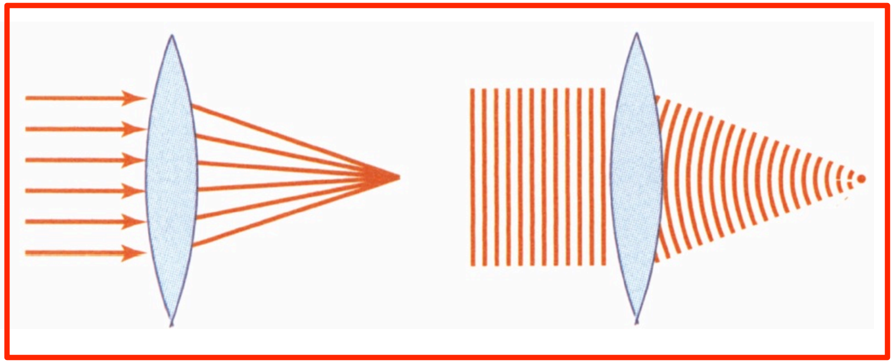
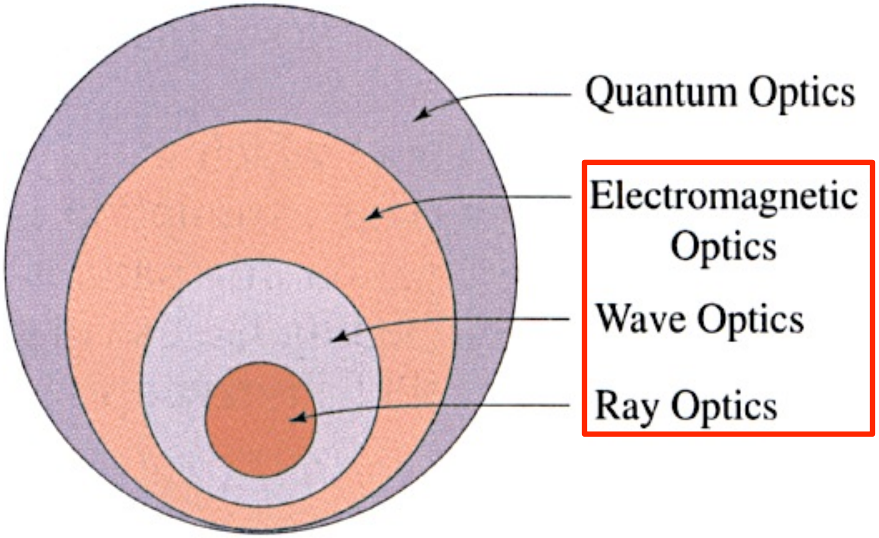
9 – Display Technology

Today…

- Most topics today are based on principles we have covered previously in the course…



Credit: *Fund. Photonics – Fig. 2.3-1*



Credit: *Fund. Photonics – Fig. 1.0-1*

- Topics:

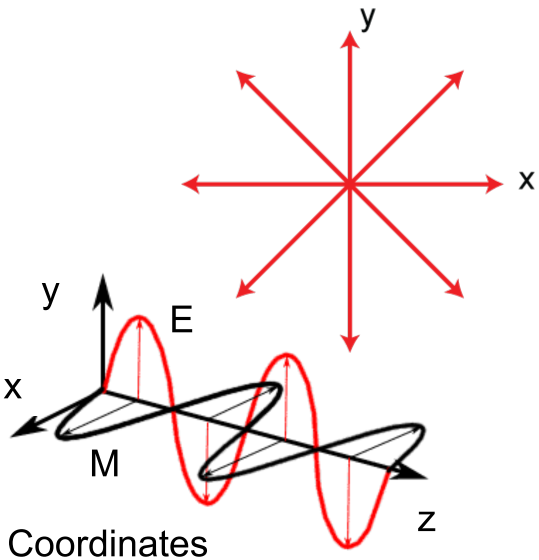
(1) Transmissive Displays
  - Focus on LCDs (dominant transmissive technology)
  - Basic operating principles
  - Active Matrix Drive

(2) Emissive Displays
  - OLEDs!
  - Active Matrix Drive

(3) Reflective Displays
  - Electrophoretic (E-Ink)
  - MEMS (Qualcomm)

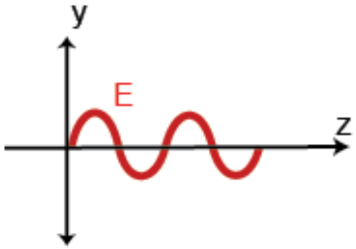
Polarized Light

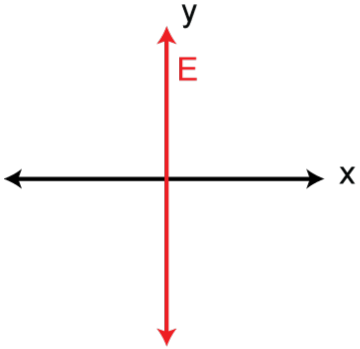
- Unpolarized light



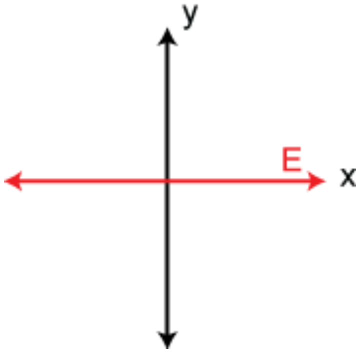
Coordinates

- Linearly polarized light…

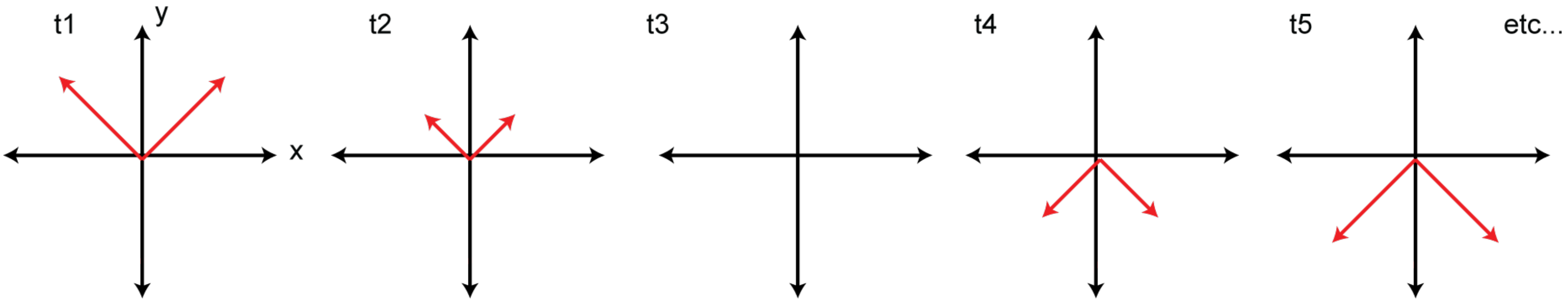




90 deg. rotated…

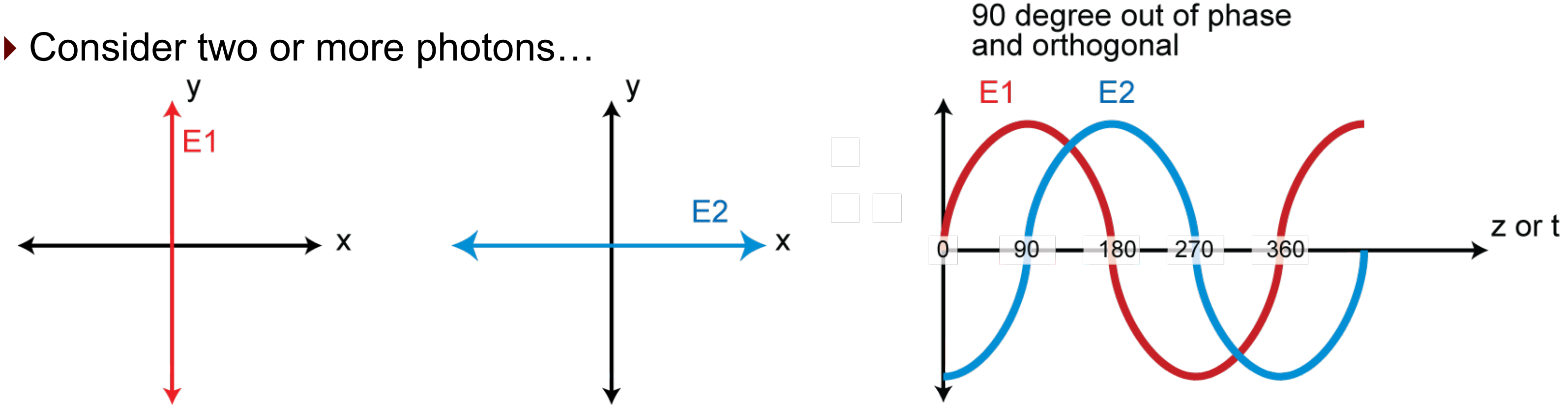


- Also linearly polarized light (think resultant for vectors…)

