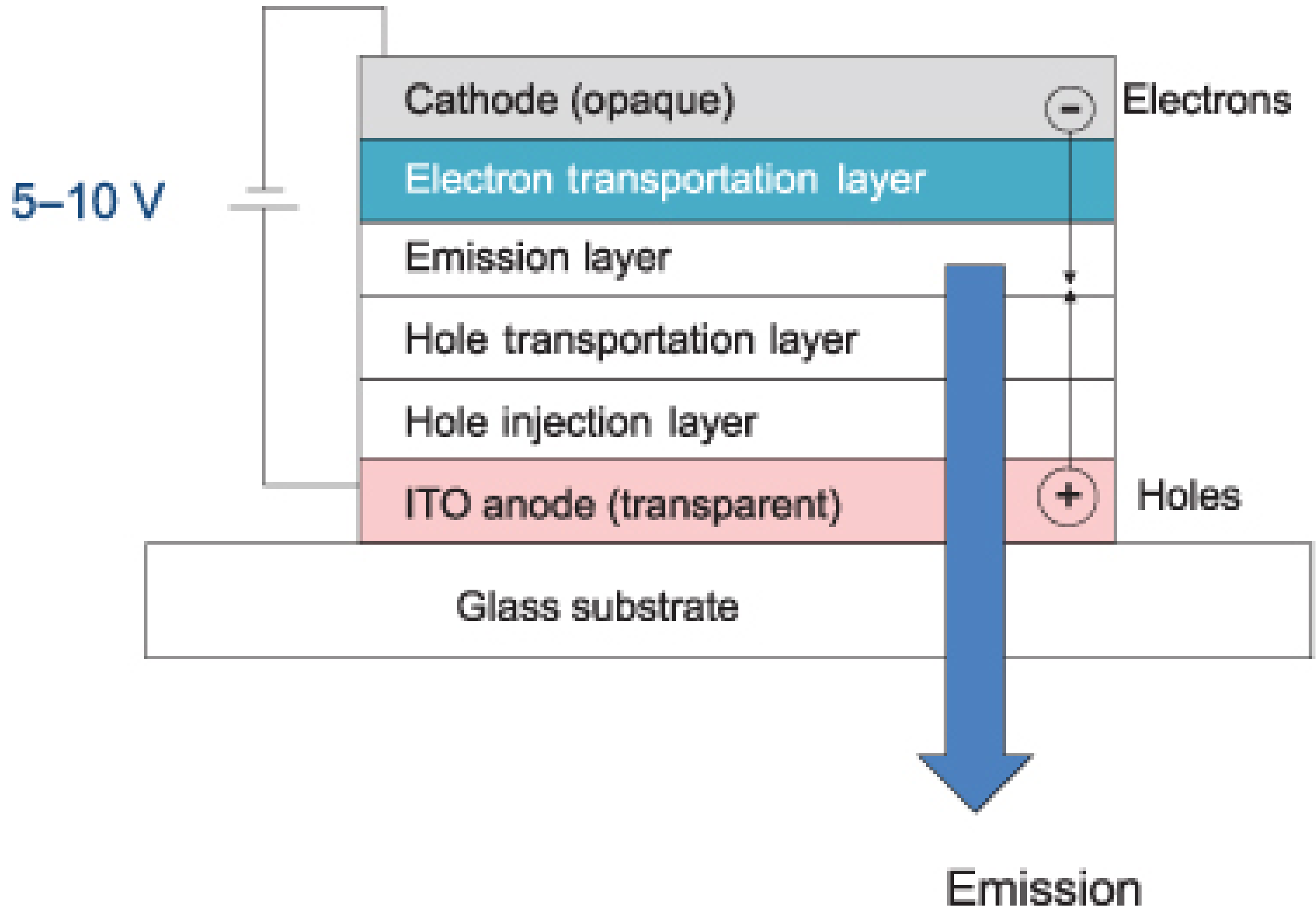
LCD vs. OLED


(a)
Data driver
Gate driver
Inverter
Lamp (CCFL or LED)
Reflector
Light guide
Prism sheet
Diffuser
Polarizer
TFT substrate
Counter substrate
Polarizer
(b)
Data driver
Gate driver
TFT substrate
Counter substrate

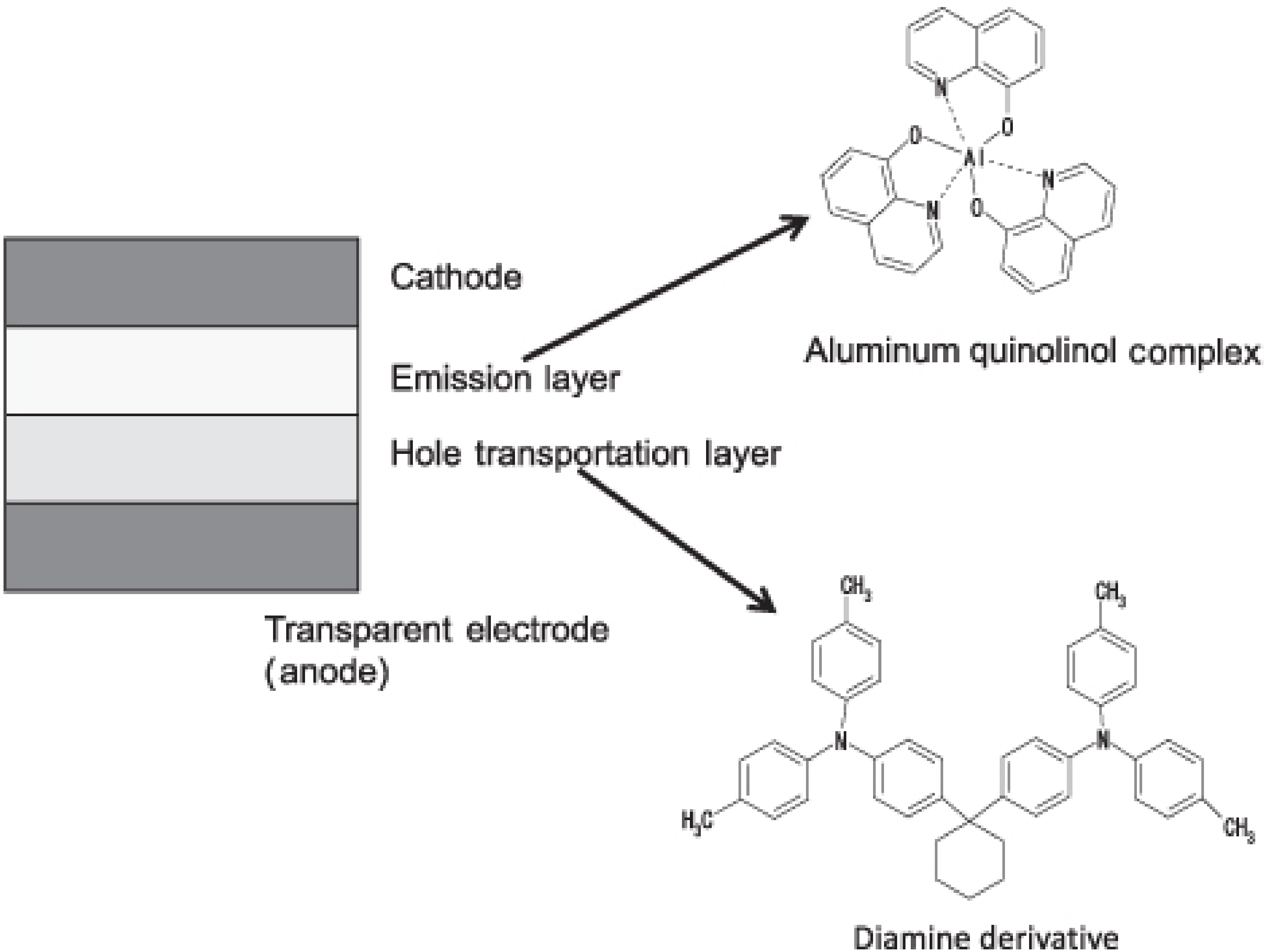
Organic Light Emitting Diode (OLED) Displays



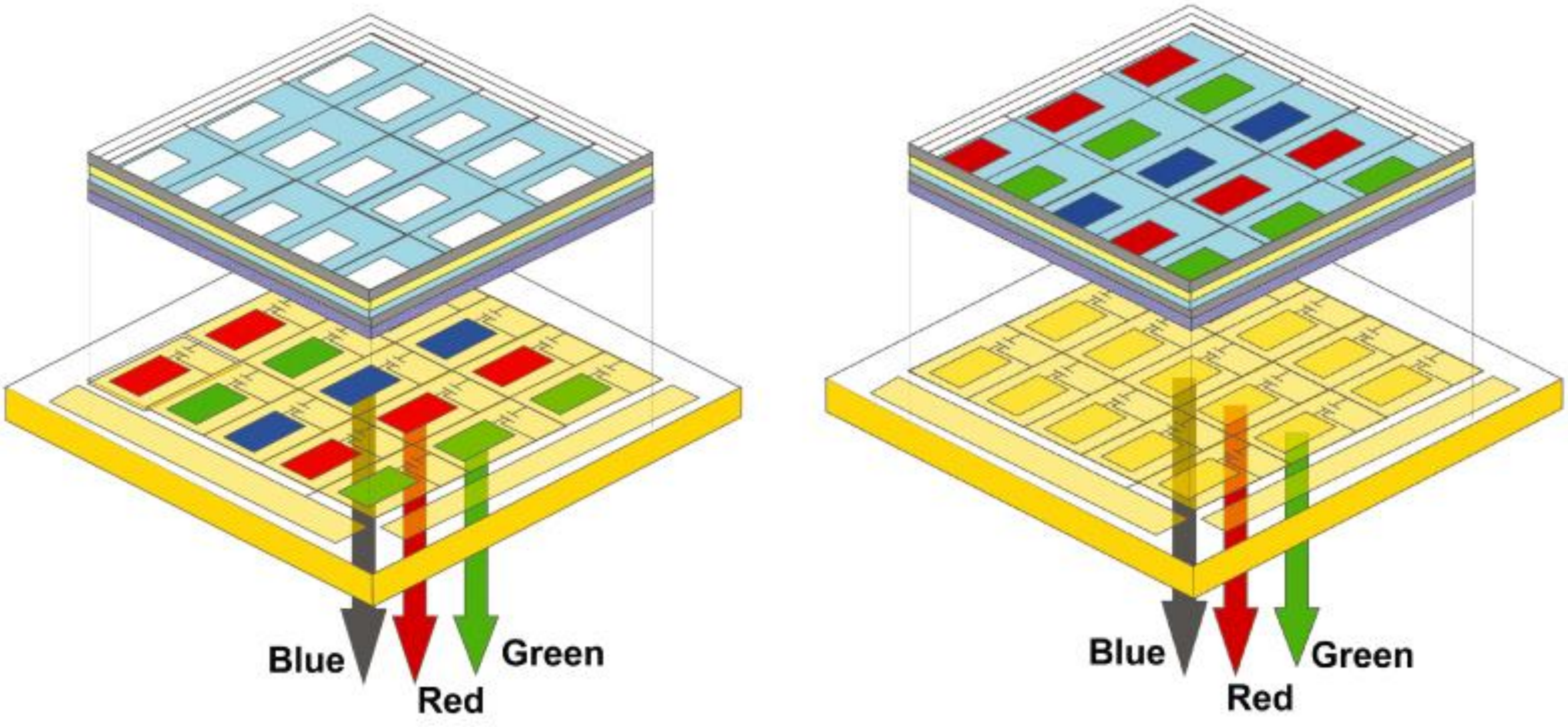
Organic Light Emitting Diode (OLED) Displays



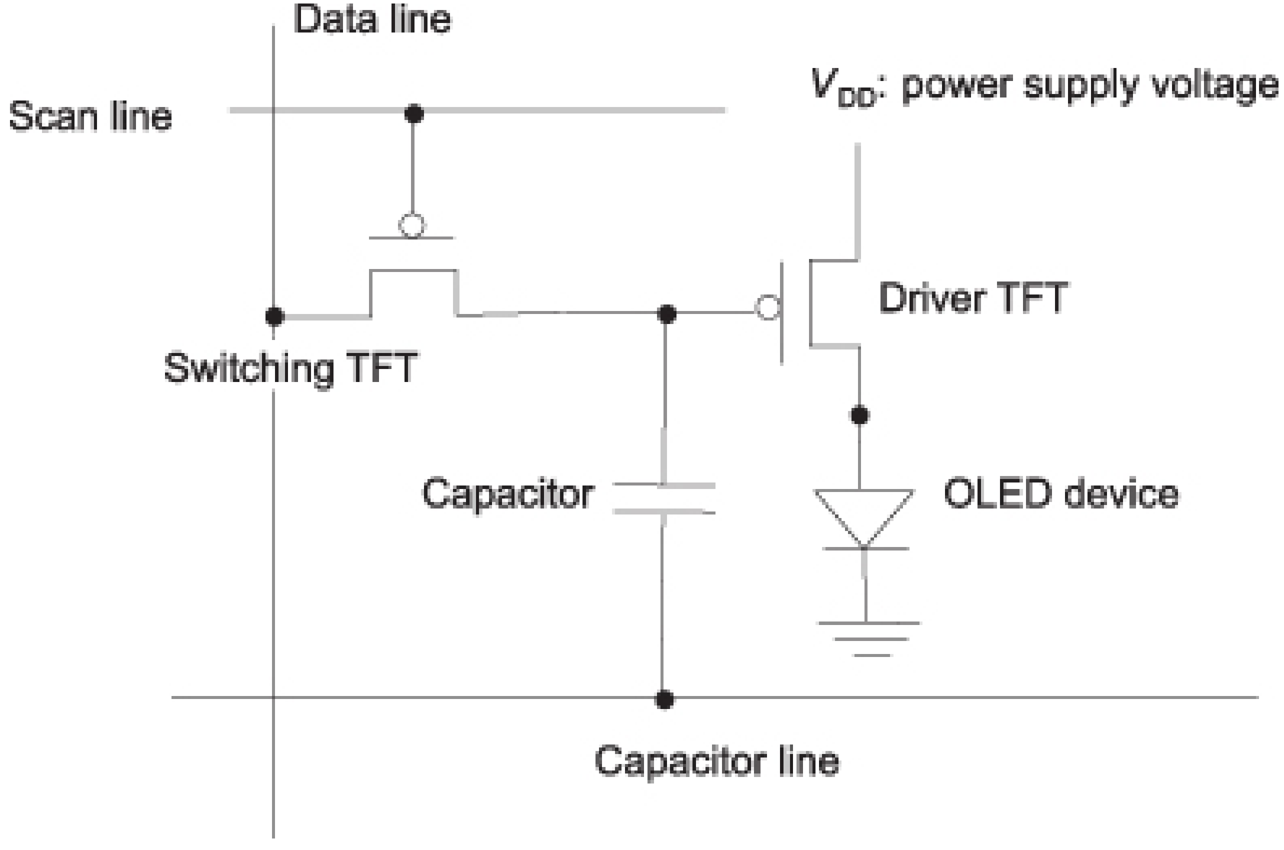
Organic Light Emitting Diode (OLED) Displays



White & RGB OLEDs



OLED Driving (Typical)

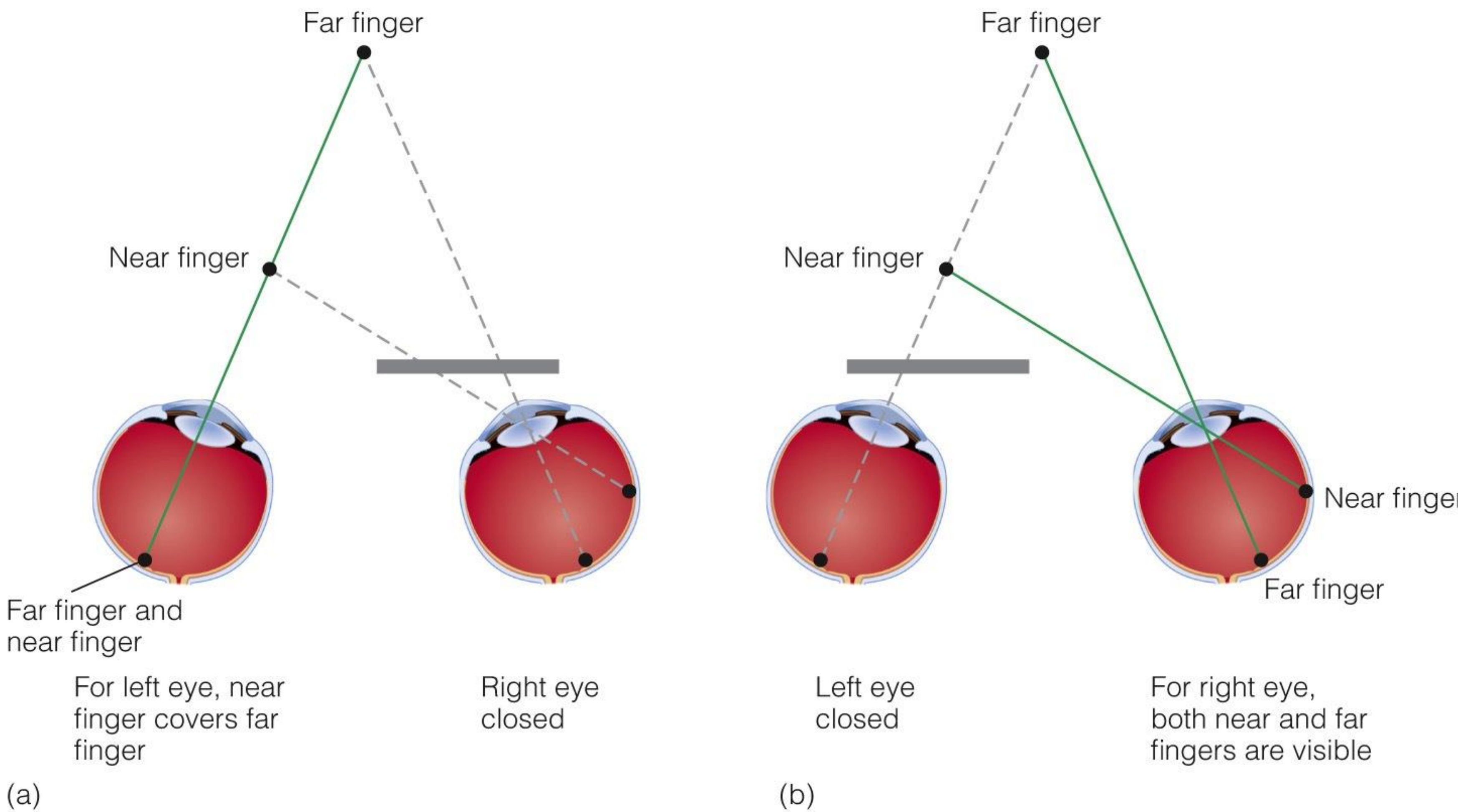


3D Displays

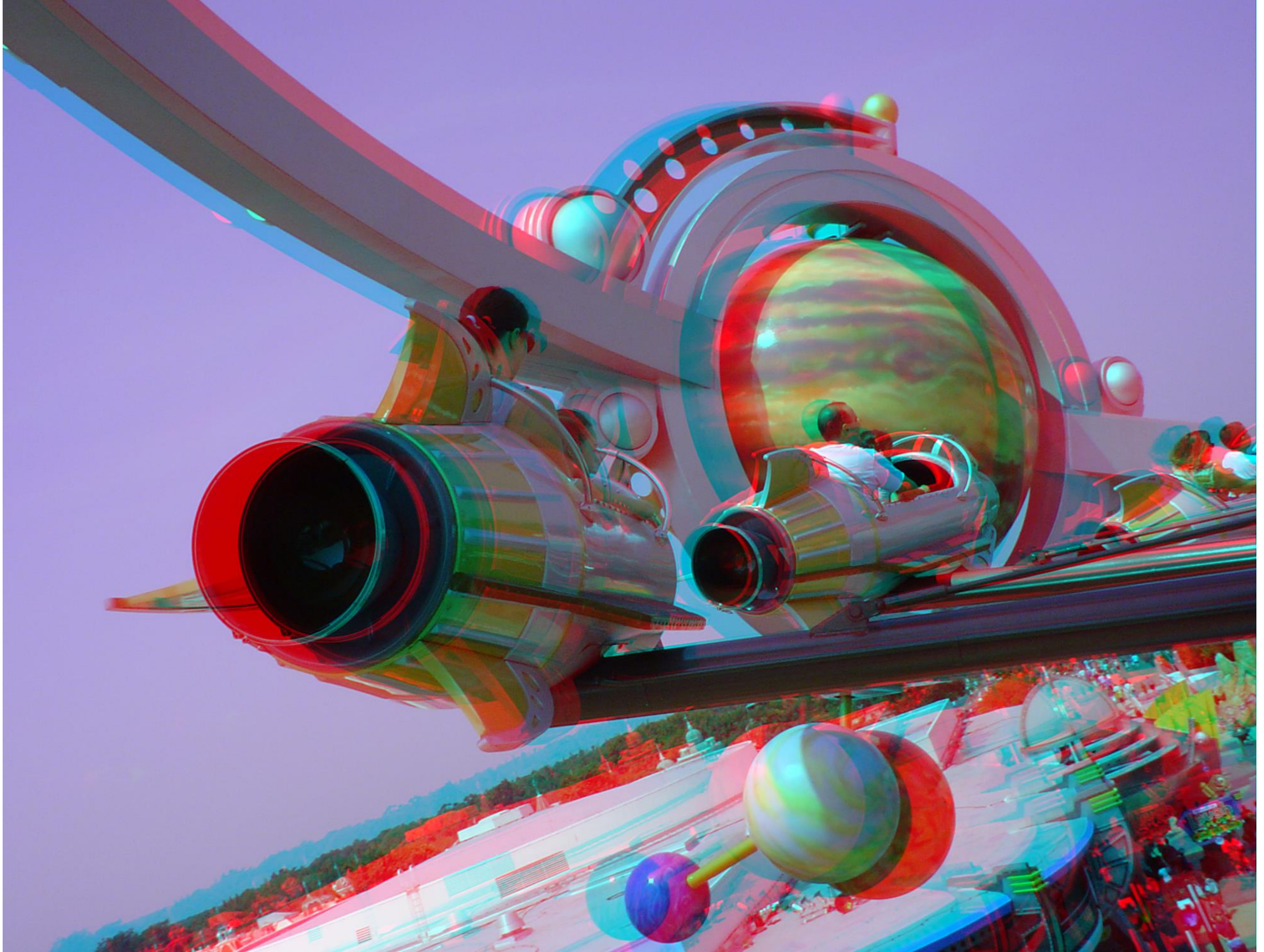
Recall:
Visual Cues for Depth Perception

