

Lecture 10: Display and Lighting Systems

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Computer Imaging & Graphics

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Display and Camera

Modeling and Rendering

Sources of Color

Display and Lighting

Photographic Optics

Image Sensor

Image Signal Processing

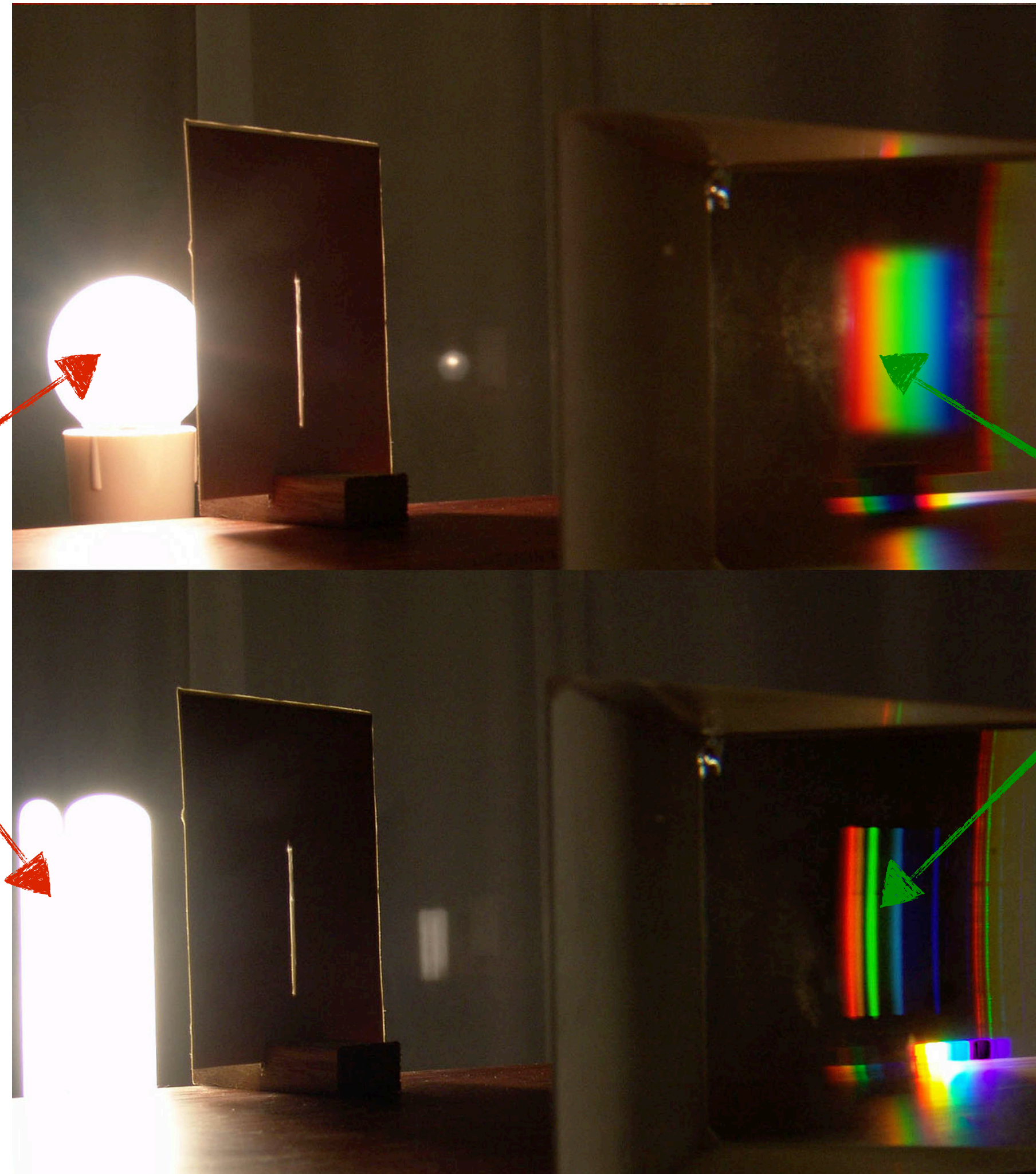
Image/Video Compression

Immersive Content

Display vs. Lighting

Apparent Color vs. Spectrum

The two lights have similar
apparent color, but are
they the same light?

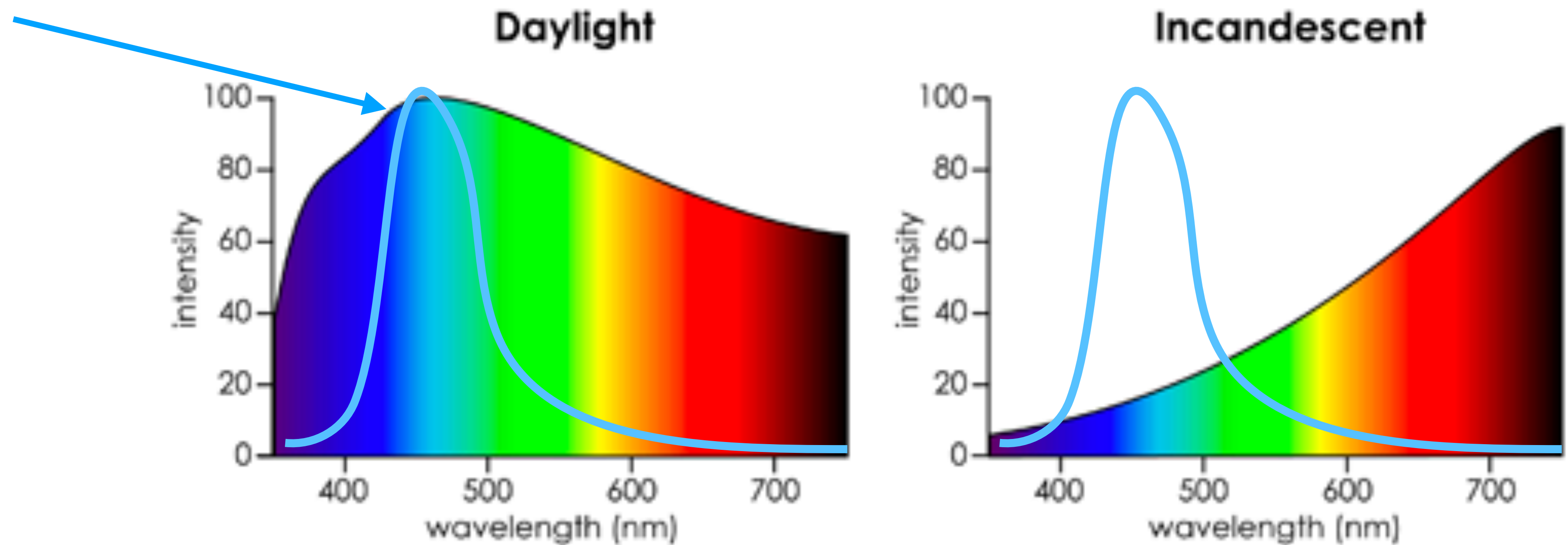


No! Lights with the
same apparent color
could have very
different spectra.

Do Spectra Ever Matter?

Assuming these two lights are metamers, which one is better at “revealing the color” of the object with the given spectral reflectance?

Reflectance spectrum
of the object



Do Spectra Ever Matter?

To reveal the “true color” of an object, the light source needs to emit wavelengths that the object reflects.

Of course there is nothing called “true color”. What’s the objective reality is the reflectance spectrum of the object.

But we do have a common color perception of an object, and that perception is obtained/formed with respect to a typical lighting under which the object is usually viewed.

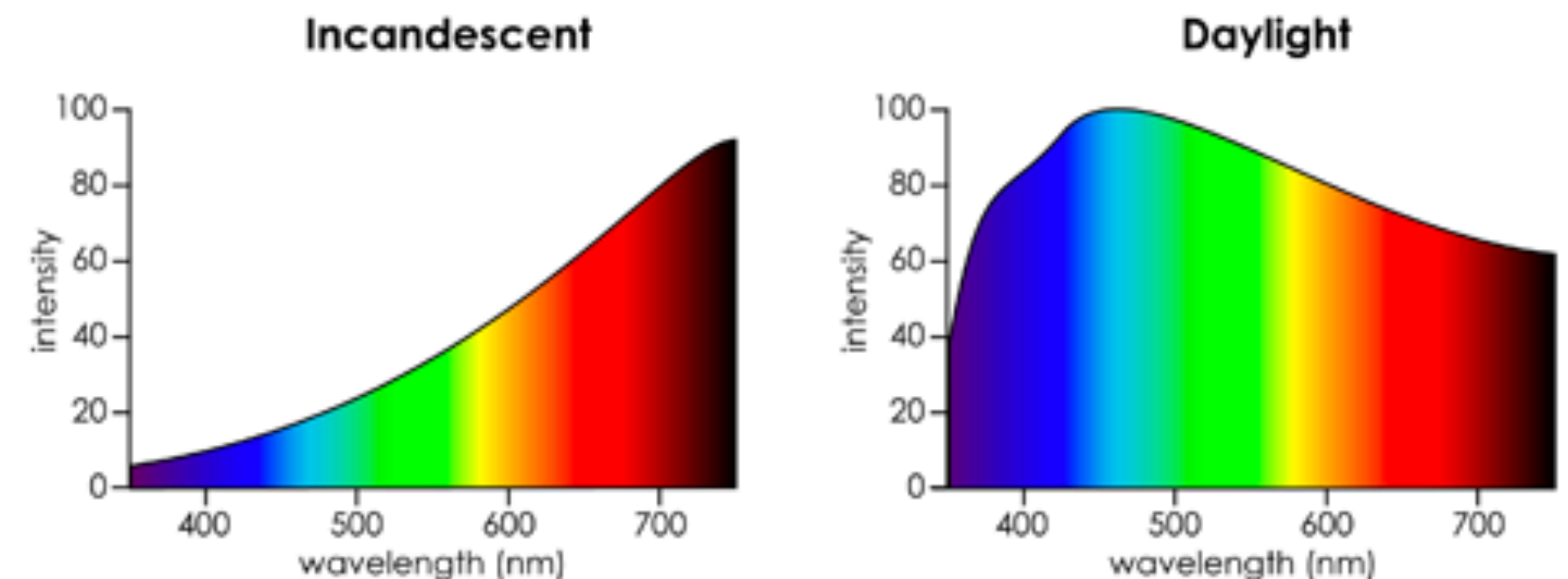
Color Rendering

Color rendering concerns with the ability of a light source to reveal the “true color” of an object, which is the color of an object under a “reference” light.

- The choice of reference light is somewhat arbitrary, but it’s generally white, e.g., daylight.

The reference light is:

- A blackbody radiation (some form of **incandescent** light) when CCT is below 5000K.
- A standard illuminant D (some form of **daylight**) when CCT is above 5000K.

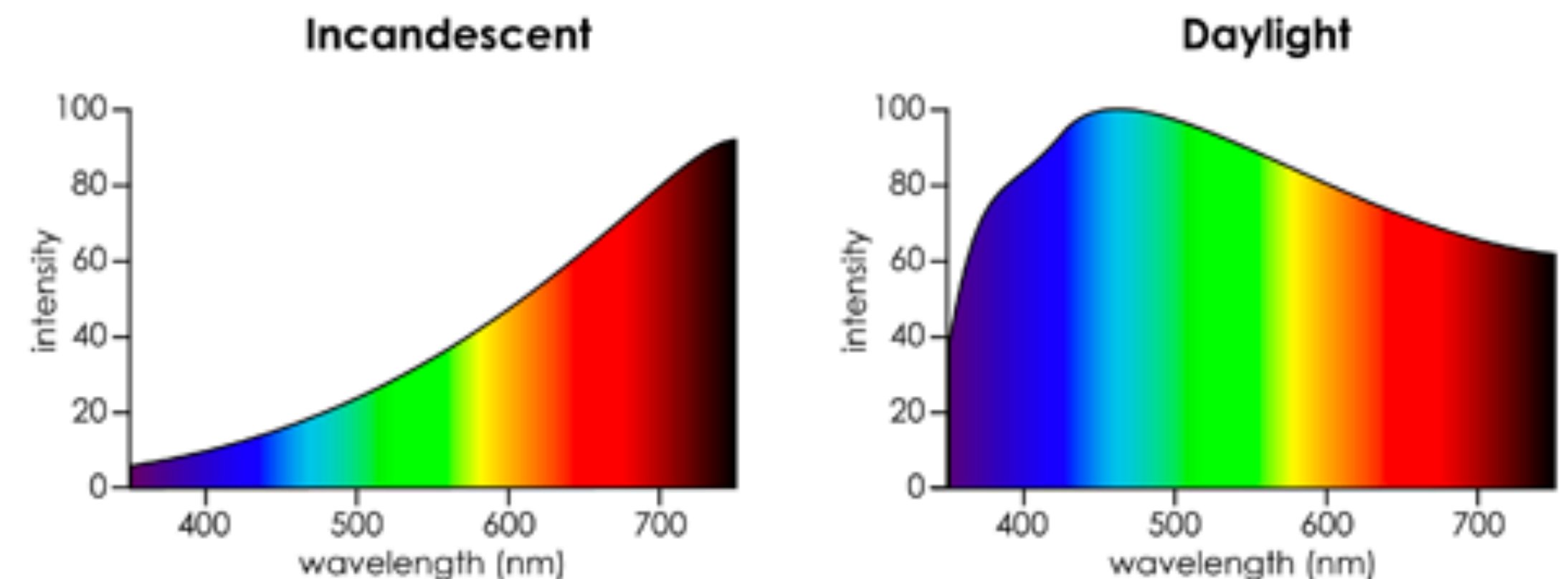


Color Rendering Index (CRI)

A metric standardized by CIE.

CRI quantifies the coloring rendering capability of a given light source w.r.t., a **reference** light under the same correlated color temperature.

- CRI is defined only for light sources that are approximate white, i.e., the chromaticity distance to the Planckian locus is below a threshold.

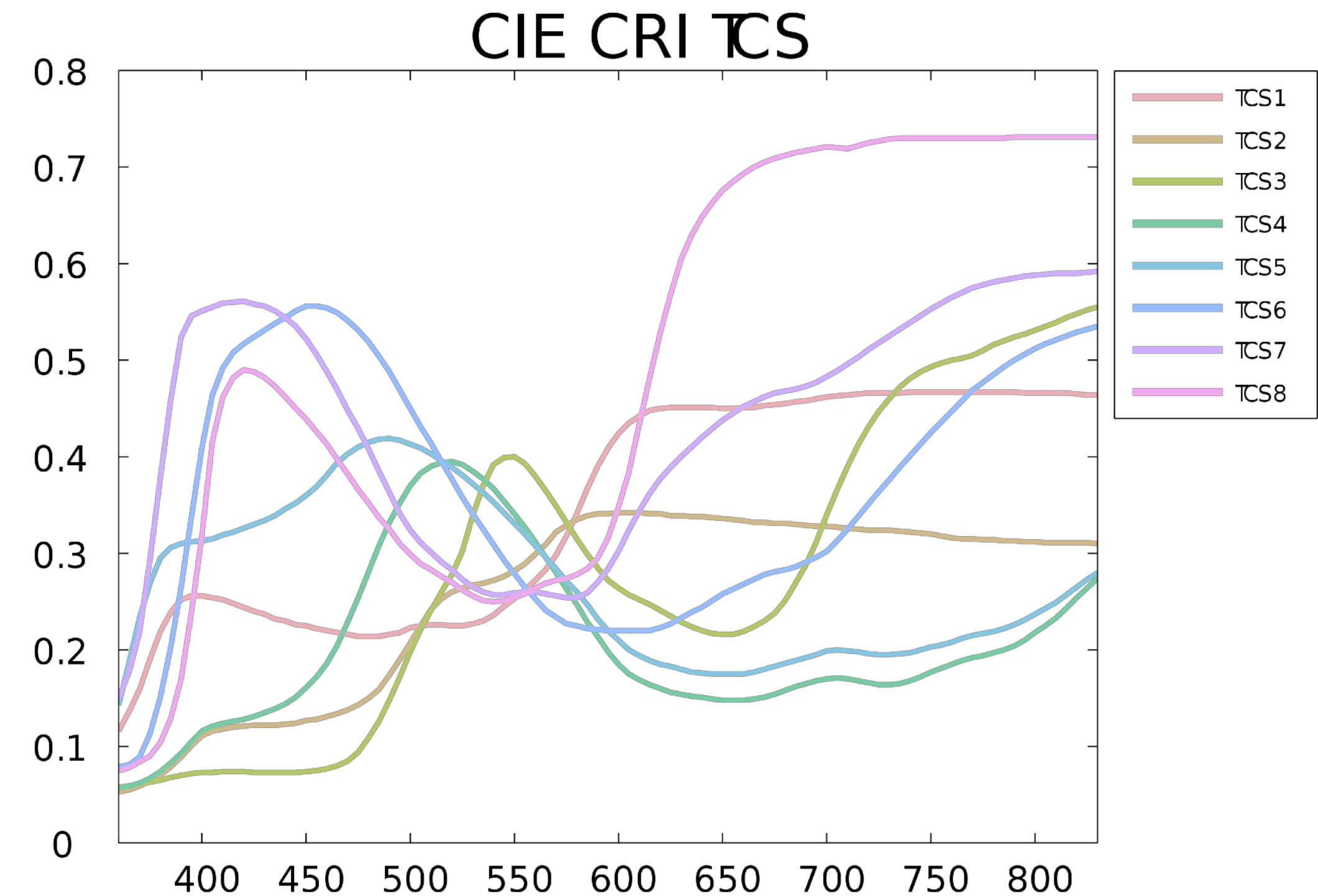


Calculating Color Rendering Index (CRI)

Pick a set of calibration materials with given spectral reflectance.

For each material, illuminate it with both the test light and the reference light. Calculate the two sets of xy-chromaticities, apply von Kries chromatic adaption, and calculate the distance in the xy diagram.

Take some form of average across the samples and normalize to 100.



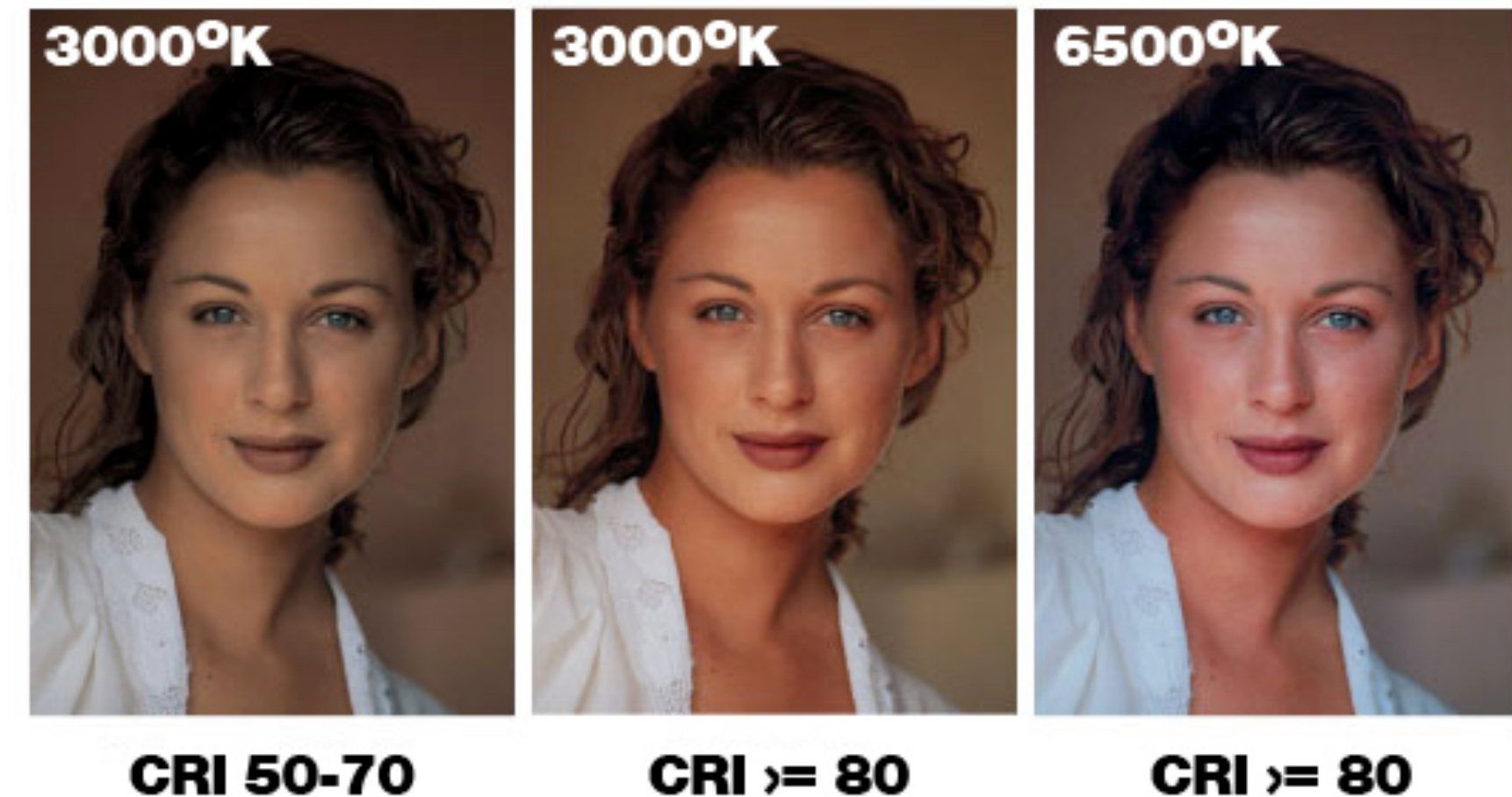
Reflectance spectra of the calibration samples (CIE 1995)

Interpreting CRI

Lights that are more similar to the reference lights (incandescent or daylight) have higher CRIs. Reference lights have a CRI of 100.