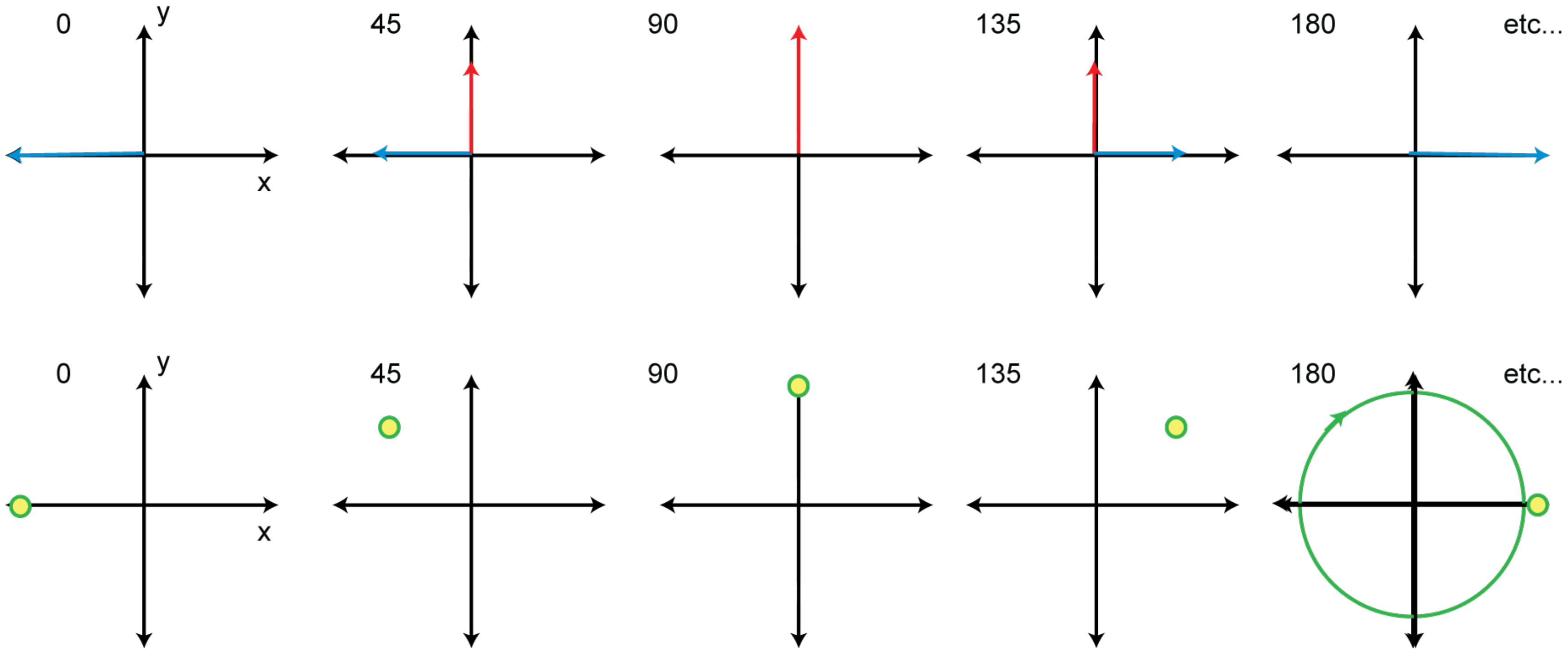


Polarized Light

- Consider two or more photons…

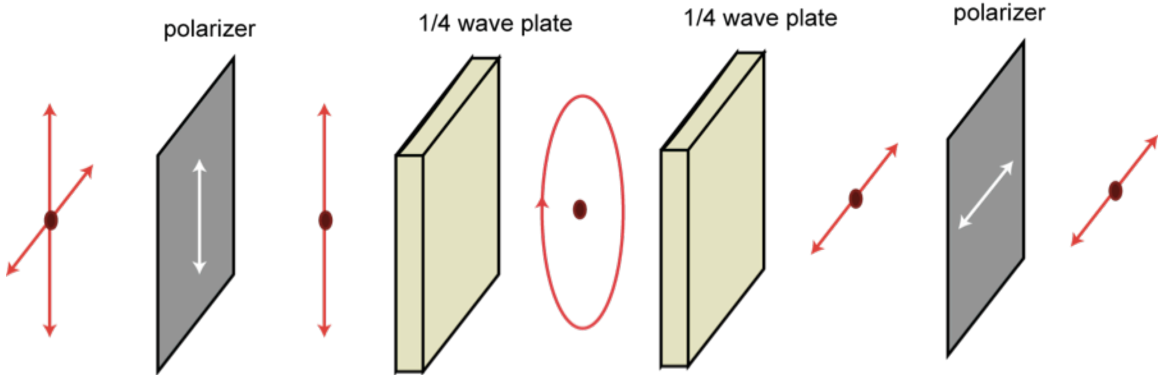


- *So what type of polarization is this?*

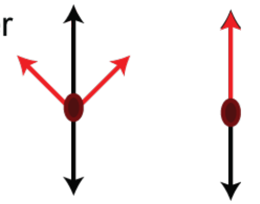


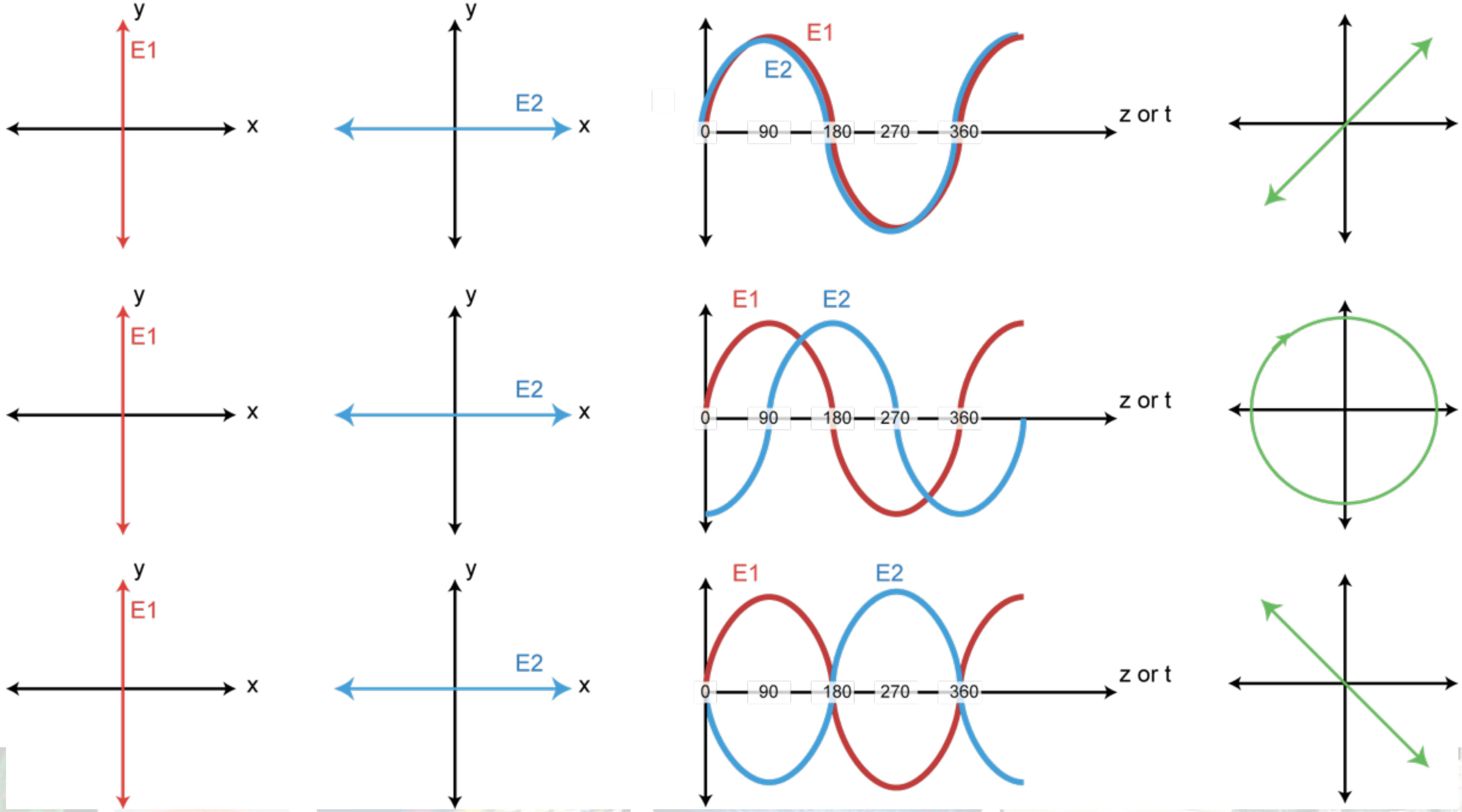
A <u>circularly polarized wave </u>may be resolved into two linearly polarized waves, of equal amplitude, 90 degrees apart, and with their planes of polarization at right angles.

Birefringence



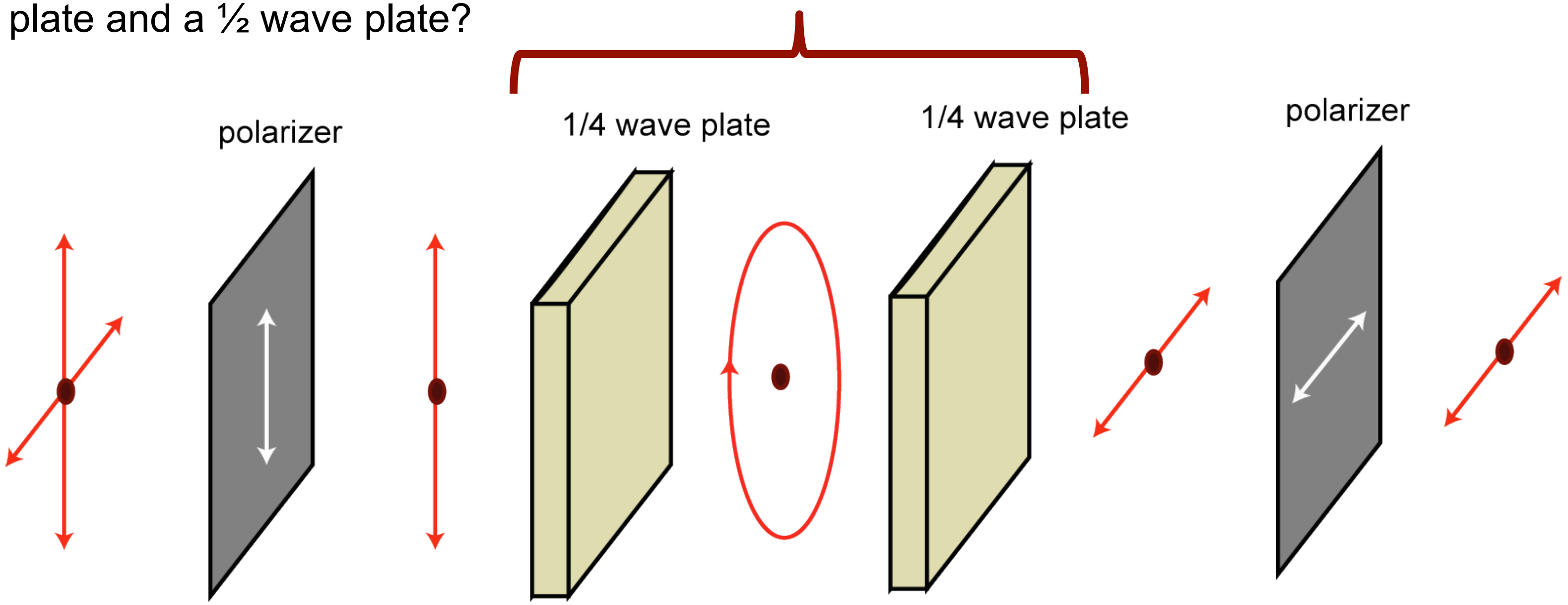
remember these are the same...





Wave Plates

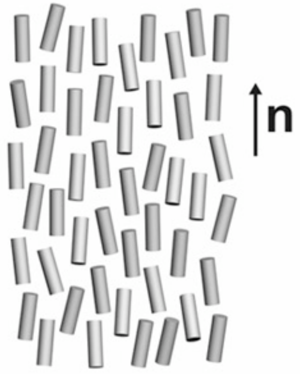
- So what if we could electrically switch several states between NO wave plate and a ½ wave plate?