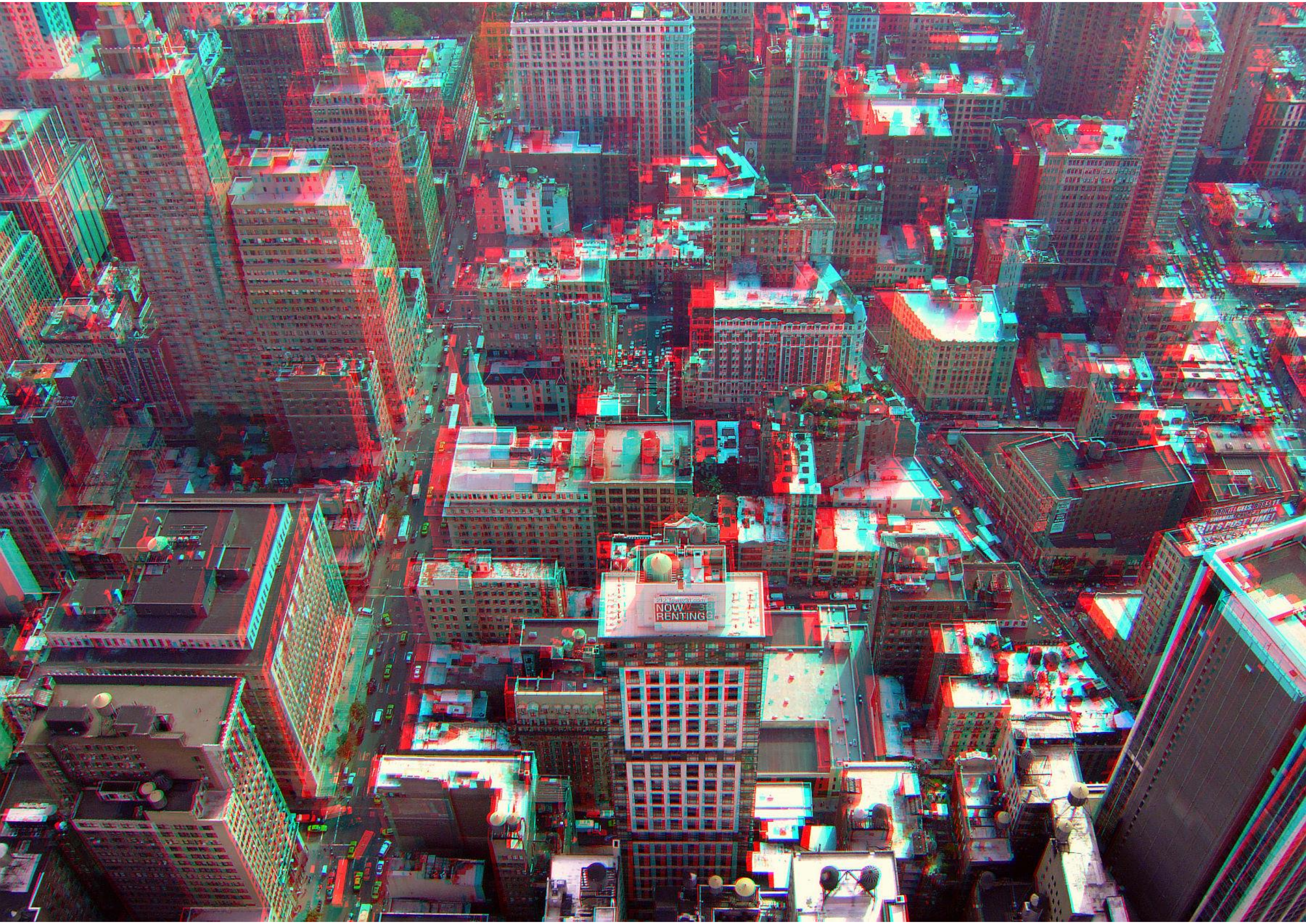
- Binocular disparity
- Oculomotor cues
- Motion cues
- Pictorial cues

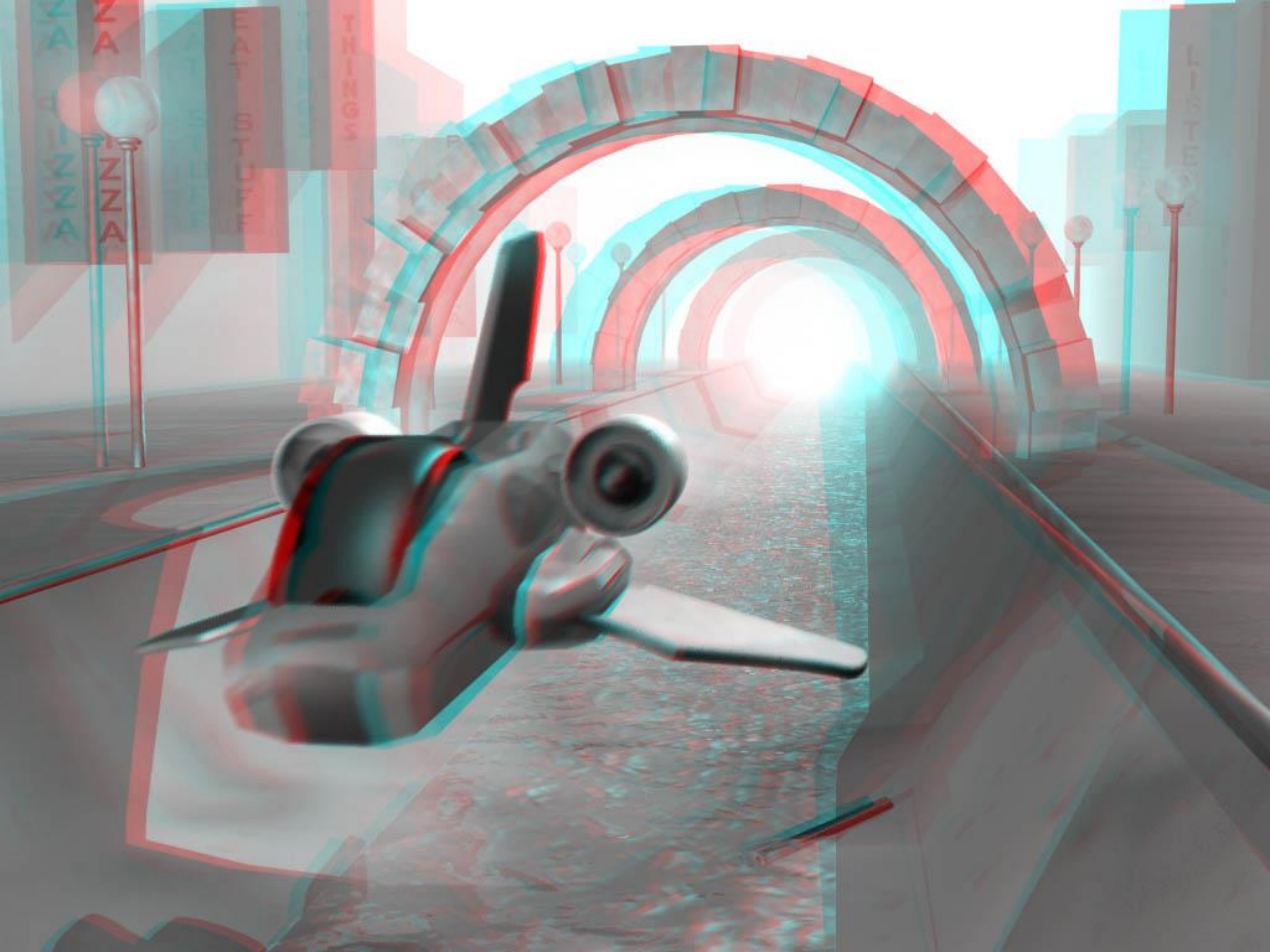
Recall: Binocular Disparity

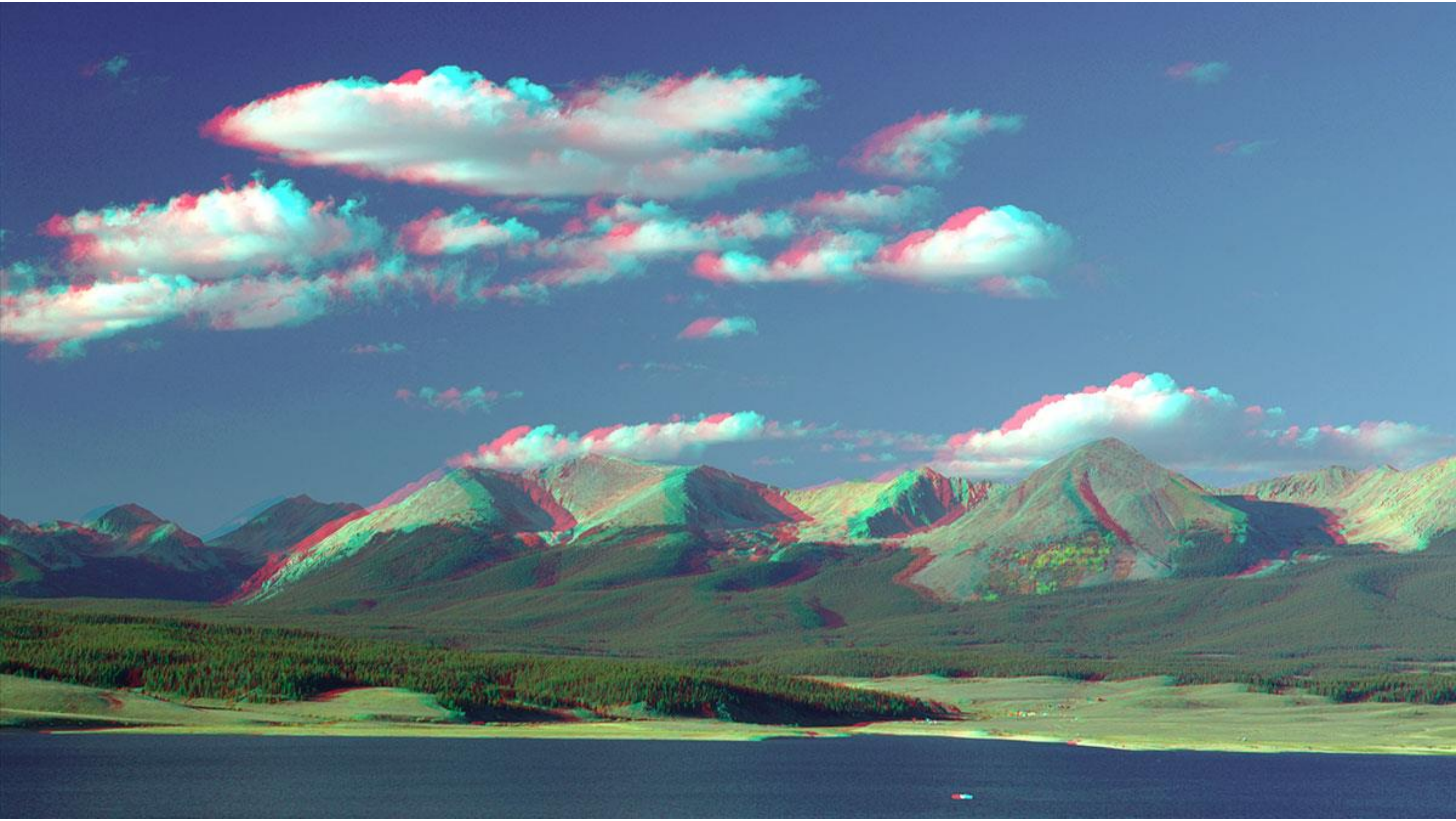


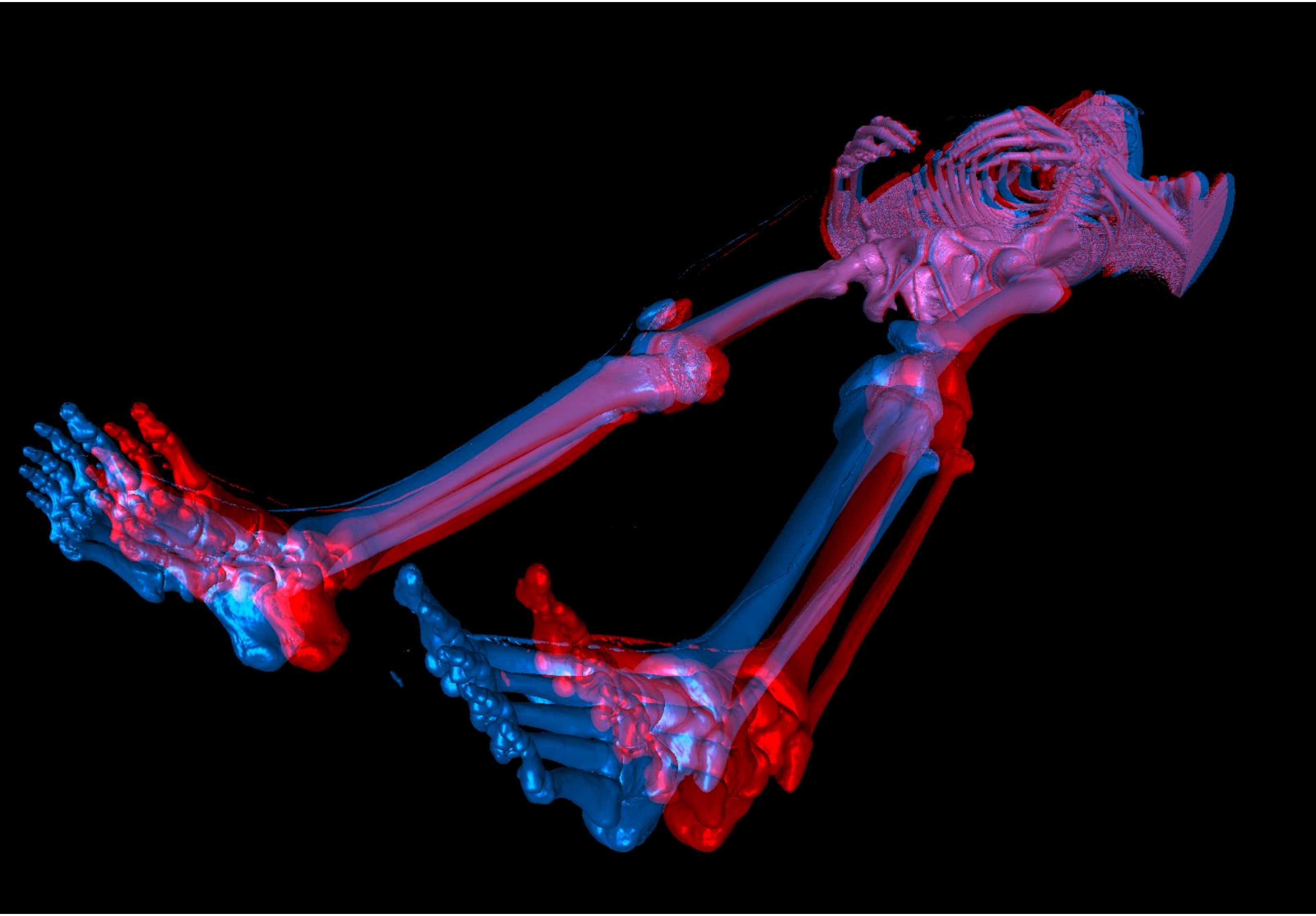
Anaglyph 3D (Red & Cyan Transmissive Filters)