Generally, lights with continuous spectra have higher CRIs.

- A continuous spectrum better integrates across the entire visible range.



Display vs. Lighting

We directly look at lights from the display.

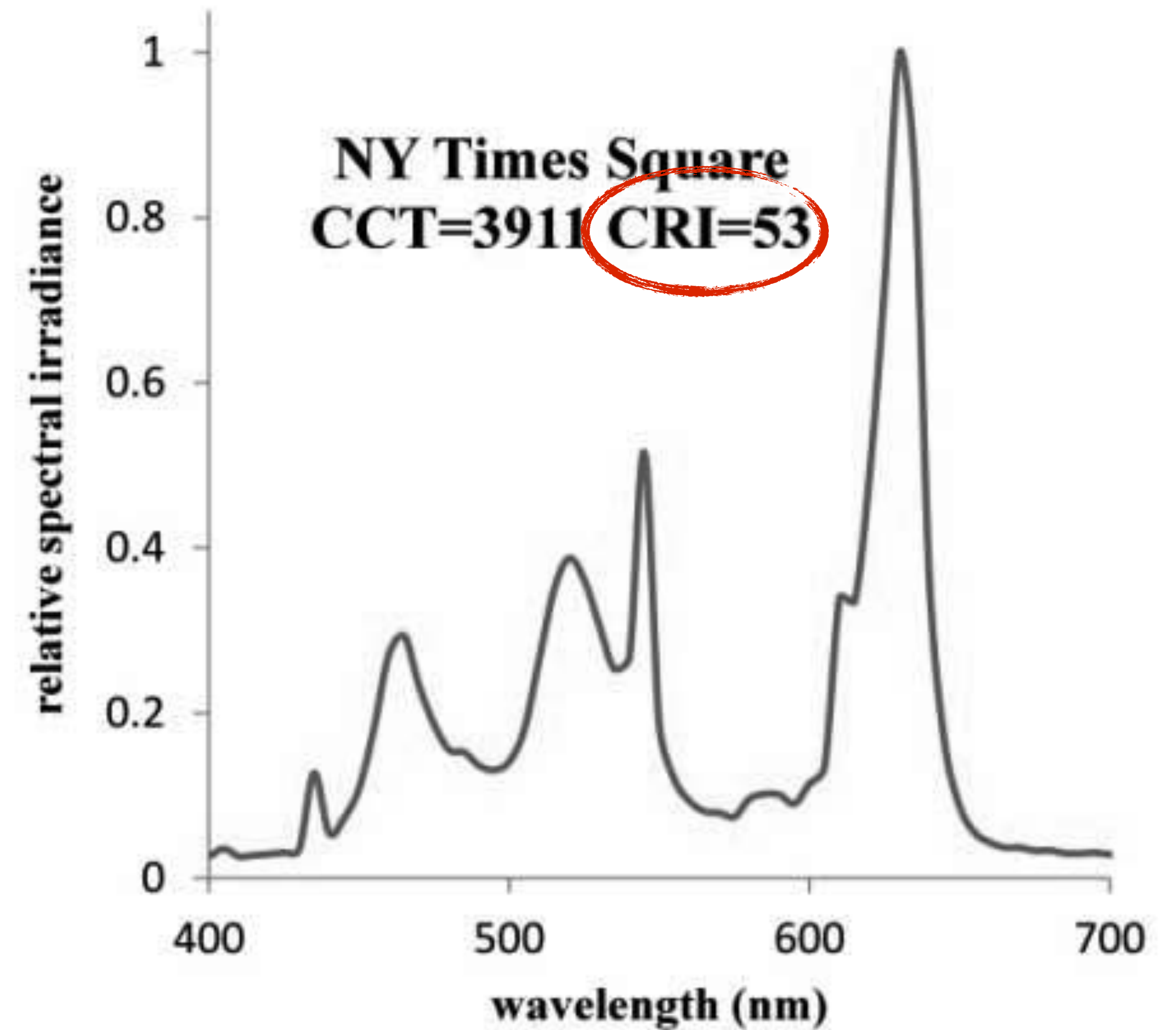
- Reproducing the color (using metamerism) is key. Spectrum is not important.

We don't directly look at lights. We use a lighting system mostly to light an object so that we can see the **color of the object**.

- CRI matters the most. Spectrum becomes important.

What happens when we use displays for lighting?

Display vs. Lighting

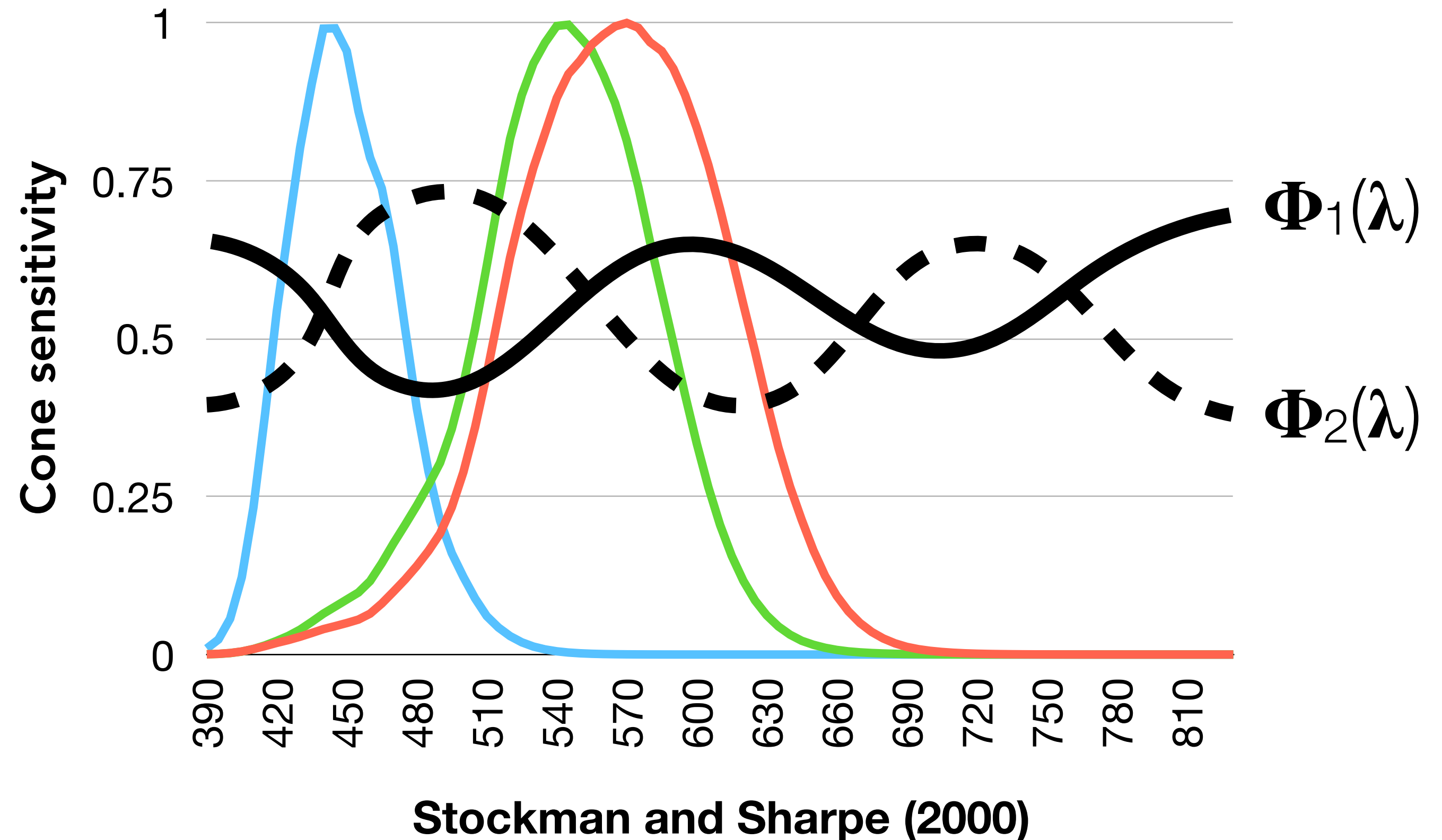


Displays

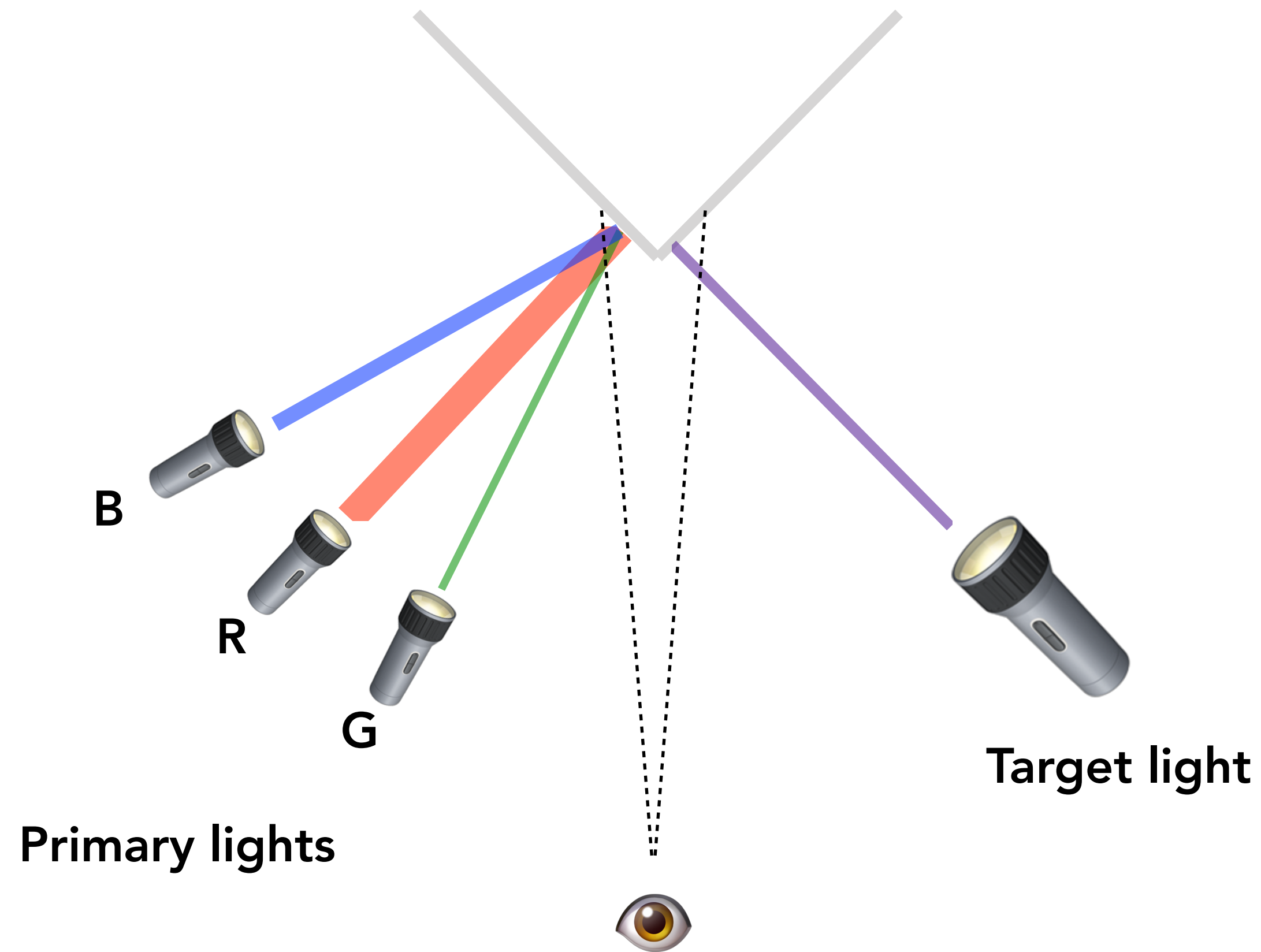
Recall: Metamerism

The two lights are metamers of each other if their LMS responses match.

$$\begin{aligned}\sum_{\lambda} \Phi_1(\lambda)L(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)L(\lambda) \\ \sum_{\lambda} \Phi_1(\lambda)M(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)M(\lambda) \\ \sum_{\lambda} \Phi_1(\lambda)S(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)S(\lambda)\end{aligned}$$



Recall: Trichromatic Theory of Color

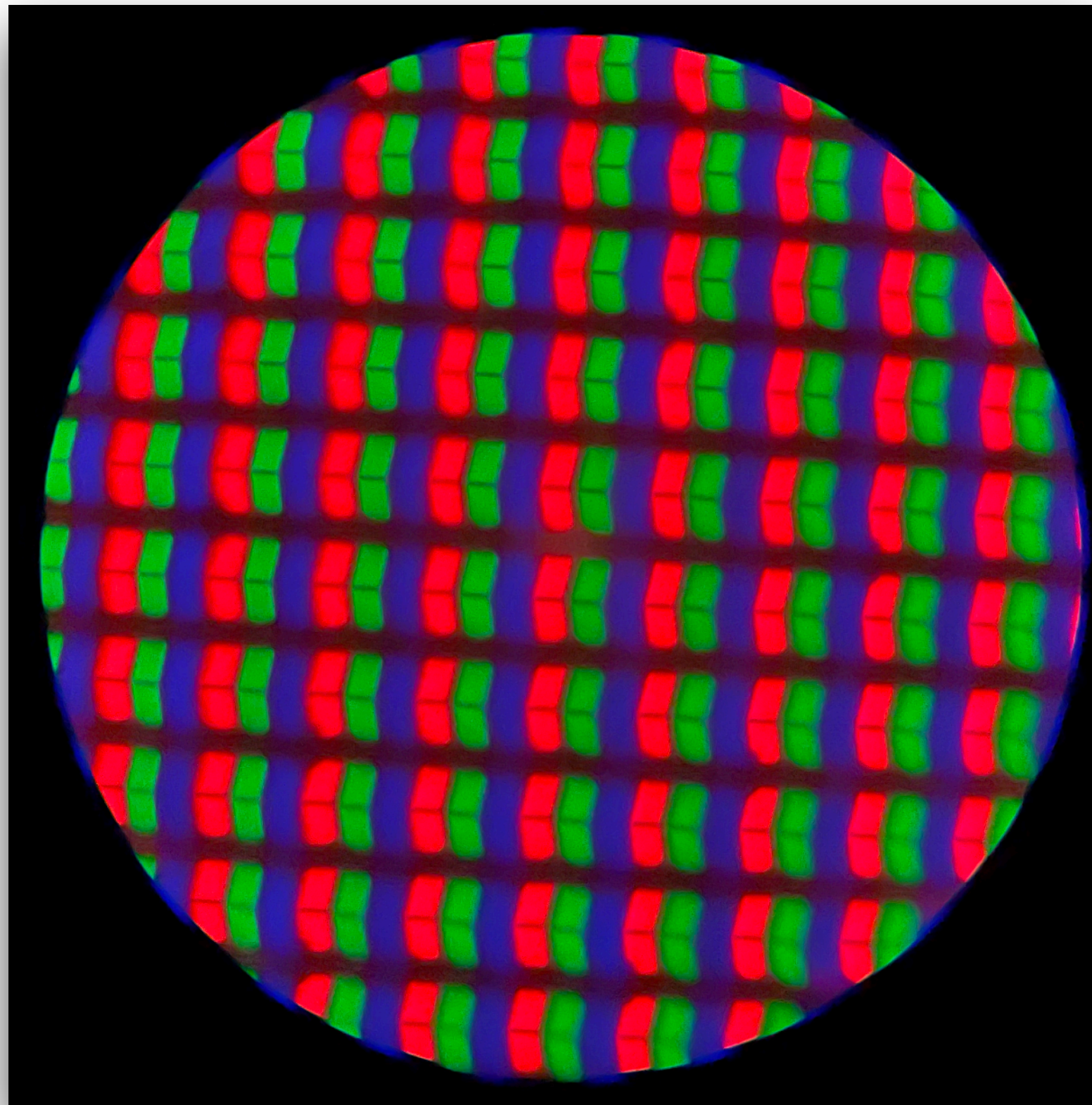


We can match the color of a given light by mixing three primary colors.

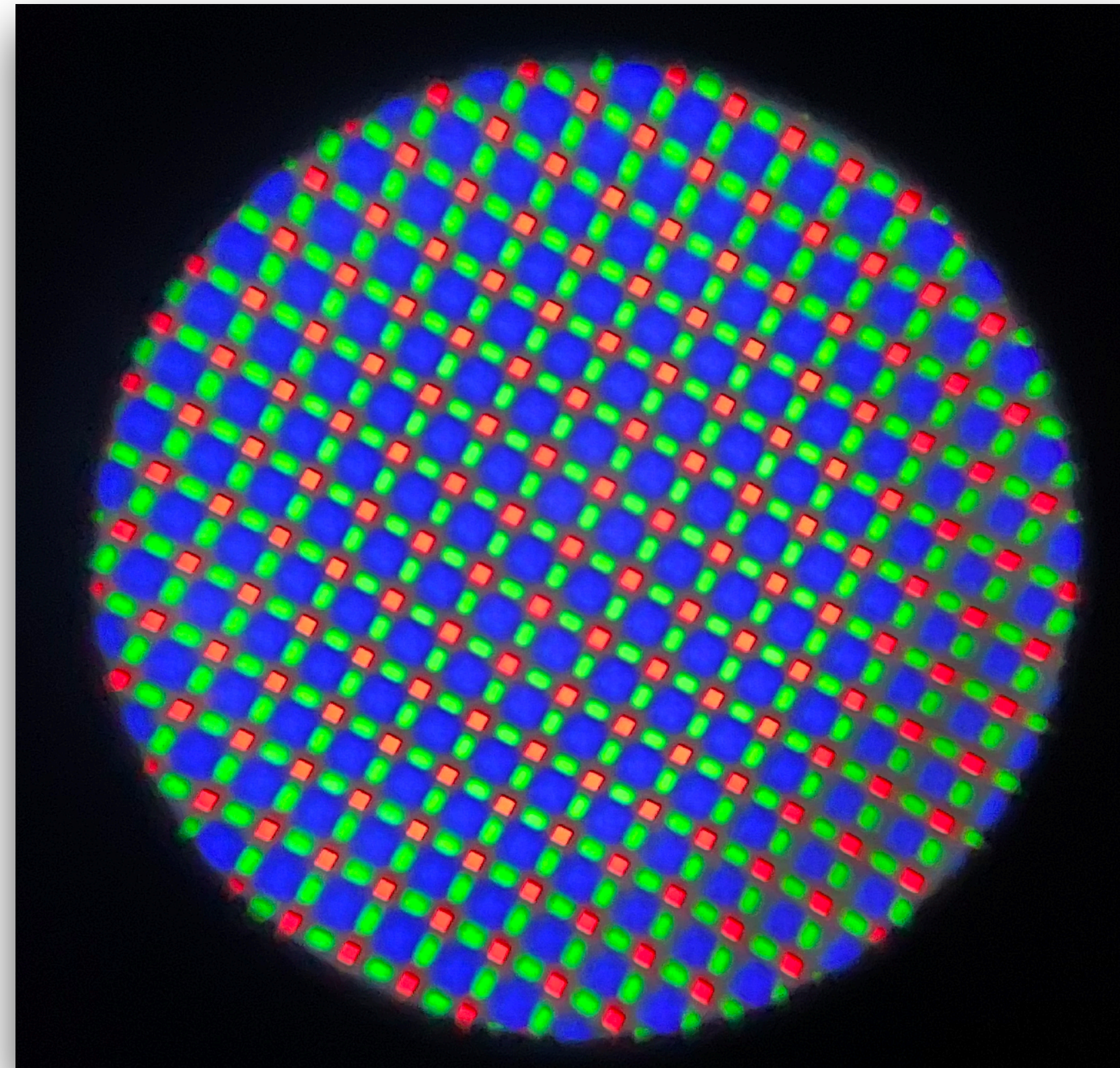
- Provided that the primaries are carefully chosen so that the target color falls within the gamut of the color space.

For displays, this means we don't need to produce the exact light **spectrum** if our goal is simply to produce the desired **color**.