Liquid Crystal Displays

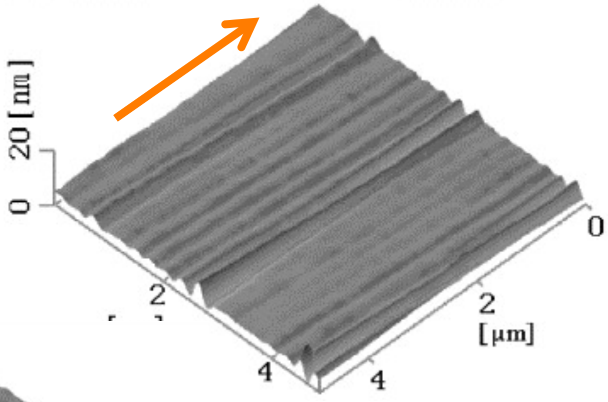
- This is a diagram of Nematic liquid crystal..

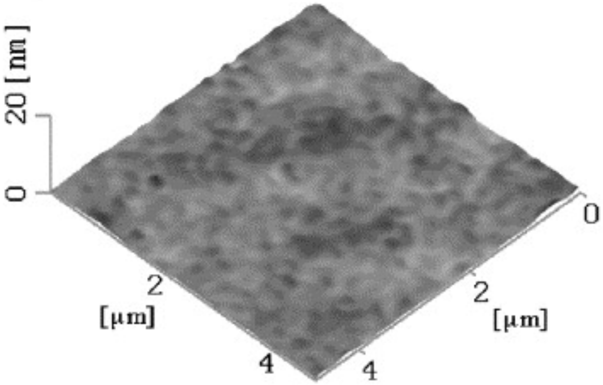
Why called a crystal?
Why birefringent?



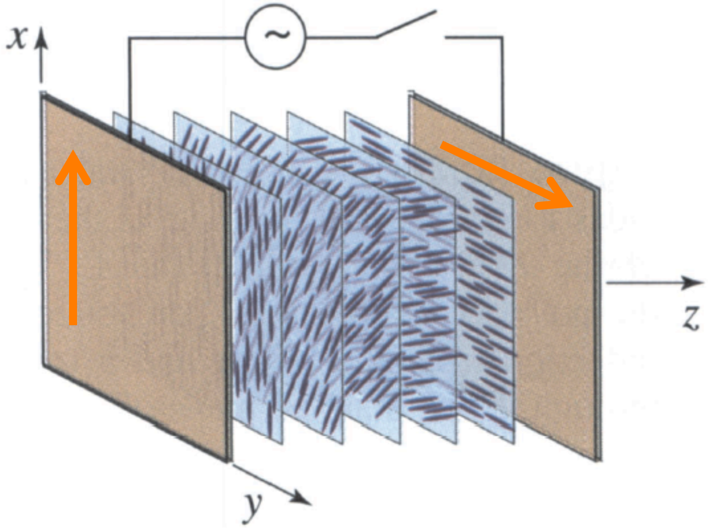
Credit Kent State.

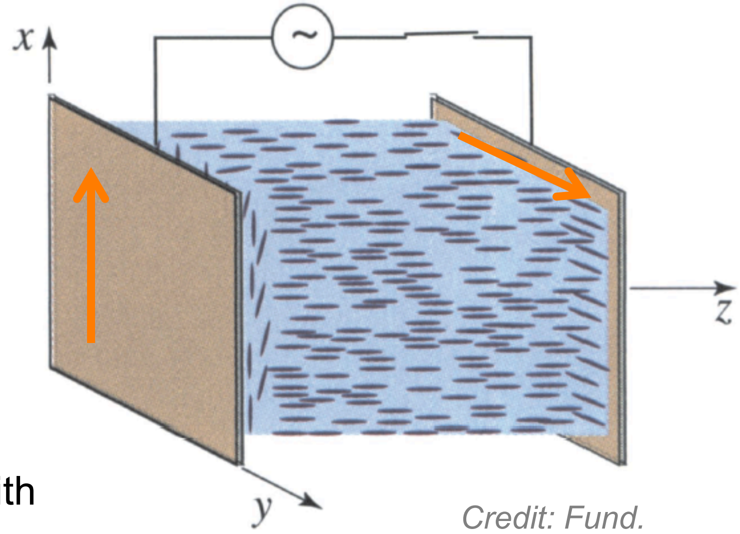
- You can create a *Twisted* Nematic (TN) cell by directional 'rubbing' of polyimide with a cloth, which makes parallel grooves that the liquid crystal molecules line up with. To make it twisted, put between two such plates rotated by 90 degrees!





- Apply voltage! Molecules align with the E-Field!

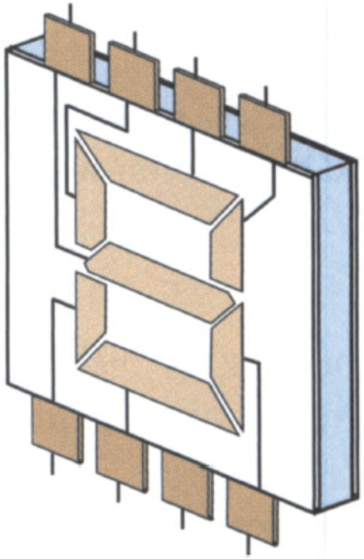


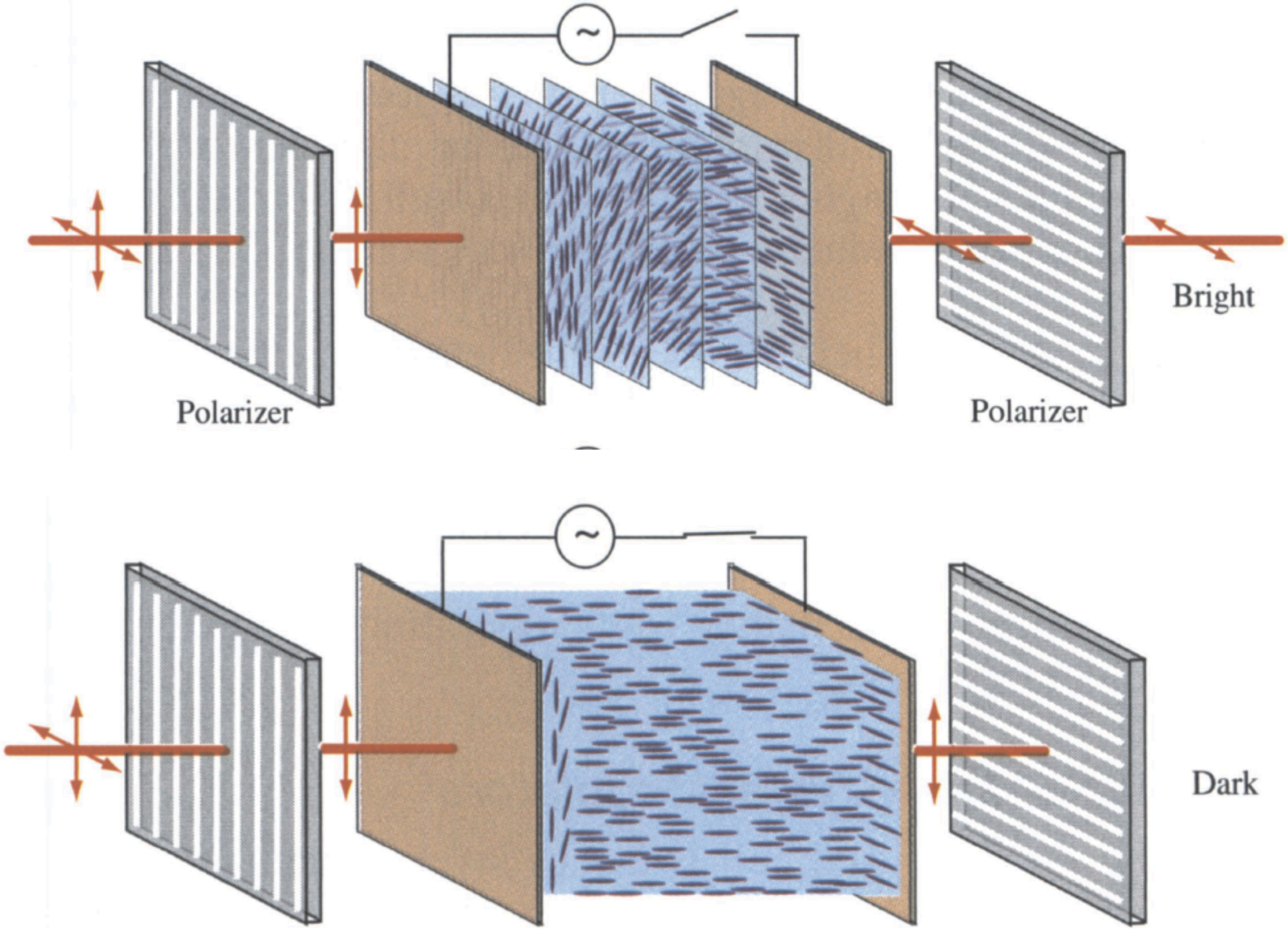


Credit: Fund. Photonics – Ch 20.

Liquid Crystal Displays

- Switchable ½ wave plate!

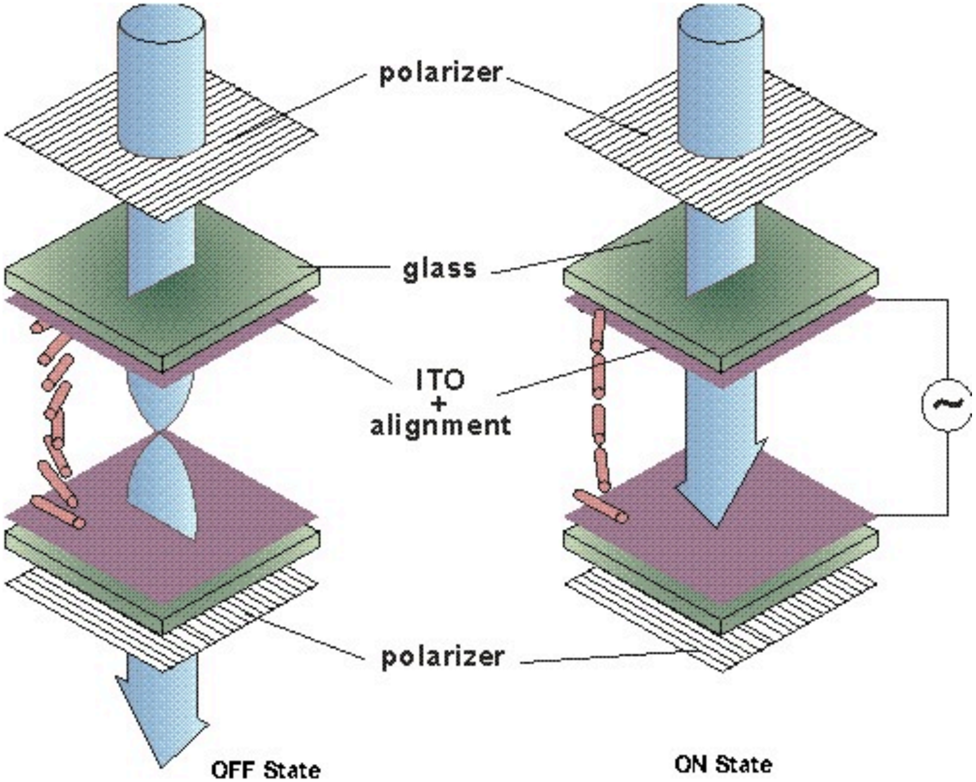




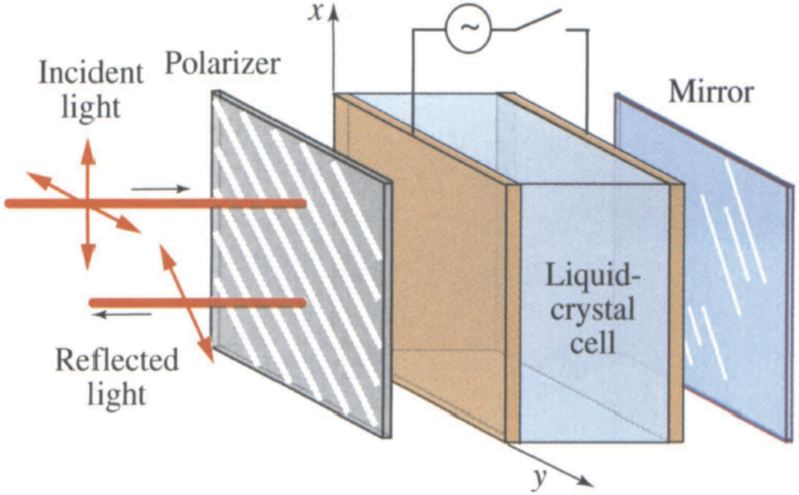
Credit: Fund. Photonics – Ch 20.