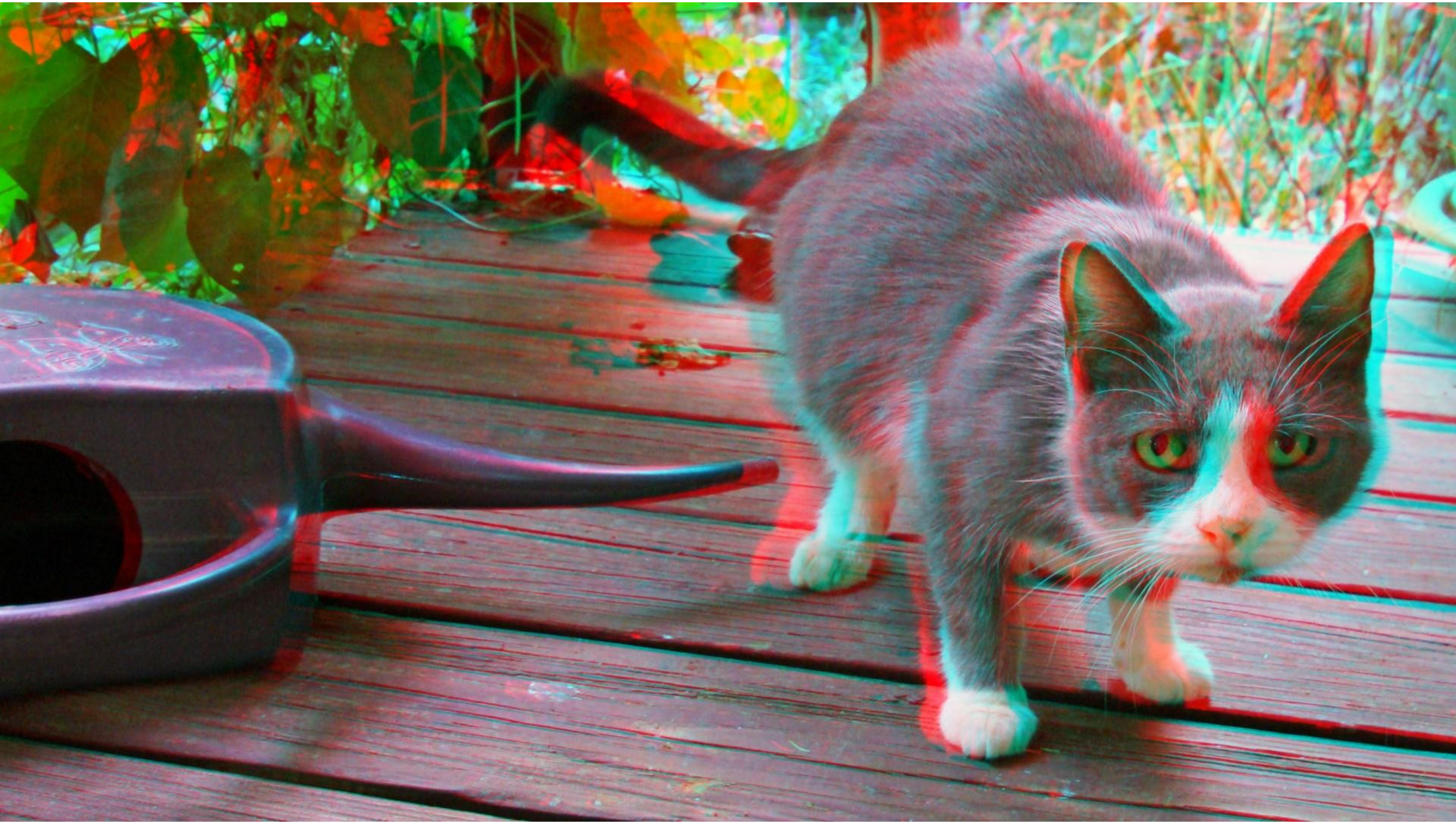



NOW
RENTING

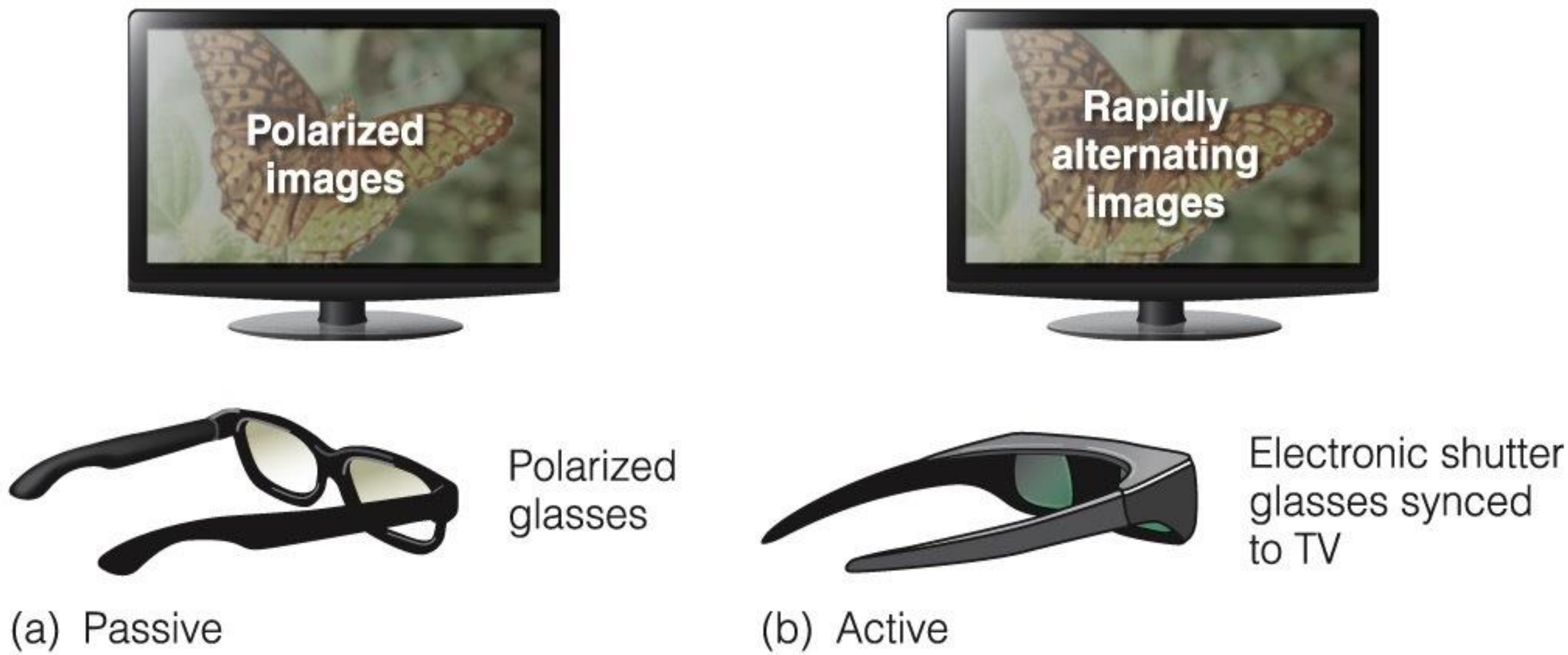

PIZZA
EAT STUFF
THINGS



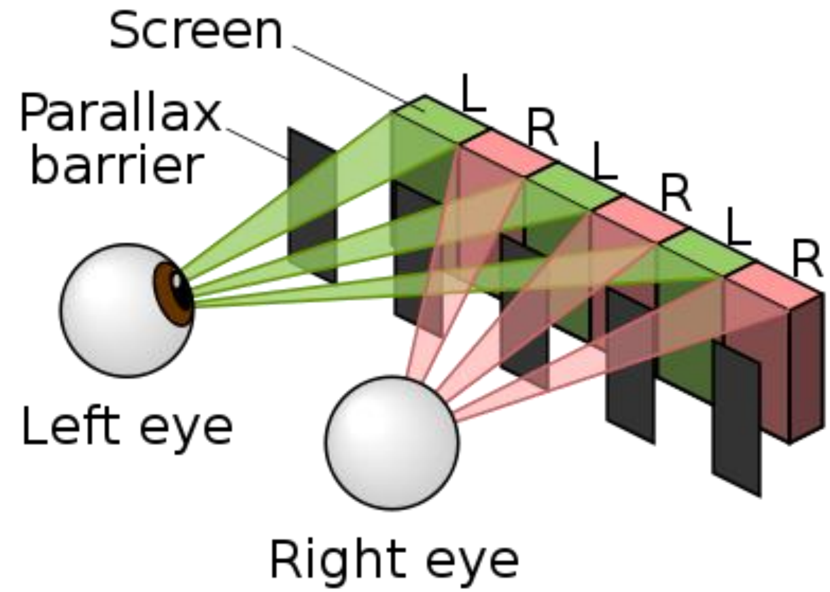


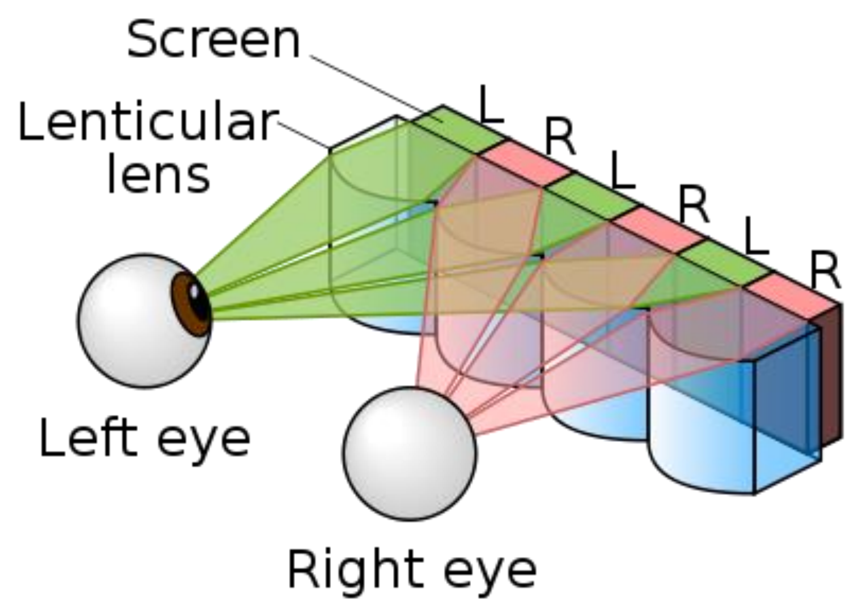


Achromatic Glasses



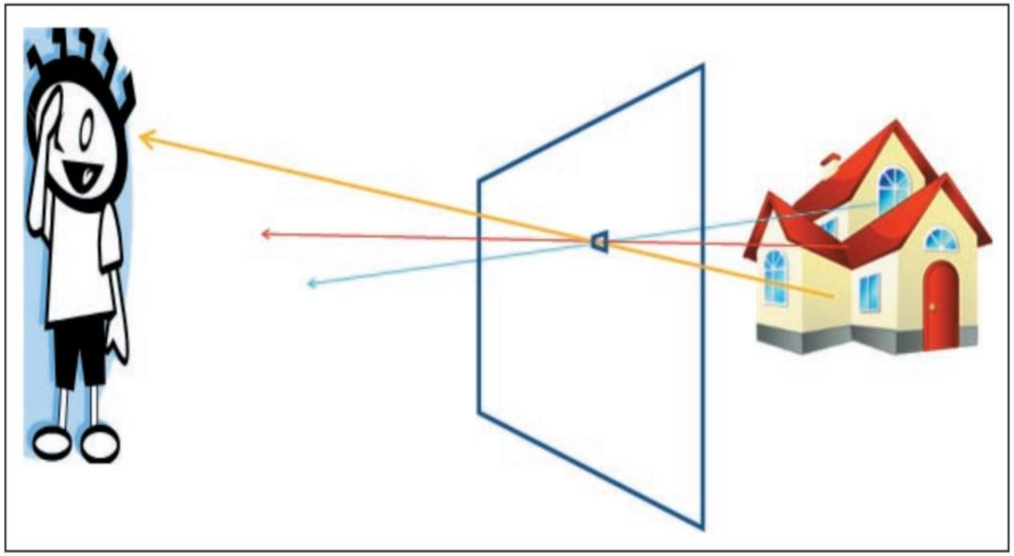
Autostereoscopic 3D Displays (No Glasses)





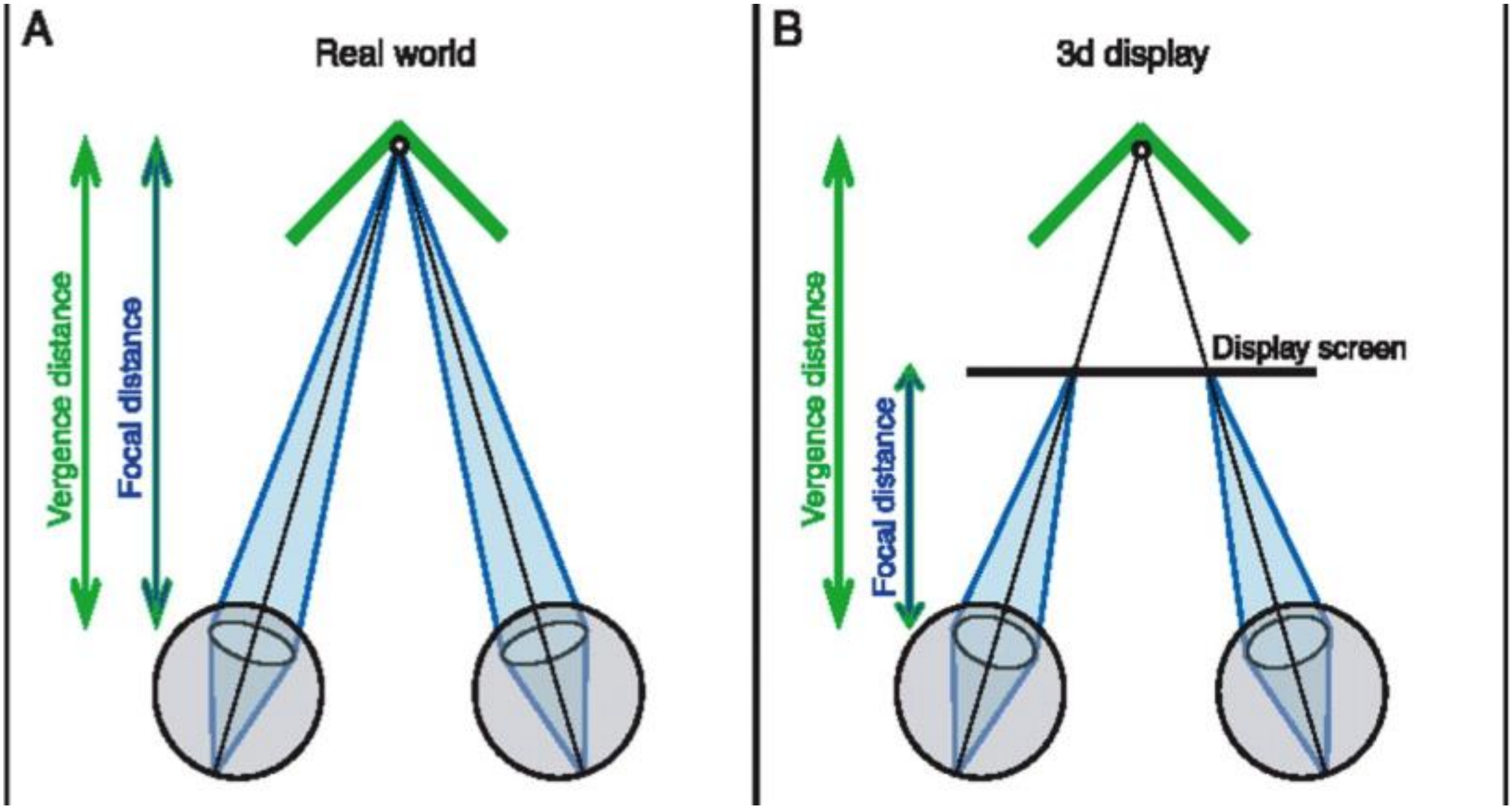
Towards "True" 3D Visual Experiences: "Light-Field Displays"

- Stereopsis
  - Each eye sees a different perspective view
- Relative motion
  - An eye sees a different view as the viewer's position is changed
- Focus
  - Consistent accommodation-convergence and focus/blur cues

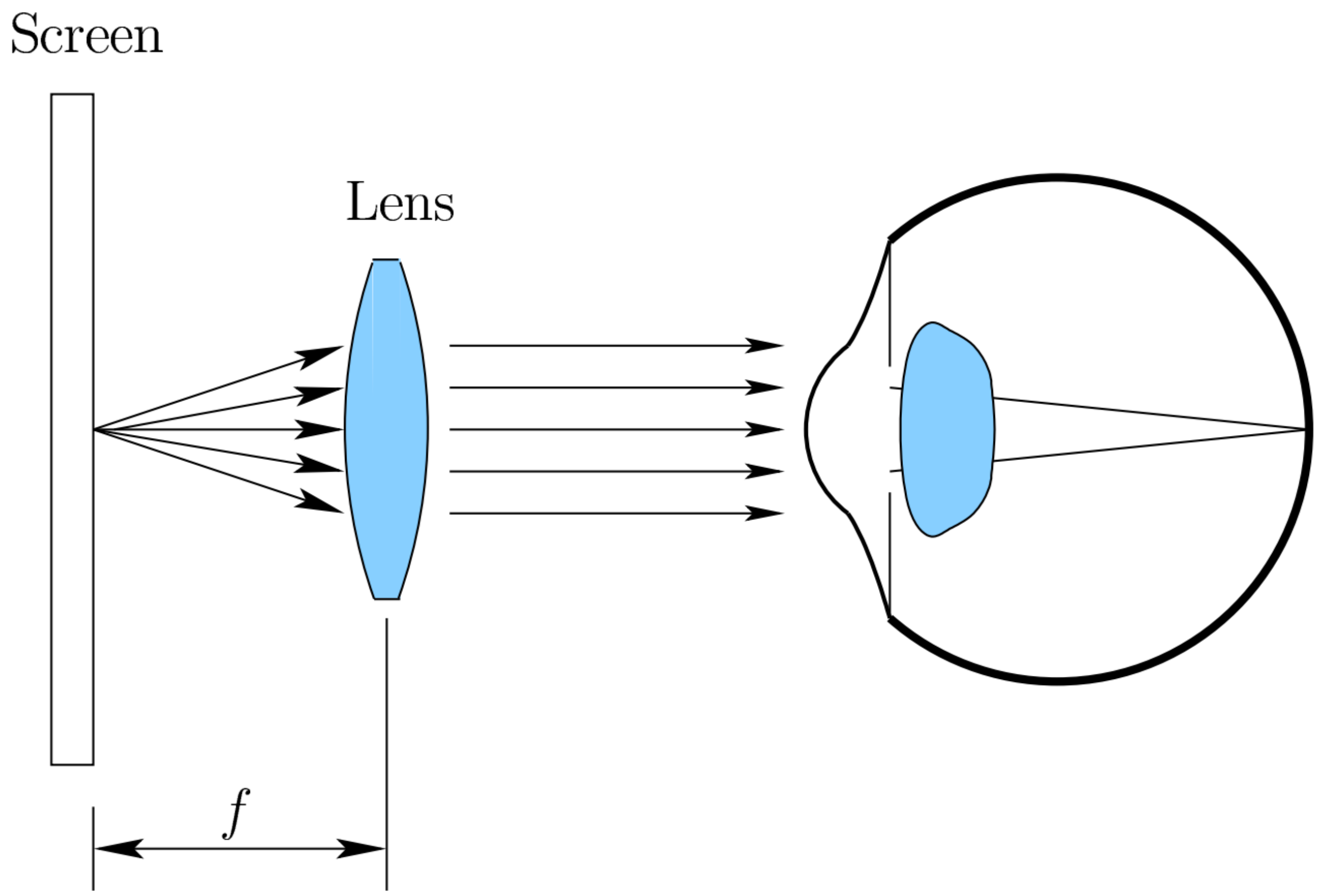


P. J. Bos and A. K. Bhowmik, "Liquid-Crystal Technology Advances toward Future "True" 3-D Flat-Panel Displays," Inf. Display 27, 6 (2011).

Convergence-Accommodation Mismatch

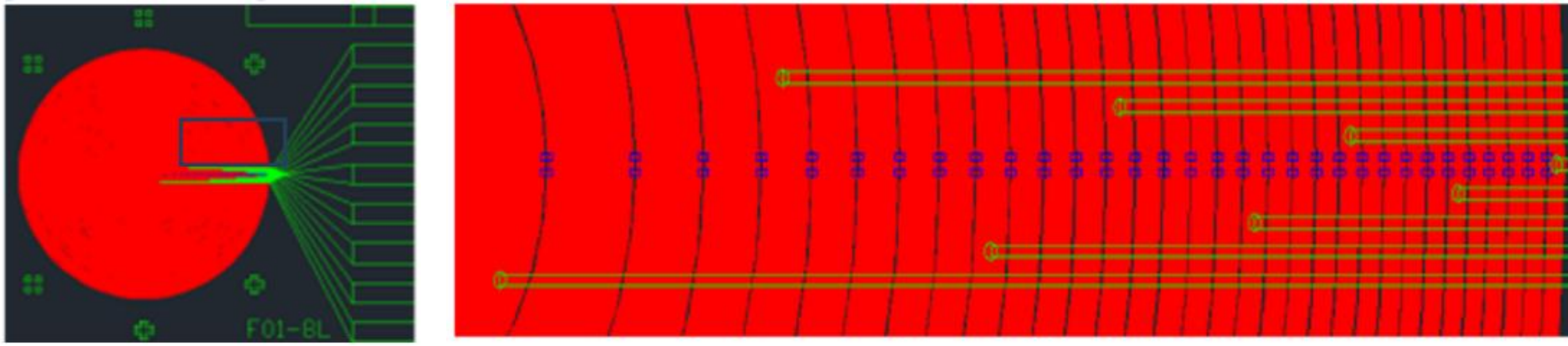


M. Banks, Berkeley

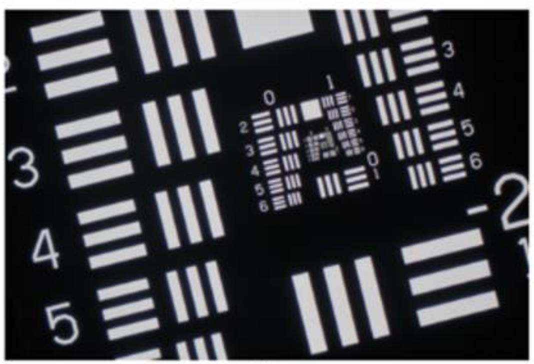


In VR headsets, the lens is placed so that the screen appears to be infinitely far away.

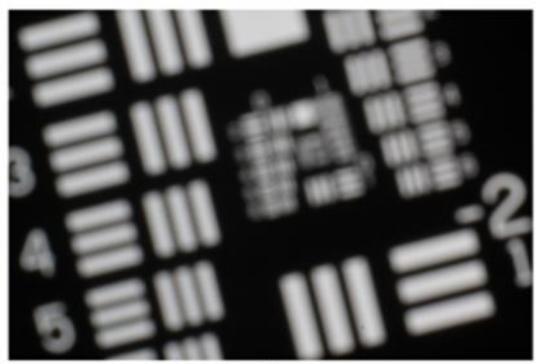
Adjusting Accommodation with Tunable Lens



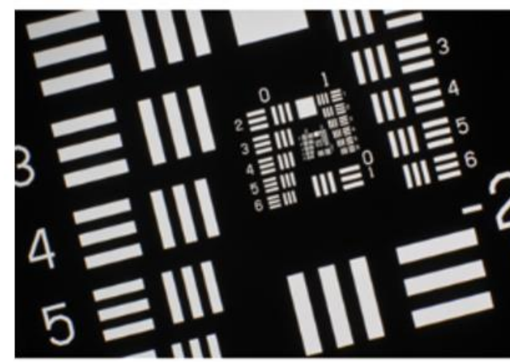
Electrode structure of a tunable LC lens. Right: expanded view of the region shown within the rectangle of the left picture.



LC lens with voltage applied to provide 400mm focal length



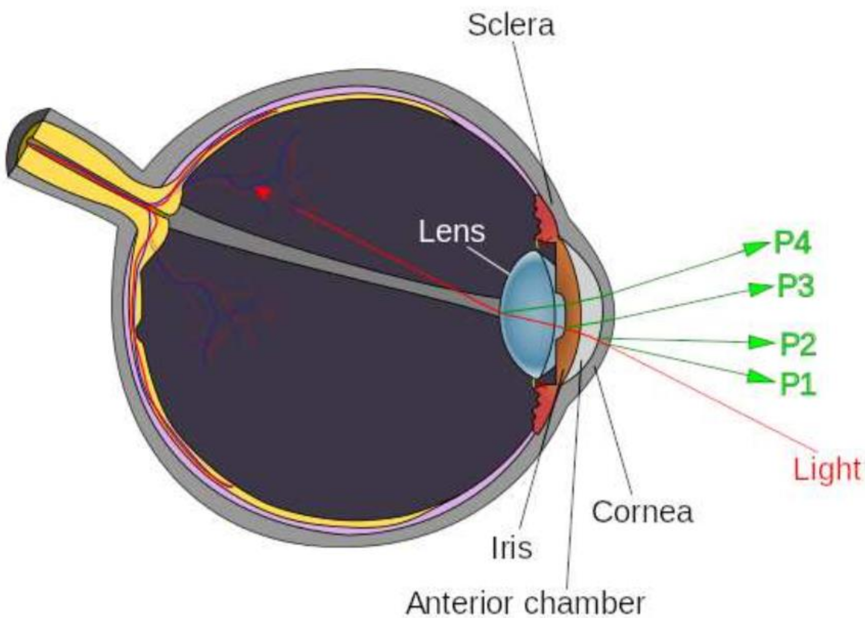
LC lens with zero volts applied



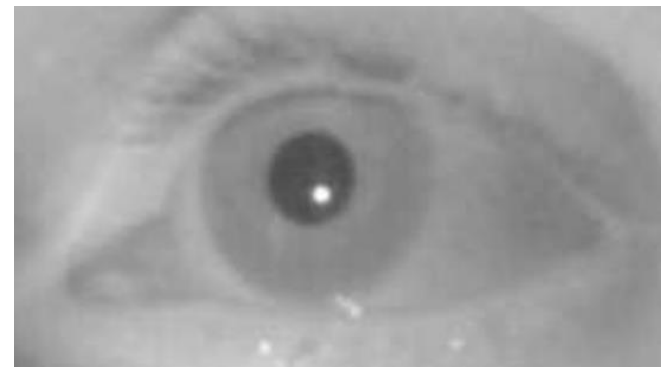
Glass lens with 400mm focal length for comparison

P. Bos, L. Li, D. Bryant, A. Jamali, A. Bhowmik, SID 2016

Eye Gaze Tracking



The first and sometimes the fourth Purkinje images of an IR light source are used for eye tracking



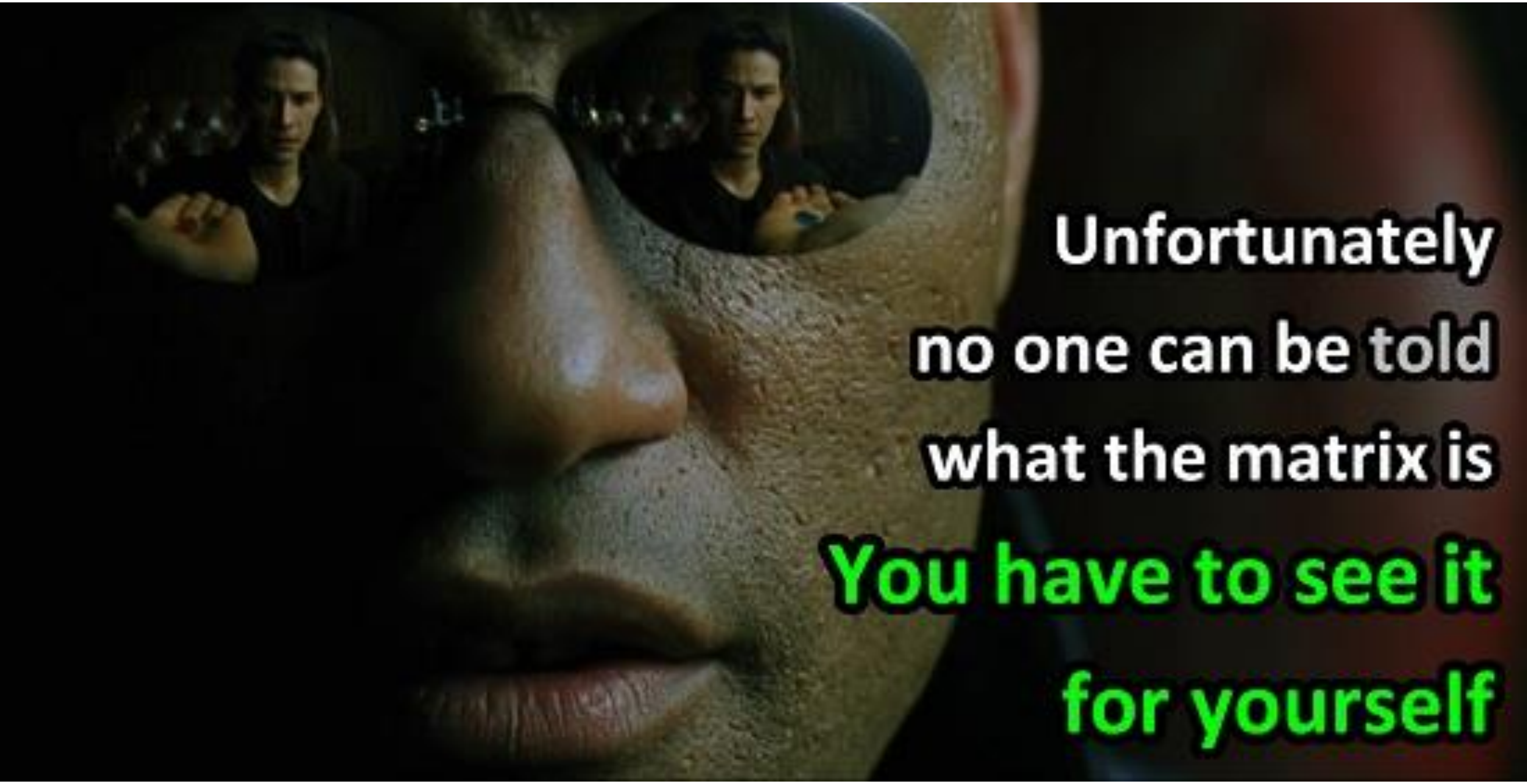
The first Purkinje image generates a bright reflection

Additional benefit of eye-gaze tracking in the future: **foveated rendering** to substantially reduce the graphical computation workload!