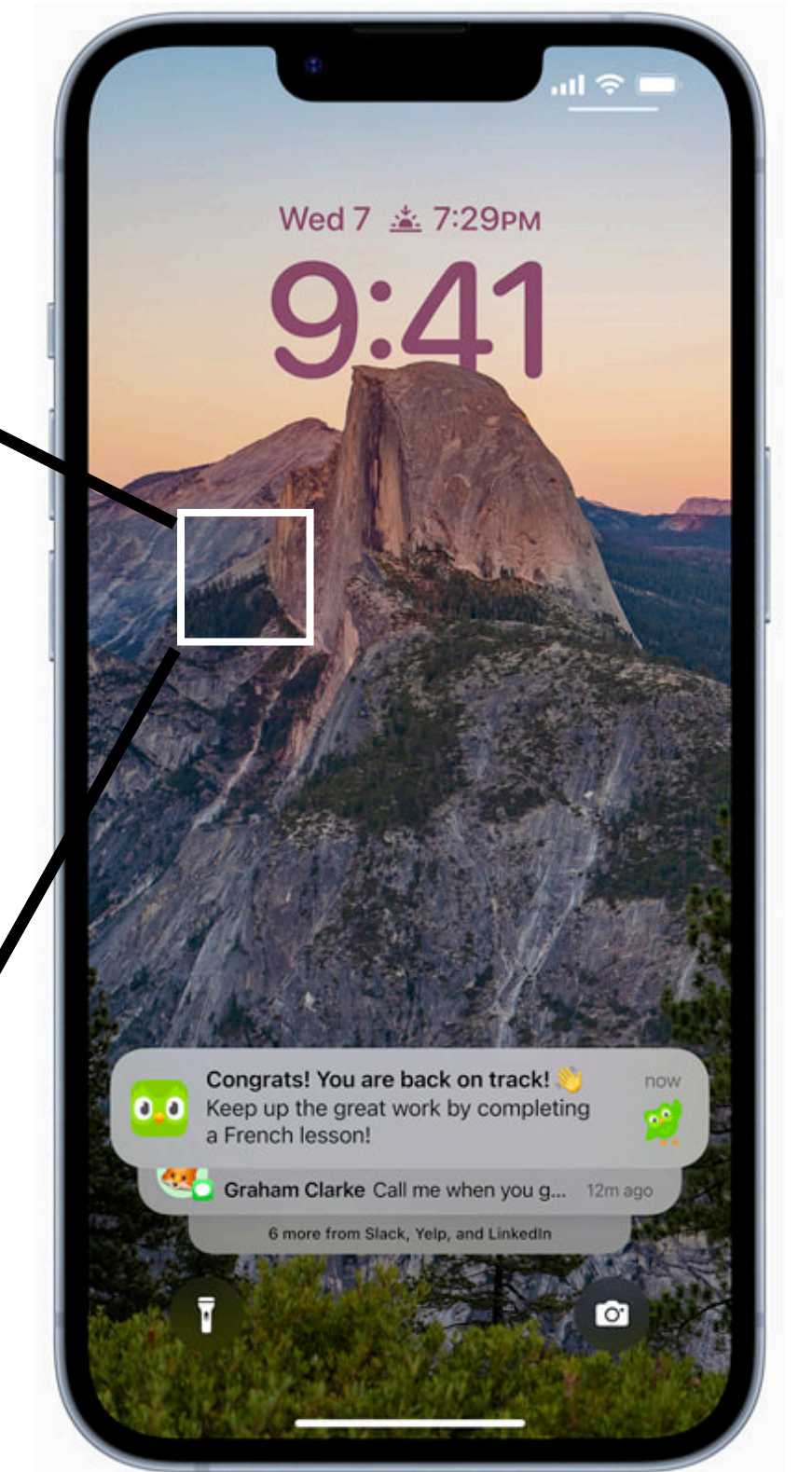
Basic Principle: Spatial Integration



iPhone 6

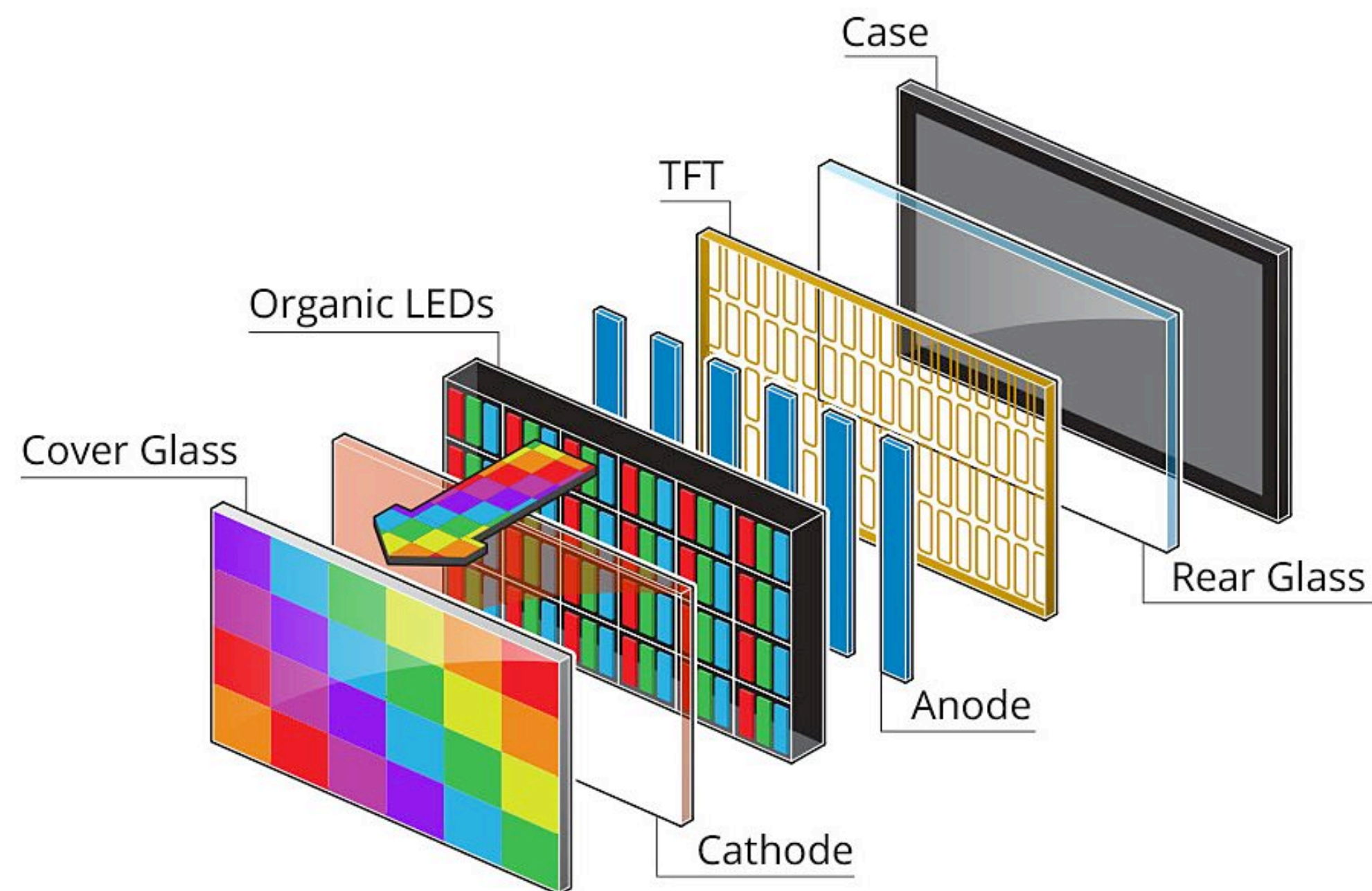


iPhone 14 Pro

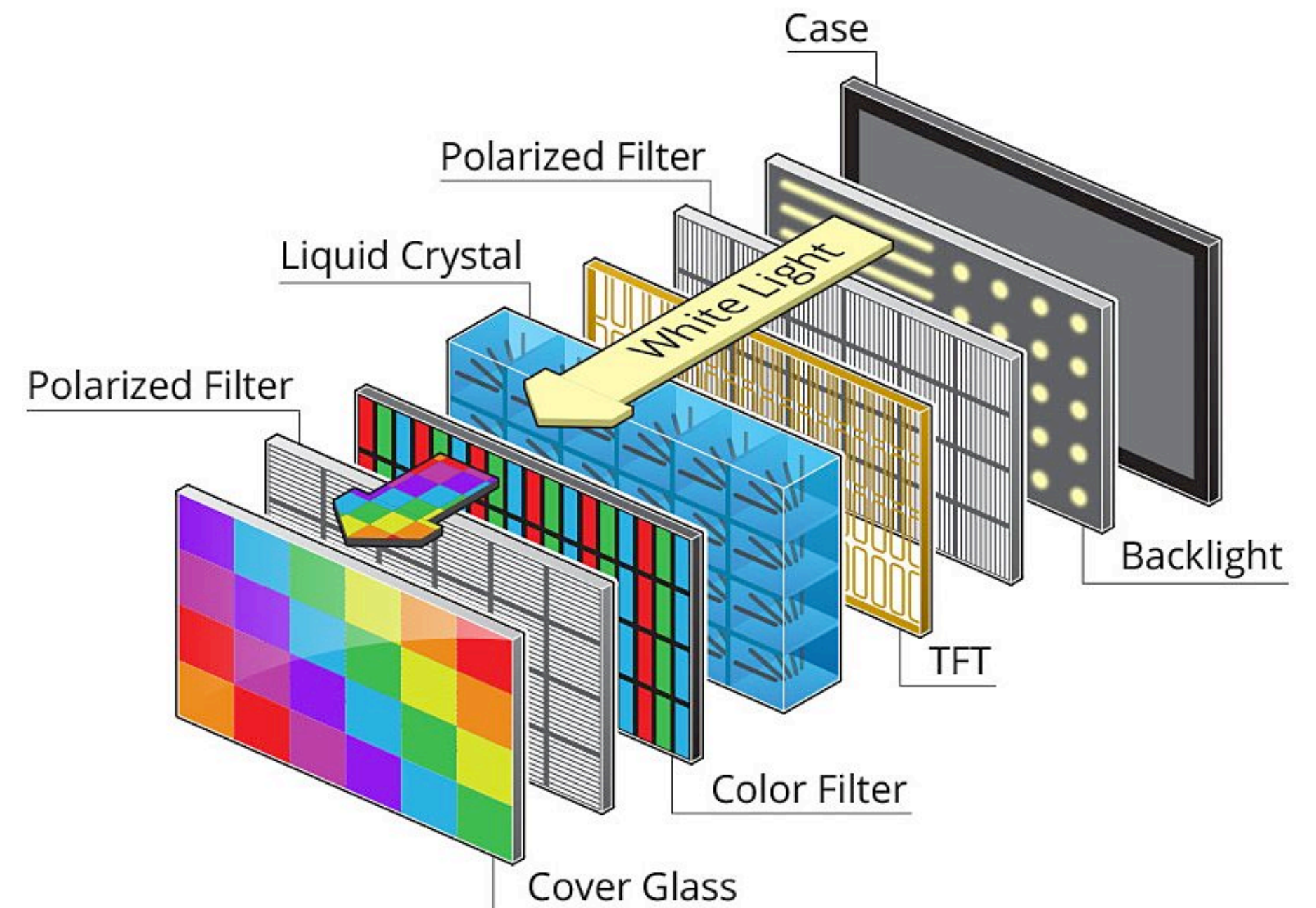


Two Main Display Mechanisms

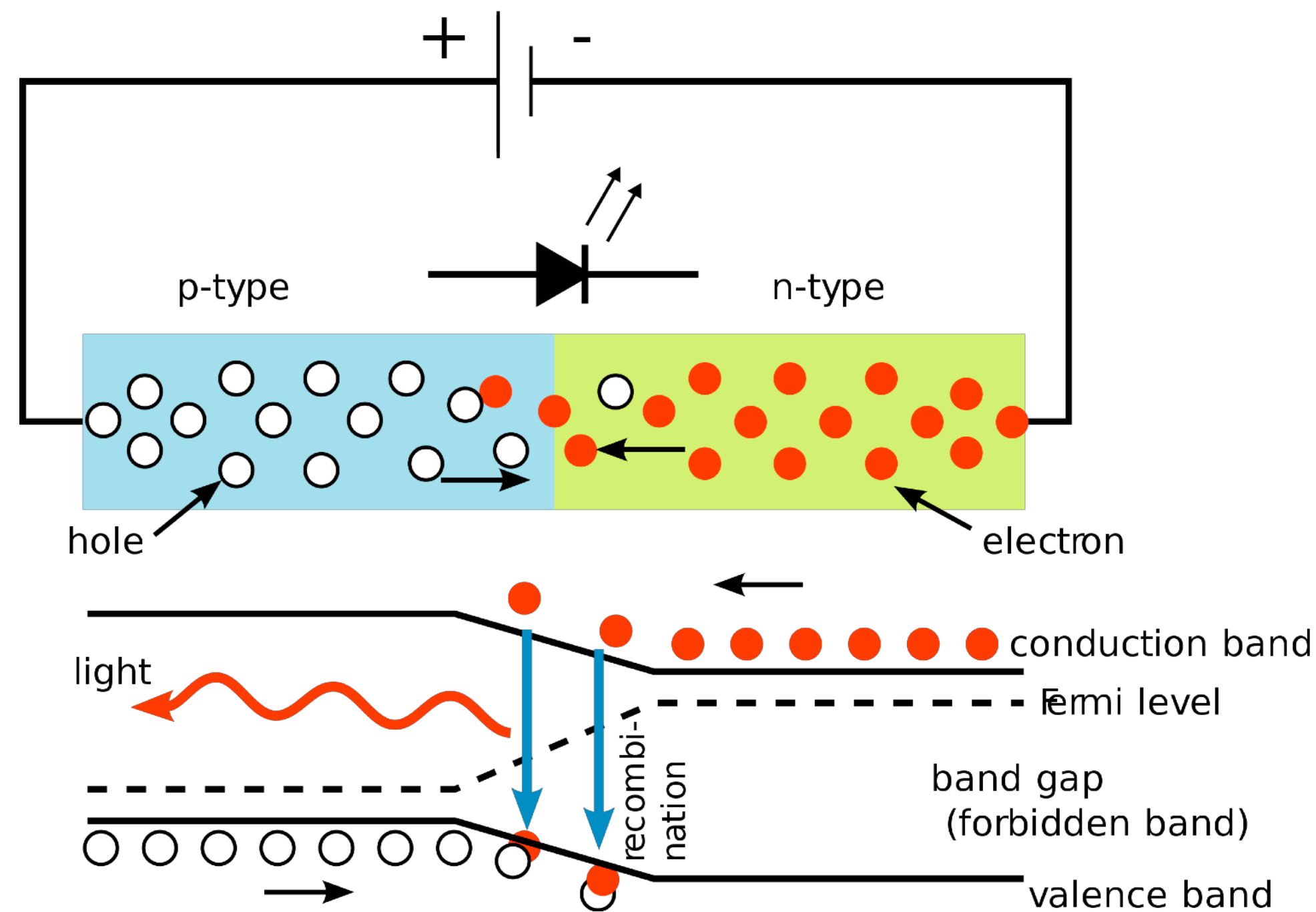
Emissive Displays (e.g., OLED)



Light-Filtering Displays (e.g., LCD/Projector)



Light-Emitting Diodes: Photons From Electrons



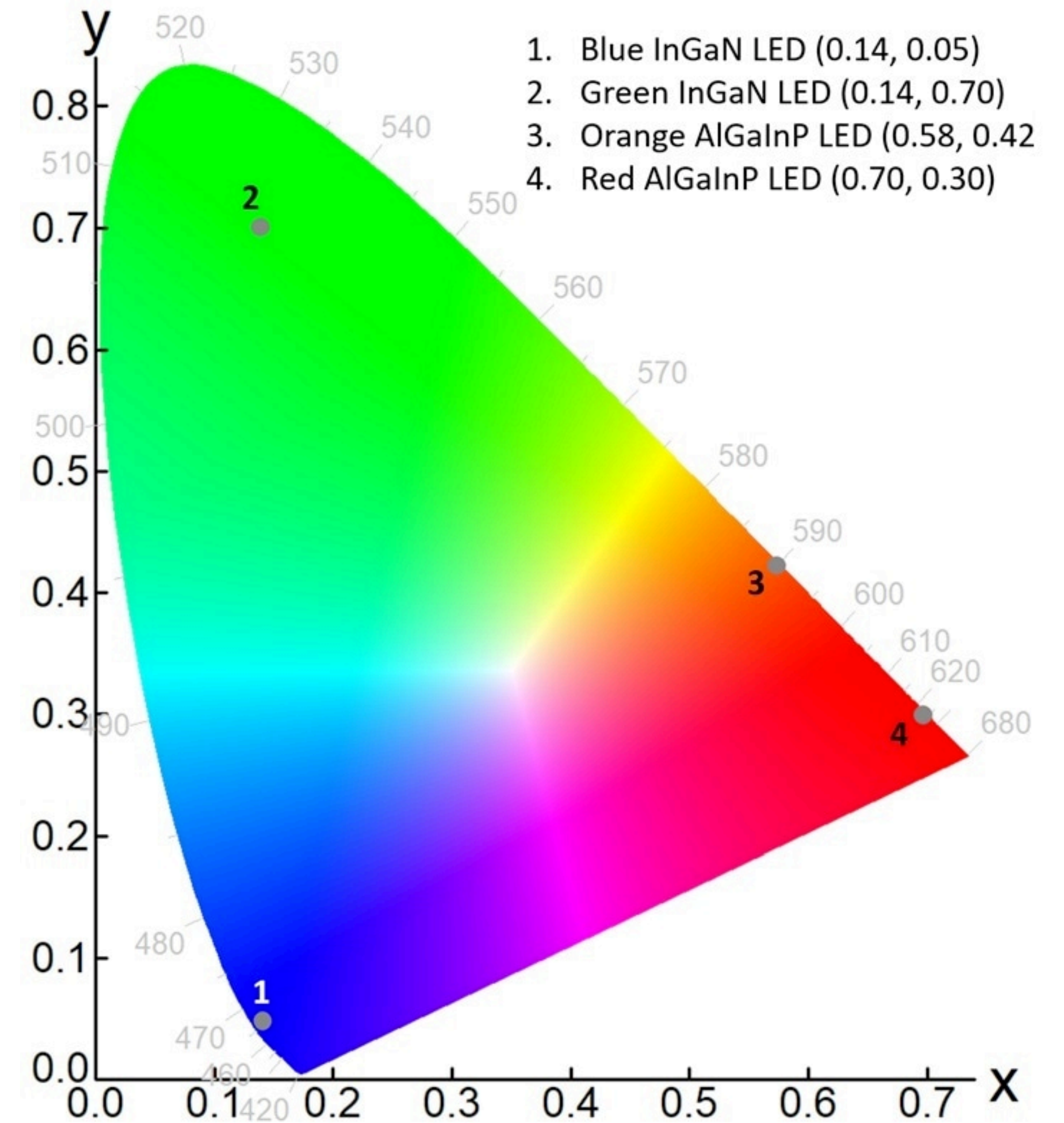
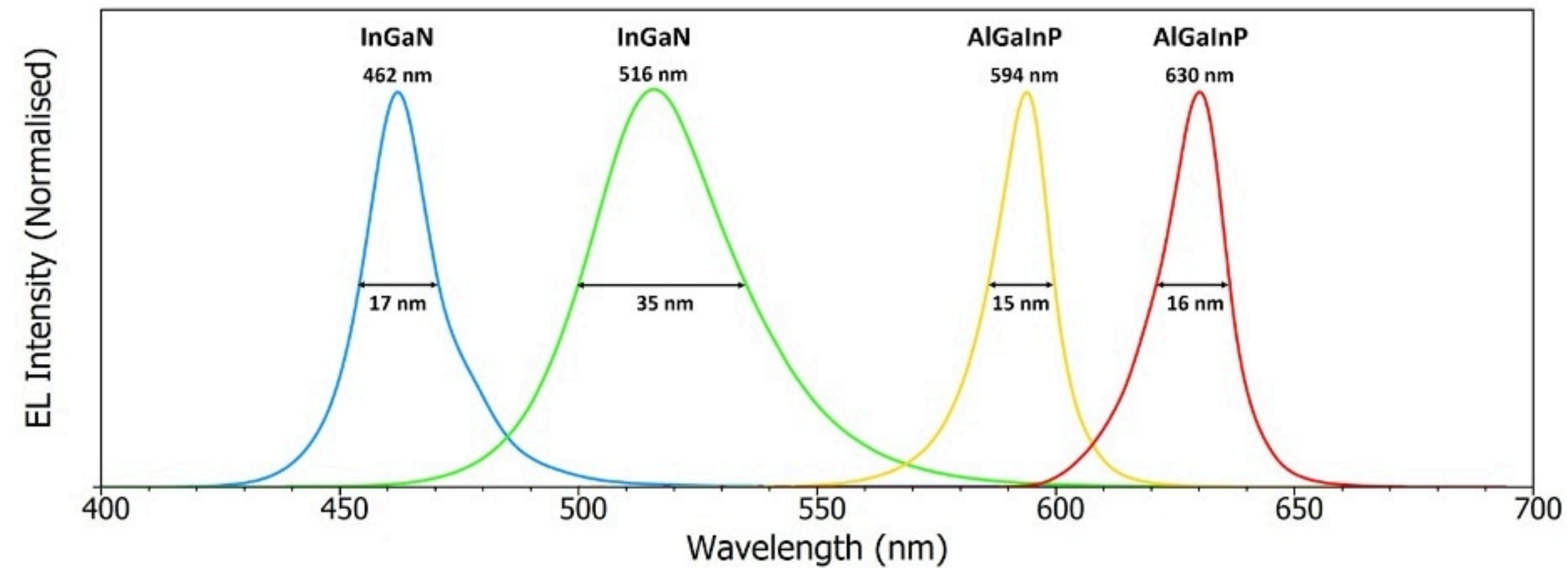
External power creates potential differences that move electrons from the n-side (higher energy state) to the p-side (lower energy state), releasing photons.

