Color printing

Inks, CMYK, color separations
Color Printing: Separations

- CMY and CMYK continuous tone
- Undercolor removal
  (gray component removal)
- Spatial sensitivity to separations
Lights (Additive) and Inks (Subtractive)
Absorption and Reflection

Beers-Lambert

Probability of absorption

\[ p(\lambda, \delta) = a(\lambda)\delta \]

Suppose that the ink has a thickness, \( T = N\delta \). Probability of reflection is

\[
\begin{align*}
  r(\lambda, D) &= (1 - a(\lambda)\delta)^N = (1 - a(\lambda)\frac{T}{N})^N \\
  \lim_{N \to \infty} (1 - a(\lambda)\frac{T}{N})^N &= e^{-a(\lambda)T}
\end{align*}
\]

When \( T \) is large, the chance of reflection is low. When \( T \) is small (near zero), the chance of reflection is high.
Optical Density

Optical density, $D$, is related to the thickness and chance of reflection

$$D(\lambda, T) \equiv -\log_{10} r(\lambda, T) \approx 2.3a(\lambda)T$$

Superimposing two layers of ink causes their optical densities to sum.

$$D(\lambda, T_1 + T_2) = -\log_{10} r(\lambda, T_1 + T_2) \approx 2.3a(\lambda)(T_1 + T_2)$$

The change in the reflectance of the light, however, is nonlinear

$$r(\lambda, T_1 + T_2) = \exp(-2.3a(\lambda)(T_1 + T_2))$$
Each type of ink controls the amount of light reflected in a different waveband – red, green, or blue.
Cyan Density Controls Red

Reflectance

High density

Medium density

Zero density

Wavelength (nm)

Magenta: controls green
Yellow: controls blue
Cyan density controls red
Subtractive Colors

Red controlling
Red = Magenta + Yellow

Blue controlling
Green = Cyan + Yellow

Green controlling
Blue = Cyan + Magenta
Overlay Demonstrations
Tone Reproduction Curves

Black ink level (dv)

Magenta ink level (dv)
Separations and Original Compared

\[ C = 1 - R \]
\[ M = 1 - G \]
\[ Y = 1 - B \]

R,G,B image
Gray Component Removal

\[ K(x,y) = \min(C(x,y), M(x,y), Y(x,y)) \]
CMYK Separations With GCR
CMYK Separations Without GCR
Spatial Effects: CMY All Blurred
Spatial Effects:
Only K Blurred
Reflectance Spectra of Real Inks

HP printer in my lab.
Transformations: CMYK to RGB
nonlinear, improvised

Print large numbers of patches (5-10K)

Magenta print level

Measure (X,Y,Z)

Cyan print level

Locally linear transformations
Globally nonlinear
Maps (C,M,Y,K) to XYZ
Display Technology

1. Liquid Crystal Displays (LCD)
2. Plasma Display
3. Digital Light Projector
4. Organic LED
What Are Liquid Crystals?

- Liquid crystals (LC) are complex, anisomeric organic molecules
  - fluid (they move like a liquid)
  - molecular order (properties of a crystal)
  - exhibit optical anisotropy (mechanical, electric, magnetic anisotropy, too)

- These crystals can be founded several different states (‘phases’)

![Smectic](Image1)
![Nematic](Image2)
![Cholesteric](Image3)
LCs and birefringence

Light is refracted into two wavefronts, polarized at right angles to one another, traveling at different velocities.

This splitting of light is known as birefringence (derived from the term bi-refraction).
LCs and birefringence

One of the light waves, termed the ordinary ray, travels straight through the crystal (its image remains stationary); this image is fixed as we rotate the crystal.
The other ray, termed the **extraordinary ray**, is refracted to a significant degree and appears displaced. This image precesses around the image of the ordinary ray as we rotate the crystal.
LCD: Polarization demo

We control how much light exits an LC cell by controlling the state of the LC molecules, and the polarization of the output light, with an electric field.

POLARIZER DEMO
The sub-pixels in two different LC monitors
Flexible LC Displays!
LCD components

- Light Guide Panel = Diffuser
- Holographic lens elements
- X-address
- Y-address
Brightness Enhancement Film

Rays from the source may undergo multiple total internal reflections (TIR), before emerging at close to on-axis angles with respect to the viewer. Light within the viewing cone (approximately 35° off the perpendicular) is transmitted out and light outside this angle is TIRred back into the film and recycled until it is within this cone angle.
Quantum dots for display

http://en.wikipedia.org/wiki/Quantum_dot


http://spectrum.ieee.org/consumer-electronics/audiovideo/quantum-dots-are-behind-new-displays/0

Quantum dots

Quantum dots are nanoparticles made out of a semiconductor material. They emit photons when excited. They can be tuned to emit light very efficiently (by varying their size) at precise red, green, and blue wavelengths. These are useful for controlling the LCD backlight spectrum.
Quantum dots

- Nanometers in diameter

- Can be fabricated to convert short-wavelength light (i.e., blue light) to nearly any color in the visible spectrum.