Massimo Gneo, Maurizio Schmid, Silvia Conforto, and Tomasso D'Alessio

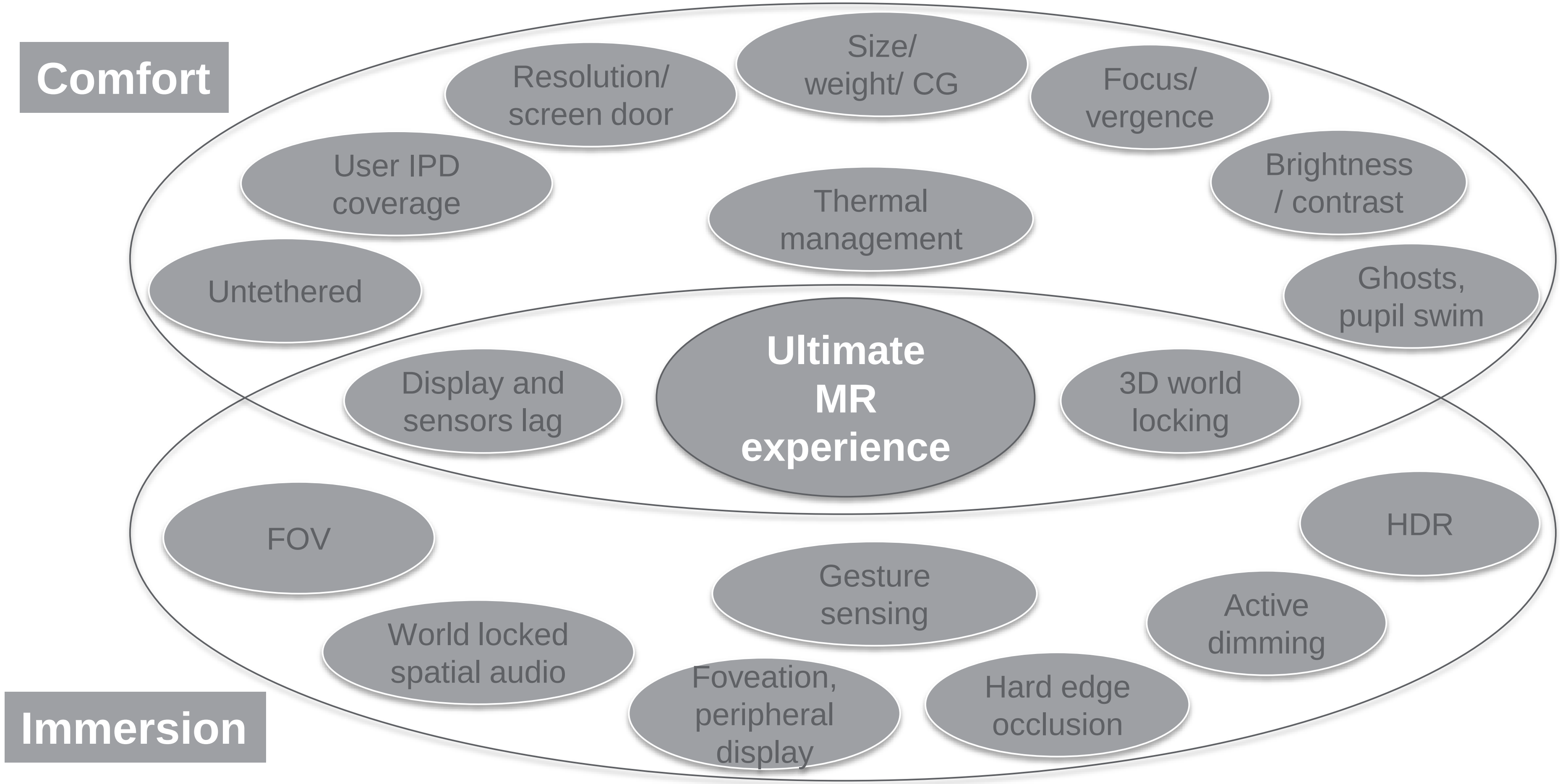
Parting Thoughts…

- Key requirements are relatively well-understood.
- Lots of progress recently in the development of technologies and components, but challenges still remain to be solved.
- Ingredients are important, but end-to-end integration (hardware, software, system, interfaces) is critical.
- Commercial success will hinge on delivering compelling applications with natural user experiences.


Unfortunately
no one can be told
what the matrix is
You have to see it
for yourself

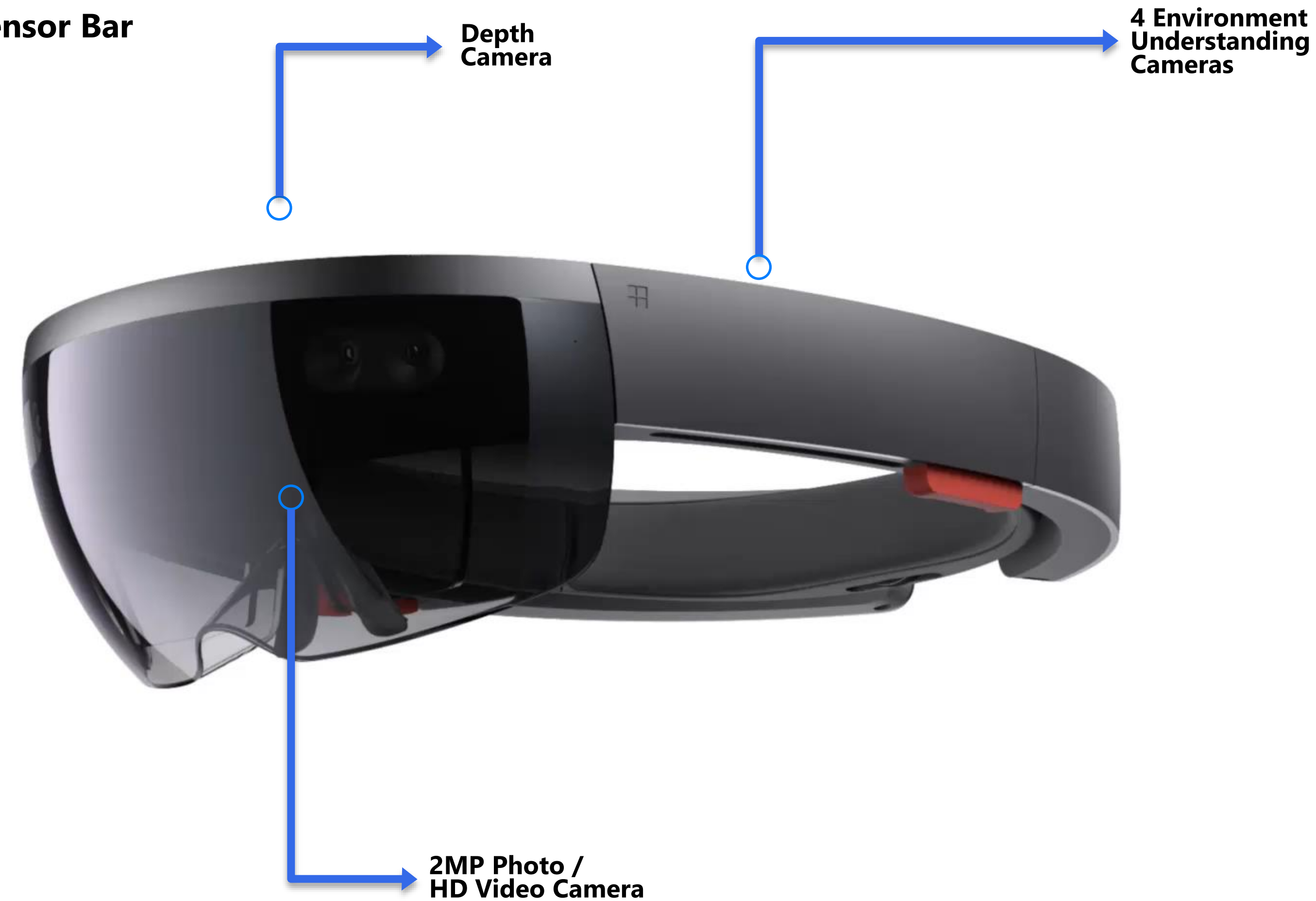
Backup Slides:

Examples of Optics for See-Through Head-Worn Displays (HWD) in Augmented/Mixed Reality Systems
&
Screen-Door Effect Reduction


Comfort
Resolution/ screen door
Size/ weight/ CG
Focus/ vergence
User IPD coverage
Thermal management
Brightness / contrast
Untethered
Ghosts, pupil swim
Display and sensors lag
Ultimate MR experience
3D world locking
FOV
HDR
Gesture sensing
Active dimming
World locked spatial audio
Foveation, peripheral display
Hard edge occlusion
Immersion

Hardware choices for HoloLens V1

HoloLens Sensor Bar



HoloLens Optics and IMU

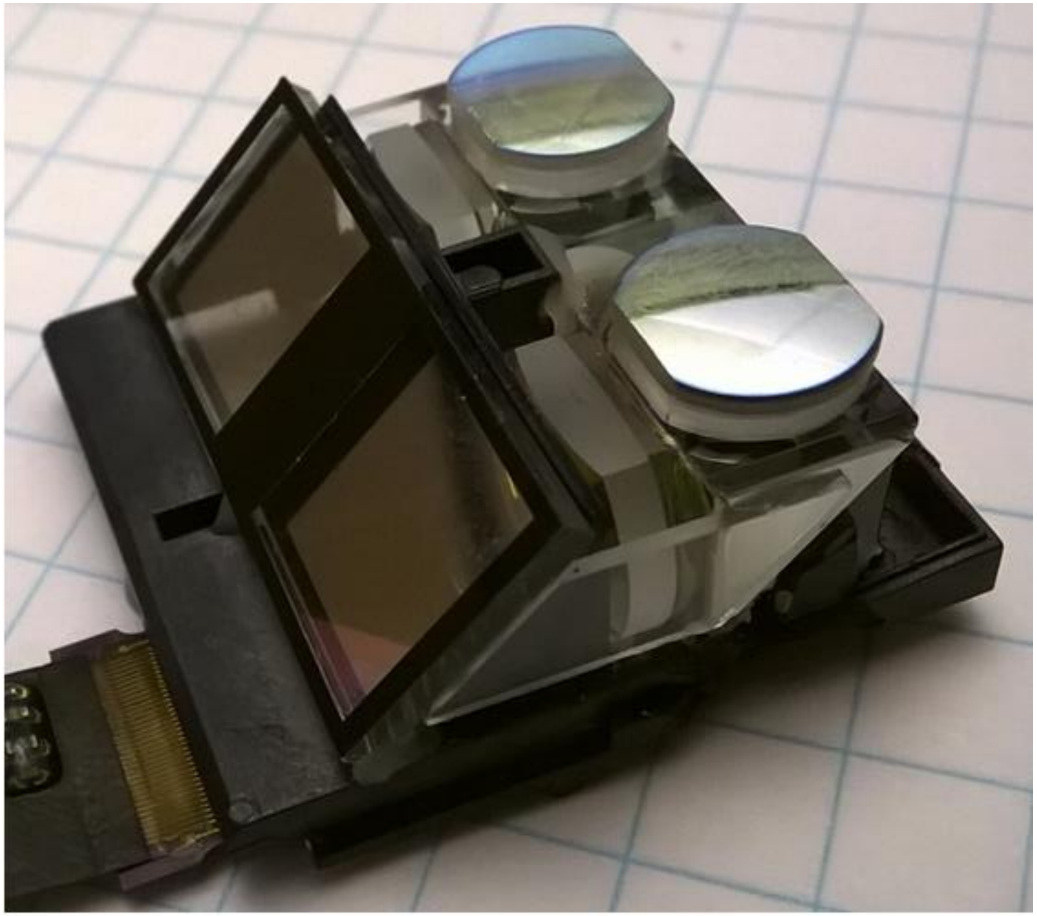
HoloLens MLB (Main Logic Board)

- **Windows 10**
- **Custom-built**
  Microsoft Holographic Processing Unit (HPU 1.0)
- **64GB Flash**
- **2GB RAM (1GB CPU and 1GB HPU)**
- **x86 architecture**

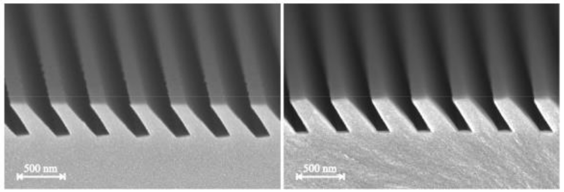
HoloLens Spatial Sound

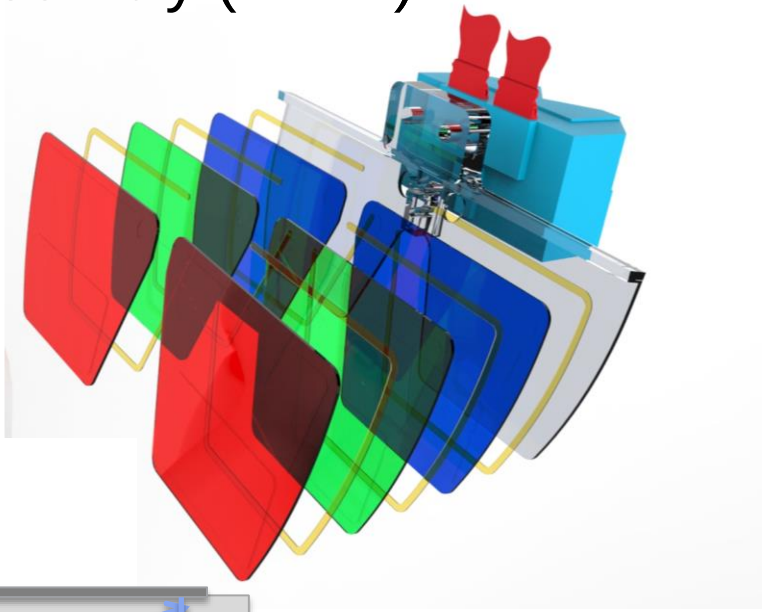
also 4 microphones for speech/beamforming

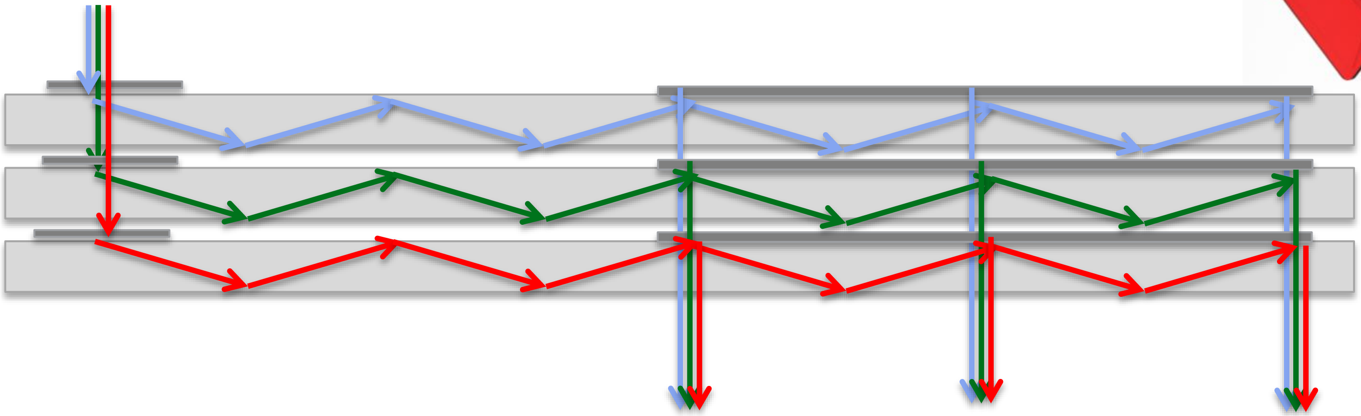
Dual eye DMA
(not including illumination optics)



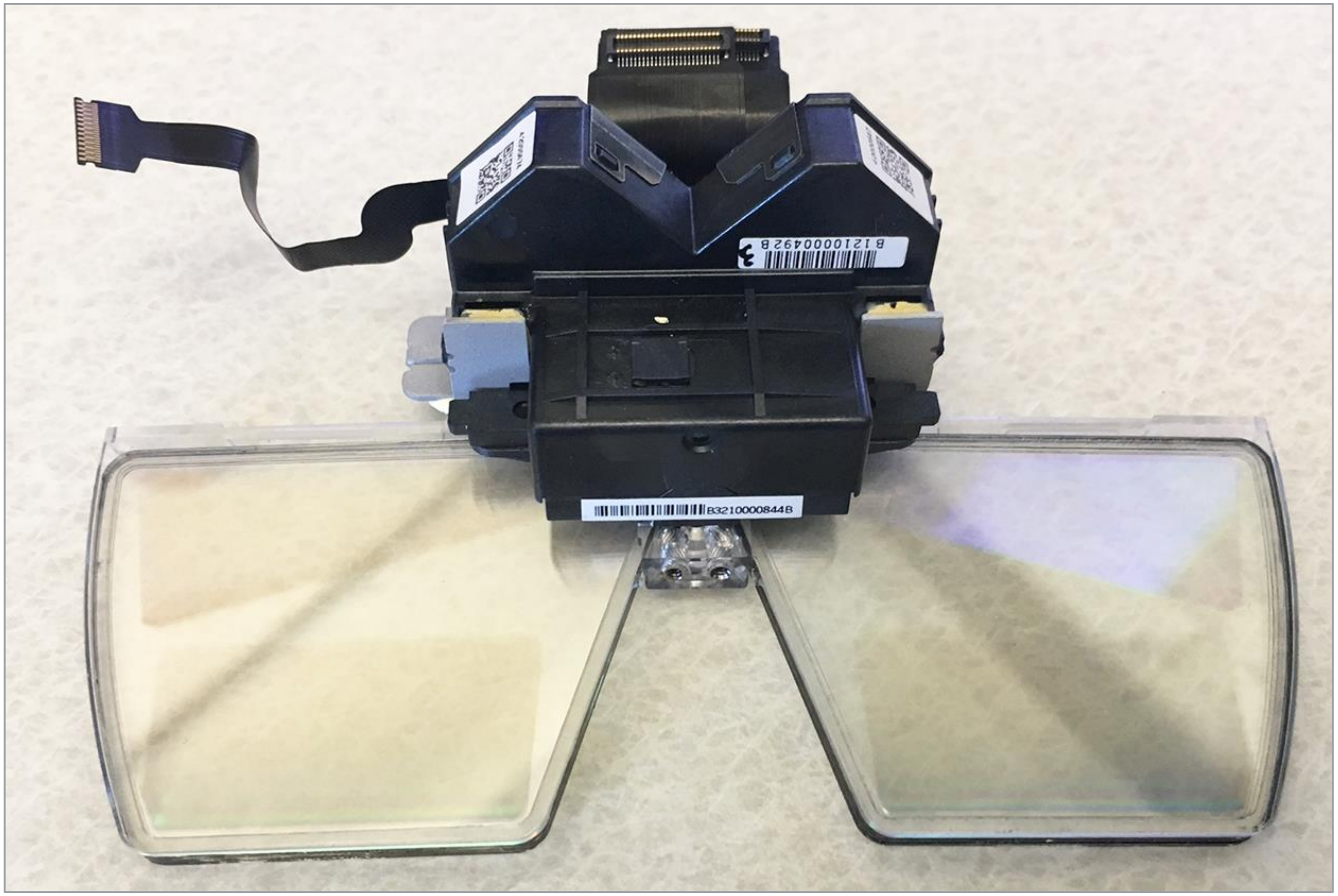
The Waveguide Module Assembly (WMA)





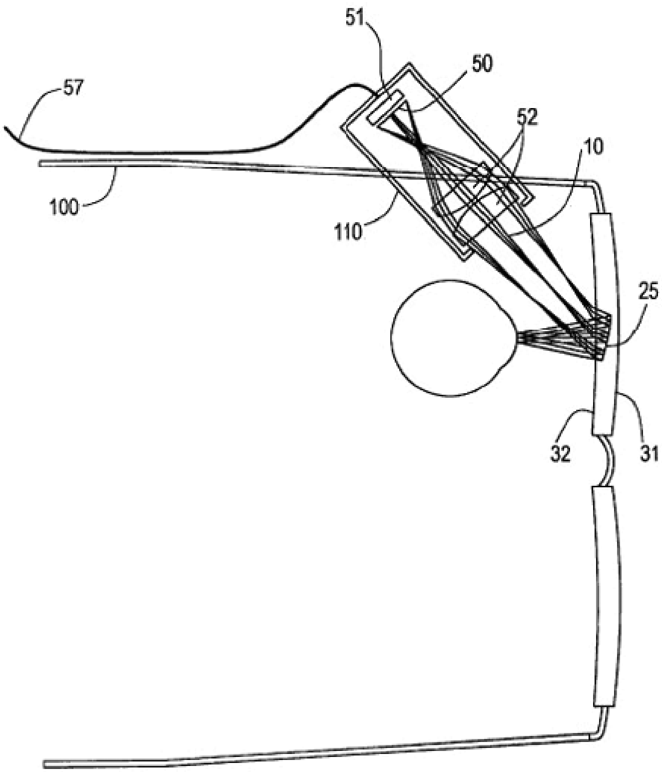


Finalized OMA

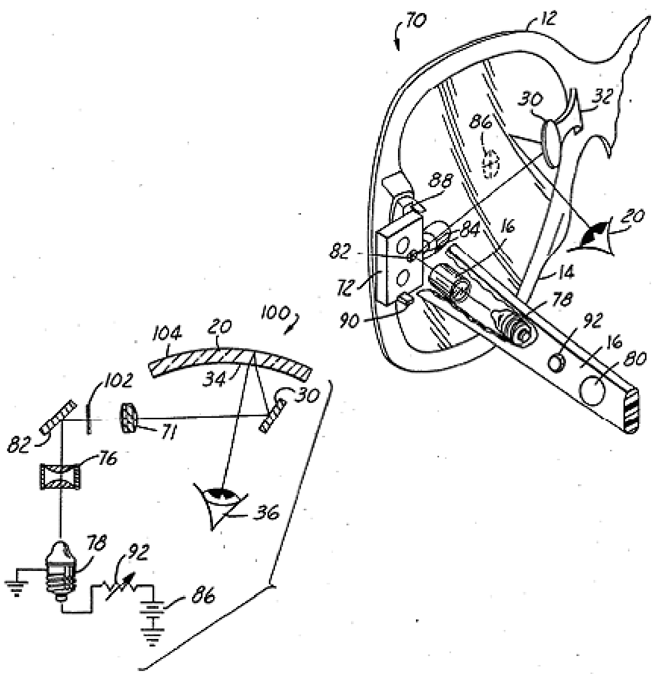


HWD Examples (Slide 1 of 18)