The photon wavelength depends on the energy gap, which depends on material.

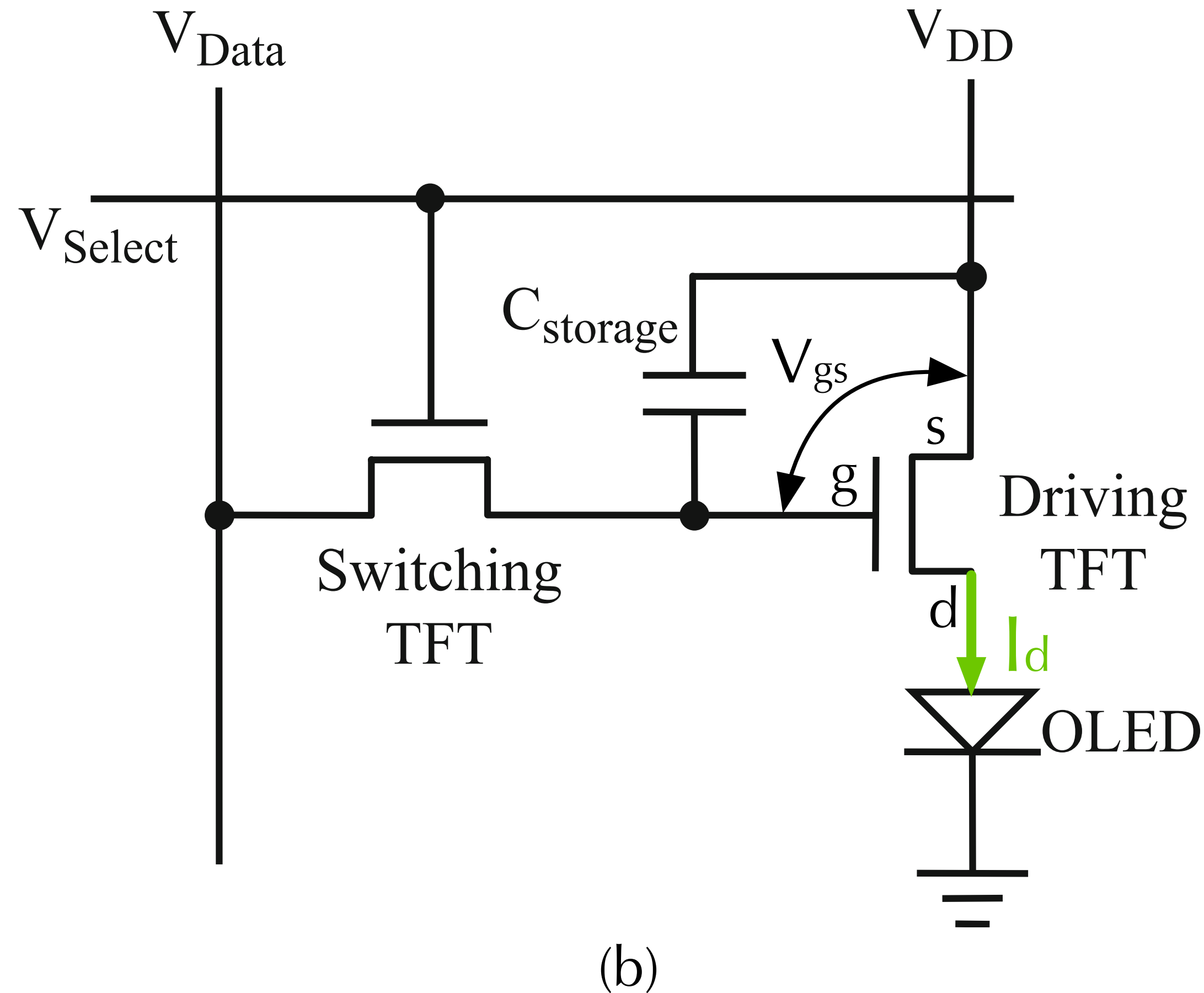
A form of electroluminescence.

- Variants: OLED, QLED, AMOLED, etc.
- Two common materials: AlGaInP and InGaN.

Light-Emitting Diodes (LED)



OLED Pixel



An OLED is a current driven device.

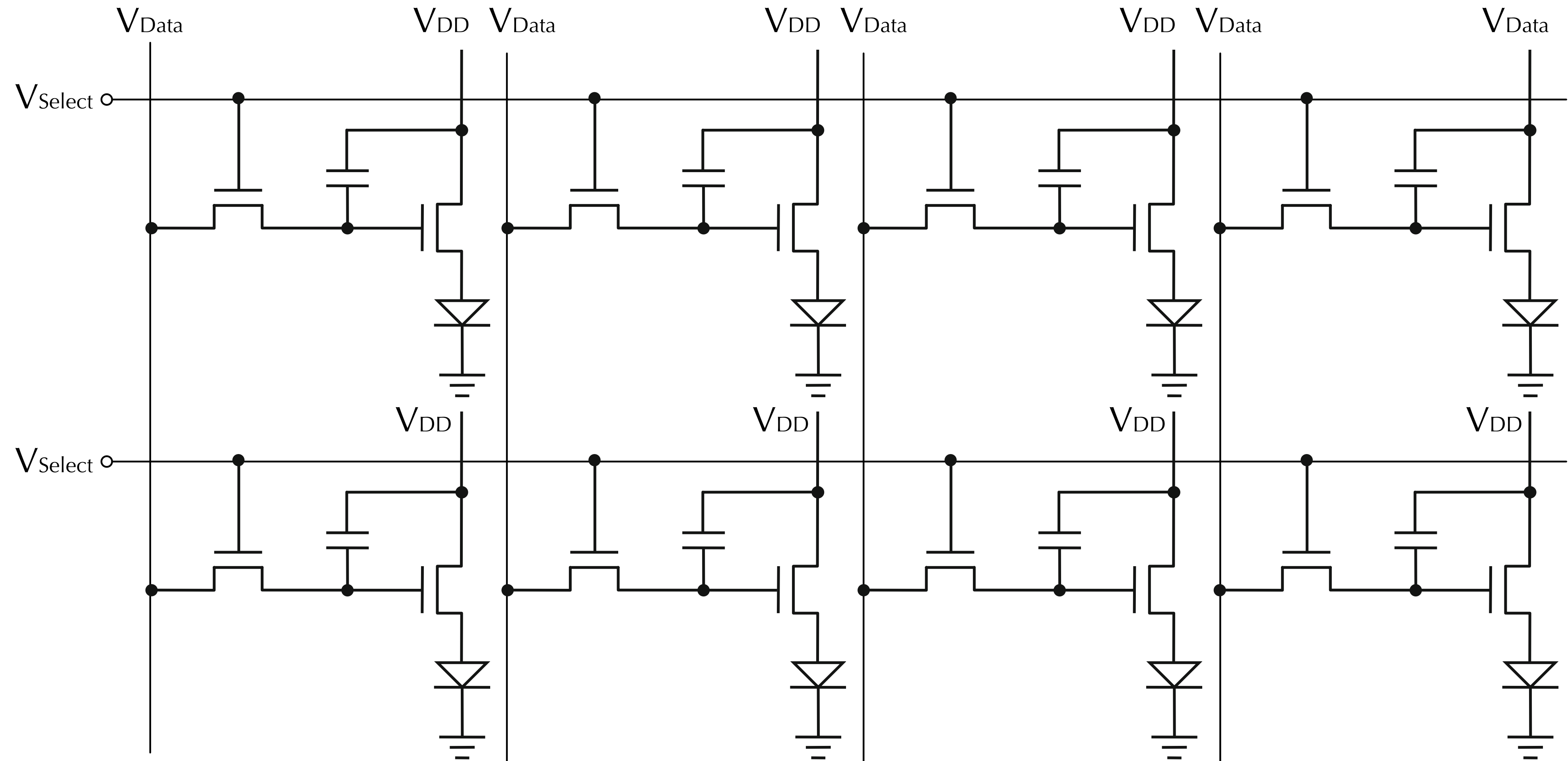
The luminance is roughly proportional to I_d .

Control V_{Data} to control V_{gs} ,
"stored" in $C_{storage}$

$$I_{OLED} = I_d = k(V_{gs} - V_{th})$$

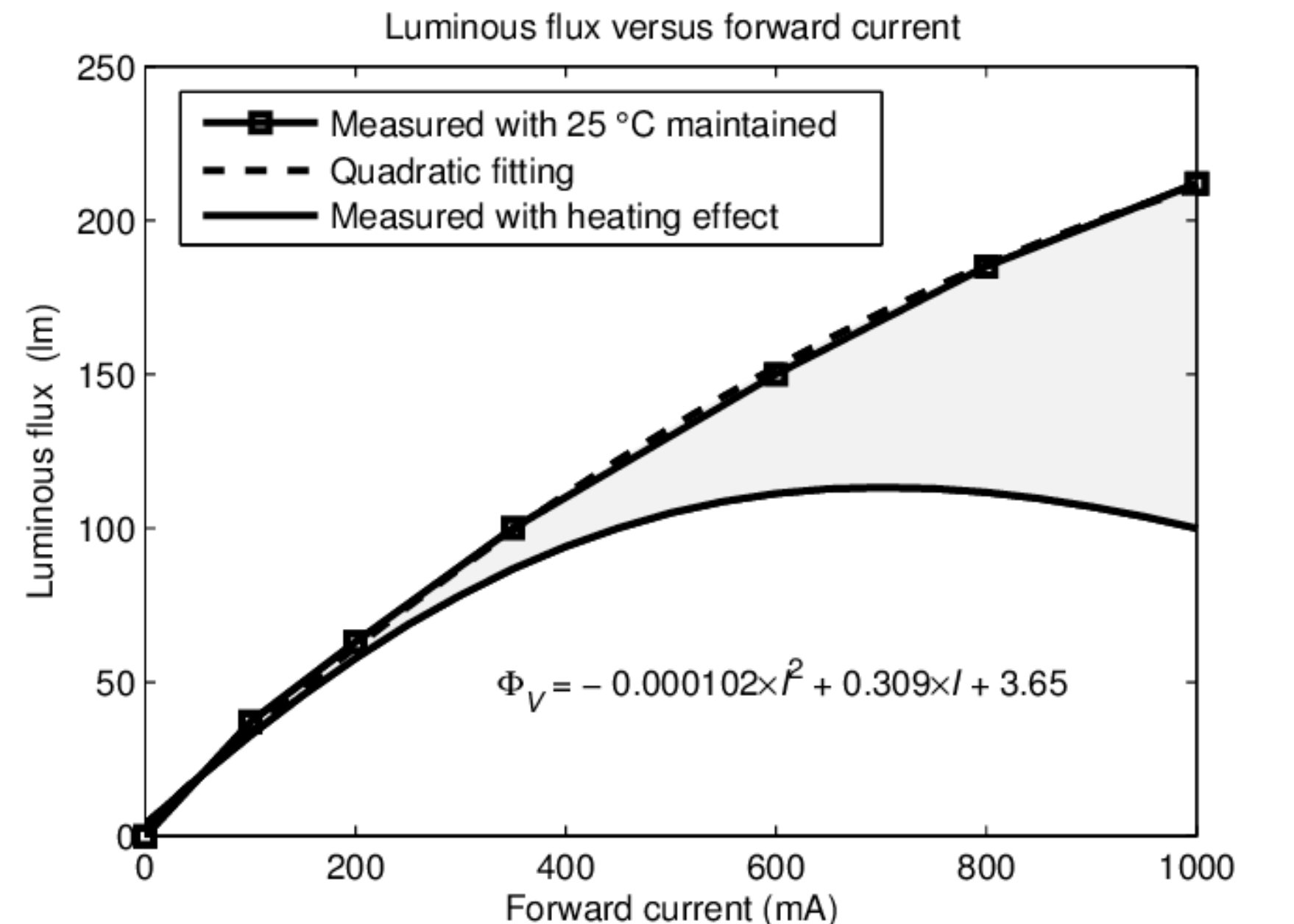
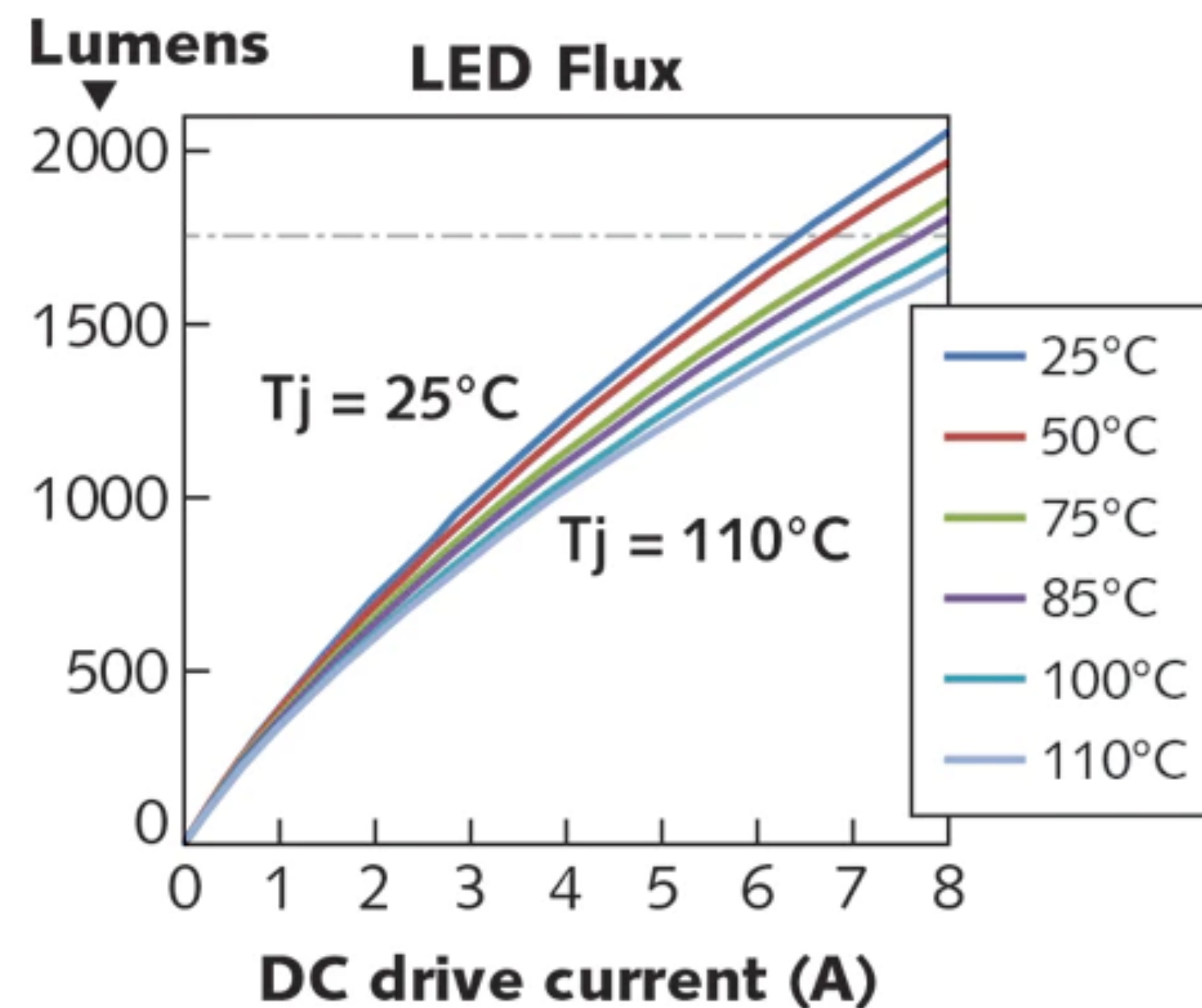
$$V_{gs} = V_{DD} - V_{Data}$$

OLED Pixel Array (AMOLED)

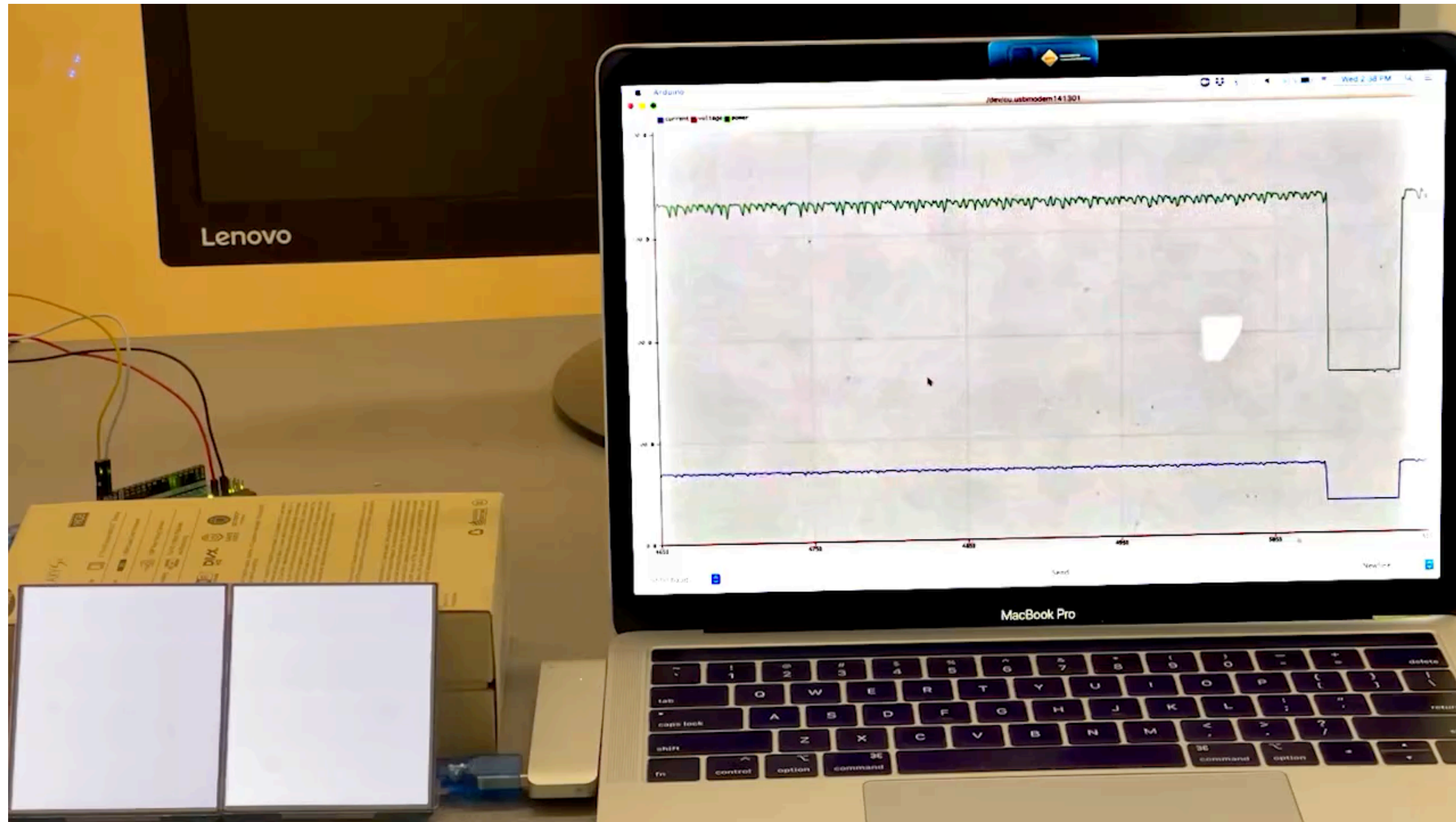


Controlling Intensity of LEDs

The **higher** is the **current** of the driver circuit and the **lower** is the **temperature**, the higher is the light output intensity (luminous flux).