- Spectral output is determined by size. (Bigger longer wavelengths)
Quantum dots used as backlights (Combined with color filters)
Plasma displays
Plasma

A typical gas is mainly made up of uncharged particles. That is, the individual gas atoms include equal numbers of protons (positively charged particles in the atom's nucleus) and electrons. The negatively charged electrons perfectly balance the positively charged protons, so the atom has a net charge of zero.

A plasma is a gas in which a certain portion of the particles are ionized (net charge). The presence of a non-negligible number of charge carriers makes the plasma electrically conductive so that it responds strongly to electromagnetic fields.
Plasma

If you introduce many free electrons into the (plasma) gas by establishing an electrical voltage across it, the free electrons collide with the atoms, knocking loose other electrons. With a missing electron, an atom loses its balance. It has a net positive charge, making it an ion.

After an electron bumps the ion to a high energy state, it will relax back down to the original energy level and release the extra energy in the form of a light photon.
Plasma display panel
(How stuff works)

• Glass sandwich

• Electrode grids in two directions for addressing individual sub-pixels

• Gas (plasma) in each pixel

• Plasma is a gas made up of free-flowing ions (gas that has been stripped of electrons)
A voltage difference is introduced across the electrodes.

A current flows through the gas in the cell.

The current stimulates the gas atoms to release ultraviolet photons.

These UV photons excite the phosphor.

Repeat many times to illuminate each of the sub-pixels.
Deformable Mirror Devices (DMD)
Digital Light Projectors (DLP)
Digital Mirror Device (DMD, also called DLP) 
A Field Sequential Color Display
Principle of the DLP/DMD

http://www.dlp.com/

Figure 1. Fans in a stadium reflecting light toward a blimp. (a) Light is projected from a spotlight toward fans in the stadium. When cued by a numbered signal, these fans hold up their reflective seat cushions and tilt them toward or away from a blimp. By doing so, the fans in the stadium are reflecting pixels of light toward the blimp. The result is that the light pattern created by the seat cushions projects an image onto the surface of the blimp. (b) A distant viewer sees the image on the blimp.

(source, TI, Yoder white paper)
DLP System

Figure 2. DLP system operation. (a) In much the same way the image was formed on the side of the blimp, DLP forms images for video. Shining light on the DMD and tilting the mirrors creates a digital image. Color is added by placing a red, green, and blue color wheel filter system in the optical path. As the wheel spins, the mirrors are tilted on for the exact amount of time required for each color. At any given instant, only one of the primary light colors is hitting the DMD, but when the filter system spins fast enough, the colors blend to create a full-color digital image. (b) A viewer sees an image on the screen from a DLP projector.
Detail of the DLP
The tilt of the mirror determines whether the light goes into the image.
Intensity control is achieved through temporal modulation (pulse width modulation).
Field Sequential Artifacts

What the fovea sees

Eye movement

Time
Figure 3. Actual photographs of (a) liquid crystal display (LCD) pixels and (b) DLP pixels. Projected images are made up of thousands of small pixels; DLP pixels (b) are more uniform and more closely spaced than the polycrystalline silicon (poly-Si) pixels seen in view (a). Based on a superior pixel structure, DLP offers a higher fill factor and better image quality.
LCD vs. DLP Images

SVGA poly-Si LC projector and an SVGA DLP projector.

Detail of the eye of a polar bear.
Marketing caption says: “Note the ‘high level of pixelation in the LCD photo compared to that of the seamless DLP photo.” Fill-factor is an issue.
Organic LED (OLED)
OLED Principles

When a thin layer of certain organic materials is sandwiched between appropriate Anode and Cathode materials, and a modest positive voltage is applied, the material between the two electrodes will glow. This phenomenon is known as *electrophosphorescence*. 
OLED: Display and pixel

1000 angstroms is one micron
10 angstroms is one nanometer
500 nm is 5000 angstroms
OLED Principles

With careful selection of the organic material and the anode and cathode material, the entire structure can be very thin (500 nm).