Liquid Crystal Dipslays

- Notice how the birefringence is always maximally aligned (maximum effect) as the polarization is rotated!

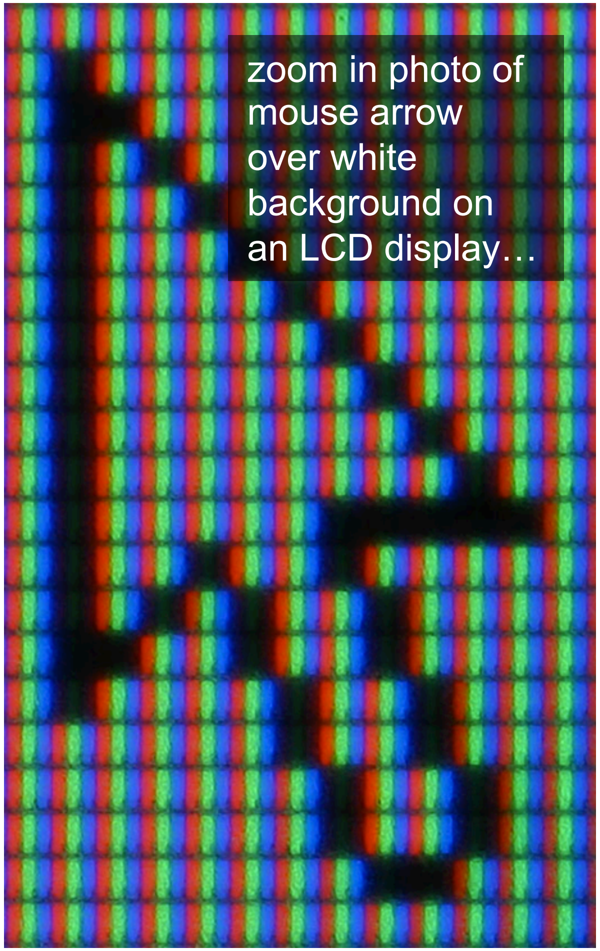


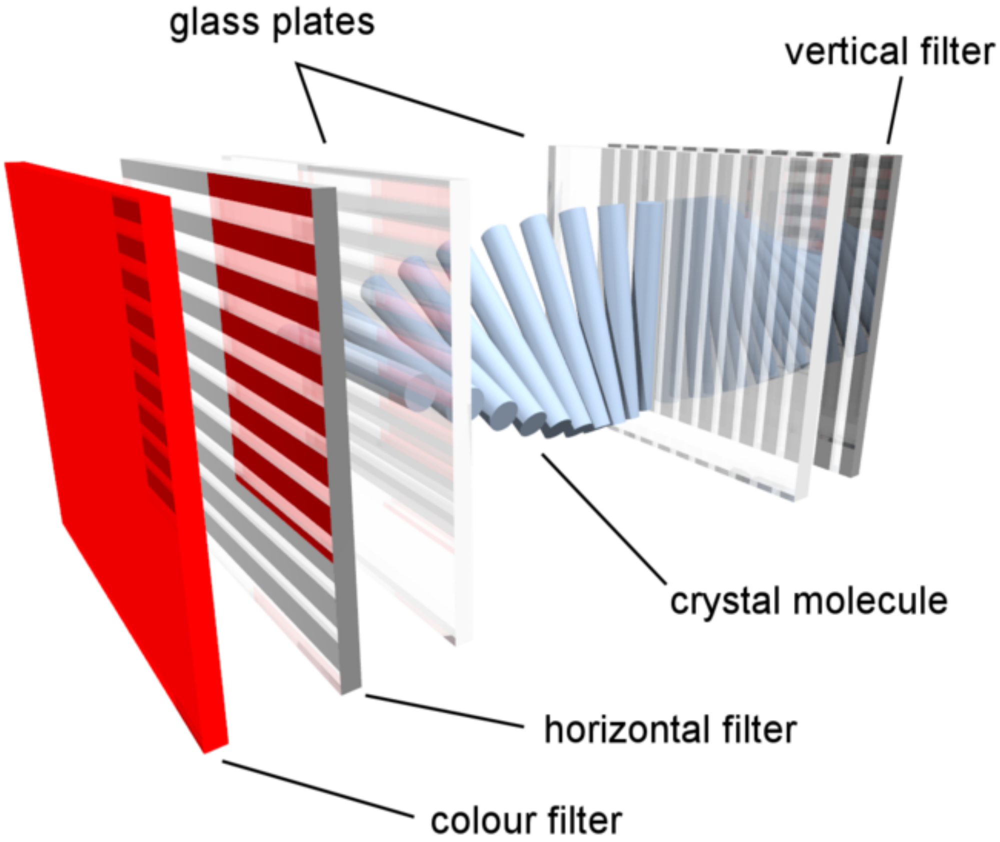
- If you wanted to make this a reflective device (like LCD wrist watch), how would you change the thickness of the liquid crystal? How many polarizers would you need?



Credit: Fund. Photonics – Ch 20.

- Add a white backlight and color filters to make it full color…


zoom in photo of mouse arrow over white background on an LCD display…



- See the video links on blackboard: *‘Week 9 – YouTube LCD 1 & 2’.*

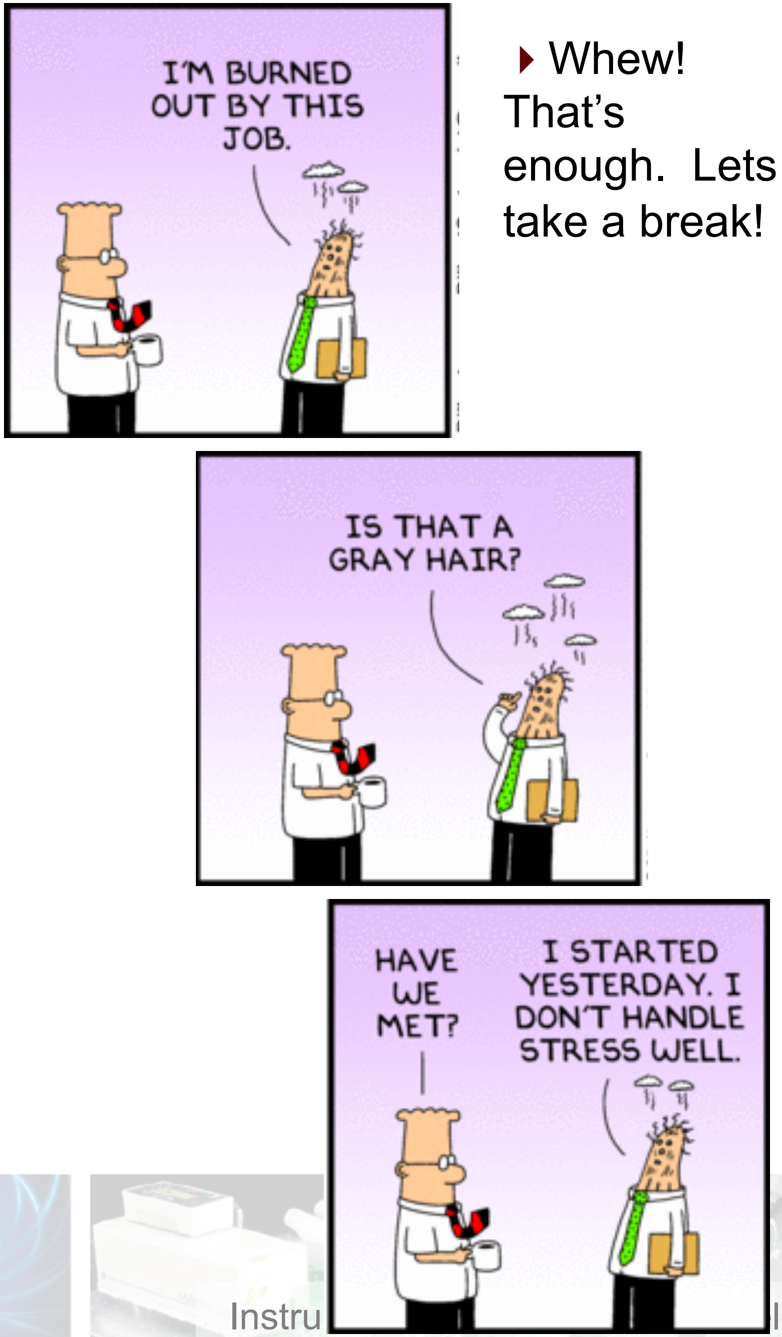
Review! Take a break!

- So what type of optical element does the liquid crystal inside an LCD display act like, in order to turn the pixel ON or OFF?

(a) A switchable absorber (clear or absorbing).
(b) A switchable polarizer.
(c) A switchable quarter wave plate.
(d) A switchable half wave plate.

- If I had an LCD pixel in front of me without polarizers (you will do this in the lab this week!) and switch it with voltage under room lighting I should see:

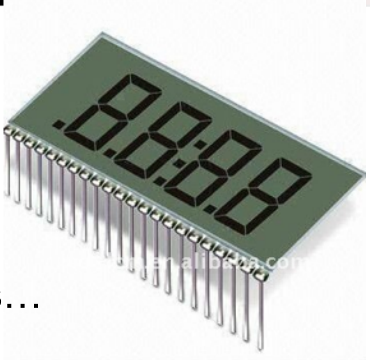
(a) Nothing.
(b) A switch between transparent or black.
(c) Sparks flying.
(d) I have no idea, I have not been in lab yet.