Spitzer. Eyeglass Display Lens System Employing Off-Axis Optical Design.
US 6,353,503
Mar. 5, 2002



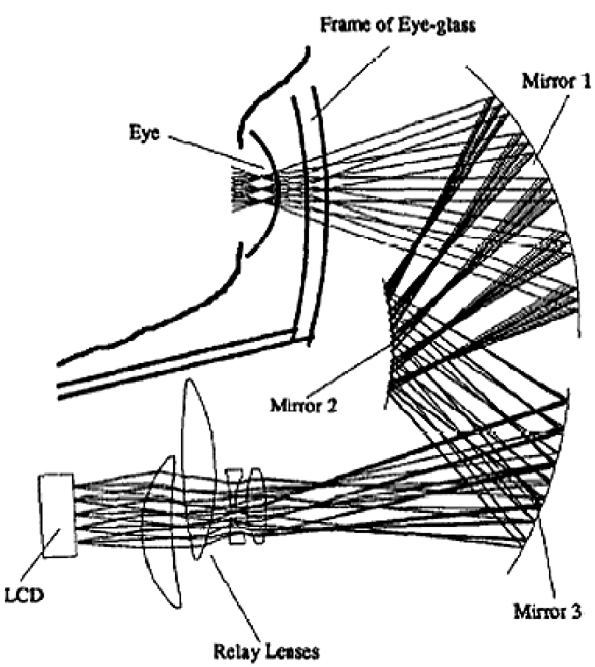
Bettinger. Spectacle-mounted ocular display apparatus.
US 4,806,011
Feb. 21, 1989



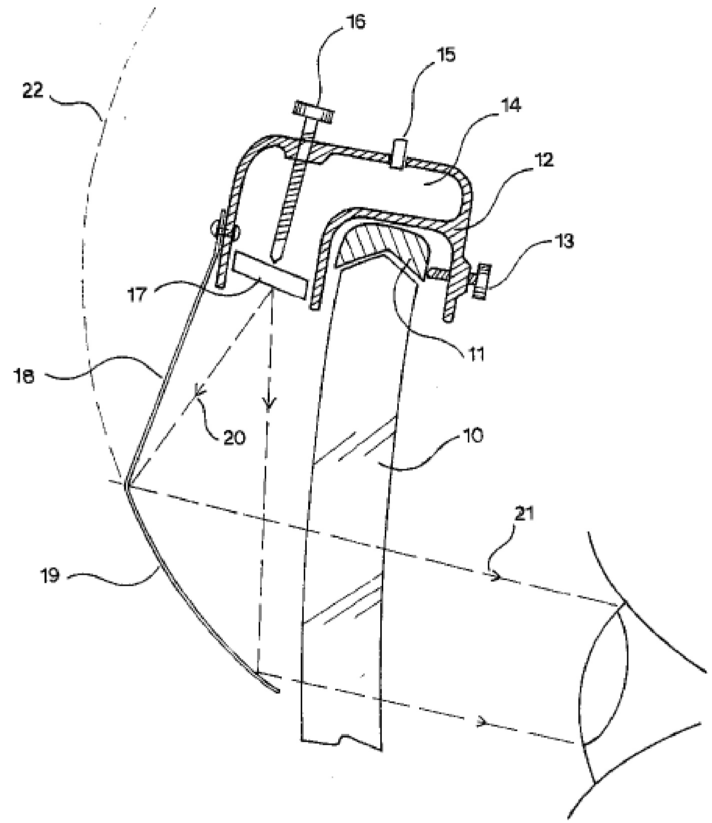
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 2 of 18)

Hoshi *et al.* Off-axial HMD optical system consisting of aspherical surfaces without rotational symmetry. In Proc. of SPIE Vol. 2653



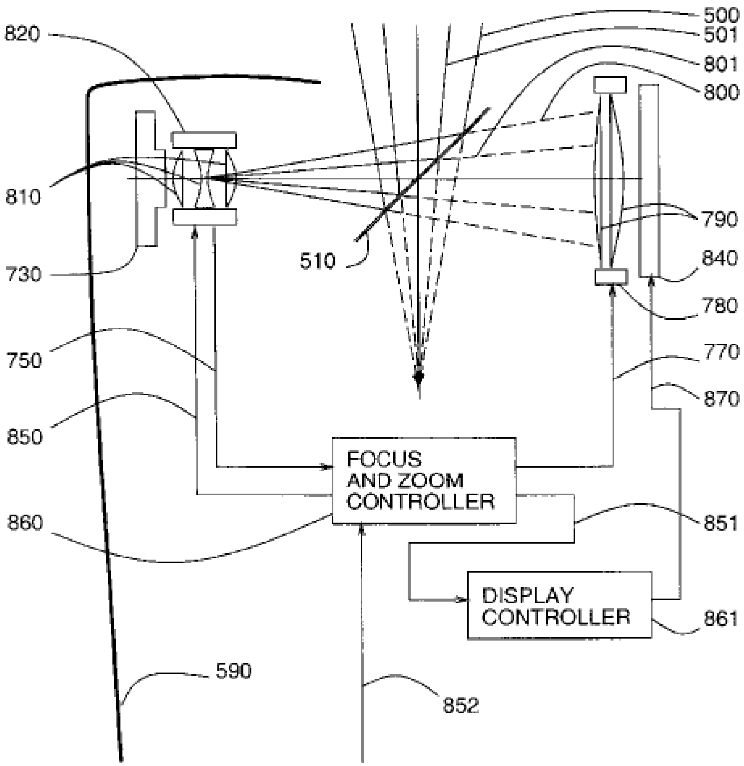
Perera. Display Projection Optical System for Spectacles or Sunglasses.
US 4,867,551
Sep. 19, 1989



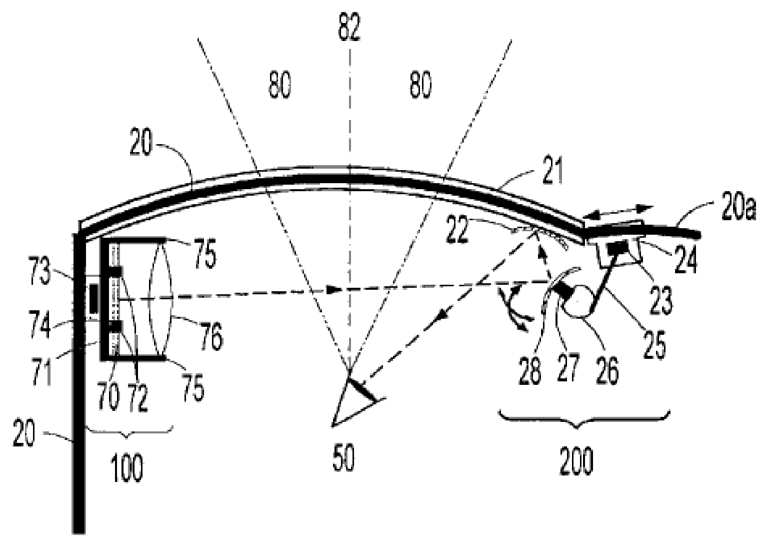
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 3 of 18)

Mann. Wearable Camera System With Viewfinder Means.
US 6,307,526
Oct. 23, 2001



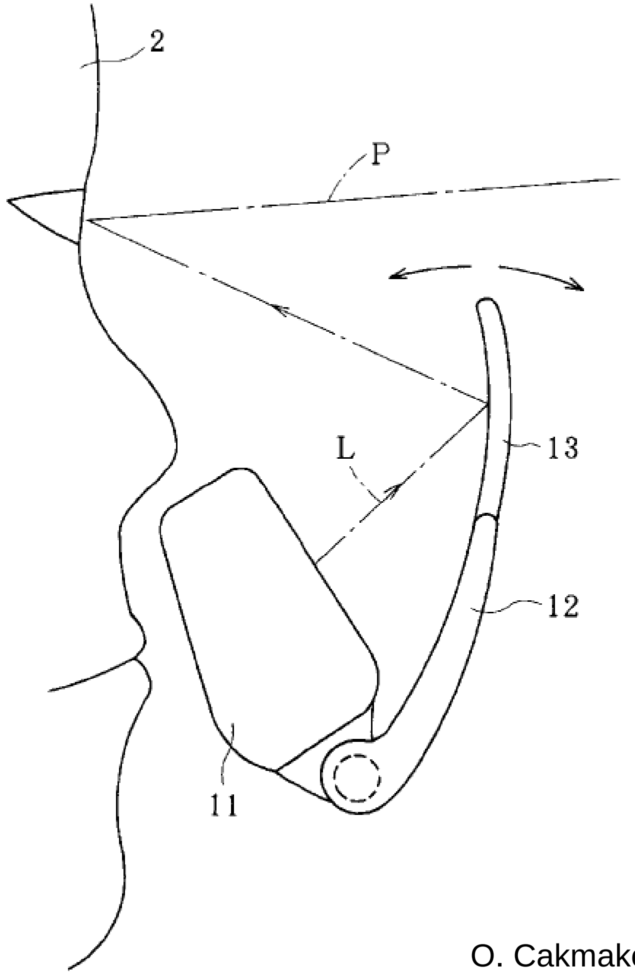
Geist. Head-mounted virtual display apparatus with near-eye deflecting element in the peripheral field-of-view.
US 6, 771,423
Aug. 3, 2004



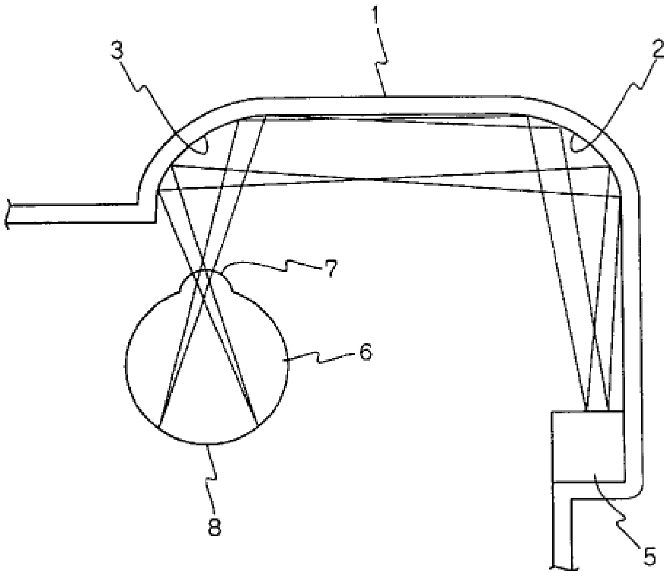
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 4 of 18)

Amafuji. Head Mounted Display Device.
US 6,359,602
Sep. 19, 2002



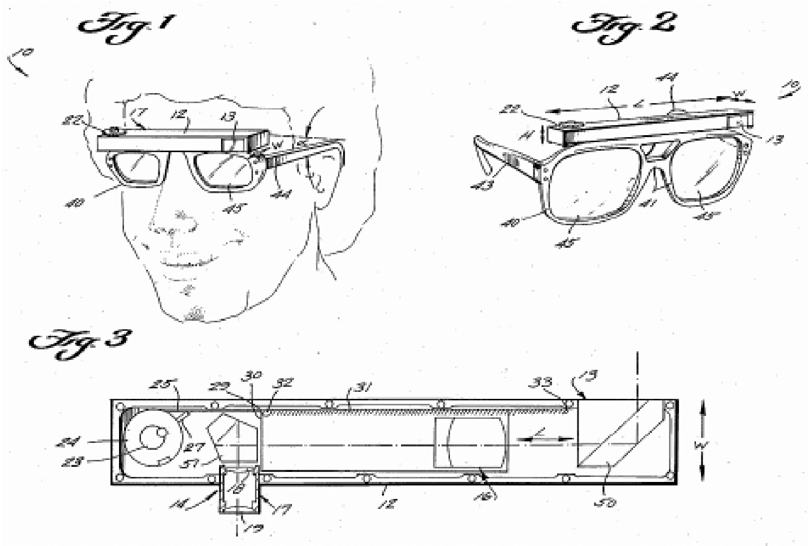
Kuriyama. Image Display Apparatus
US 6,081,304
Jun. 27, 2000



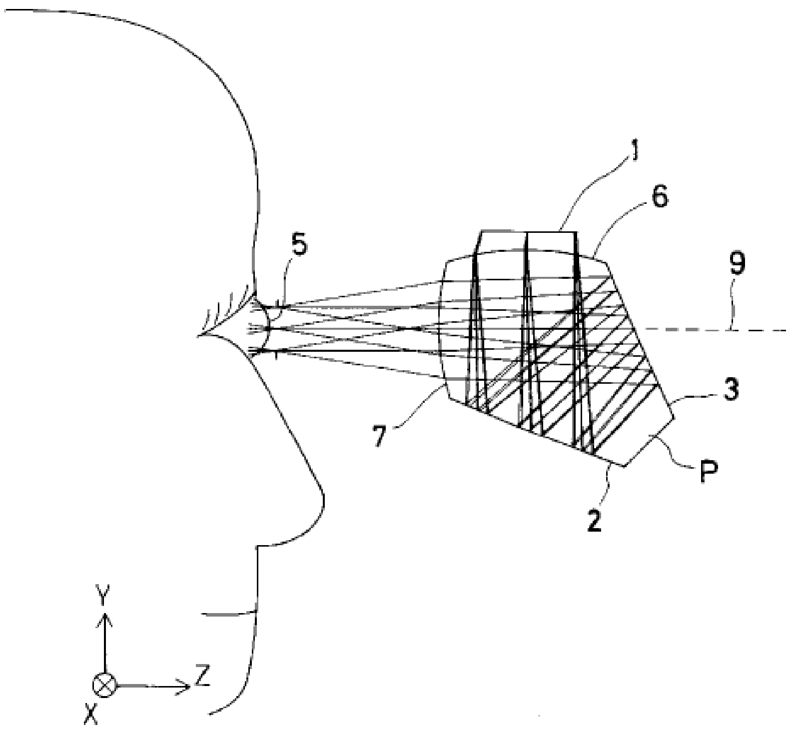
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 5 of 18)

Pekar. Vision enhancing system.
US 4,704,000
Nov. 3, 1987



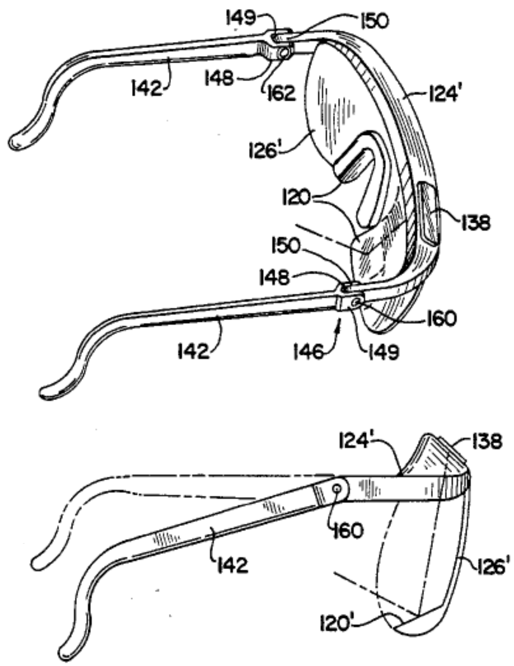
Togino. Prosm Optical System.
US 5,991,103
Nov. 23, 1999



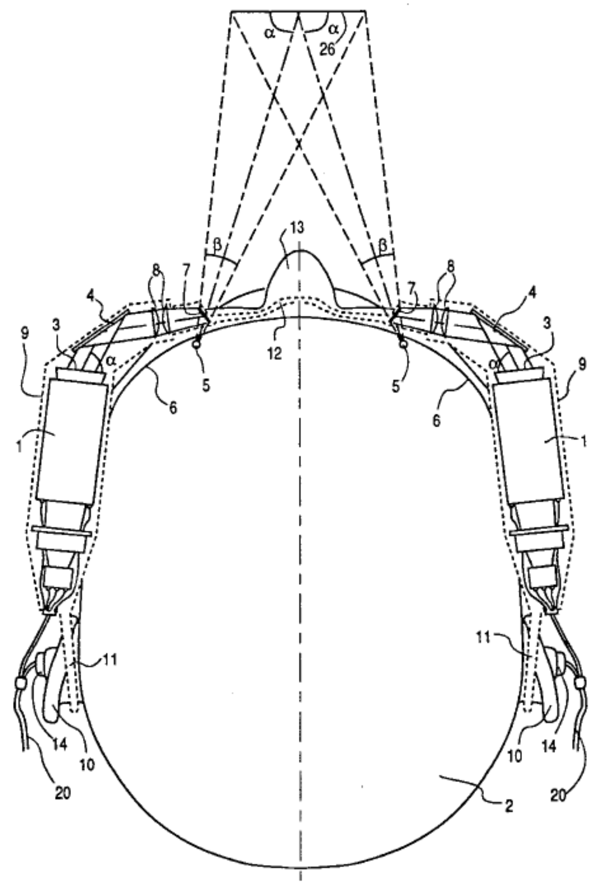
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 6 of 18)

Furness. Display System for a Head Mounted Viewing Transparency.
US 5,162,828
Nov. 10, 1982



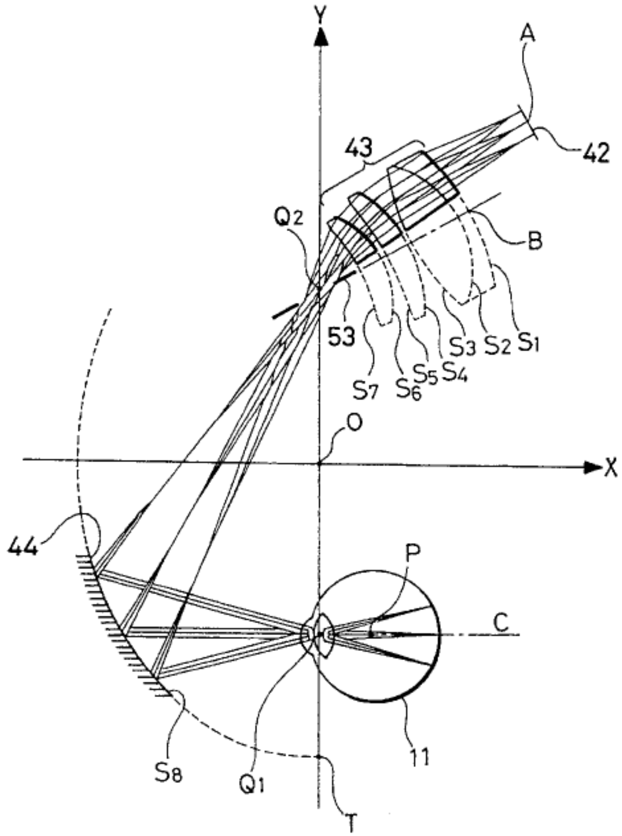
Holakovszky. Stereoscopic video image display appliance wearable on head like spectacles.
US 5,129,716
Jul. 14, 1992



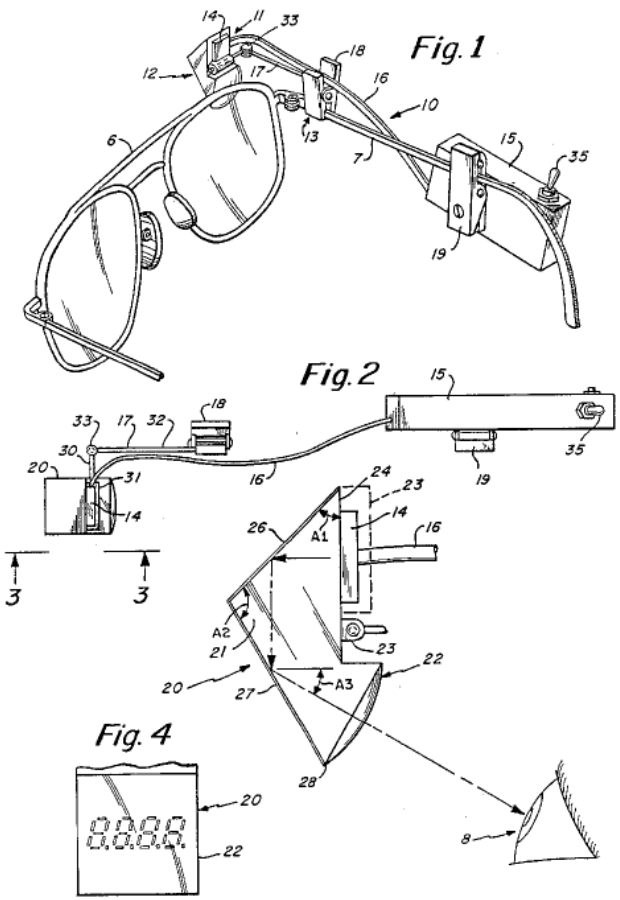
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 7 of 18)

Iba. Image Observation Device.
US 5,384,654
Jan. 24, 1995



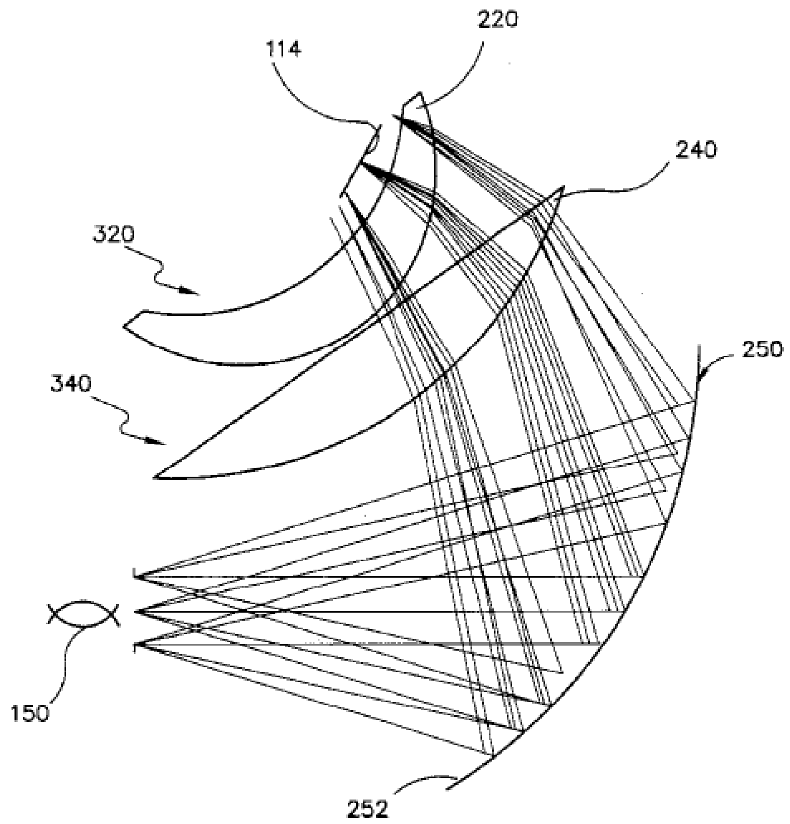
Kubik. Headwear-mounted
Periscopis Display Device.
US 4,753,514
Jun. 28, 1993