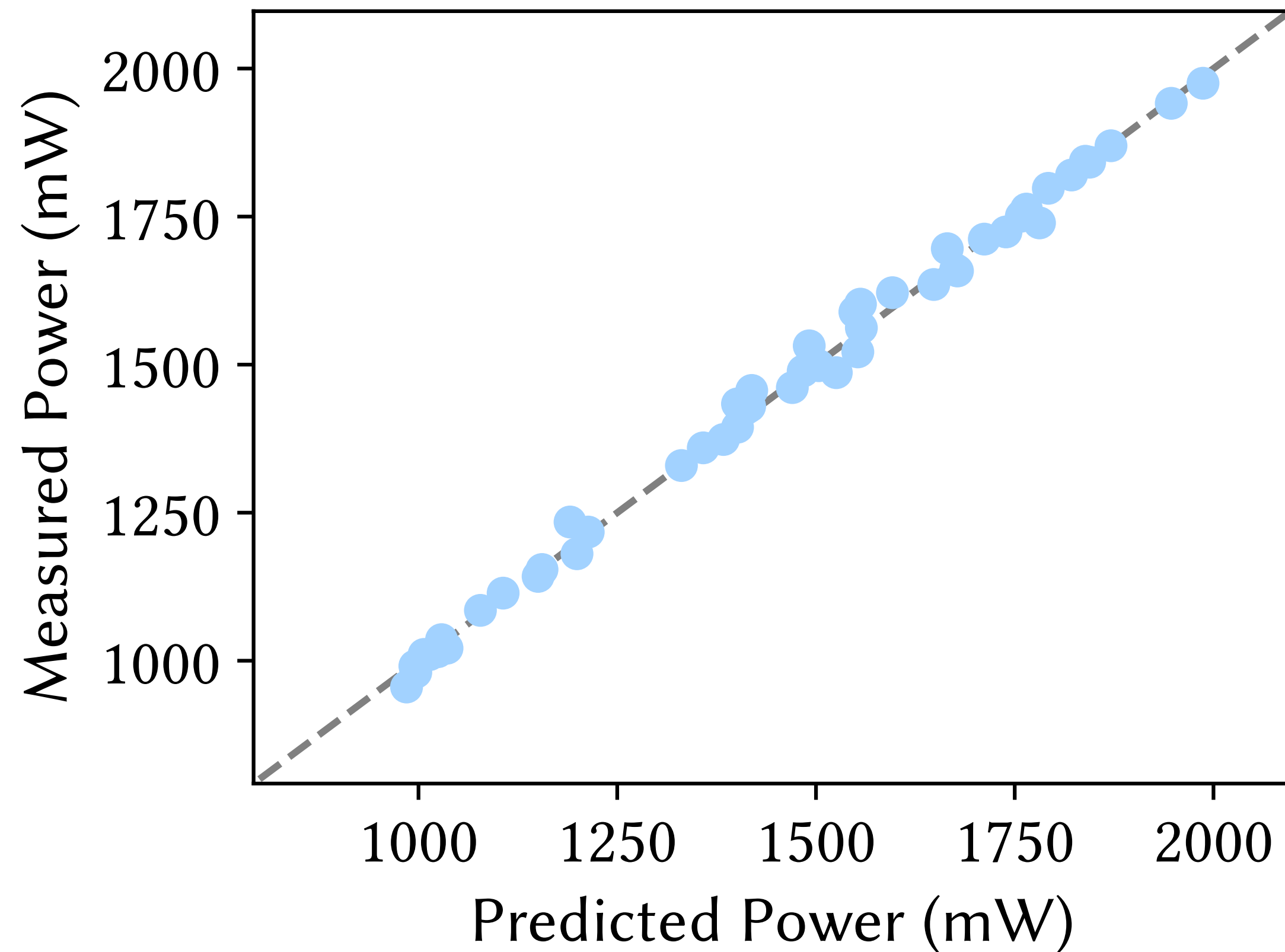


OLED Display Power vs. Color



OLED Display Power vs. Color

$$\text{Power} = 233.5 * \mathbf{R} + 209.6 * \mathbf{G} + 567.7 * \mathbf{B} + 983.8 \text{ (unit is mW)}$$



Wisecoco AMOLED Display (1200x1080)

Setup:

- All pixels display the same color.
- R, G, B are linear sRGB values (without gamma) and in the [0, 1] range.

The intercept (983.8) represents the circuit power independent of color.

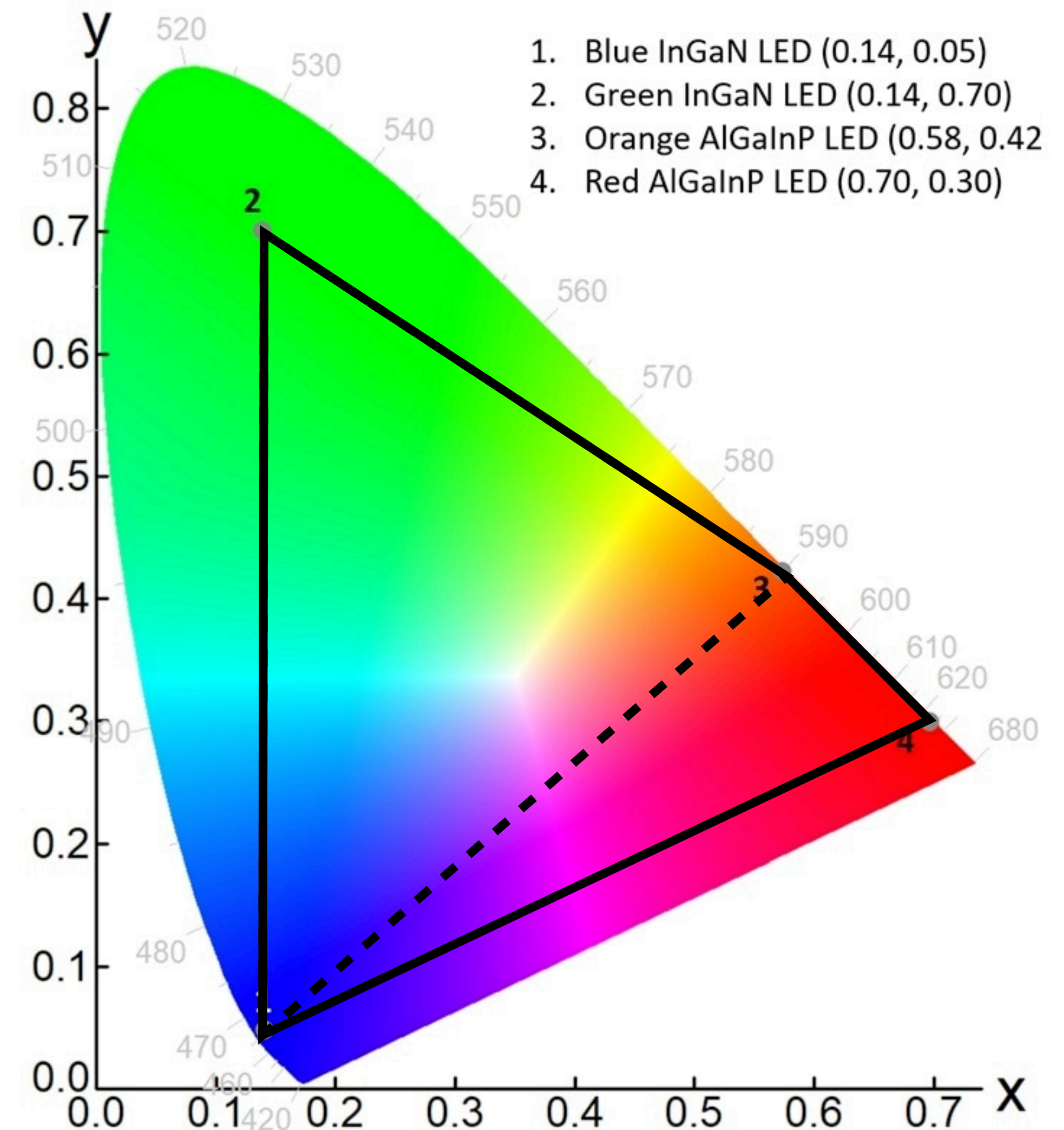
Producing White in Emissive Display

Mixing different colored LEDs.

Trade-off:

- More primaries means more stable white (one primary being off a little doesn't affect the "whiteness" much).
- More primaries means more LEDs (form factor). The luminance efficacy (lumen/watt) might be lower depending on what LEDs are used.

LEDs age at different rates; adjustment.



White LED

Backlight

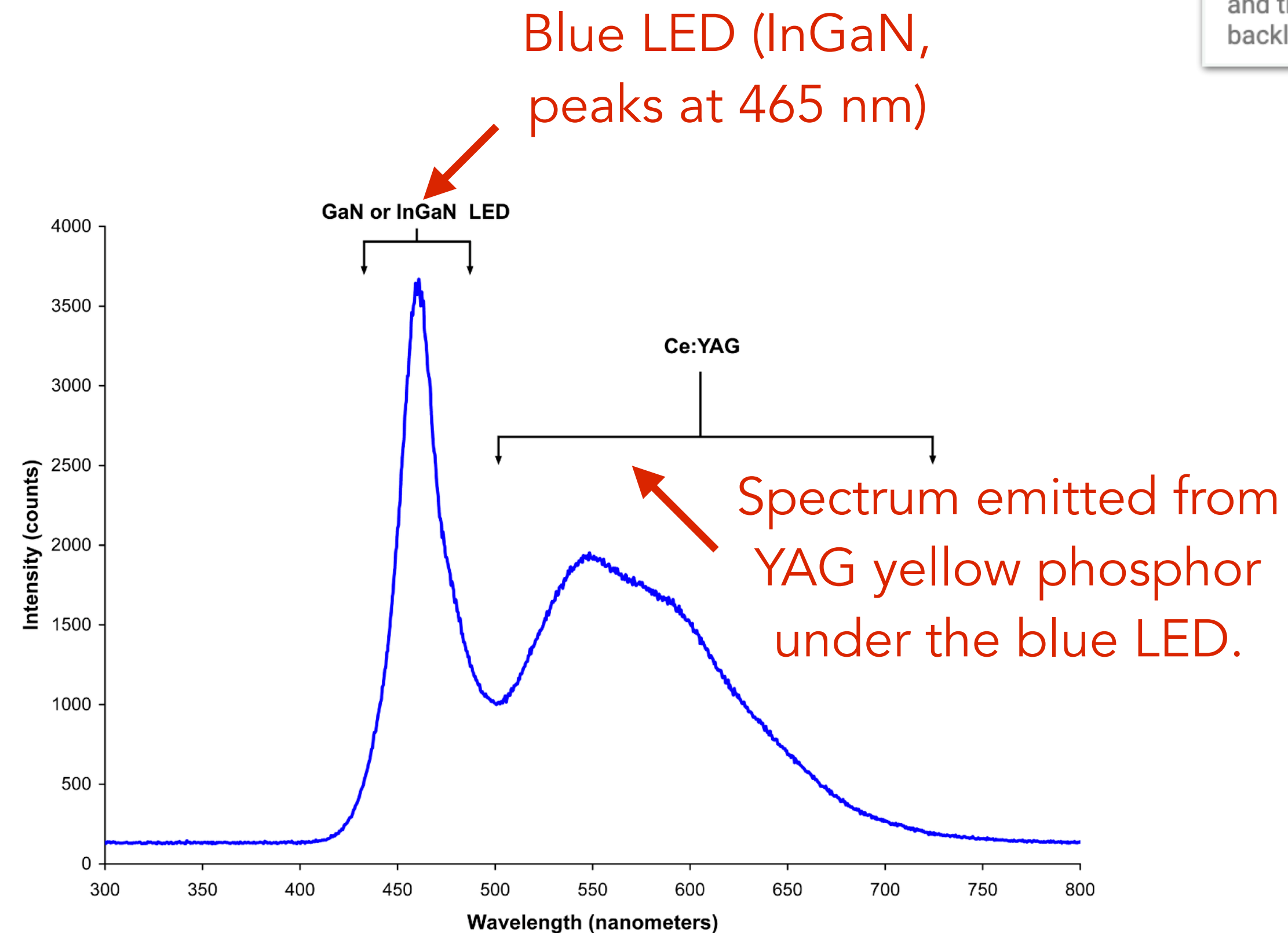
The backlight is the source of light of the LCD display panels. The type of backlight determines the image quality and the color space of the display. There are various backlights such as CCFL, LED, WLED, RGB-LED, and etc.

W-LED

From my LG LCD monitor

Use a blue LED to light fluorescent materials, which generate (usually) yellow spectrum.

- Also called “phosphor-converted white LED”.

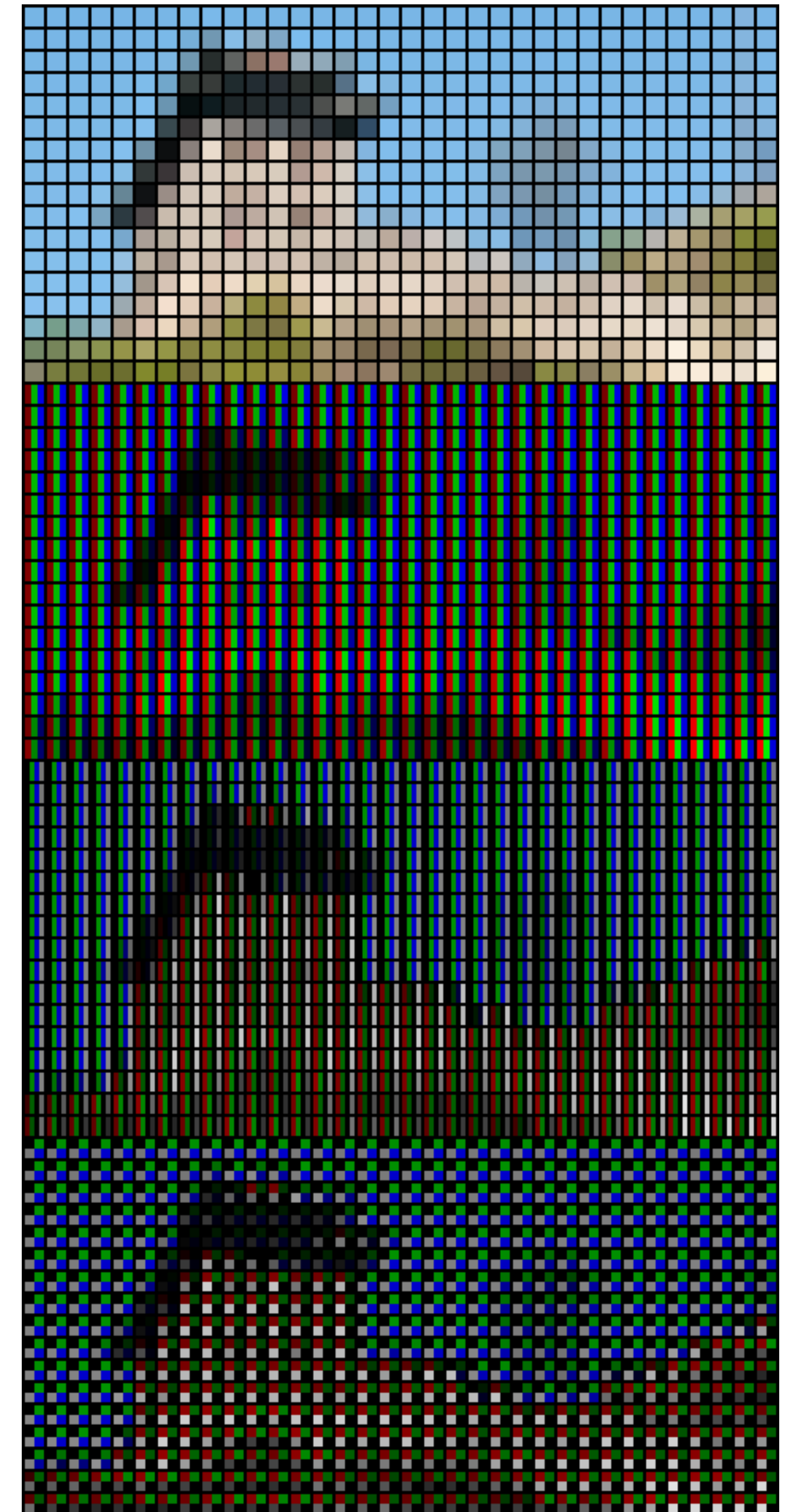
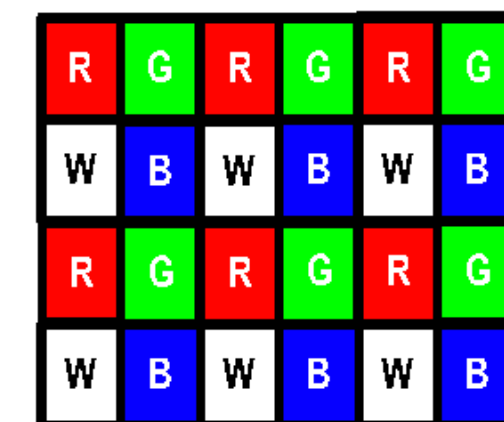
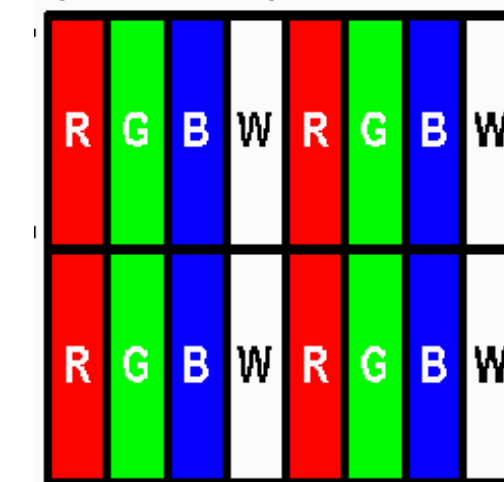
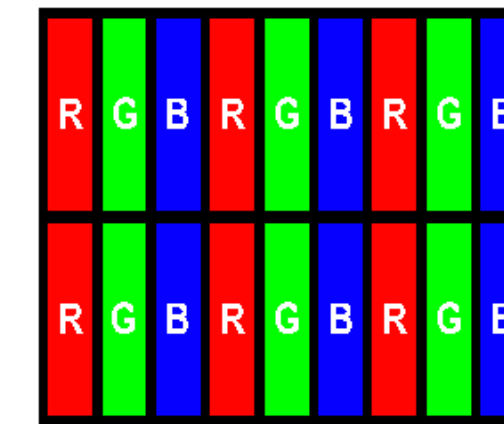


RGBW Sub-Pixel Structure

Some displays use the RGBW sub-pixel structure, which adds white sub-pixels.

Why?

- Use W in place of R+G+B to improve power efficiency
- Add W to boost brightness (think of it as adding power to each of the RGB sub pixels). Sacrifice color fidelity; common in projectors.



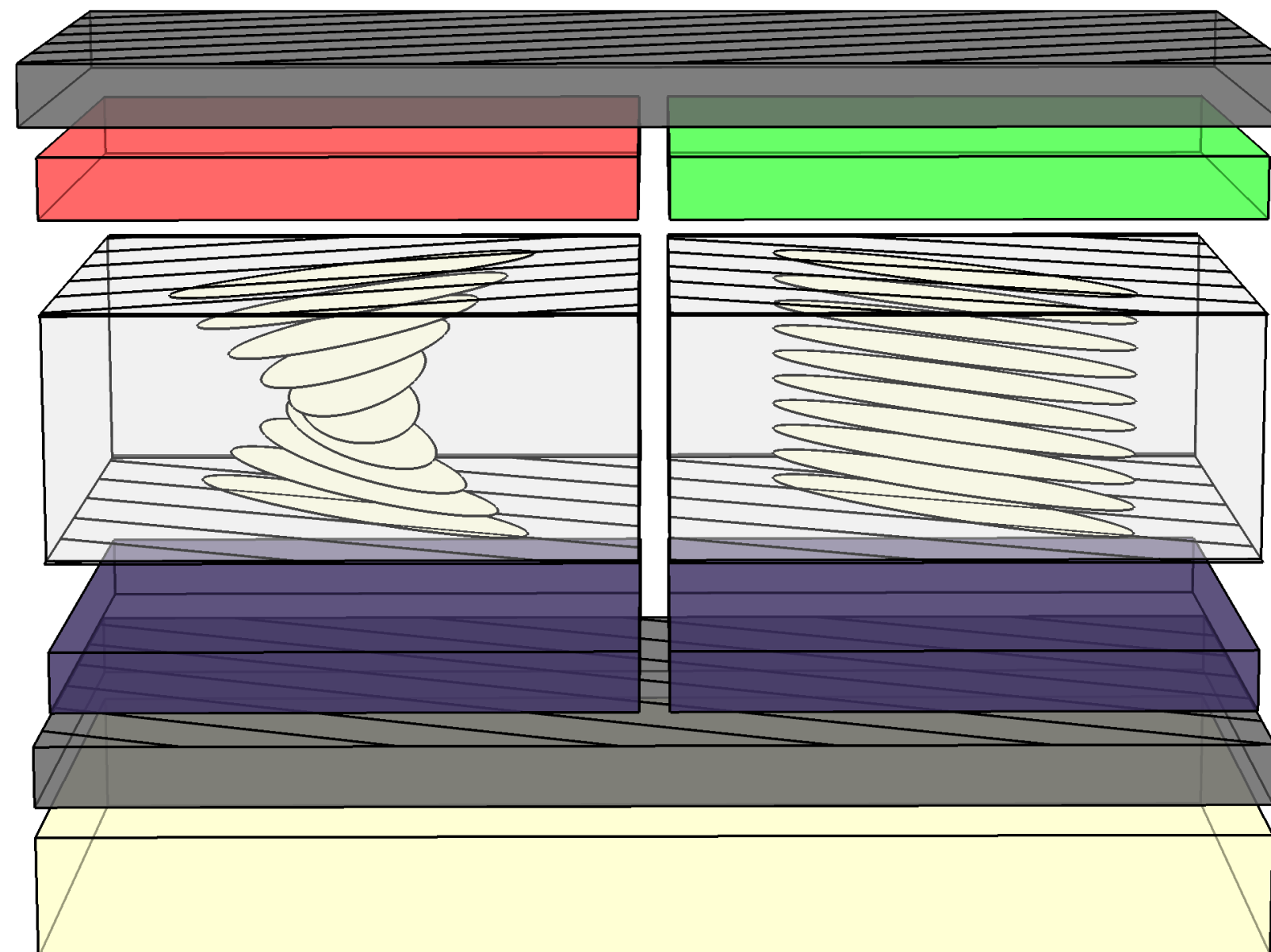
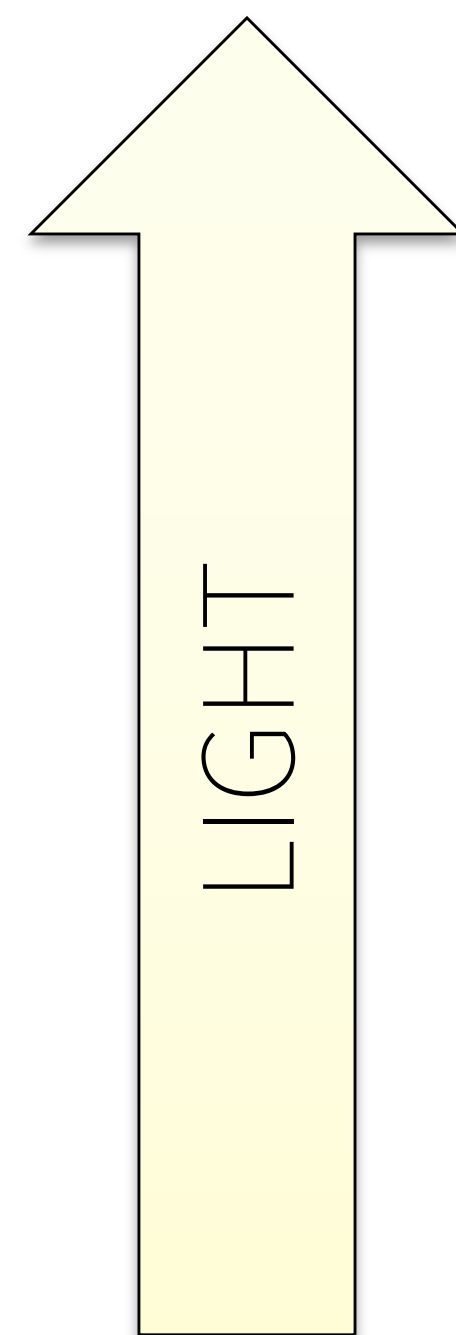
Light-Filtering Display

White light source is **filtered** and attenuated at each pixel to control color and light intensity.