- Whew! That's enough. Lets take a break!

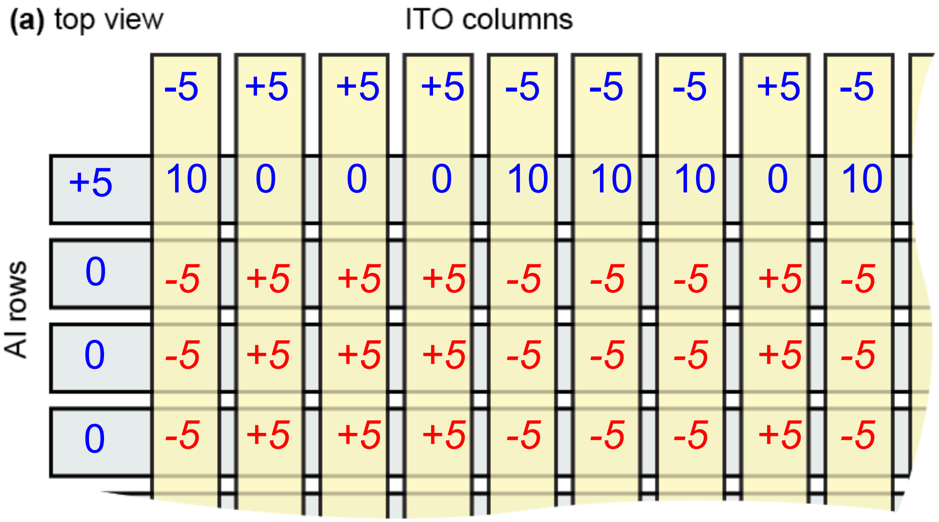
1st, How Drive Large Arrays ???

- Direct drive (segmented) displays are easy, even accommodating high voltages/currents…

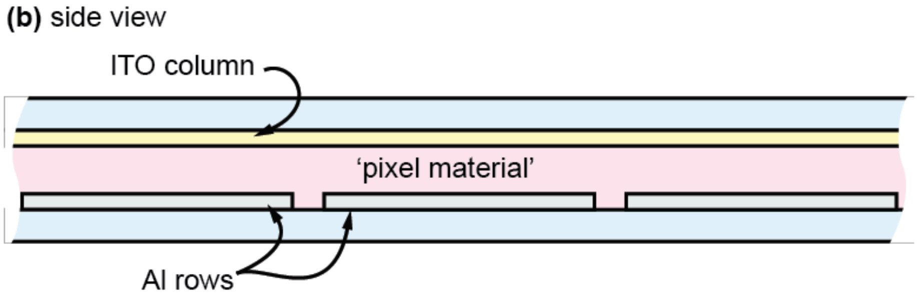


- However, if you have a pixel array of M rows and N columns you need MxN voltage controls (1000x1000=1M!)

… instead use passive matrix addressing for M+N controls (1000+1000=2000).



	-5	+5	+5	+5	-5	-5	-5	+5	-5
+5	10	0	0	0	10	10	10	0	10
0	-5	+5	+5	+5	-5	-5	-5	+5	-5
0	-5	+5	+5	+5	-5	-5	-5	+5	-5
0	-5	+5	+5	+5	-5	-5	-5	+5	-5



- Example (assume pixels need 10 V to switch).

(1) apply 5V to 1st row and data to columns, notice pixels that turn on…
(2) return row 1 to 0V then apply 5V to row 2 and write those pixels… repeat with all rows.

- Issues / limitations:

(1) if it takes 20 ms to switch the pixel, and there are 1000 rows, *that requires 20 s for one display update!*

(2) You need a threshold voltage, hysteresis, or non-linear pixel response! If need high contrast, the pixel must also be stable without voltage!

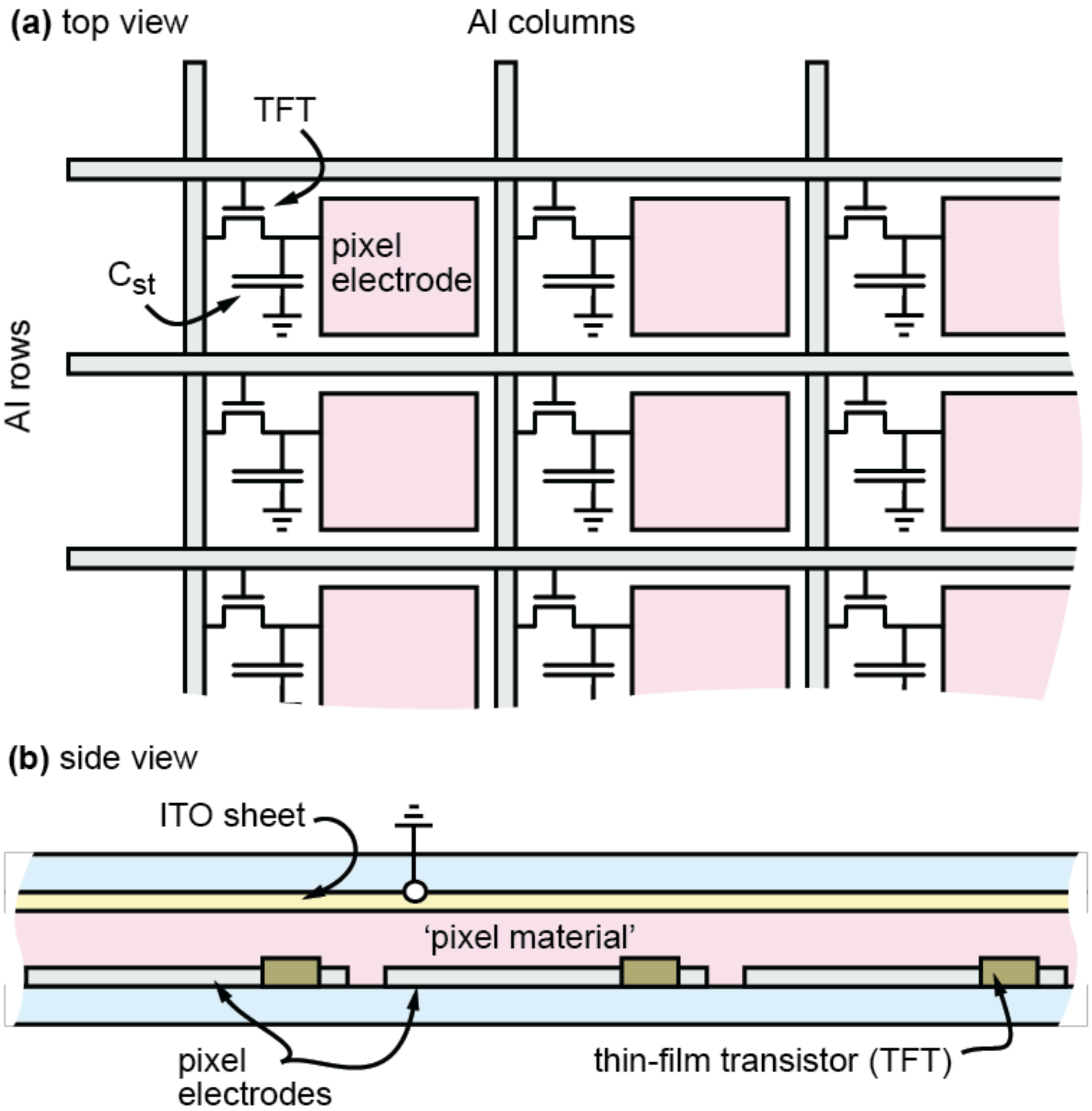
- If you want video, then you likely need active matrix… (exception is super fast pixels like MEMs or ferroelectric LC).

- If you want high quality grayscale, then you also likely need active matrix… (exception is stable without voltage or spatial dithering).

ACTIVE MATRIX: data (voltage) from column stored on pixel and Cst only when row electrode turns thin-film-transistor (TFT) ON. Why called 'thin-film'?

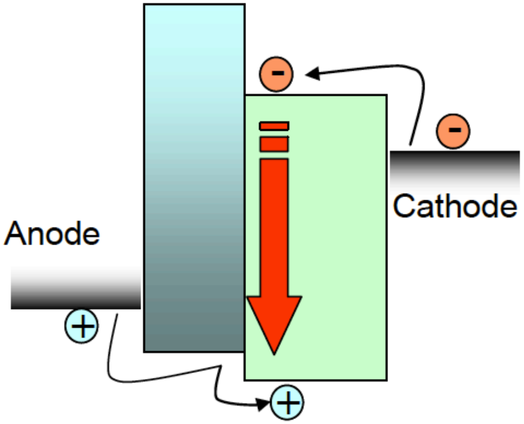
- Issues / limitations:

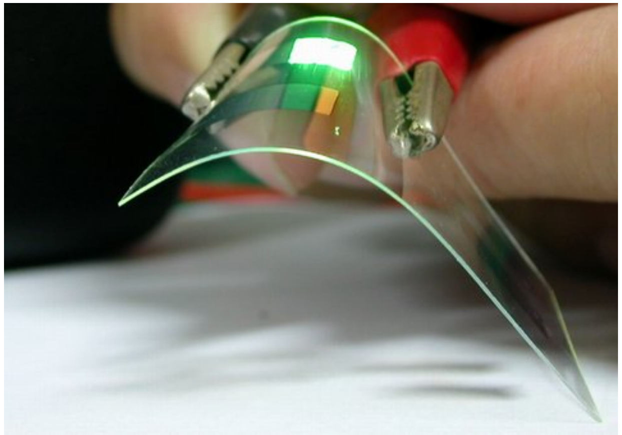
(1) TFT needs to drive the pixel capacitance in 10-40 μs (1/30/1000)
(2) TFTs block some light.
(3) Are not free! Is more expensive…



OLEDs!

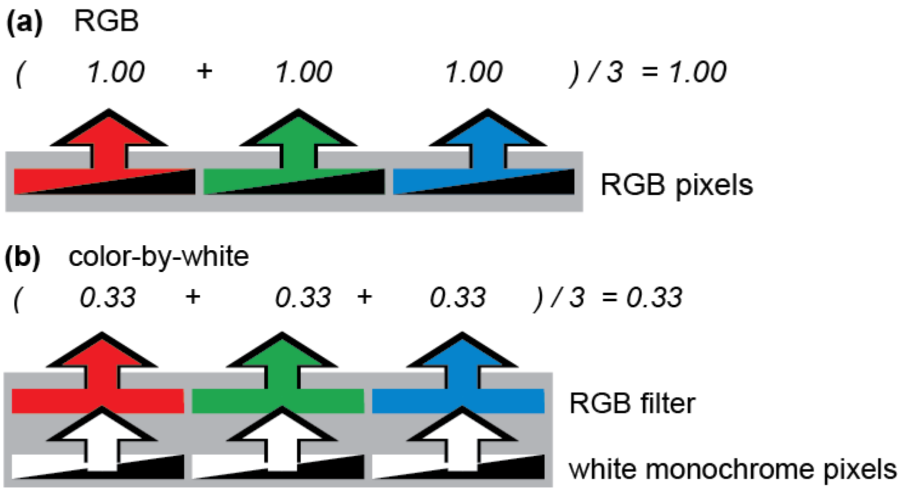
- Here is a basic organic LED (OLED) pixel structure (metal/polymer/polymer/ metal)… is like a PN junction but uses organic (plastic) semiconductors! A diode!