In Polymer OLEDs (Poly-OLEDs), the organic material is a special polymer, that can be quickly and easily applied to an appropriate substrate. This allows a simple manufacturing process that could eventually lead to high volume mass production.
Full Color OLED Technology
(Ching Tang, Kodak-Sanyo)

Active-matrix OLED displays with roughly 50 um color dot pitch have been demonstrated by Kodak/Sanyo (see figure 3).
Pioneer (Tokyo, Japan) and other companies have produced 5.2-in QVGA displays using the shadow mask method. (February 2001)
Large-scale OLEDs for sale now


OLED TVs

Find the perfect OLED television for your home entertainment system. Choose from top brands like Samsung and LG.

Electronics › Television & Video › Televisions › OLED TVs

Showing 3 Results

Sort by Most Popular

LG Electronics 55EA9800 Cinema 3D 1080p Curved OLED TV with Smart TV

$10,999.99 $6,999.00 Prime

Only 6 left in stock - order soon.

More Buying Choices
$6,999.00 new (3 offers)
$6,297.97 used (2 offers)

Samsung KN55S9C Curved Panel Smart 3D OLED HDTV

$6,347.23 used (5 offers)

LG 55” 1080p, Smart, 3D, Gallery OLED TV

$9,999.99 $7,499.00

Only 2 left in stock - order soon.
Large-scale OLEDs for sale now


OLED TVs

Find the perfect OLED television for your home entertainment system. Choose from top brands like Samsung and LG.

2015

LG Electronics 55EC9300 55-Inch 1080p 3D Curved OLED TV by LG

$3,499.00

LG Electronics 55EA8800 55-Inch 1080p 3D Smart OLED TV by LG

$3,638.73 used (2 offers)

LG Electronics 55EG9600 55-inch 4k Ultra HD 3D Curved OLED TV by LG

$5,499.00

Full Color OLED Technology

**LG's 55" OLED TV - In December 2011**

A full-HD panel

- 100,000,000:1 contrast ratio
- Fast response time (1,000 times faster than LCD according to LG).
- The panel is 4mm thick,
- The whole TV weighs just 7.5Kg.
Full Color OLED Technology

Samsung
Of course.
OLED Luminance and efficiency

More voltage leads to more light

Best light to current (cd/A) at high levels
Doping the OLEDs shifts the emissions

In the most direct method, all three essential colors (Red, Green, Blue) are emitted separately by three different **electrolumophores**. Alq$_3$ can be doped with dyes that shift the emission color (undoped emits green light).
Doping the OLEDs shifts the emissions

Other electrolumophores are used for other colors. Stripes of different emitters can be deposited through shadow masks to create pixels with red, green, and blue subpixels. This approach has been used where the pixels are relatively large, but it becomes impractical for microdisplays, where the subpixels are only a few microns wide.
Color filters on a white emitting OLED

Dope the emitter with more than one dye, so that it emits white light. Red, Green and Blue passive color filters (PF), such as the ones used in liquid crystal displays, can then be used to create the red, green, and blue subpixels.

The filters can be patterned on a separate plate, using photolithography, then overlaid onto the white emitter array. This is the easiest way to make a color OLED display,

Wastes light in the filters, since from each subpixel only about one third of the white light passes through the color filter.
Color-changing OLED Architecture

The color-changing-medium (CCM) approach is unique to OLED technology and was first used by Idemitsu Kosan Co. (Chiba, Japan). In this method, a blue OLED display is fabricated on top of a color-changing medium consisting of an array of fluorescent dots. The medium converts the blue display to a full-color display by down-shifting the blue emission from the OLED to produce blue, green, and red colors. Kosan's group has demonstrated color 5.2-in. QVGA and 10.4-in. VGA devices.
OLED colors achieved

Covion spectra

Dow Chemical
Flexible OLEDs – But water is an issue

Sheila Kennedy, Harvard Univ., 1999
March 6, 2014

Bendable TVs, Connected Cars, and More from CES 2014

According to ID Contributing Editor Steve Sechrist, who attended the most recent Consumer Electronics Show in Las Vegas, this will go down as the year that both UHD and curved displays found commercial traction. Read on for a sneak peek from his upcoming article in the March/April issue.

At CES 2014, displays were at center stage, with new technology, larger OLED panel sizes, the proliferation of curved LCD TVs, and even bendable panels that curve to enhance the immersive viewing experience, then flatten to create a picture frame or “artistic” image surface. All this, plus enhanced interactivity and of course higher pixel density, were dominant themes.