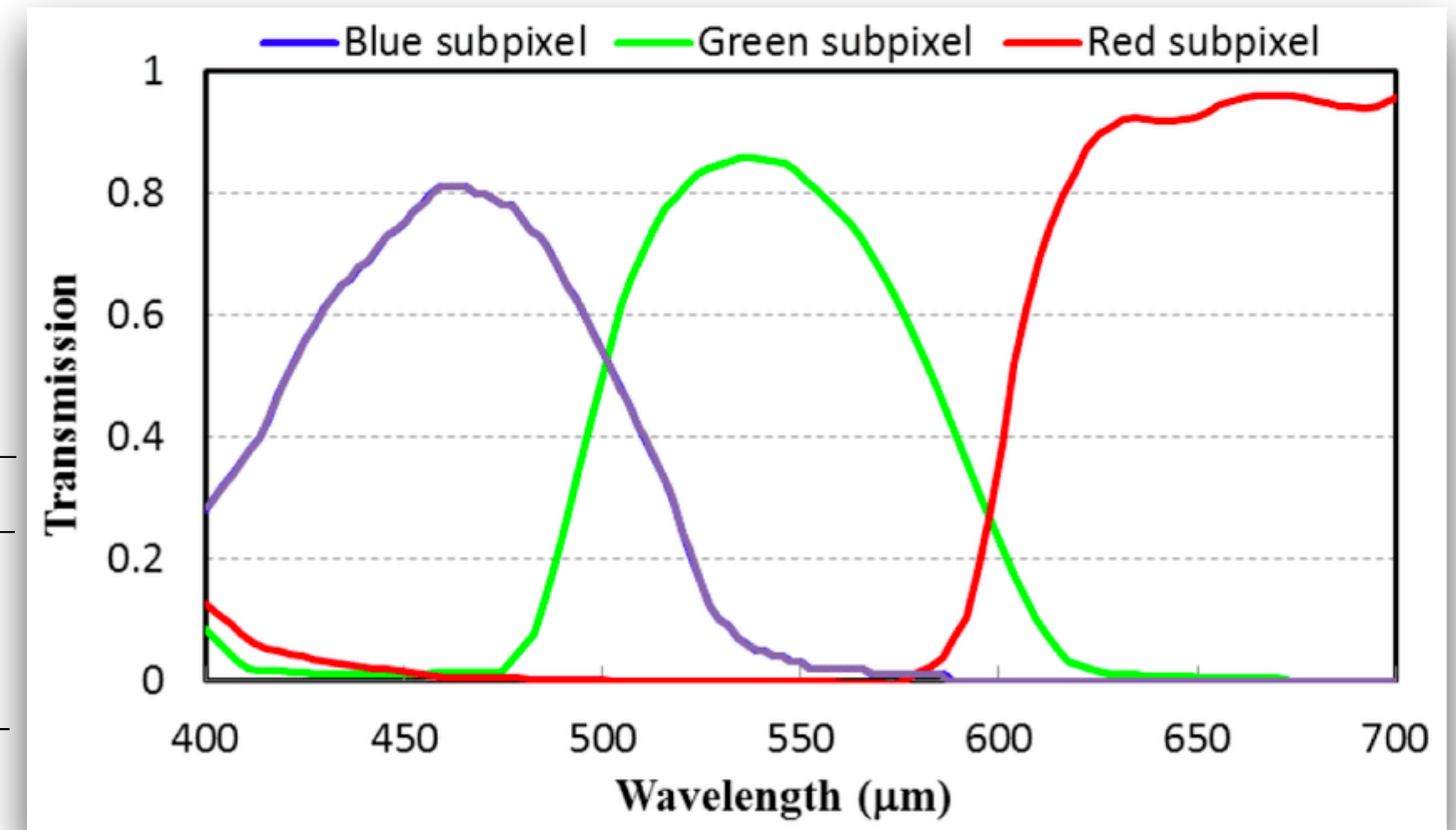
Used in Liquid Crystal Displays (LCD) and DLP projectors.



Controlling Intensity of LCD Pixels



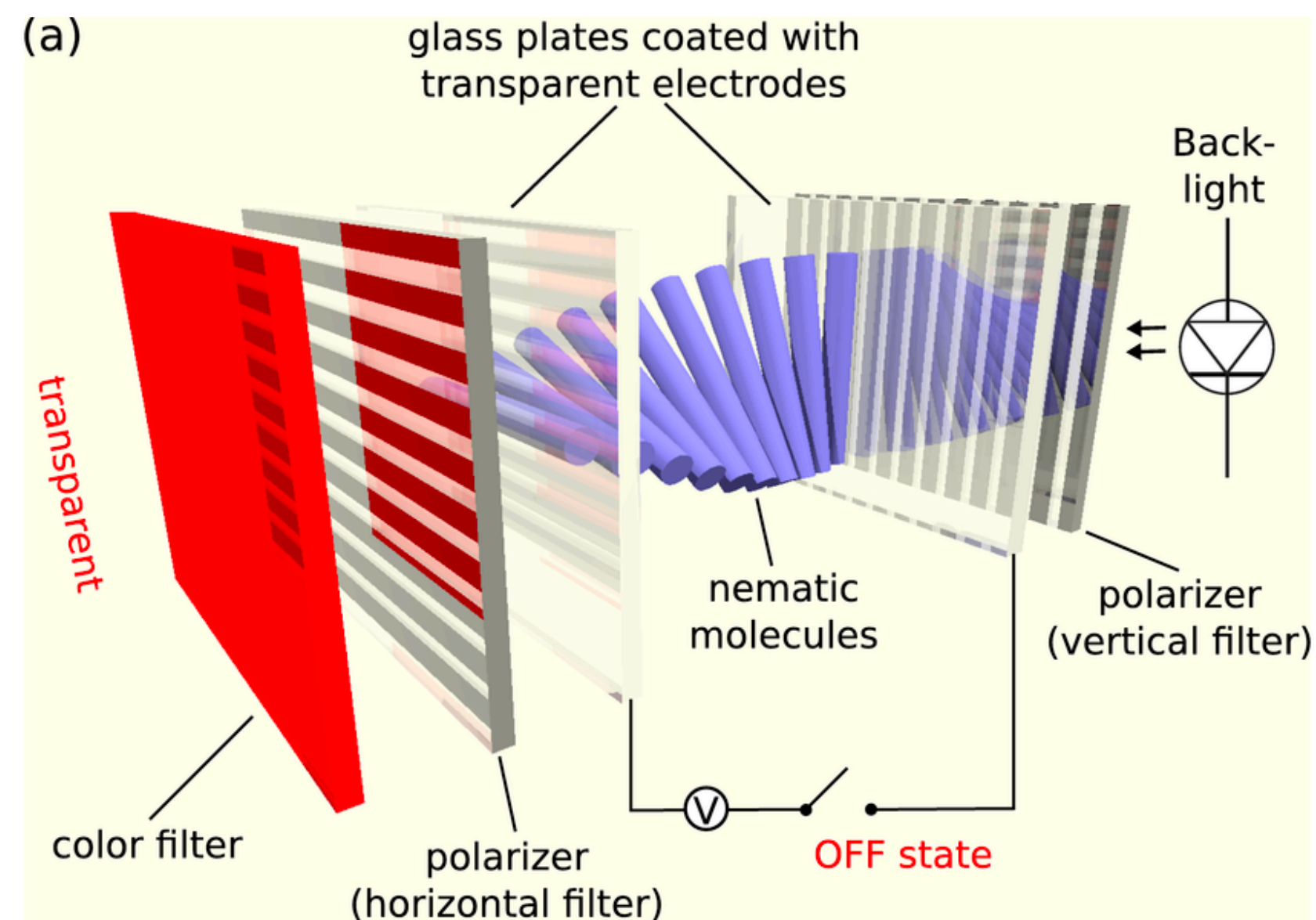
- TFT and Electrodes
- Rear Polarizer
- Backlight



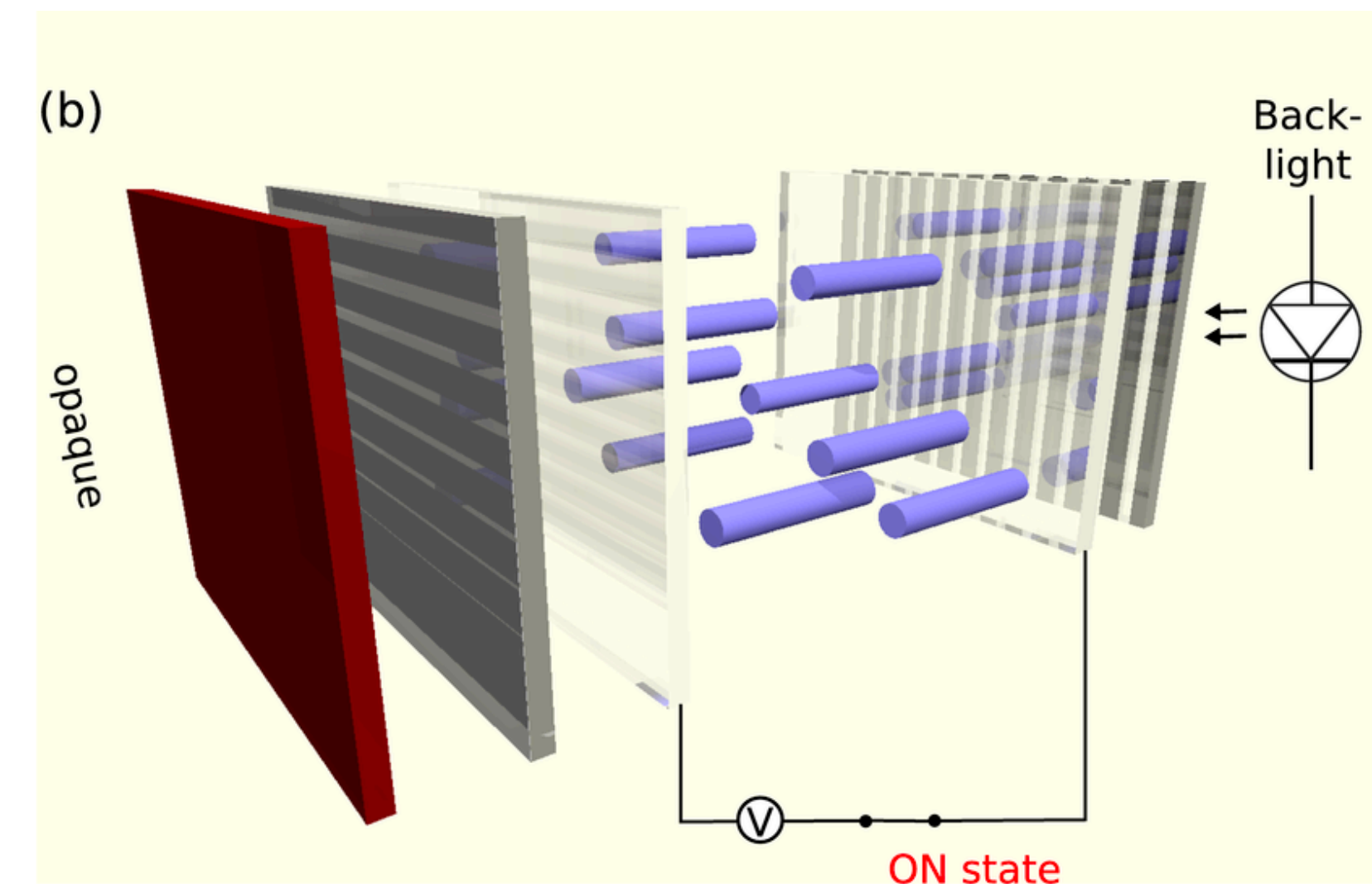
White back light

Controlling Intensity of LCD Pixels

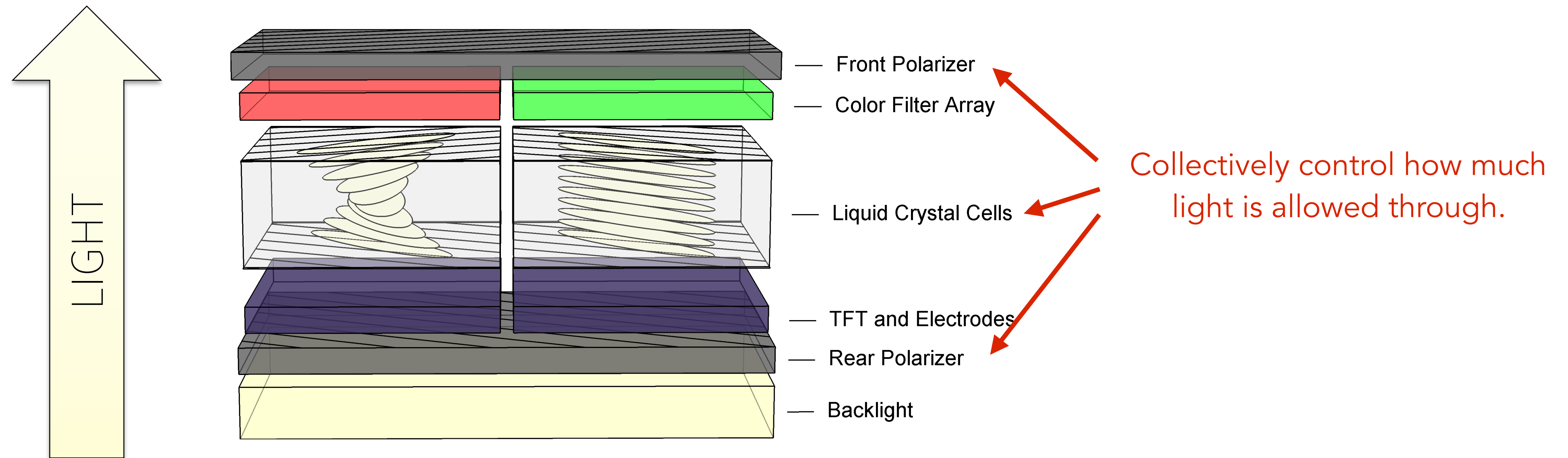
In natural state, the liquid crystal rotates light by 90° so that light passes through the output polarizer.



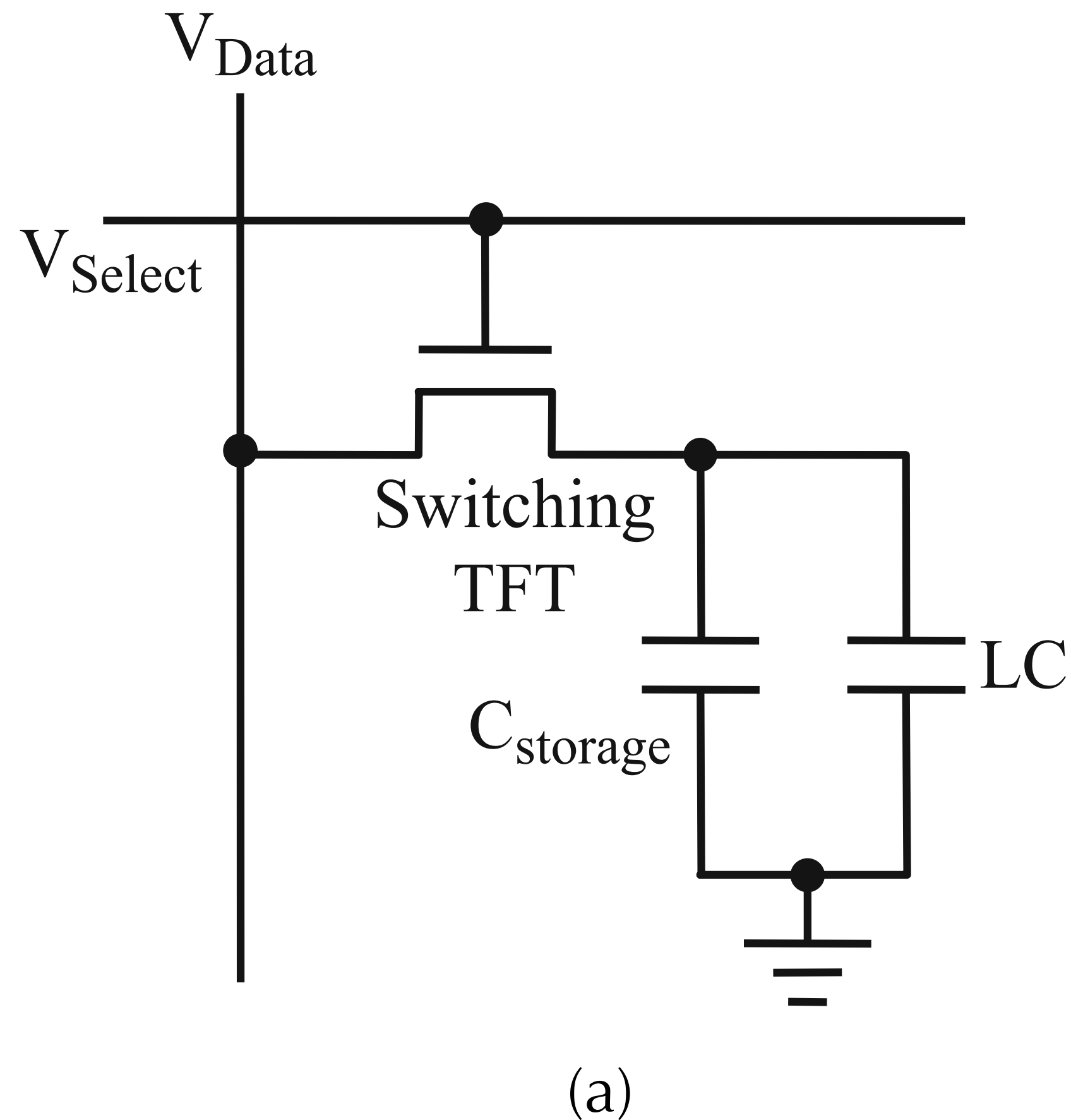
When applied electric field, the liquid crystal causes no change to light, which is blocked by the output polarizer.