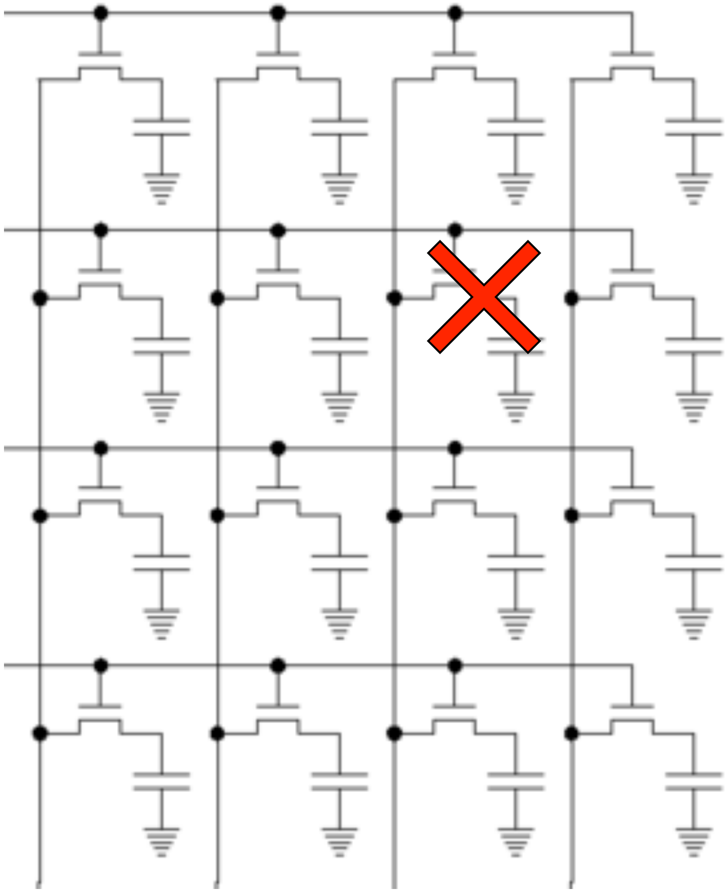
- The anode is typically transparent, typically made of low-cost In_2O_3 doped 10% SnO_2, called 'ITO'. *Is a heavily doped wide-bandgap semiconductor.*

- Two ways to make a full color OLED display… what is the major advantage/disadvantage for each?

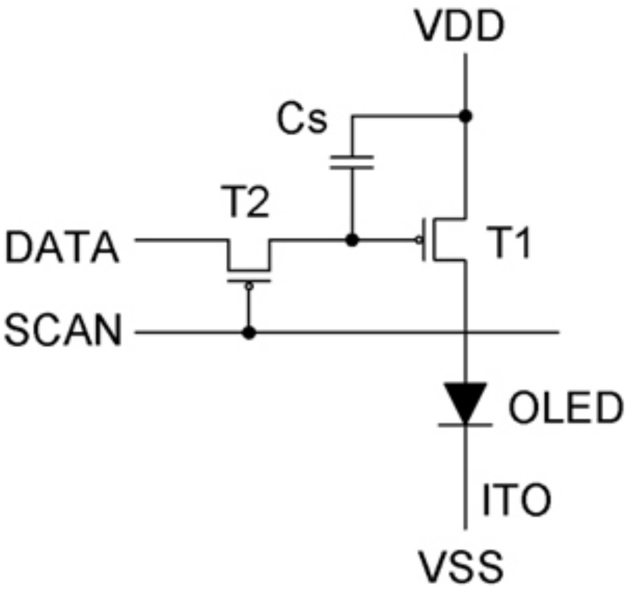


OLED Active Matrix

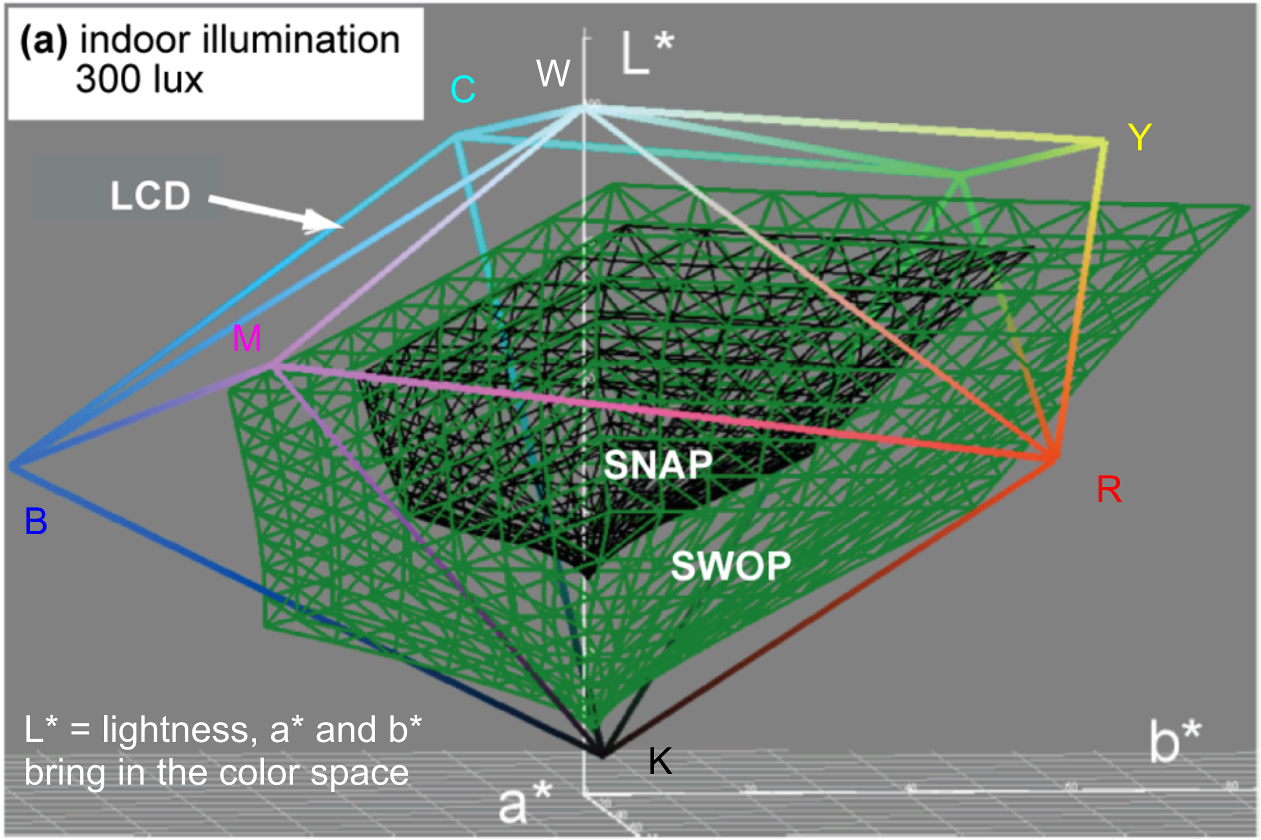
- So why won't conventional active matrix drive work for an OLED display?



- So here is one approach…. How does it work?



Reflective Displays (e-Paper)



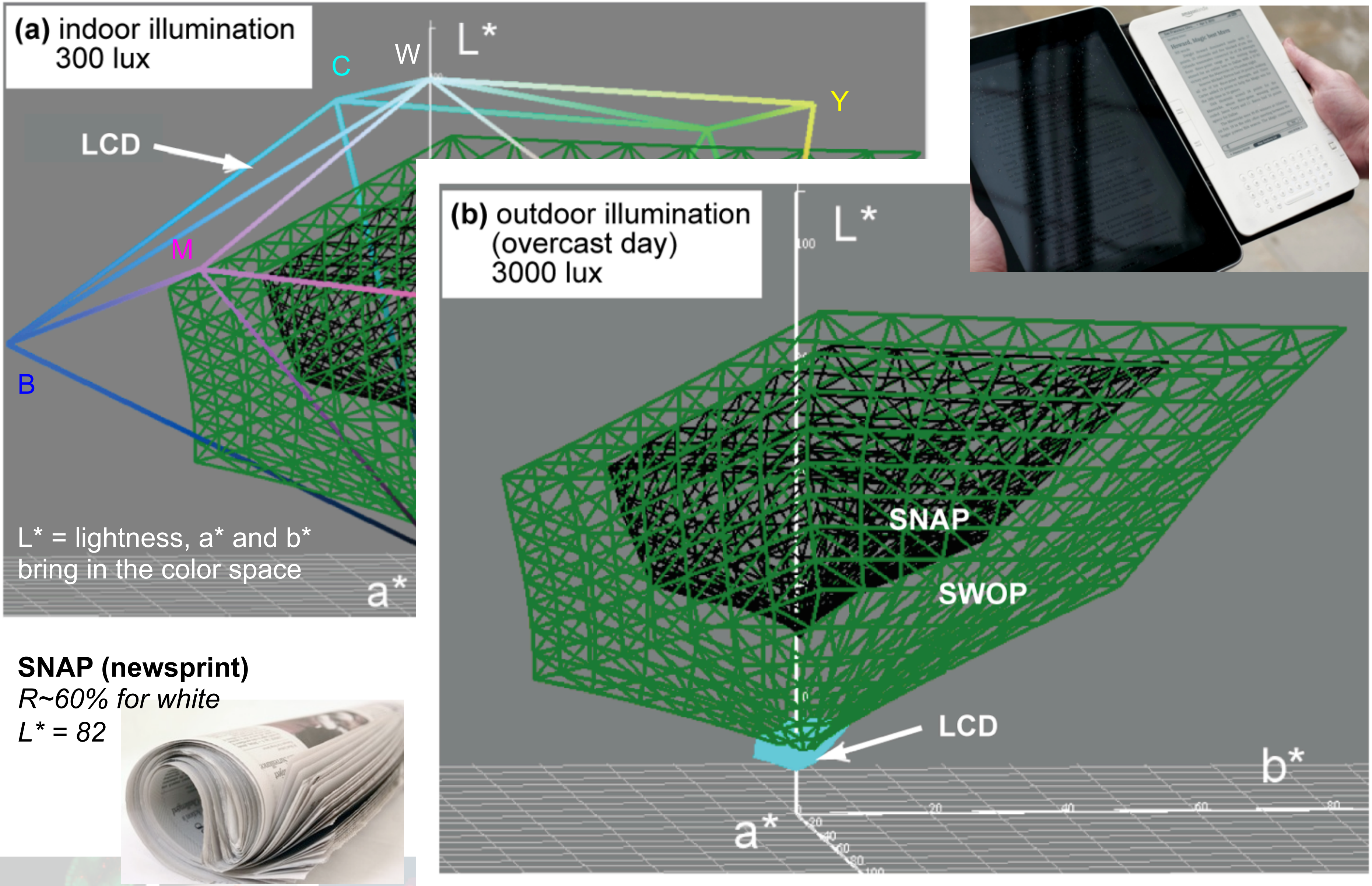
L* = lightness, a* and b* bring in the color space