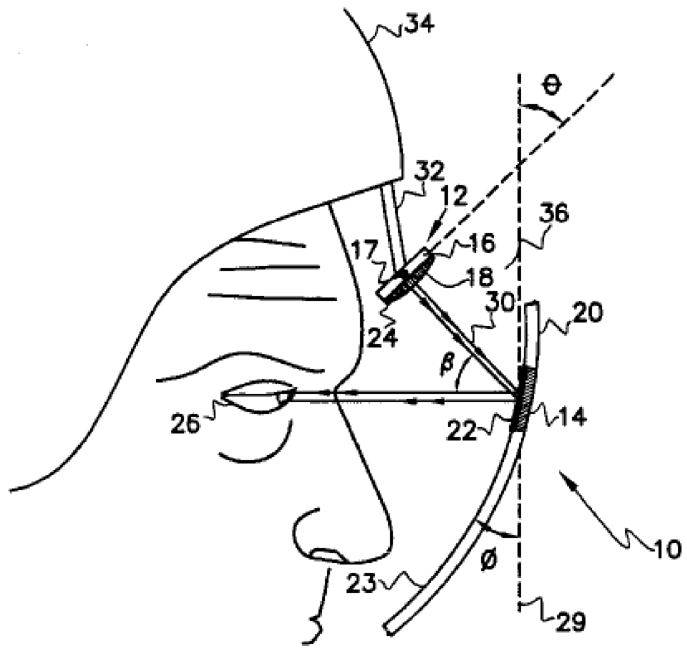
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 8 of 18)

Ferrin. Headgear Display System Using Off-axis Image Sources.
US 5,576,887
Nov. 19, 1996



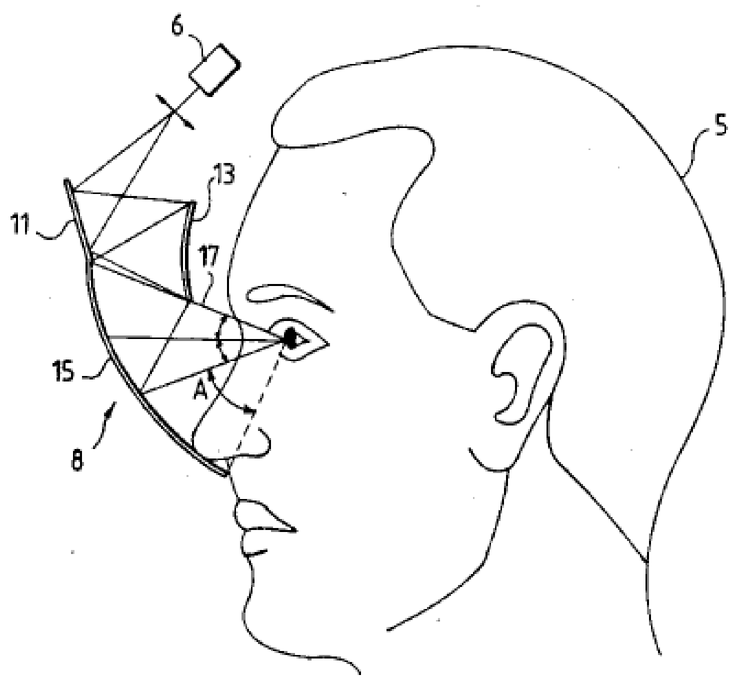
Lippert. Visor Display with Fiber Optic Faceplate Correction.
US 5,309,169
May 3, 1994



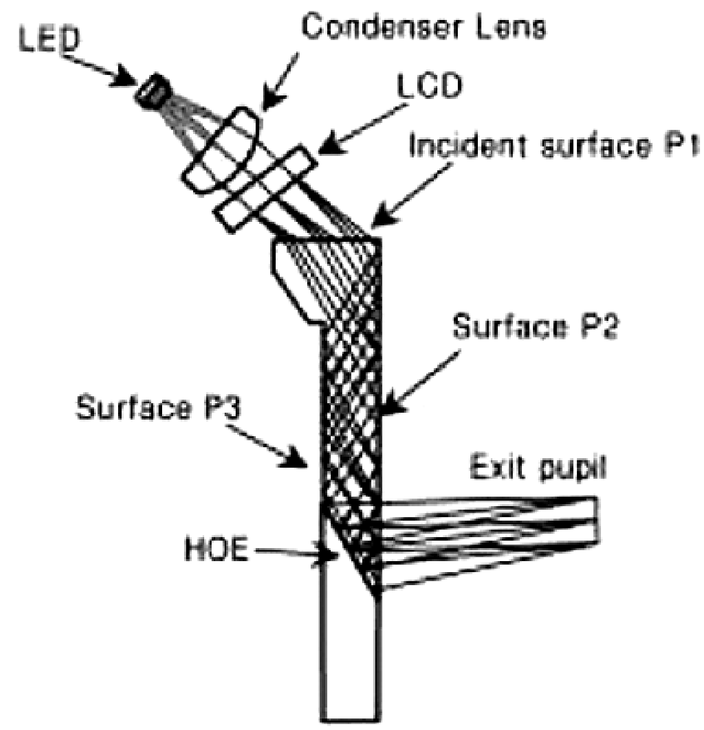
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 9 of 18)

Lacroix. Device for the Display of Simulated Images for Helmets.
US 5,184,250
Feb. 2, 1993



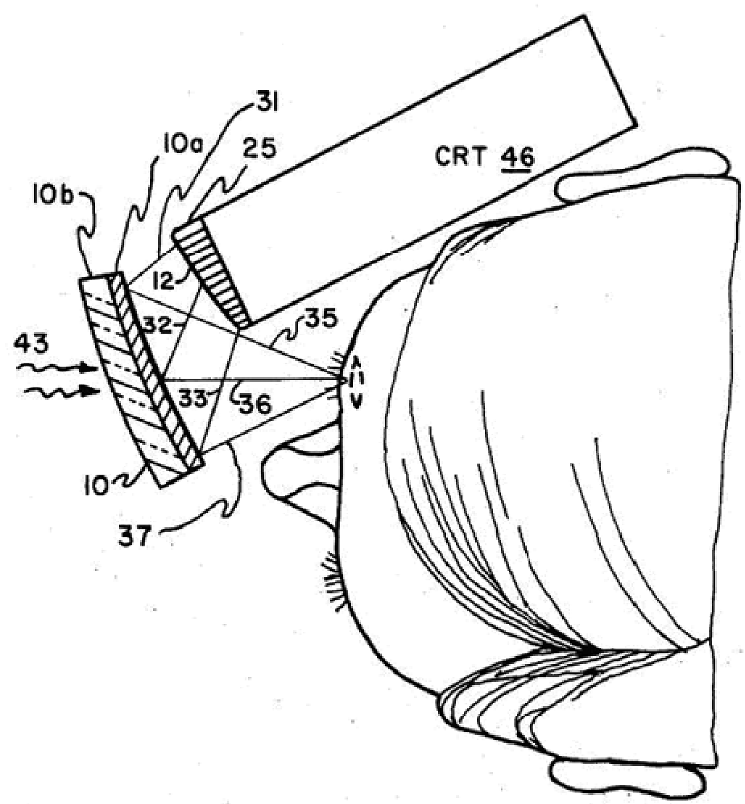
Kasai. A Forgettable Near-Eye Display.
ISWC 2000



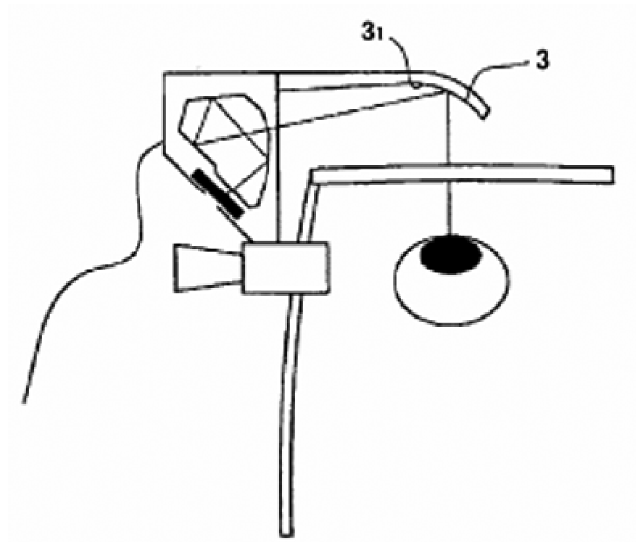
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 10 of 18)

Bosserman. Toric reflector display.
US 4,026,641
May 31, 1977



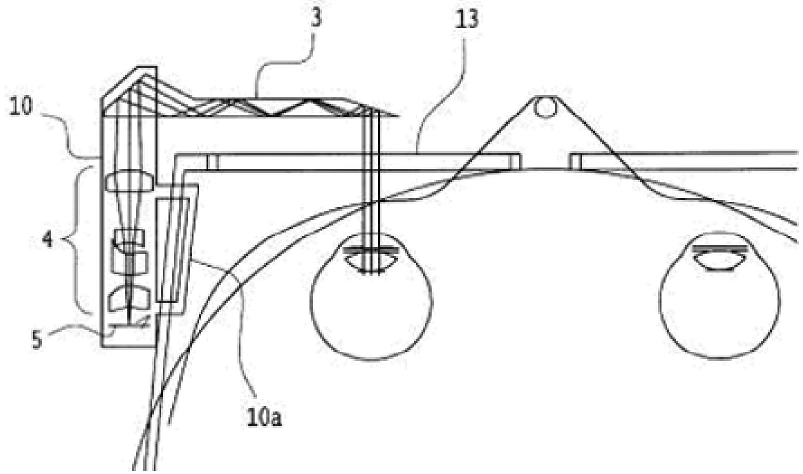
Nagaoka. Light weight head mounted image display device.
US 6,697,200
Feb. 24, 2004



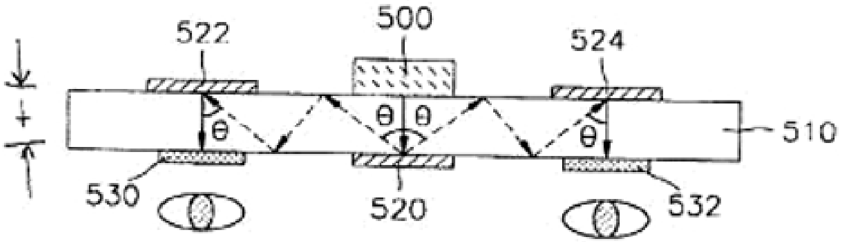
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 11 of 18)

Takeyama. Observation optical system.
US 6,710,902
Mar. 23, 2004



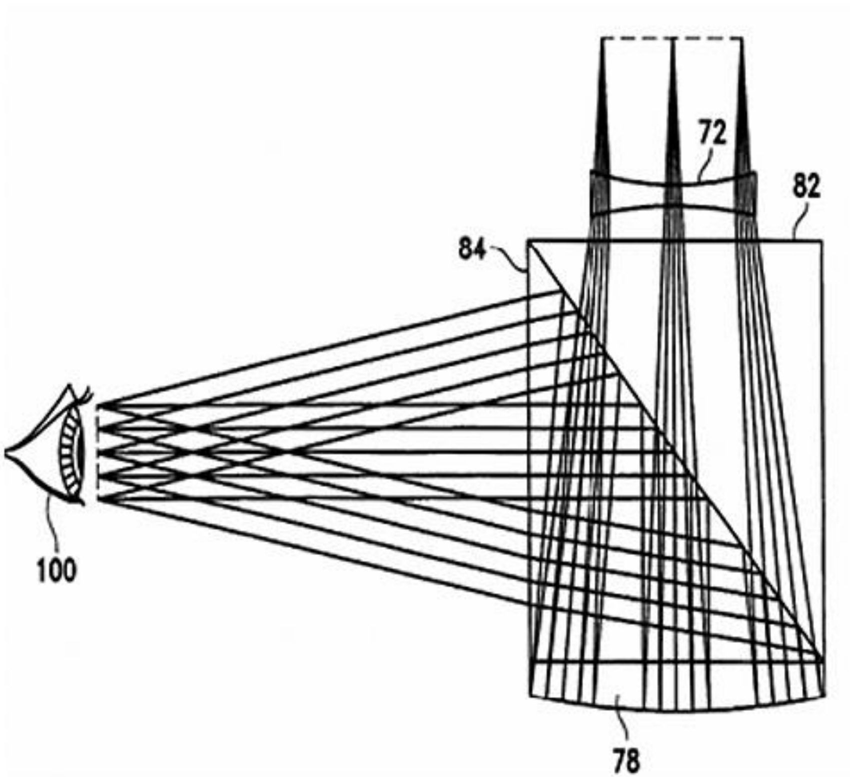
Song. Wearable display system.
US 6,882,479
Apr. 19, 2005



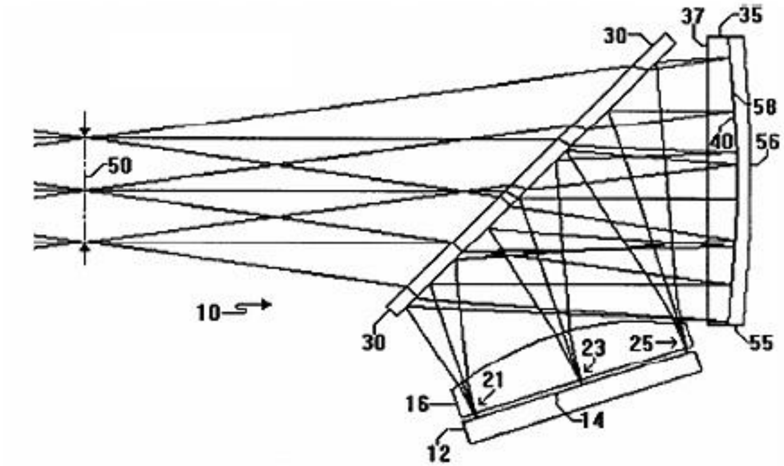
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 12 of 18)

Robinson. Video headset.
US 5,696,521
Dec. 9, 1997



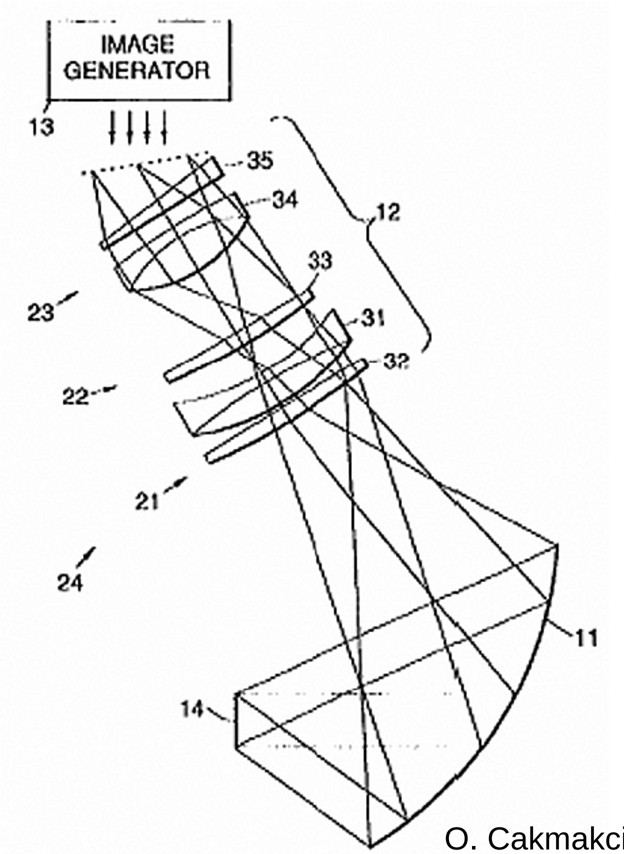
Fritz. Head mounted display
using mangin mirror combiner.
US 5,838,490



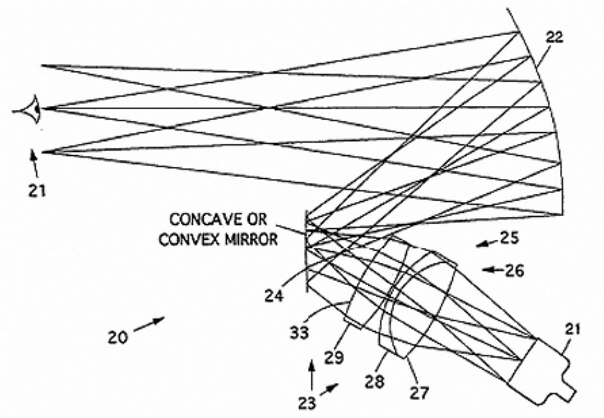
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 13 of 18)

Chen. Helmet visor display employing reflective, refractive and diffractive optical components
US 5,526,183
Jun. 11, 1996



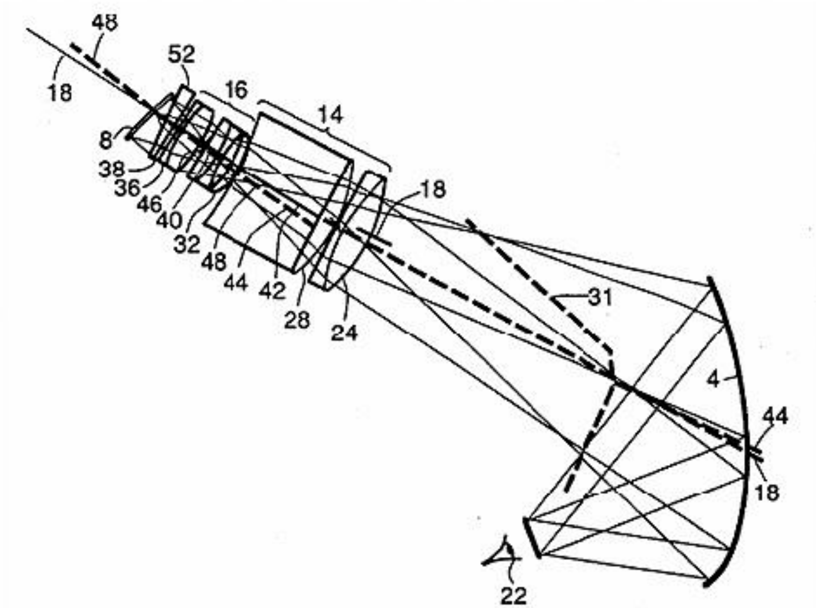
Chen. Wide spectral bandwidth virtual image display system.
US 5,436,763
Jul. 25, 1995



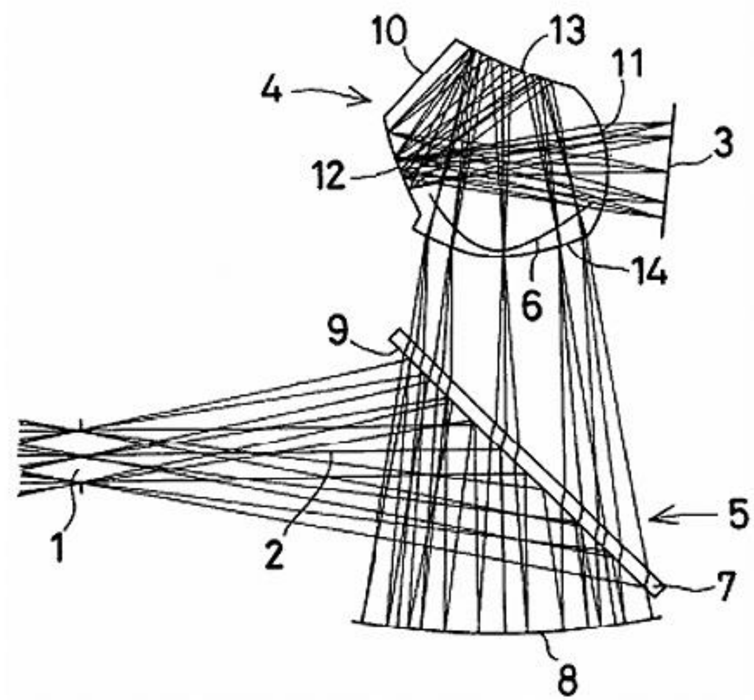
O. Cakmakci, et al., “Head-Worn Displays: A Review,” J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 14 of 18)

Chen. Ultra-wide field of view, broad spectral band visor display optical system.
US 5,499,139
Mar. 12, 1996



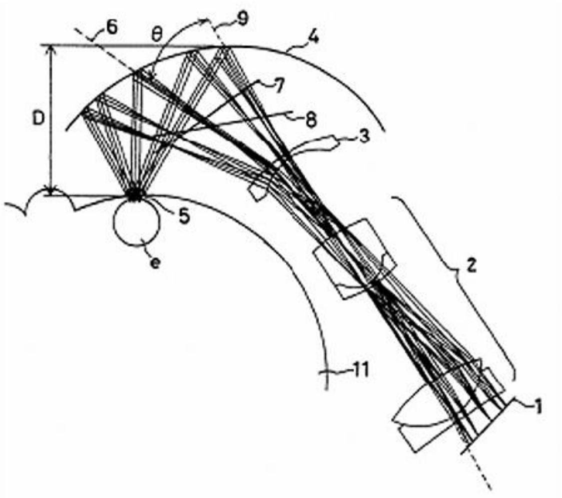
Takeyama. Image display apparatus.
US 6,342,871
Jan. 29, 2002



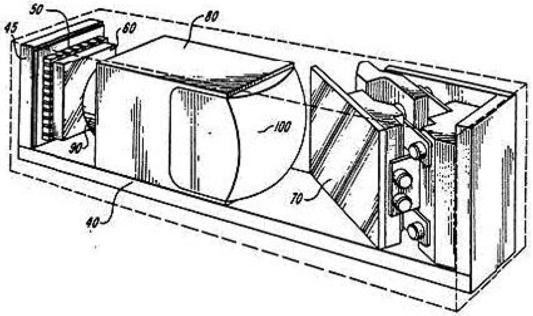
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 15 of 18)