Controlling Intensity of LCD Pixels



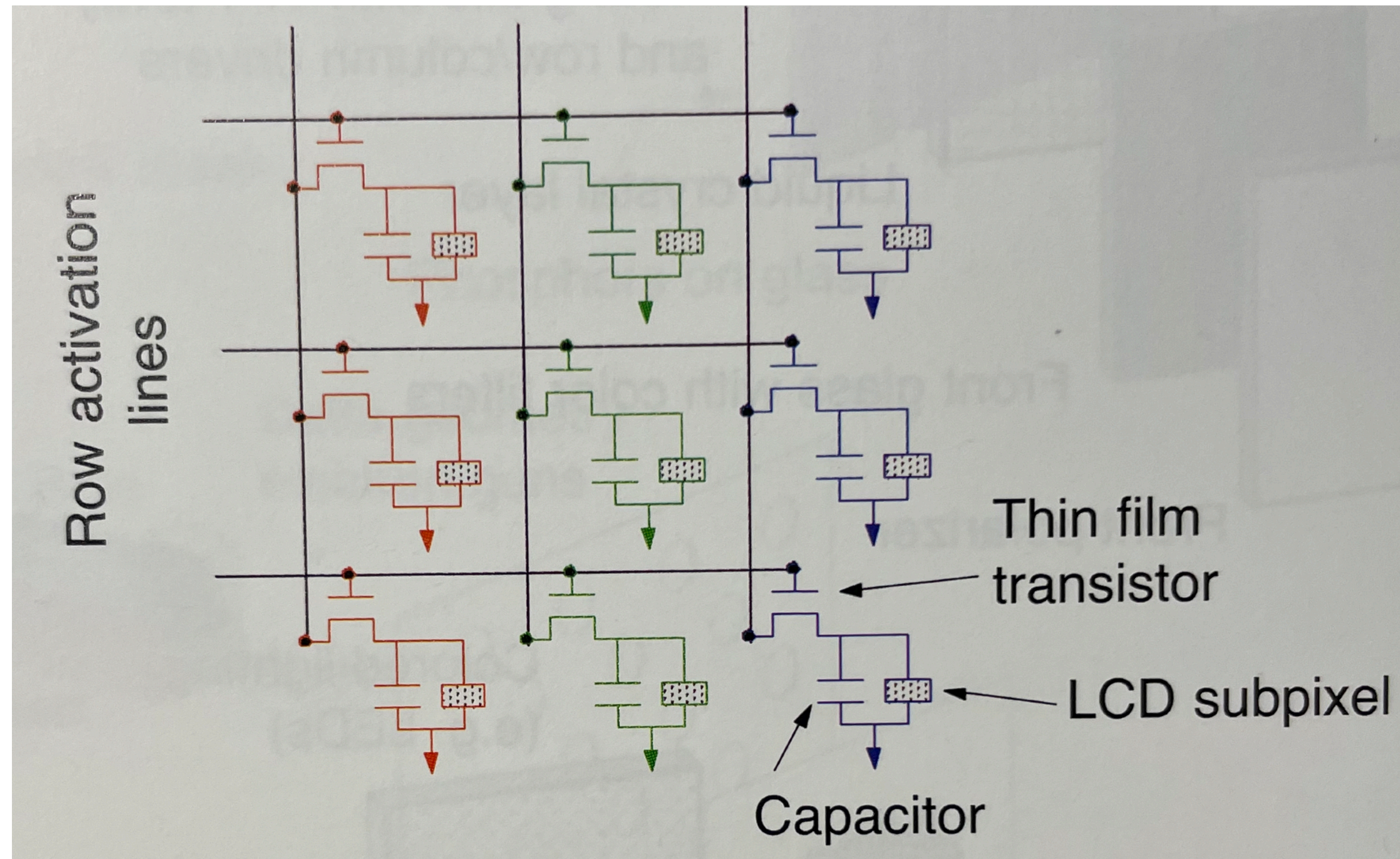
LCD Pixel



An LC cell is a voltage driven device; there is almost no current flowing through the LC.

Same as OLED: store the voltage into $C_{storage}$ by programming V_{Data} .

LCD Pixel Array Circuit



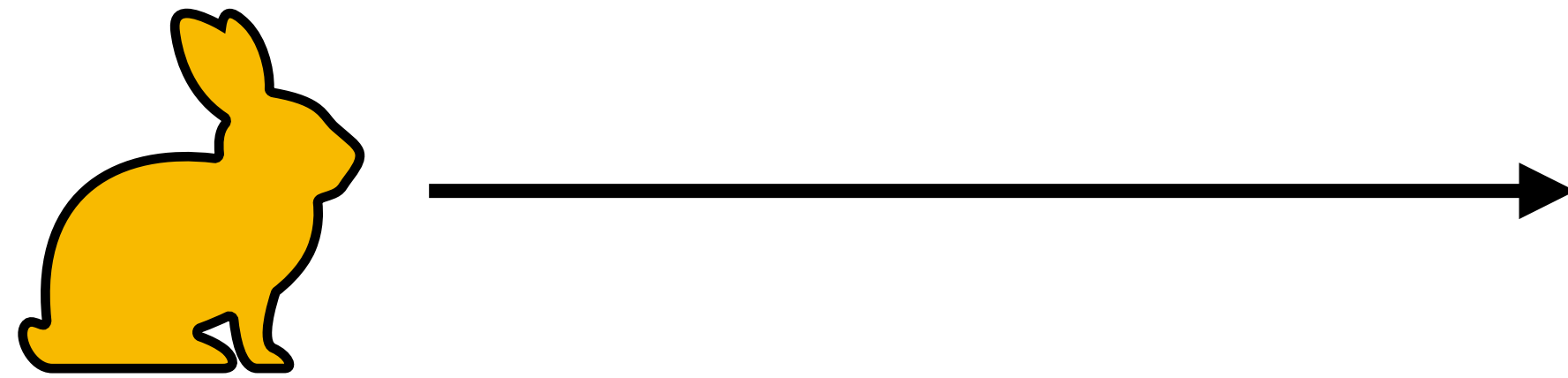
Array-like structure, similar to OLED/SRAM. Each row is refreshed separately.

The thin film transistor acts as an access switch. The capacitor holds the charge before next refresh.

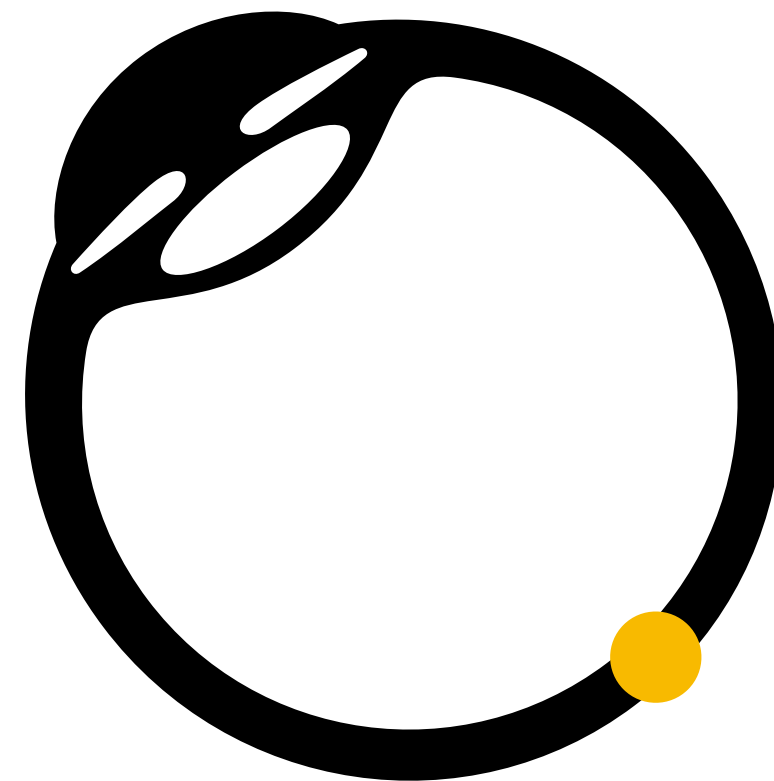
“Low-Persistent” Displays

Refresh Rate and Motion Blur

Actual Object
Movement
(Continuous)

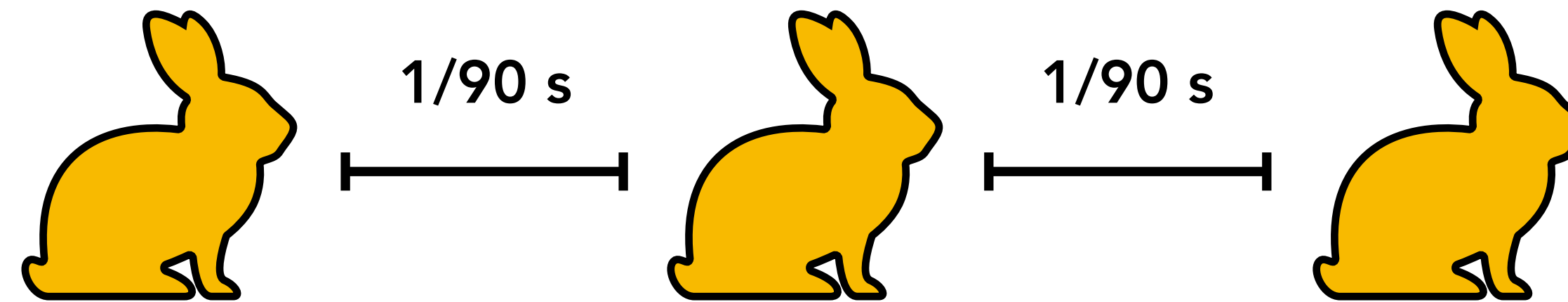


Eye Pursuit
(Continuous)



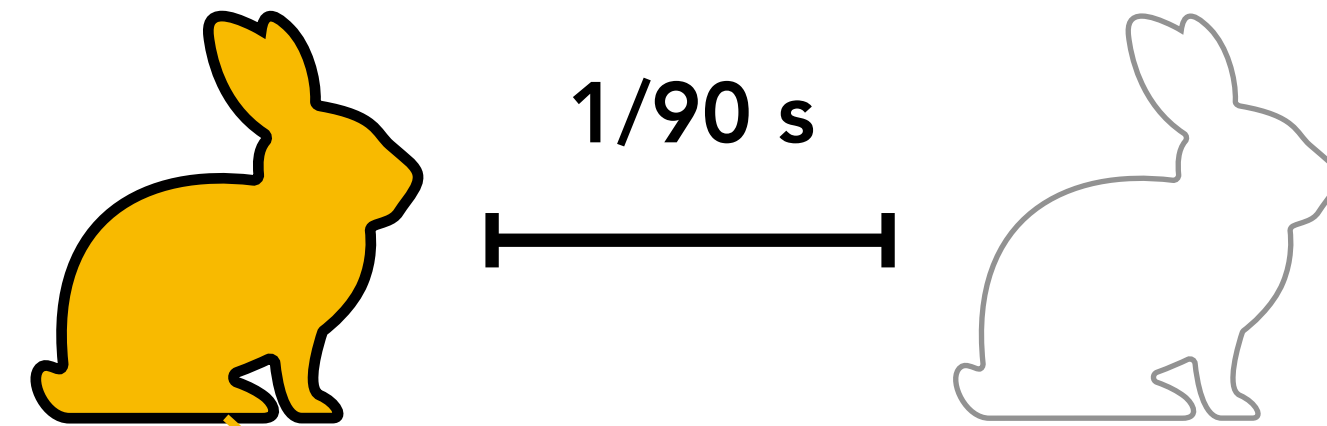
Refresh Rate and Motion Blur

Displayed
Frames
(Discrete)



Refresh Rate and Motion Blur

Displayed
Frames
(Discrete)



Eye Pursuit
(Continuous)



Refresh Rate and Motion Blur

Caused by the “sample and hold” nature of displays. Your eyes tend to perform smooth pursuit but object appears on display in discrete locations.

The end result is the object smears across your retina — motion blur.

Fixes: reduce the size of the smear

- Increase the refresh rate (cons: power increase)
- Use “low-persistence” mode: for each refresh cycle display the image only for a short period of time with a black screen for the remaining time before next frame arrives (cons: lower brightness)

Variable-refresh-rate displays have been investigated.

Sequential Color Displays

Field Sequential Color (FSC)

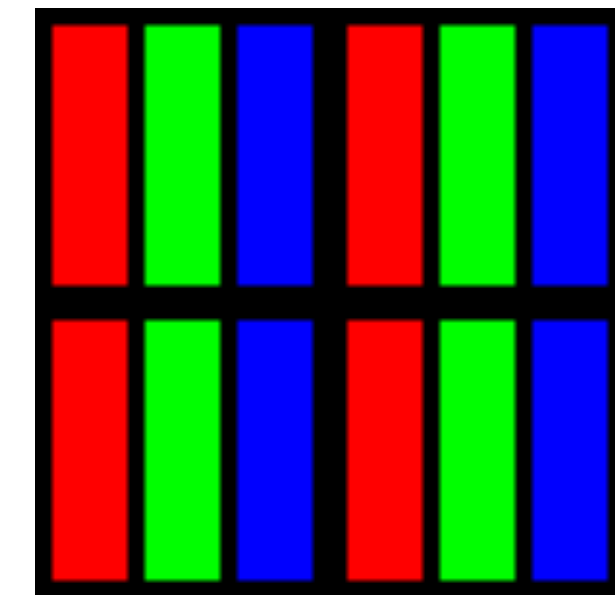
Flash each primary at a high rate. Relies on **temporal integration** in human visual system, which fuses successive images into a color picture.

Color filtering array **spatially** adds colors; FSC **temporally** adds color.

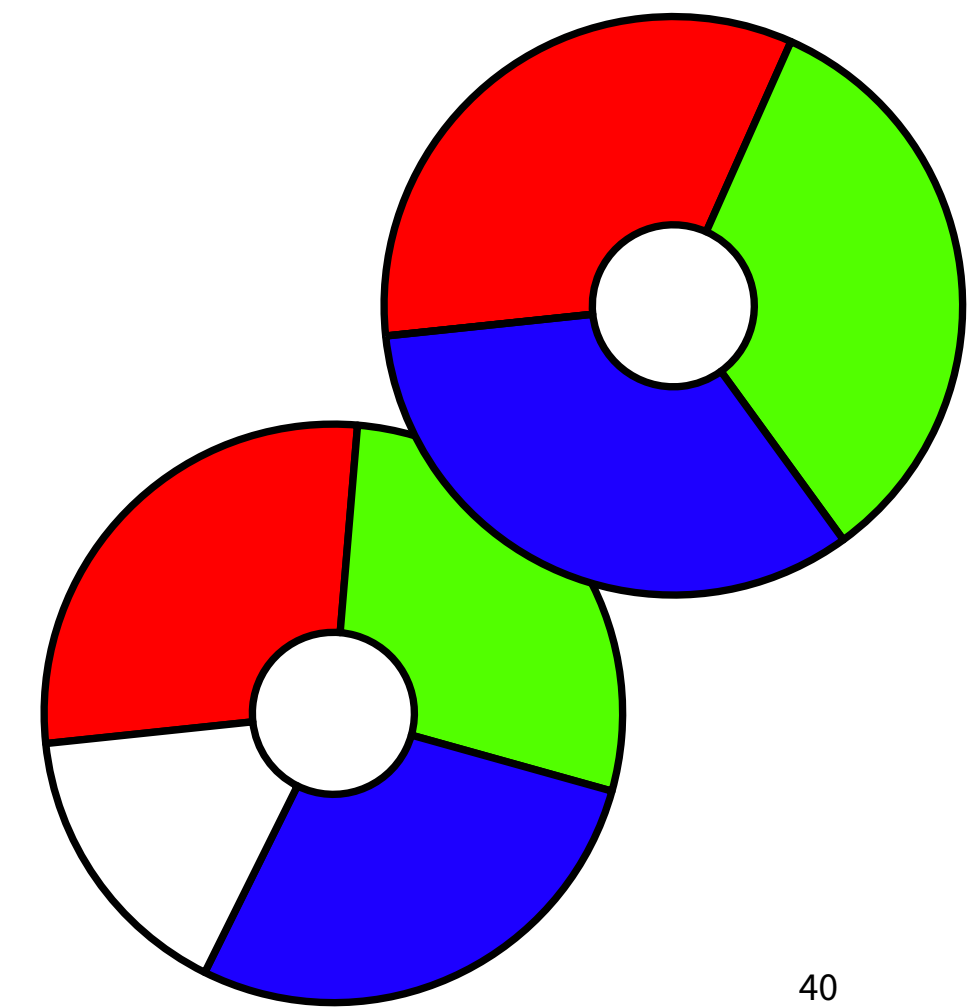
Compared to using color filtering arrays:

- + 3X higher resolution if nothing else changes.
- + higher luminous efficacy (if not using filters).
- + manufacturing cost is lower.

Color
filter array



Color
wheel



40

CBS FSC TV System

CBS debuted the FSC TV system in 1940.

- Obsolete now. Watch a [video](#) demo.

24 rotations per second. Each color is scanned twice per rotation.

Transmitted images are black and white. Each image (also called a field) is unique and is in-sync with the color filter.

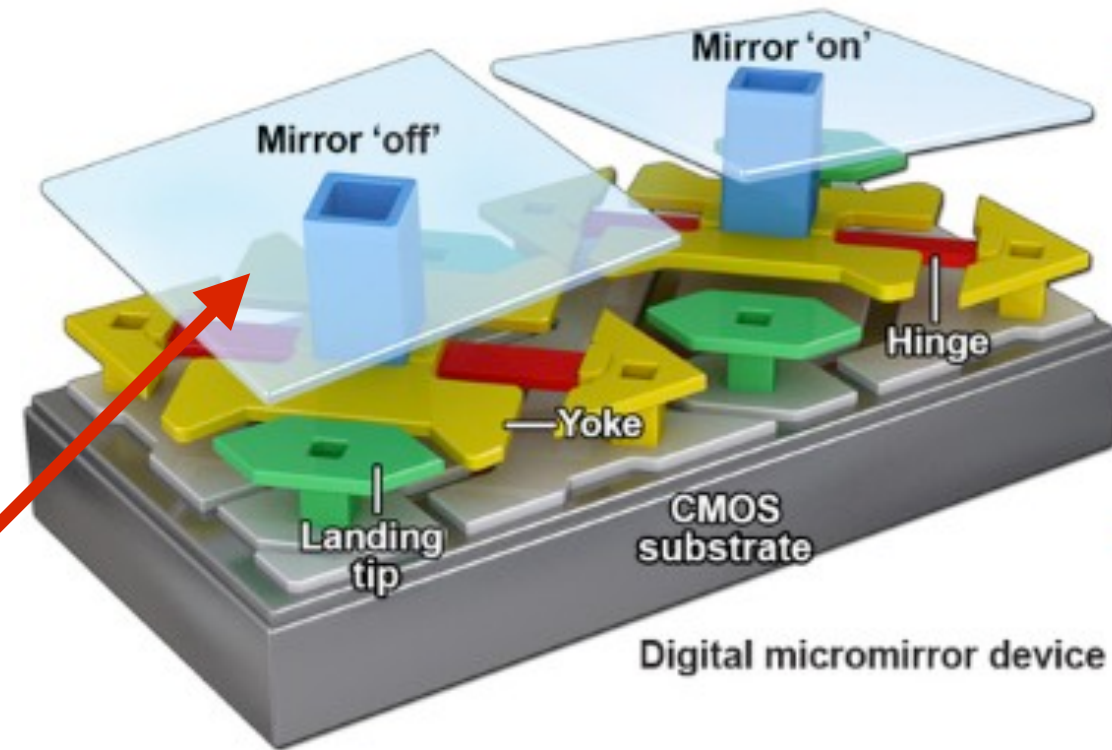
- Each B/W pixel encoded brightness.

$24 \times 6 = 144$ fields/s transmitted.

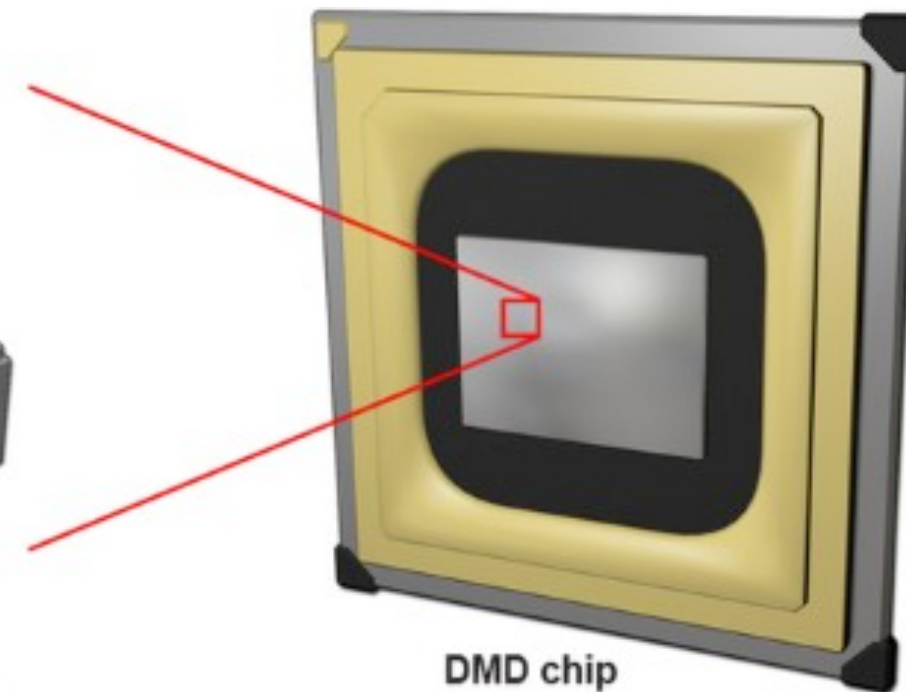


FSC in Digital Light Processing (DLP) Projectors

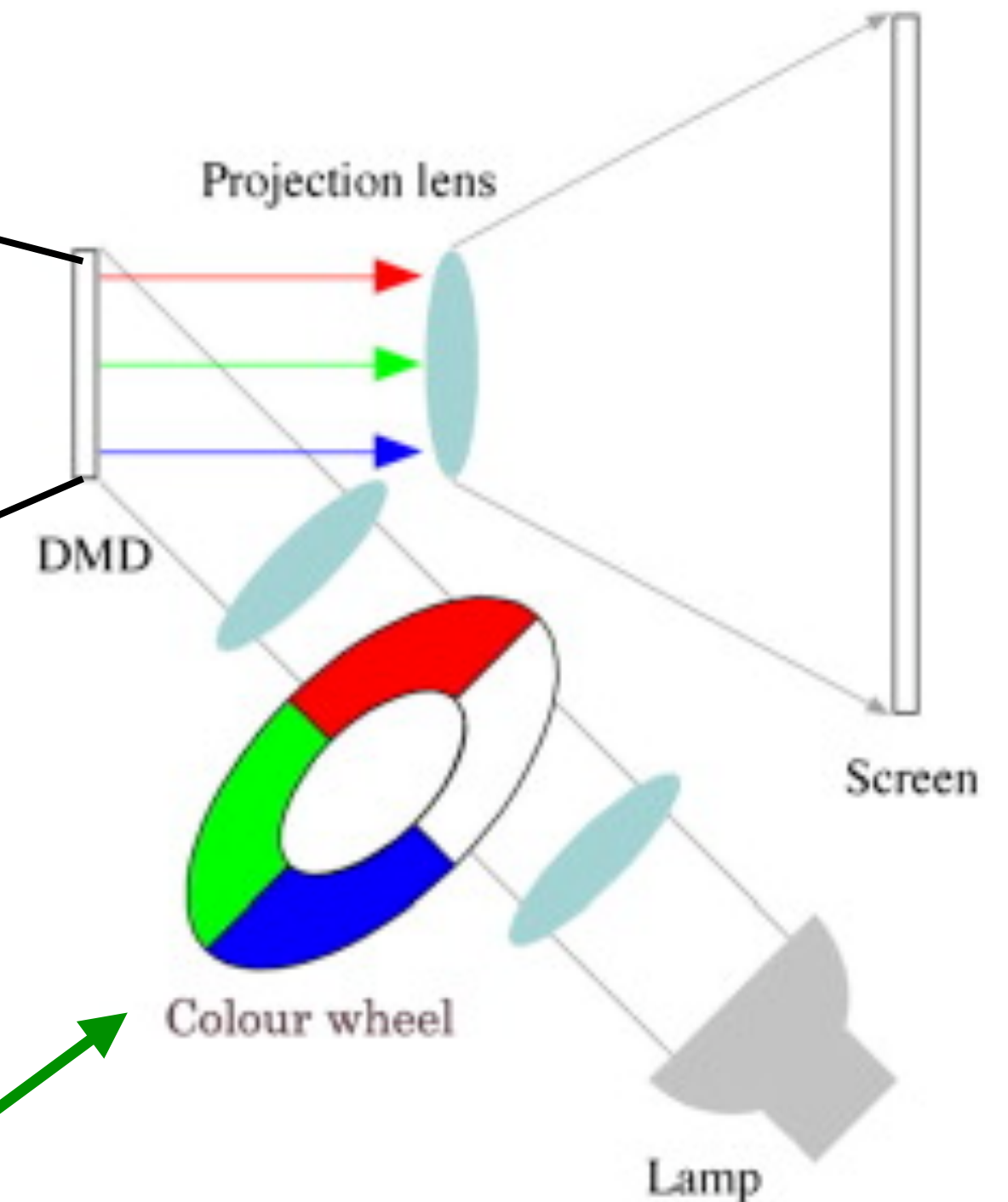
DMD (created by TI at 1987)



Per-pixel mirror controls the brightness of light at each pixel. "Off" means the mirror reflects light away from the lens. A mirror can be switch between on/off thousands of times a second and with ~1024 levels (resolution).