SNAP (newsprint)
R~60% for white
L = 82*

SWOP (magazine)
R = 76% for white
L = 90*

LCD
Not reflective.
L = 100*

Reflective Displays (e-Paper)



(a) indoor illumination 300 lux

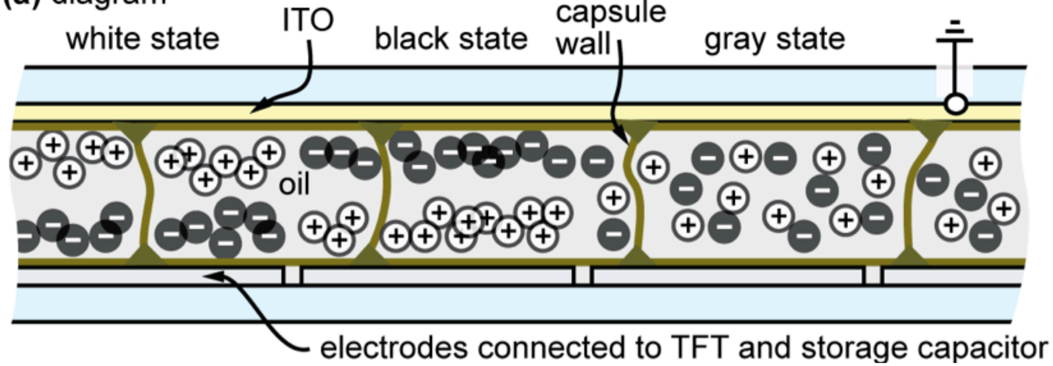
(b) outdoor illumination (overcast day) 3000 lux

L* = lightness, a* and b* bring in the color space

SNAP (newsprint)
R~60% for white
L = 82*

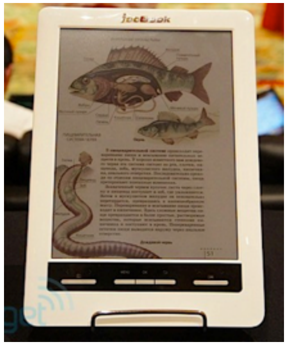
Reflective Displays: E-Ink

(a) diagram

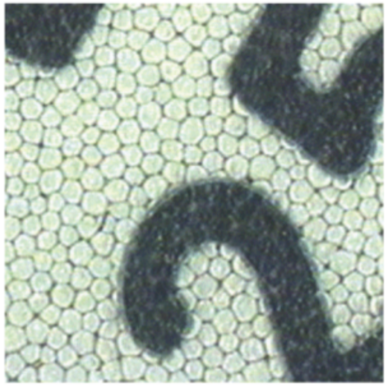


Mono (~40%)

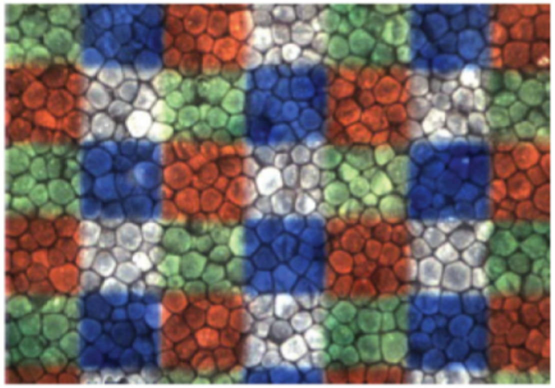
Color (~20%)



(b) photo of e-Ink capsules on segmented electrodes



(c) e-Ink film + KaleidoFlex Tech. Inc. RGBW color filter array



RGBW: max reflection ~ 50%, color fraction ~ 25%

(0.33 + 0.33 + 0.33 + 1.00) / 4 = 0.50

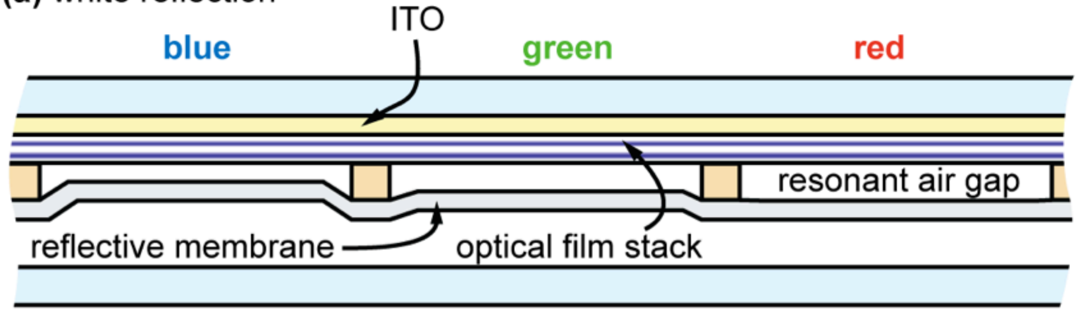
R =40%, Lambertian, ~15 V, grayscale stable, >decade of R&D. Key points:

(1) Is highly readable, high contrast, zero power, cost dropping, so will continue to flourish!

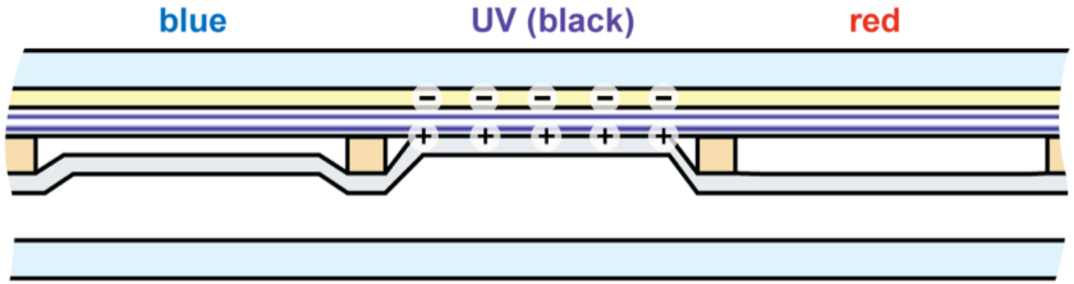
(2) Is slow (>120 ms) and needs to reset the particles to one side before going onto the next image… so good for books and signage, but not much more…

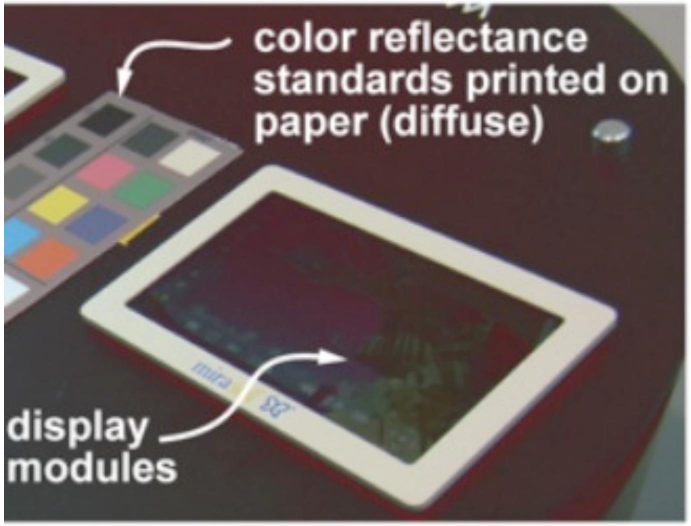
Reflective Displays: MEMS

(a) white reflection



(b) magenta reflection only





>20 years of R&D with >$2B invested.

Question 1: look at right… why the view angle dependence?

Question 2: can this provide bright white and color? Why or why not?

- If a display has 1000 rows, and is run at 60 Hz (60 frames per second, or 17 ms per frame), how much time is spent at each row to change the state of the pixel?

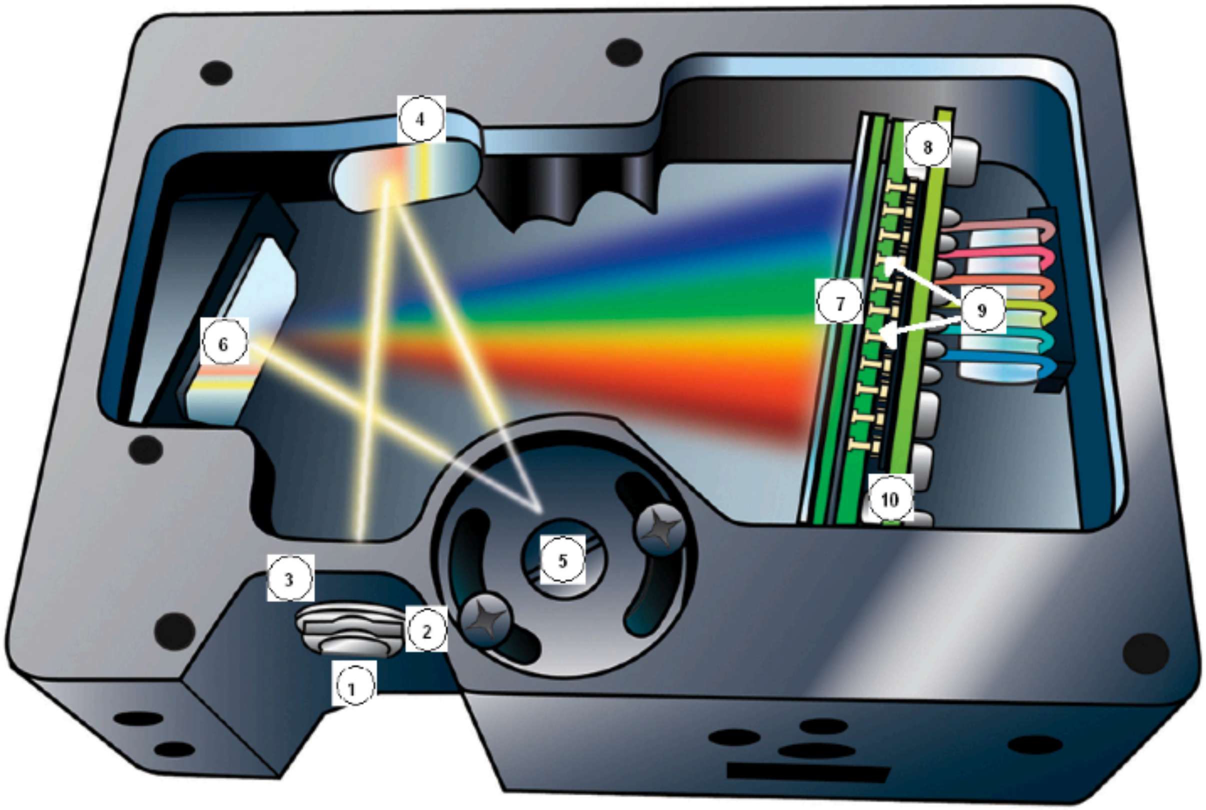
(a) 30 ms
(b) 30 μs
(c) 17 ms
(d) 17 μs

- Not so fast! One more short video, part (c), on how the spectrometer used in lab this week works.