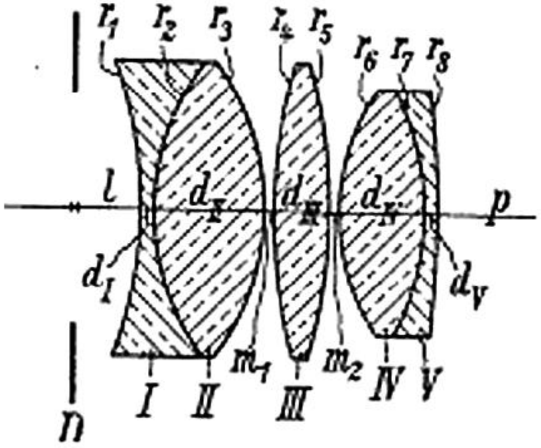
Togino. Visual display apparatus
US 5,436,765
Jul. 25, 1995



Becker. Head Mounted Display for
Minian Video Display System.
US 5,003,300
Mar. 26, 1991



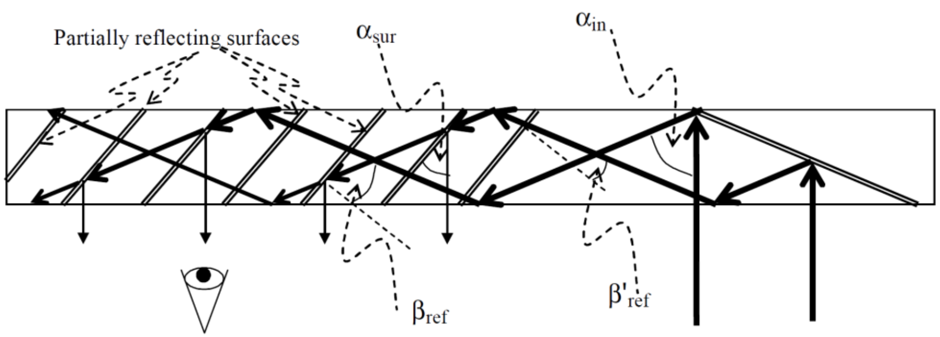
Erfle. Ocular.
US 1,478,704
Dec. 25, 1923

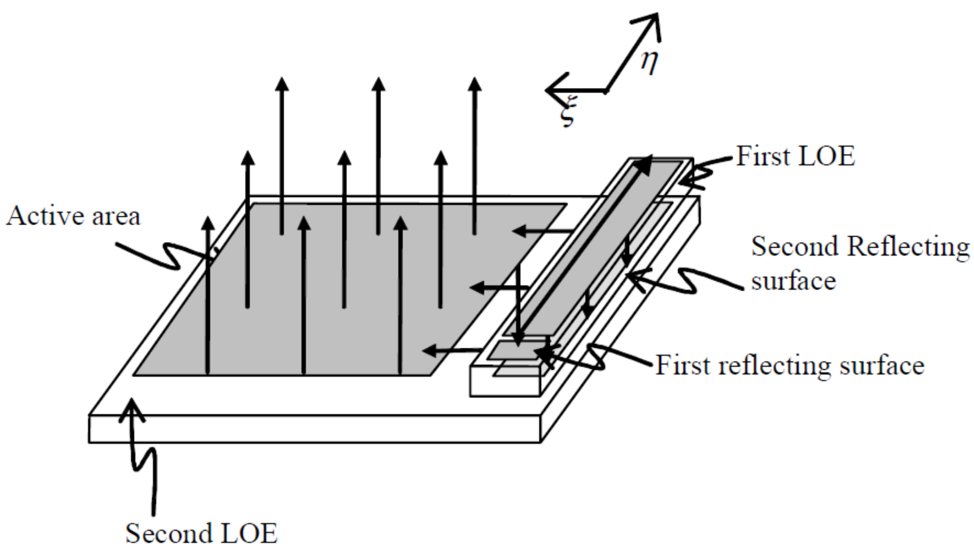


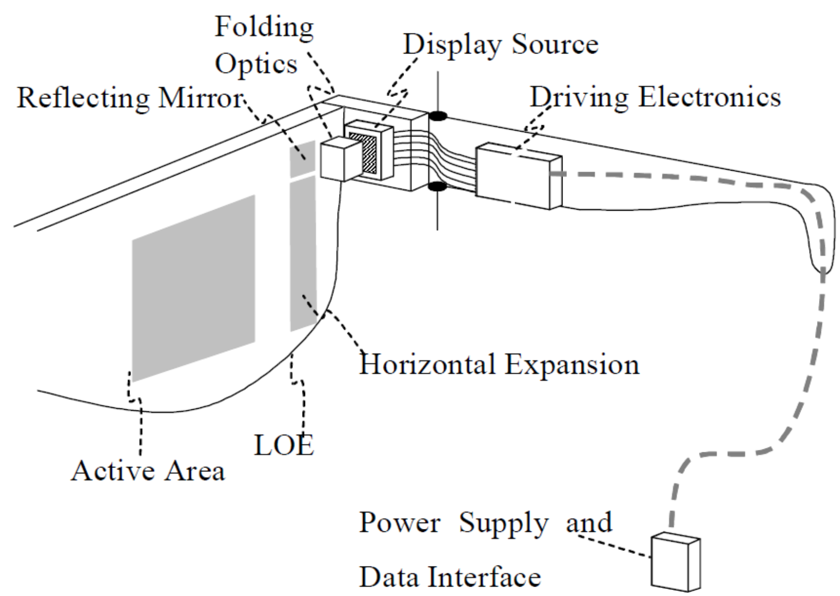
O. Cakmakci, et al., "Head-Worn Displays: A Review," J. Disp. Tech. 2, 199, 2006

HWD Examples (Slide 16 of 18)

Waveguide with Cascaded Mirror-Array (Lumus)



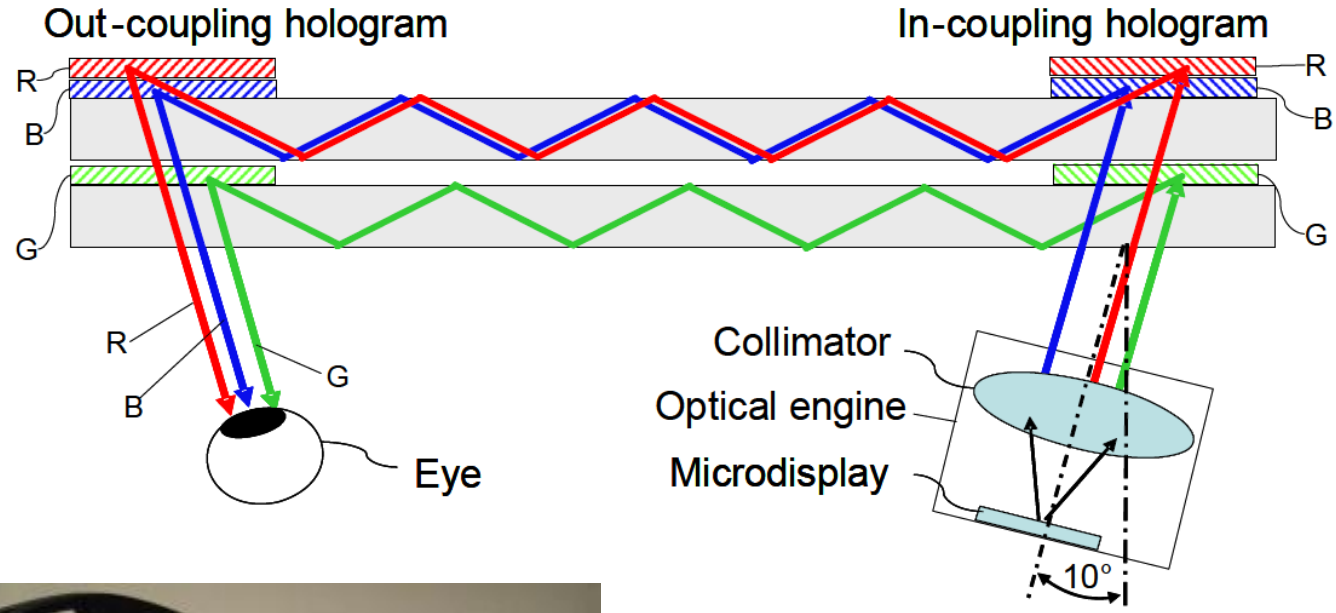




Y. Amitai, SID Symposium Digest of Technical Papers, 2005

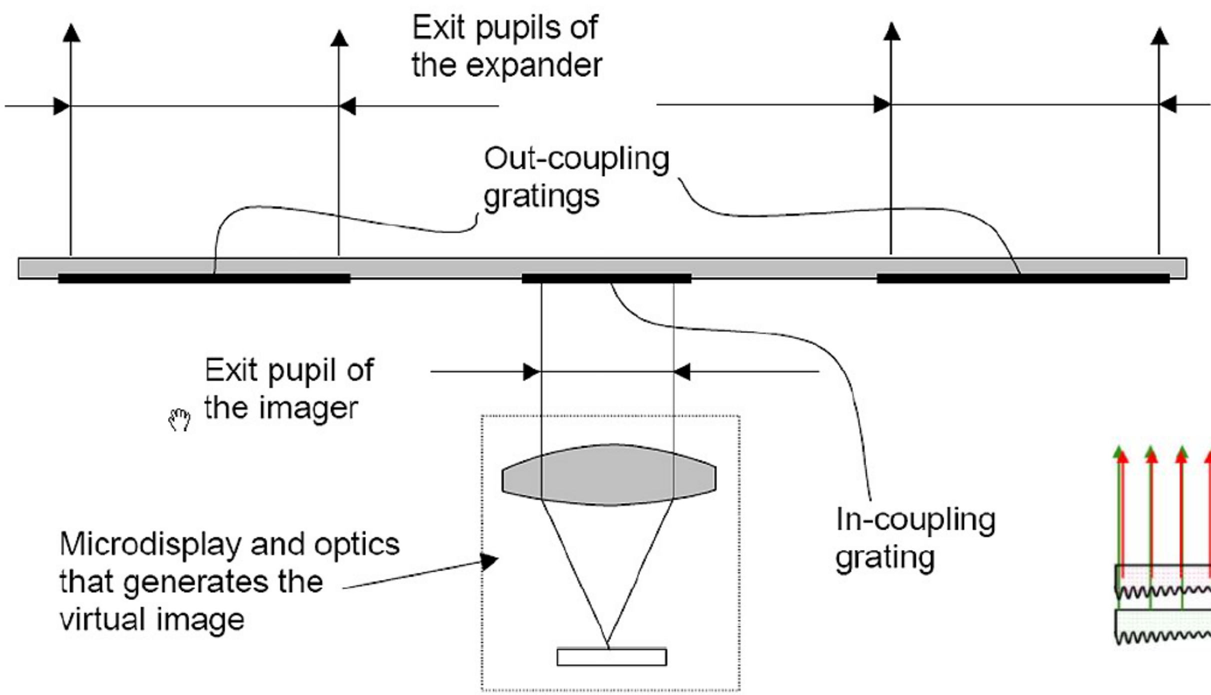
HWD Examples (Slide 17 of 18)

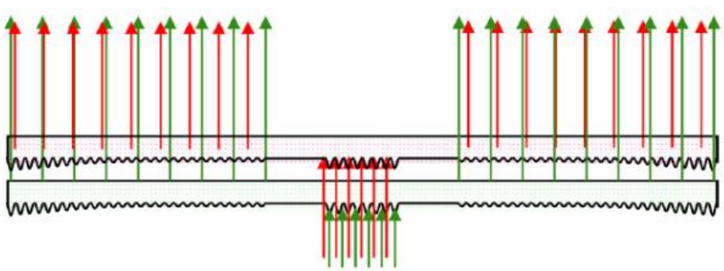
Holographic Planar Waveguide (Sony)



H. Mukawa, et al., SID Symposium Digest of Technical Papers, 2008

HWD Examples (Slide 18 of 18)
Diffractive Waveguide (Nokia, Vuzix)

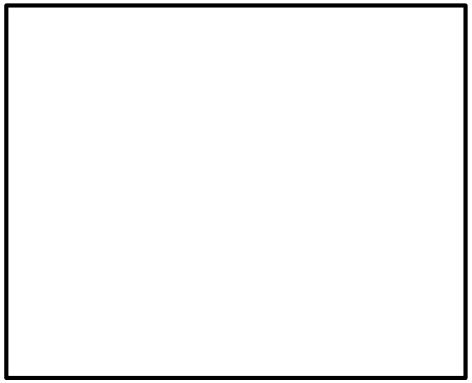




T. Levola, Journal of the SID 14/5, 2006

The Origin of Screen-door Effect (SDE)

Ideal white image



Actual White image in VR

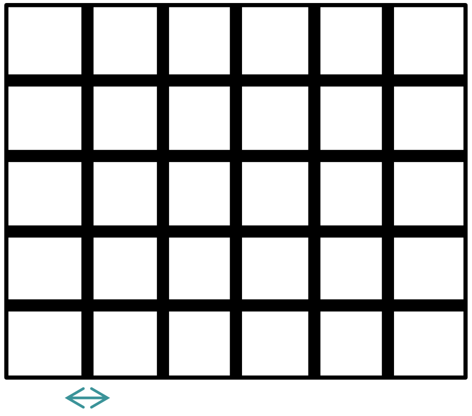
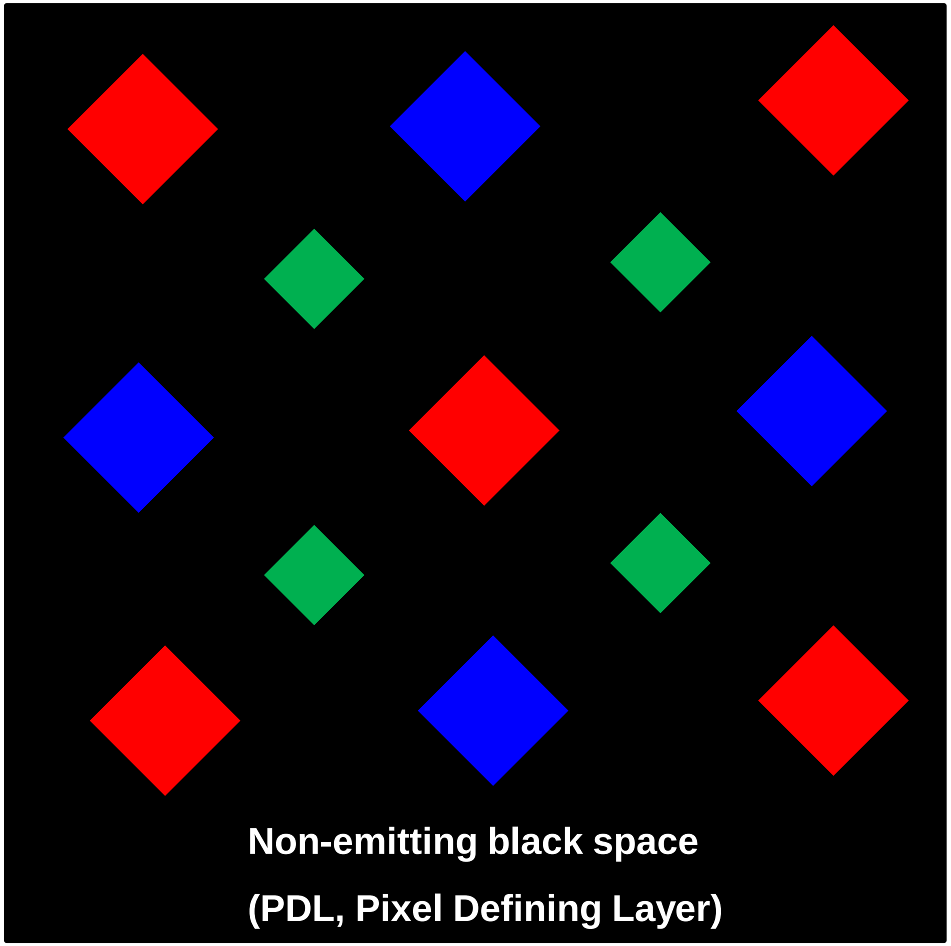
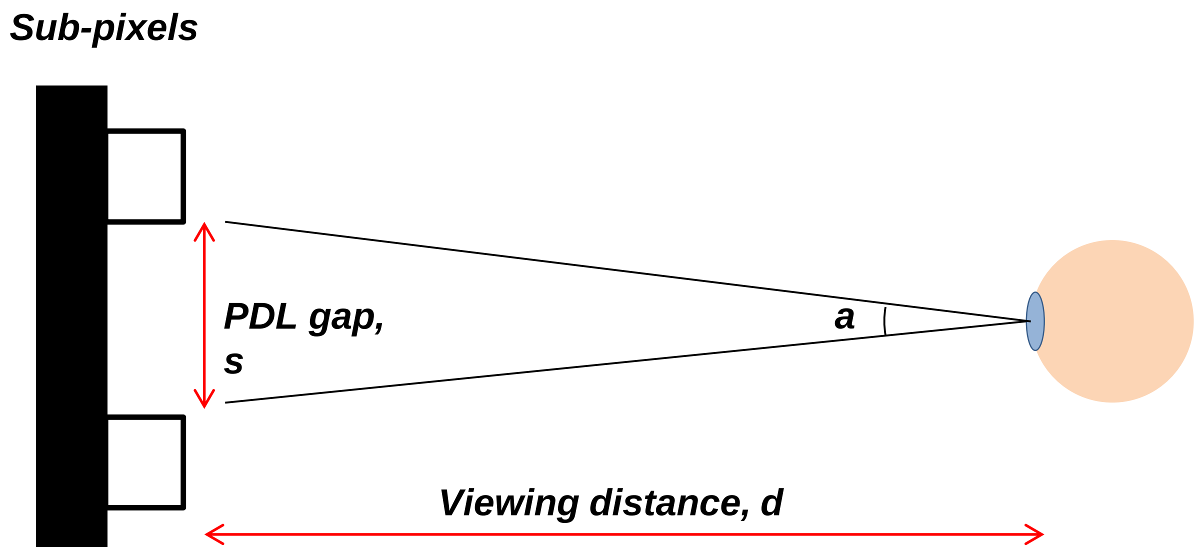


Illustration of typical OLED pixel structure



Reducing non-emitting area or increasing open aspect ratio is possible solution for SDE

Required display specification for "SDE-free"

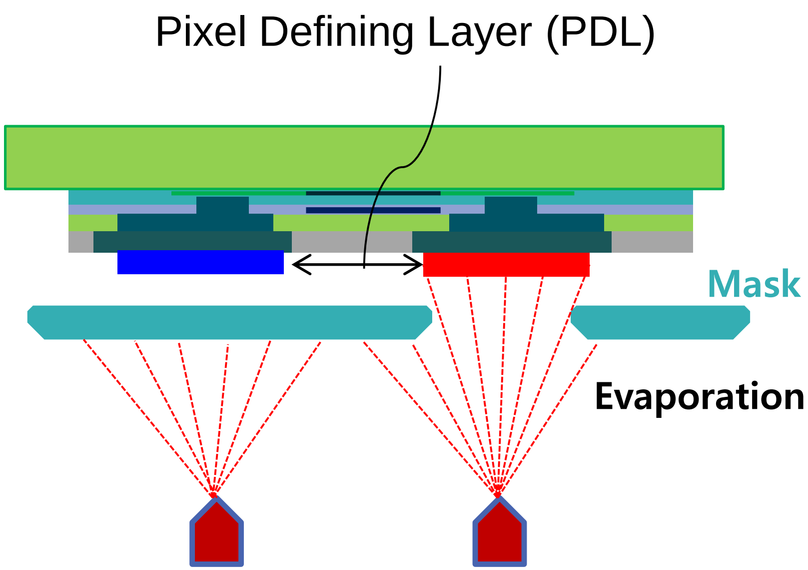


$$\tan\left(\frac{a}{2}\right) = \frac{s}{2d}$$

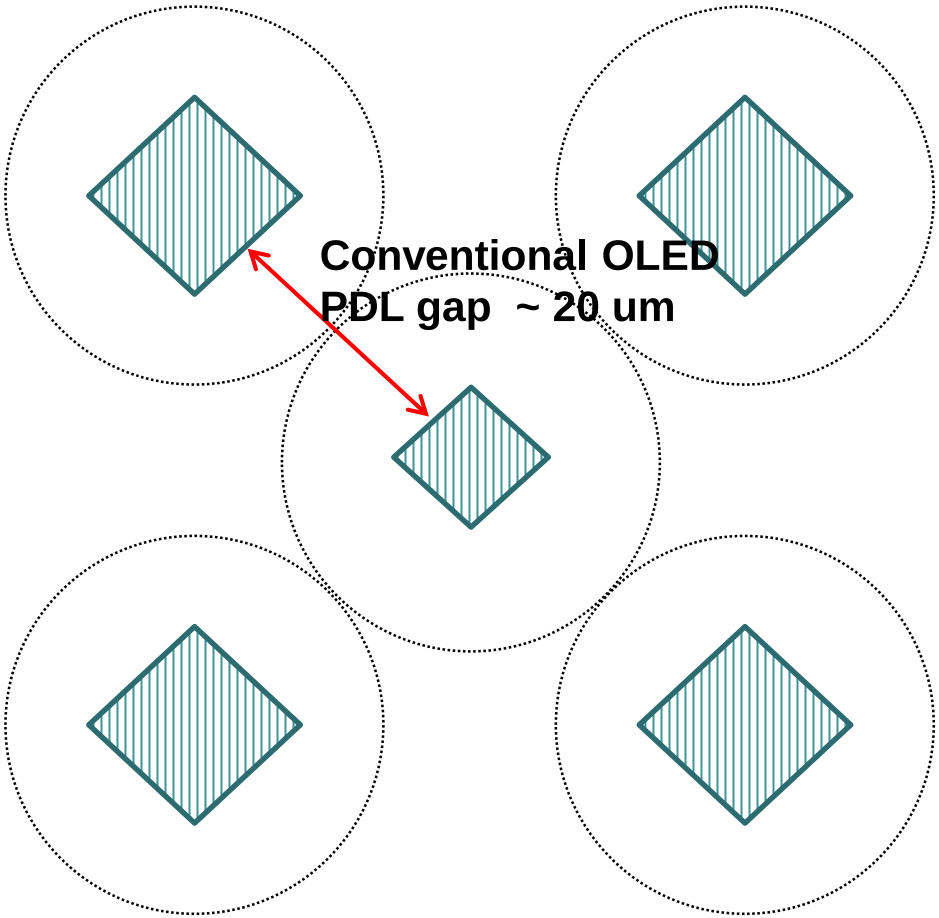
For 20/20 (foot), 6/6 (metre), 1.0 (decimal) vision acuity

s **= 11.6 um** is required for SDE-free

Physical limitation for reducing SDE in OLED

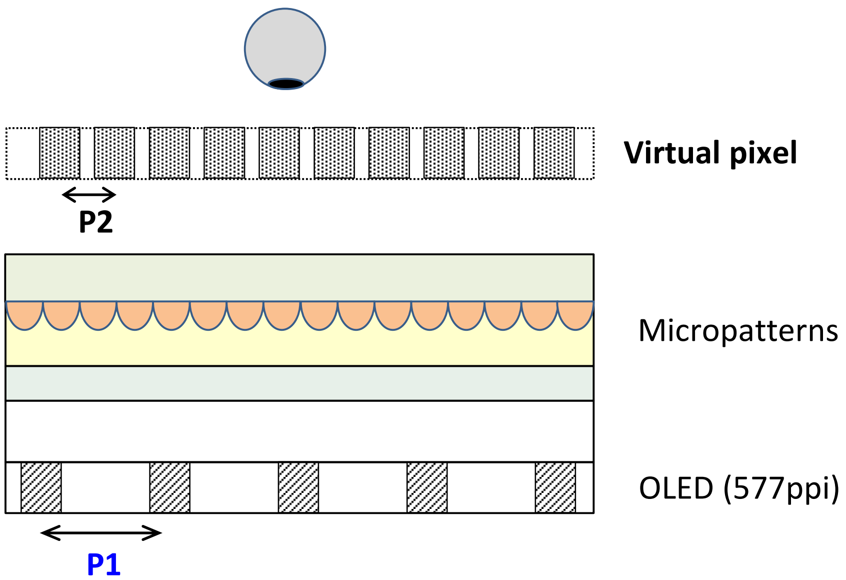


PDL gap defined by evaporation of OLED source material

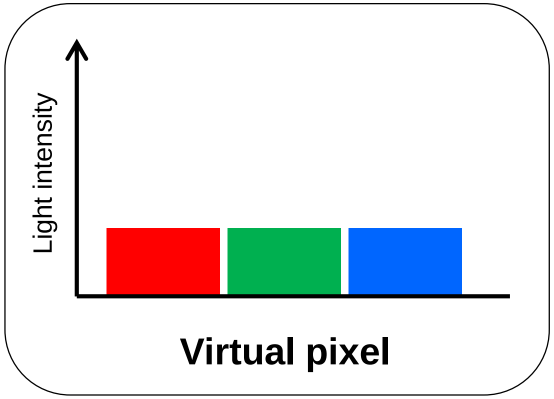


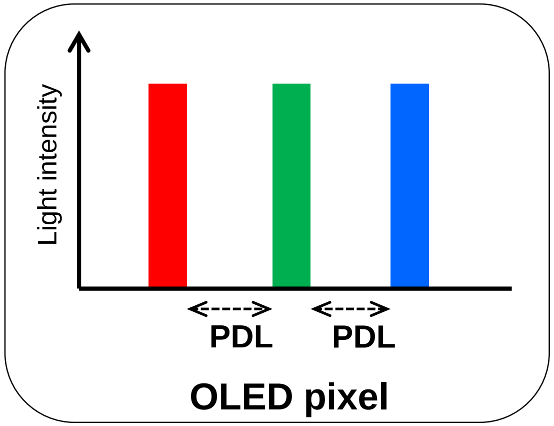
- ❑ PDL gap under 12 um is very challenging due to the limitation of evaporation method.
- ❑ If small PDL gap is achieved, consumption power and production cost will increase.