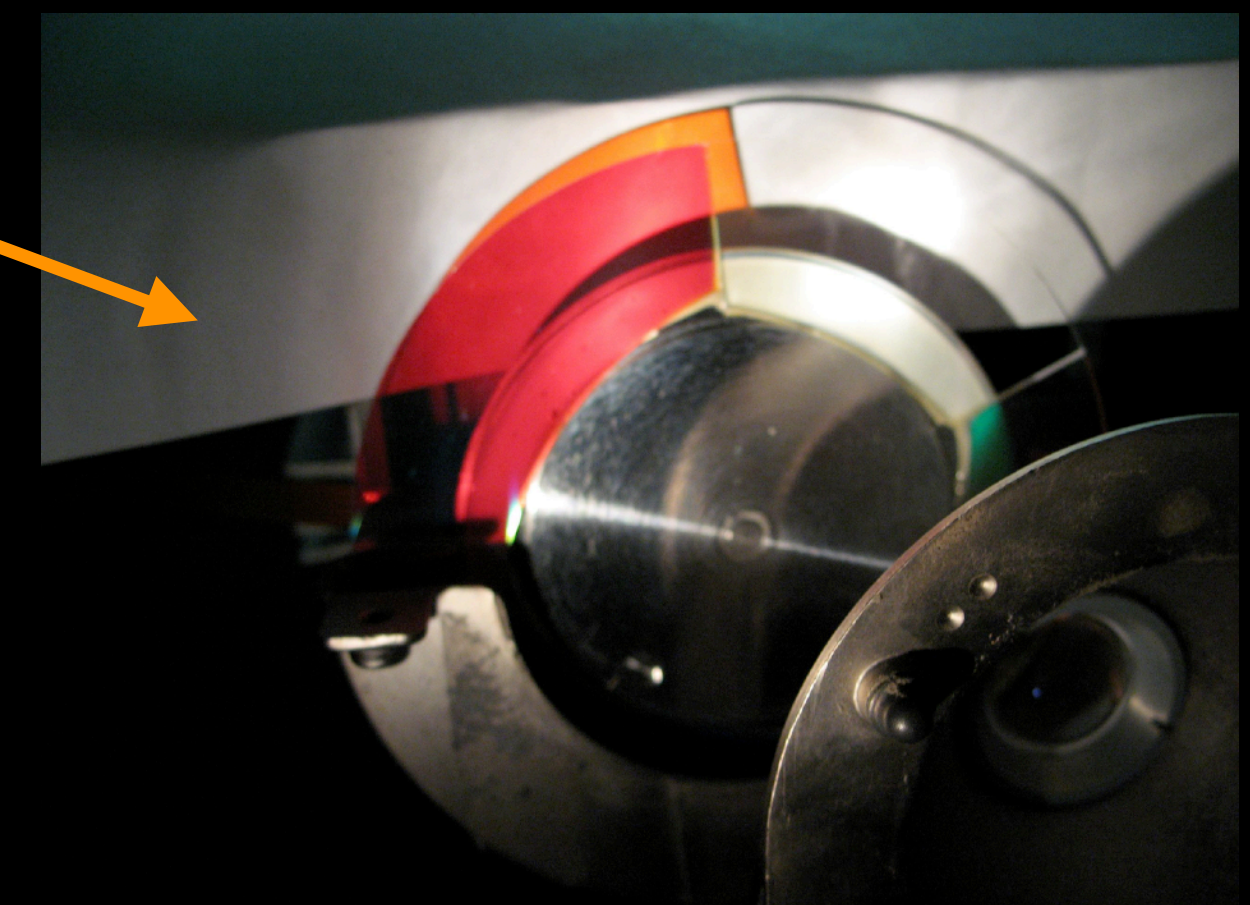
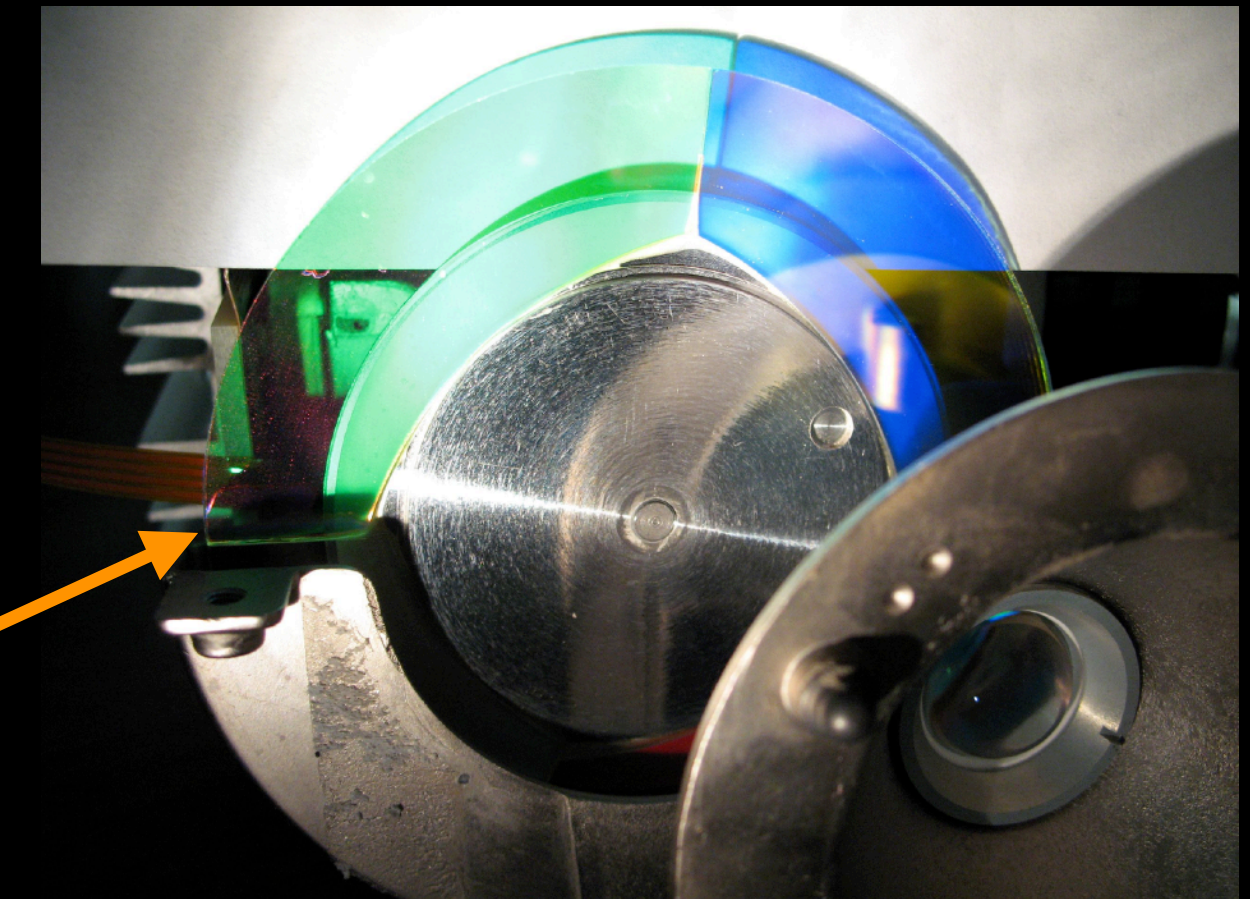
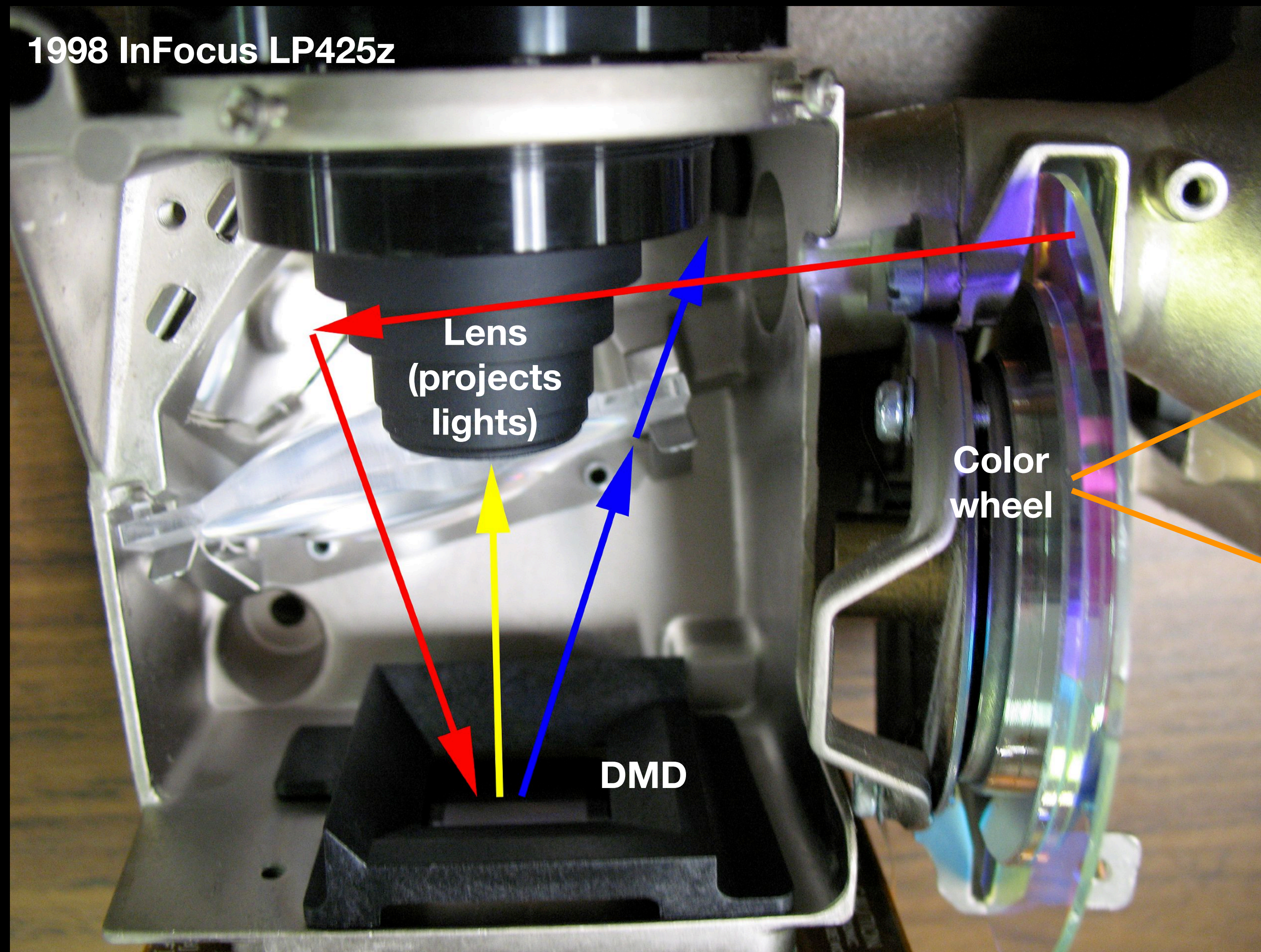
The spinning color wheel (only 1 in the projector) controls the color of each pixel.



The mirror orientation and the color wheel rotation must be perfectly in-sync. ~10 spin/s.



1998 InFocus LP425z

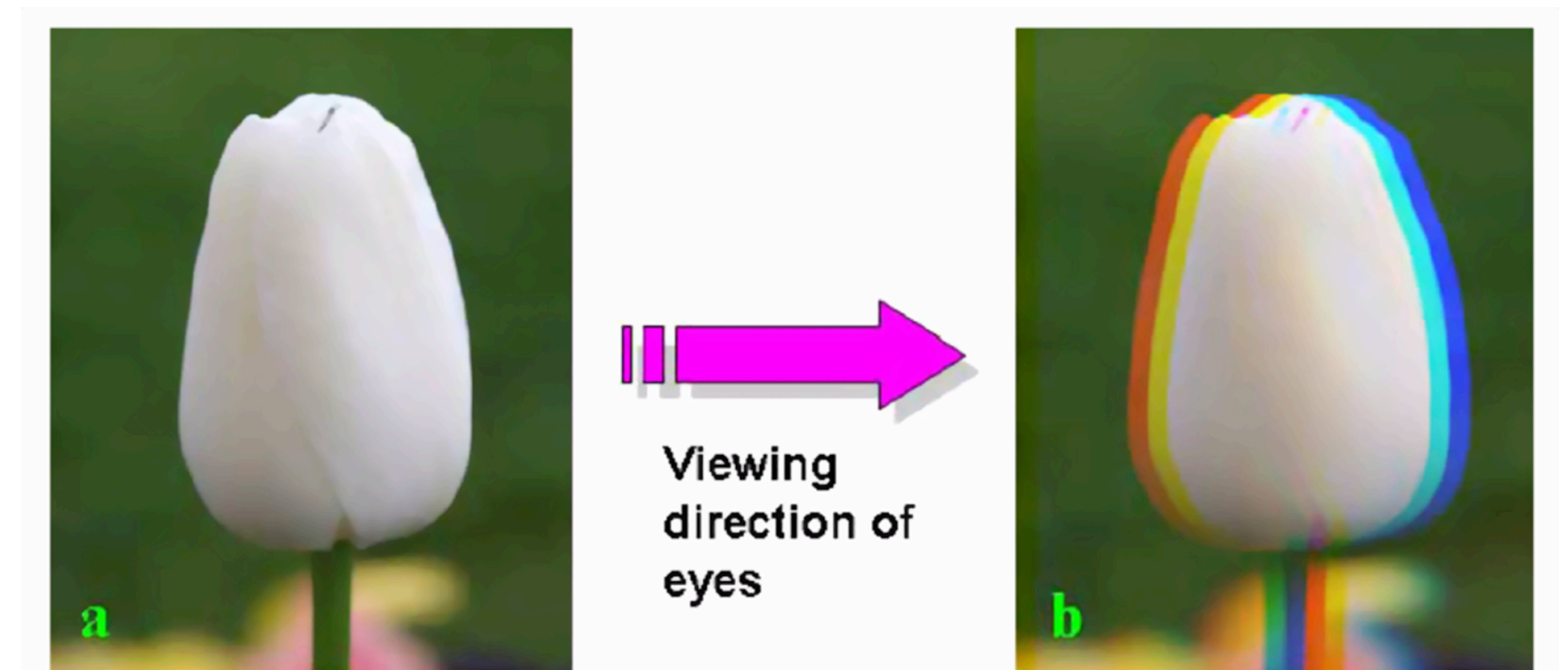
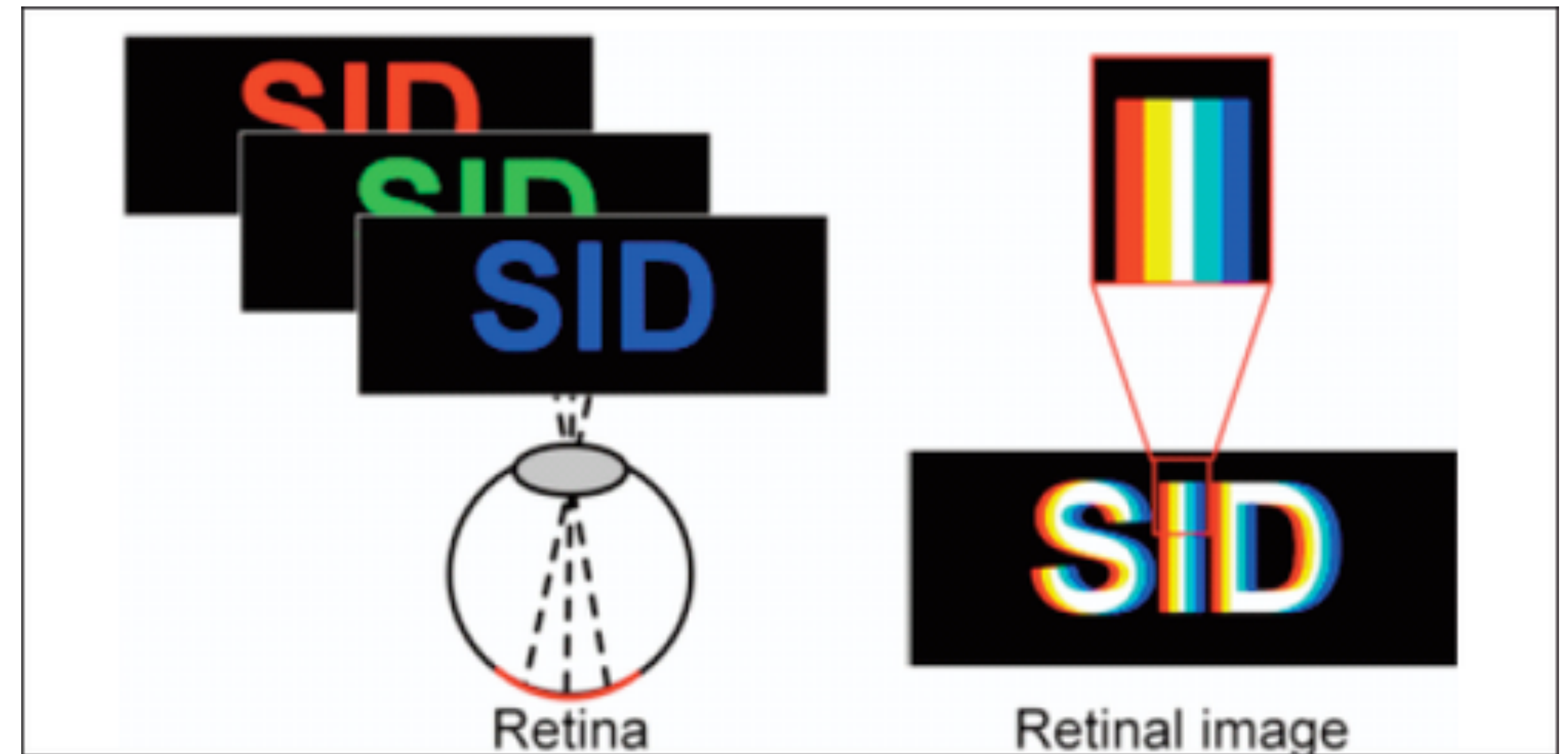


Color Breakup in FSC

Are your eyes are tracking a moving object the three color channels of the same object are sequentially captured on retina.

- In spirit similar to motion blur from low refresh rate.

A good explanation [here](#).



Things to Take Away

Displays and lighting systems serve fundamentally different purposes.

- For displays we care about the color reproduction quality.
- For lighting systems we care about its “color rendering” quality.

Displays rely on metamerisms. Two main display types: LCDs and LEDs

- Low resistant displays
- Sequential color displays