Spectrometer!

Spectroscopy is used for detection and identification of different elements/compounds/light and in solving problems in the fields of forensics, medicine, oil industry, optics, lighting, displays, lasers, communications, atmospheric chemistry, pharmacology, etc.

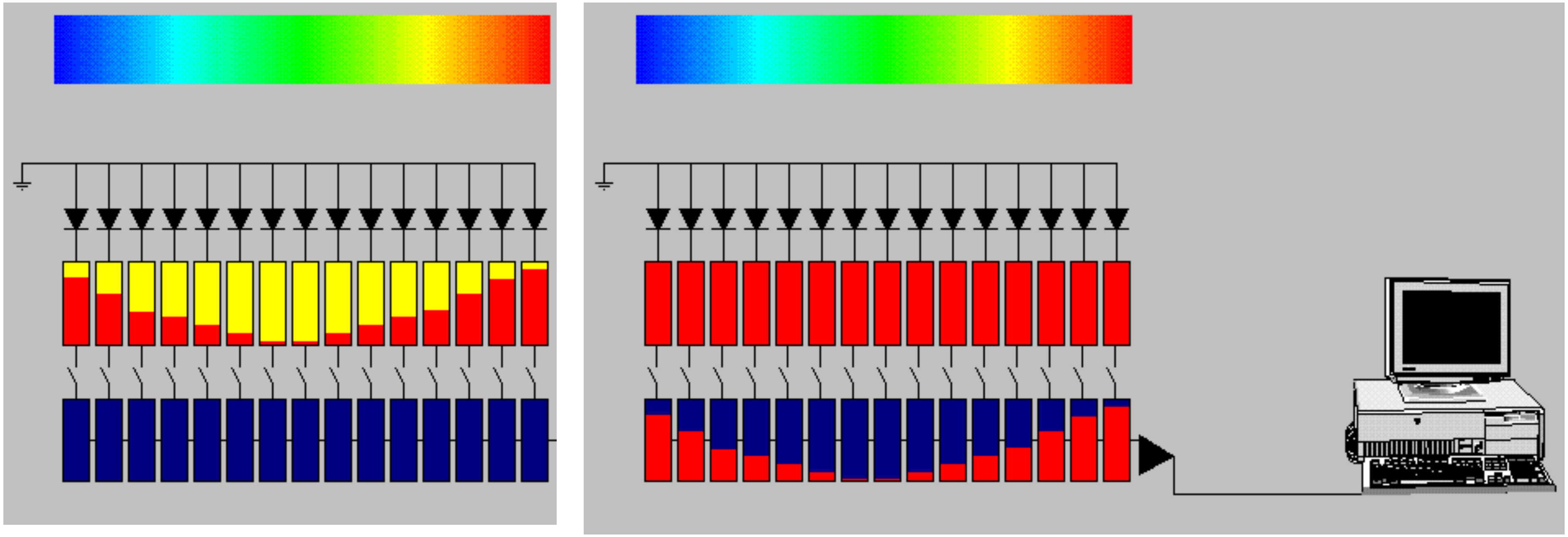
FUN to use!



(1) SMA Connector (auto-aligns jacketed fiber).
(2) Slit (5-200 μm). Wider slit, more light, but less spectral resolution as light hits the detector array.
(3) Filter restricts to only the wavelength range specified for the spectrometer.
(4) Collimating mirror (self explanatory)
(5) Diffraction Grating (different wavelengths diffract at different angles!)
(6) Focusing mirror (steers diffracted light to right locations on detector array.
(7) Detection lens (cylindrical lens, focuses light from tall slit onto small linear array of detectors).
(8) Detector (an linear CCD array of photo detectors).

Spectrometer!

- From Ocean Optics: Light impinges on photodiodes (CCD pixels). These reverse-biased photodiodes discharge a capacitor at a rate proportional to the photon flux. When the integration period of the detector is complete, a series of switches closes and transfers the charge to a shift register. After the transfer to the shift register is complete, the switches open and the capacitors attached to the photodiodes are recharged and a new integration period begins. At the same time that light energy is being integrated, the data is read out of the shift register by an A/D converter. The digitized data is then displayed on the PC.



Light Outcoupling

- Light out-coupling is a major issue when light is scattered internally…

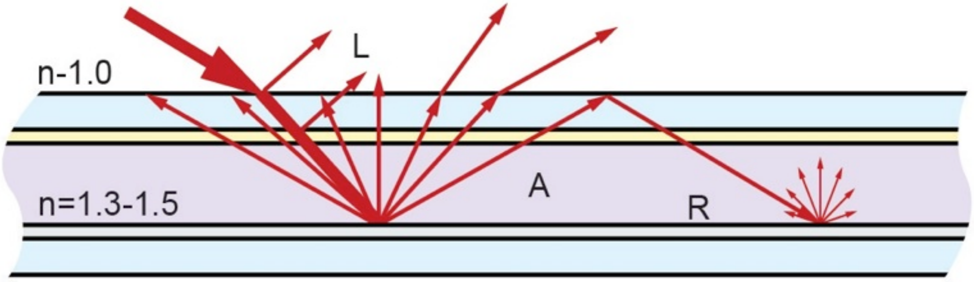
… total internal refection causes light to return back to the imperfect reflector and be partially absorbed, again, again, and again.

F = Fresnel loss as light comes in for 1st time
A = absorption loss
R= reflection efficiency at backside
P = probability to be at angle where no total internal reflection occurs

- Consider e-Ink, assuming n=1.5 for the fluid, you find that internally the pixels are R=60%, but after light out-coupling loss it drops to 40%. Ouch!

- For any high resolution display, you need a the reflector inside the pixel… so what can you do?

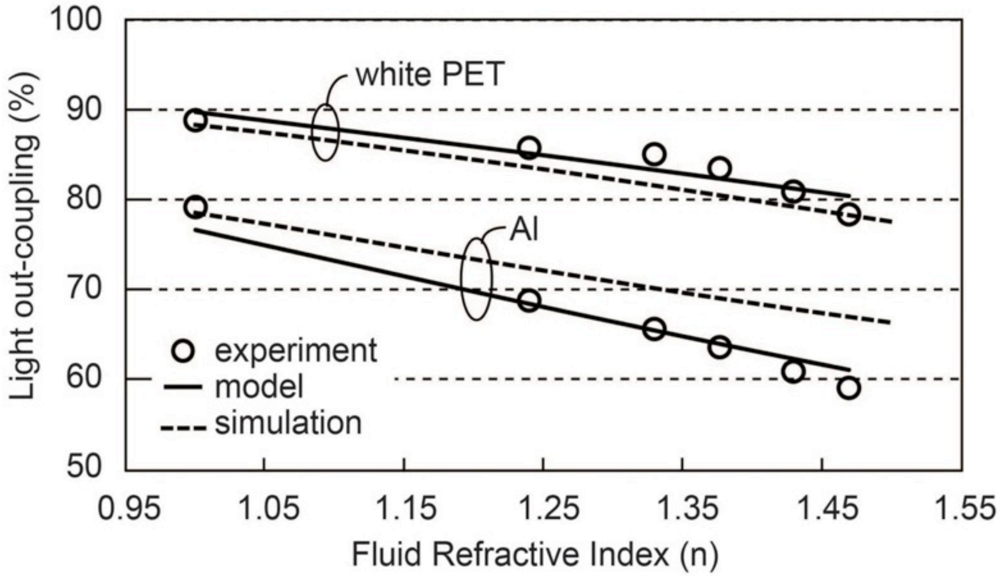
- reduce refractive index (n)
- make R as high as possible



$$LO_1 = (1-F)RAP \qquad LO_2 = LO_1 \times RA(1-P)$$

$$LO = LO_1 + LO_2 + LO_3 + LO_4 \ldots$$

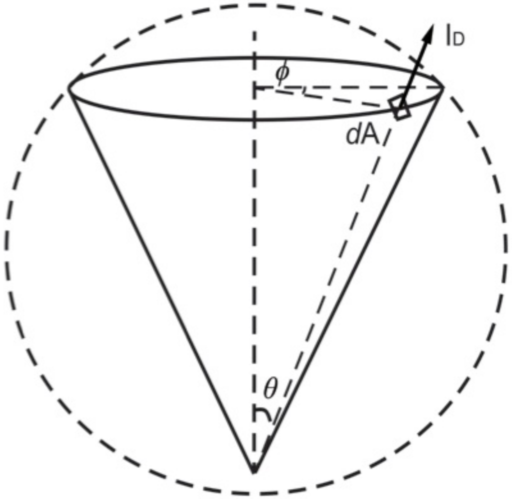
$$LO(\%) = F + \frac{(1-F)RAP}{1-RA(1-P)}$$



- Here is a derivation we did recently for e-Paper out-coupling… **P=1/n^2**

- E-paper has internal surfaces that are often diffuse (Lambertian, see week 1 lecture).

- This same model applies to OLEDs, but they are isotropic (emit light in all directions, not lambertian), so **P= 1/4n^2**



In this derivation, it is assumed that the reflections are all Lambertian, where the light intensity (I_D) for any direction (θ) follows Lambertian cosine law as:

$$I_D = I_0 \cos(\theta)$$

where I_0 is the incident light intensity normal to the reflective surface. The total light L within a cone (open angle 2θ) can be calculated as

$$L = \int I_D \cdot dA$$

Where $dA = r^2 \sin\theta \, d\phi \, d\theta$ is the area on the cap of the cone. Combining these equations we have:

$$L = \int_0^{\theta} \int_0^{2\pi} I_0 r^2 \cos(\theta) \sin(\theta) \cdot d\phi \cdot d\theta = \pi I_0 r^2 \sin^2(\theta)$$

Because the reflected light is diffusely reflected within a medium of refractive index $n < 1.5$, and because the other adjacent layers all have refractive >1.5, there is no total internal reflection until the light hits the interface with air, which is typically glass/air. Assume the glass refractive index is n_g. Then the largest incident angle at the interface is $\theta_{\text{imax}} = \sin^{-1}(n/n_g)$, where n is the refractive index of the medium where the diffuse reflection occurs. The critical angle at glass/air interface is $\theta_c = \sin^{-1}(1/n_g)$. Light with an incident angle beyond this value will be reflected back into glass. Therefore the out-coupled light fraction P can be calculated as:

$$P = \frac{L_c}{L_{i\,\max}} = \frac{\sin^2(\theta_c)}{\sin^2(\theta_{i\,\max})} = \frac{1}{n^2}$$