OLED with a diffraction grating layer



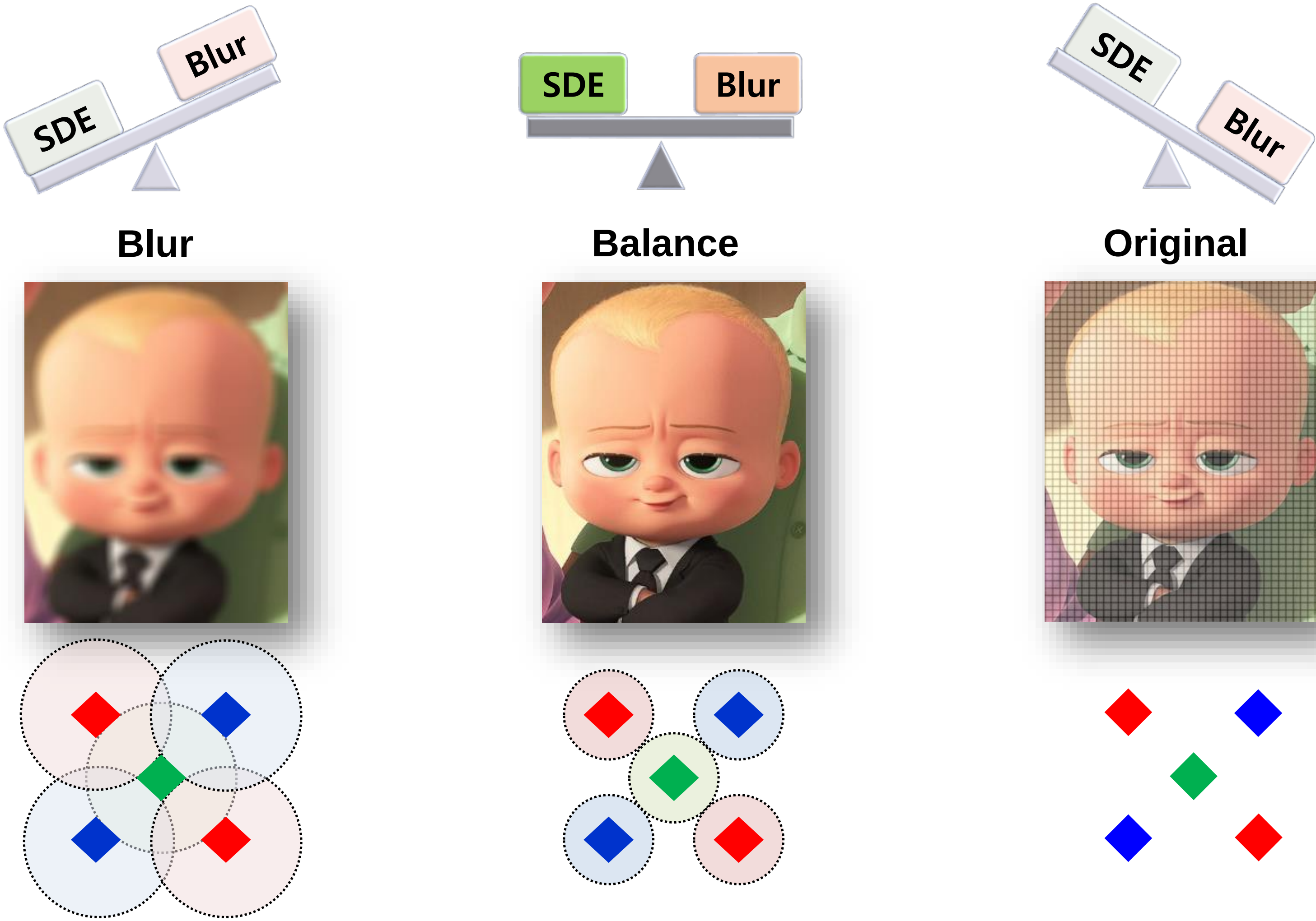
Micropattern can be specifically designed based on panel information (thickness, refractive index, pixel pitch)





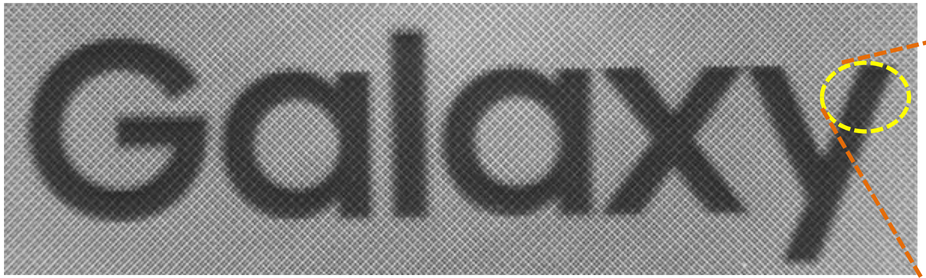
Open aspect ratio of OLED can increase by optical diffusion of pixel light (PDL gap virtually decreases)

SDE mitigation and its side effect (blur)

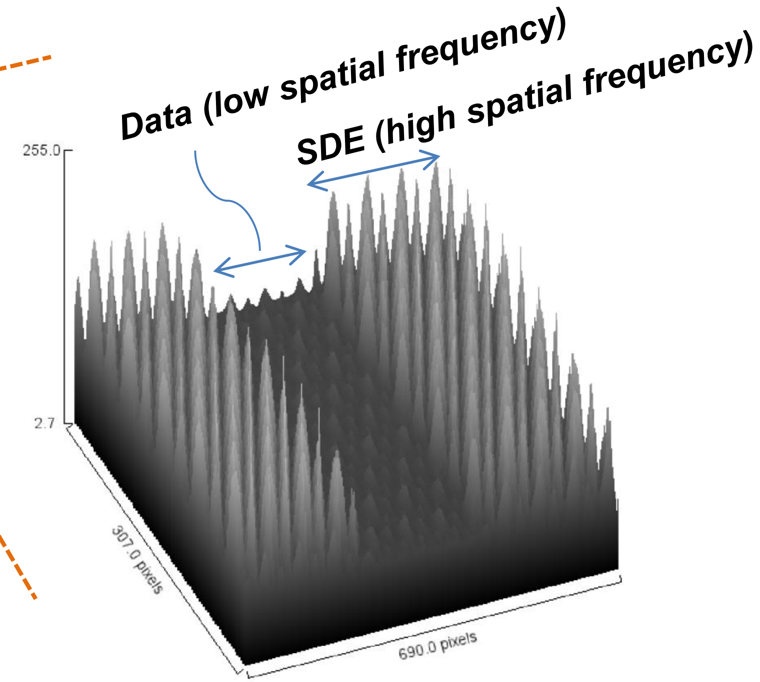


Optimization between SDE mitigation and blur is critical to develop solution. Therefore, a quantitative evaluation tool is required.

Quantitative analysis method for SDE and blur



Bare OLED screen showing SDE



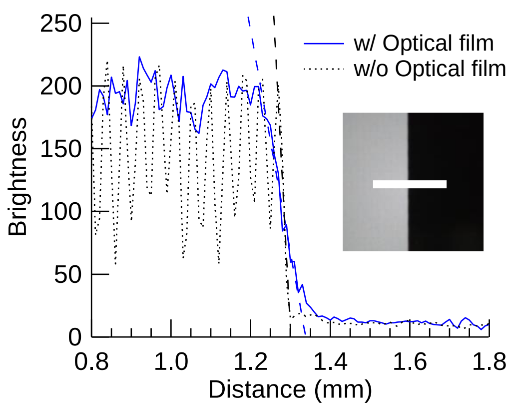
1) SDE estimation (SDE Index)

SDE Index

$$= \frac{\sum \text{High order spatial frequency power (SDE)}}{\text{Zero order spatial frequency power (Data)}}$$

(By 2D Fourier Transform)

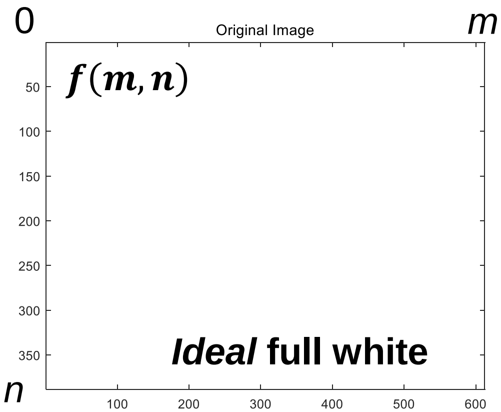
2) Blur estimation



Slope at the edge between black and white

SDE analysis by 2D Fourier transform

Image space

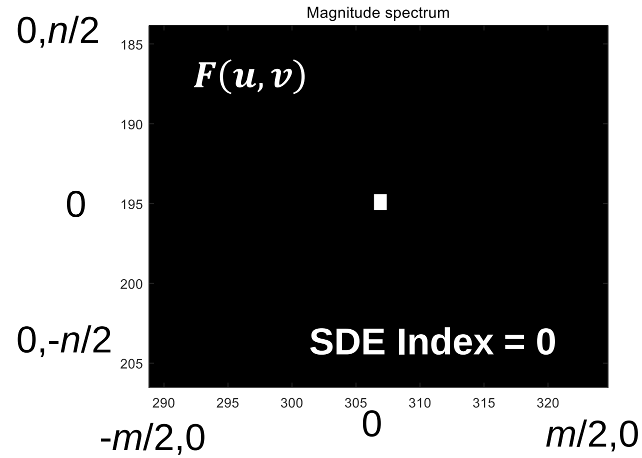


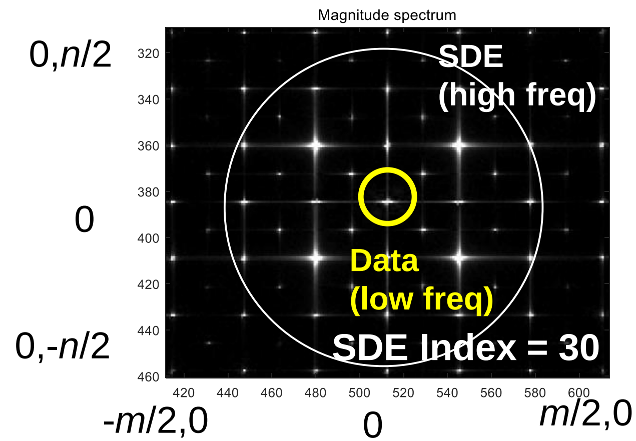
2D FFT

$$F(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)e^{j2\pi(ux+uy)}dxdy$$

Magnitude of (u,v) = frequency
Direction of (u,v) = orientation

Frequency space

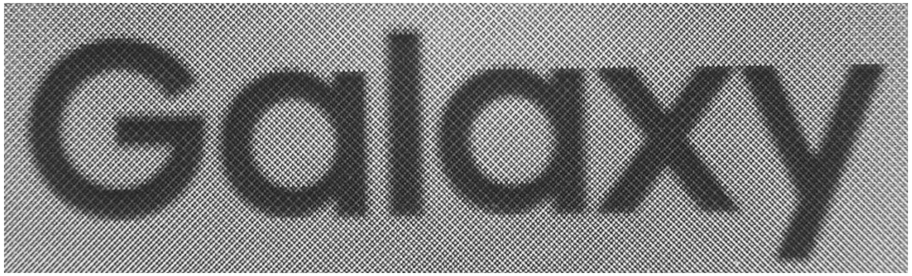




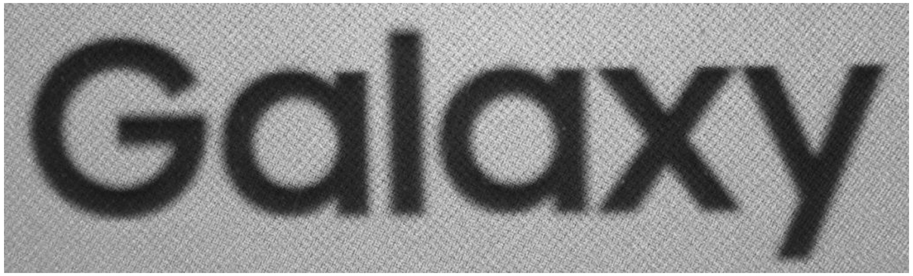
$$\text{SDE Index} = \frac{\sum \text{High order spatial frequency power (SDE)}}{\text{Zero order spatial frequency power (Data)}}$$

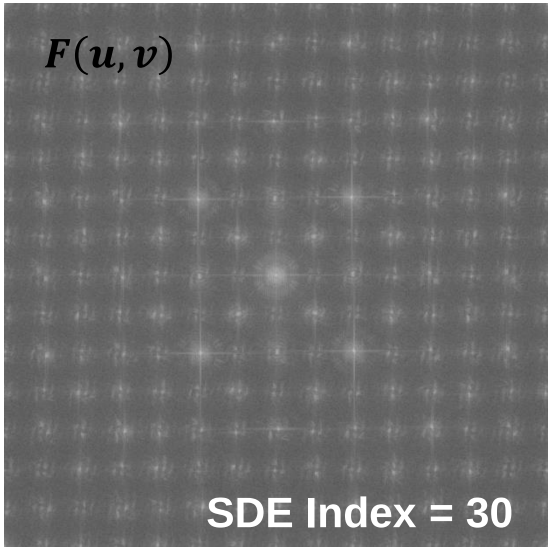
Evaluation of SDE mitigation

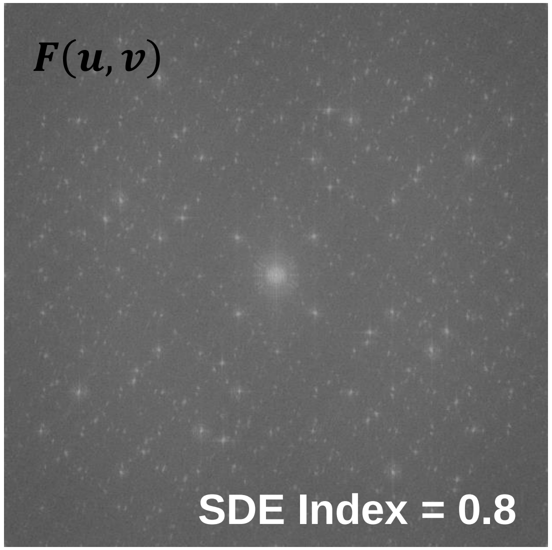
w/o Optical layer



w/ Optical layer



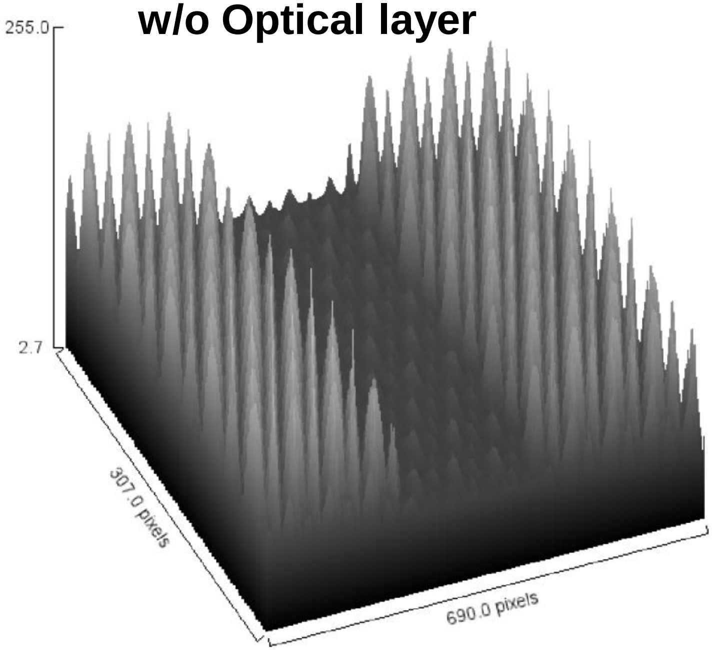




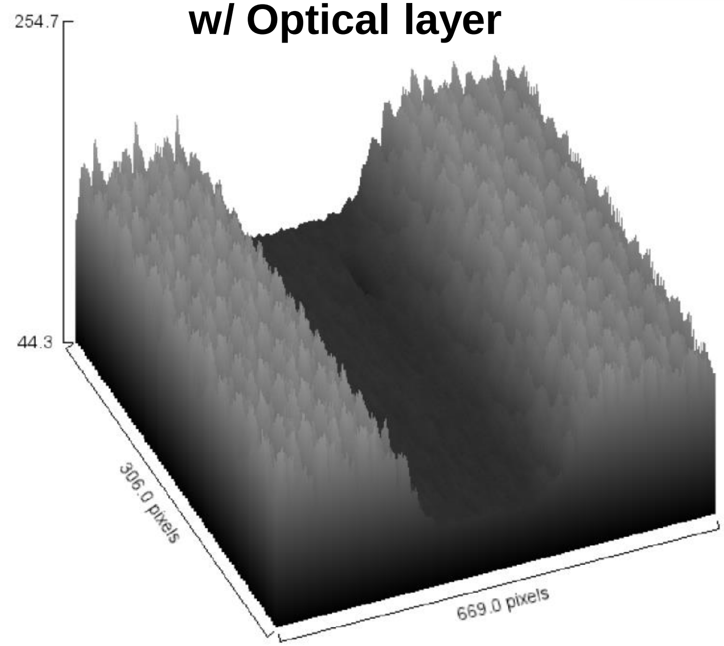
- ❑ SDE mitigation can be visually and quantitatively analyzed by 2D FFT.
- ❑ It reveals that adding a diffraction grating layer into OLED display is effective for reducing SDE in VR.

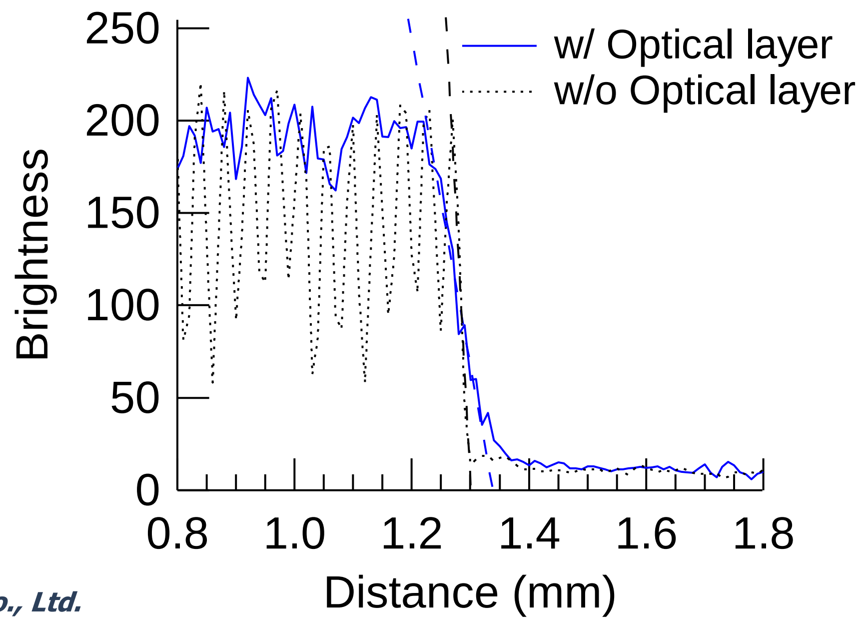
Estimation of blur

w/o Optical layer



w/ Optical layer





Sharpness index

$$= \frac{\Delta \text{Brightness}}{\Delta \text{Pixels}}$$