Before heading into the details of those displays, it’s worth mentioning that an equally impressive highlight of the show was the demonstrated progress in automotive telematic and safety systems – the connected car, which leans heavily on the advanced chip technology previously found more often in phones and game devices. The idea is to bring smartphone features into the car, sharing navigation destinations, other travel information, and media control between smartphone and car. This is a growing trend in the auto manufacturing space, with an uptick in the number of car makers on the CES show floor. Audi, BMW, Cadillac Chevrolet/GM, Dodge, Ford, Kia, Mercedes, Tesla, and Toyota all had a significant presence at the event, showing off just what advanced CPU and GPU chips, navigation, and new on-board sensor systems can bring to the future of driving. And in view, no less than fully connected, were self-piloted vehicles with better situation awareness, shape recognition, vector analysis, and response time than any human can hope to achieve. The car is becoming the ultimate mobile device, and the consumer electronics and auto industries are now tied at the hip going forward.
Thanks!

You have been a great class.

I am looking forward to listening to you.
Bernanose and coworkers first produced electroluminescence in organic materials by applying a high-voltage alternating current (AC) field to crystalline thin films of acridine orange and quinacrine. In 1960, researchers at Dow Chemical developed AC-driven electroluminescent cells using doped anthracene.

The low electrical conductivity of such materials limited light output until more conductive organic materials became available, especially the polyacetylene, polypyrrole, and polyaniline "Blacks". In a 1963 series of papers, Weiss et al. first reported high conductivity in iodine-"doped" oxidized polypyrrole. They achieved a conductivity of 1 S/cm. Unfortunately, this discovery was "lost", as was a 1974 report of a melanin-based bistable switch with a high conductivity "ON" state. This material emitted a flash of light when it switched.

In a subsequent 1977 paper, Shirakawa et al. reported high conductivity in similarly oxidized and iodine-doped polyacetylene. Heeger, MacDiarmid & Shirakawa received the 2000 Nobel Prize in Chemistry for "The discovery and development of conductive organic polymers". The Nobel citation made no reference to the earlier discoveries. [citation needed].
What’s Next
At one time I stated: extinction. While I am now reconsidering that statement I maintain that LCD panels are on a trend to become a commodity. The manufacturing process is getting better, additional manufacturing plants open up each year to turn out more and more panels and performance is increasingly getting better. Add to that the low cost of manufacturing and additional technologies coming on board and you have a tough road ahead for plasma. Tough, but not impossible. Plasma displays are indeed competing in terms of longevity, brightness, (true) contrast ratio, power consumption and burn-in. Their black levels and color saturation are very impressive. Due to these advancements it is very likely that plasma and LCD will maintain parallel development for some time. As LCD displays become cheaper, faster and more competitive, perhaps plasma will become obsoleted - until that time I have to retract my original prediction as being too far-reaching to be practical.
Plasma TV is Dead - Pioneer Exits  
by Clint DeBoer — last modified March 04, 2008 04:00

Plasma TV is DEAD  
As we predicted several years ago, plasma technology is on its way out. Putting one of the nails in the lengthy coffin is Pioneer Corp, who is stopping ALL production of plasma display panels. Last week we reported that they had decided to stop all 42-inch panel production, however that has now been expanded to its entire plasma line. This comes via an industry source briefed on the plan and quoted by Reuters in an article released today. Rather than panic, Pioneer shares immediately jumped to a four-month high following the report - up 11.2 percent.

You heard it here first: **Plasma TV is dead.**

Pioneer is the world's fifth-largest plasma TV manufacturer and has constantly struggled for relevance against the larger Panasonic brand (Matsushita). Now, Pioneer will buy its panels from the competing brand and it will begin picking up LCD panels from... you guessed it - Sharp. This makes three major manufacturers who are backing Sharp panel production in the coming year (inclusive of both Toshiba and Sony Electronics). Our guess is that Sharp is going to be the first to market with the new line of super-thin LCD panels that fans such as myself have been dreaming about for some time.
Plasma Display Panels

The transparent display electrodes, which are surrounded by an insulating dielectric material and covered by a magnesium oxide protective layer, are mounted above the cell, along the front glass plate.
Plasma Display Panels

To ionize the gas in a color panel, the plasma display's computer charges the electrodes that intersect at that cell thousands of times in a small fraction of a second, charging each cell in turn. When the intersecting electrodes are charged (with a voltage difference between them), an electric current flows through the gas in the cell. The current creates a rapid flow of charged particles, which stimulates the gas atoms to release ultraviolet photons.
Color pixels in LCD devices
LCD Calibration Example
LCD calibration issues

Wandell and Silverstein, OSA Chapter
Liquid Crystal (LCOS) on Silicon Microdisplays

- Megapixel display devices built on single-crystal silicon
- Reflective spatial light modulators - silicon is not transparent
- High optical efficiency; dielectric mirrors at rear pixel electrode
- LCOS microdisplays are small - must be magnified via either a virtual imaging system or a projection imaging system
Liquid crystal on silicon pixel

Liquid crystal rotates (or not) the polarization angle
Virtual Images

- Virtual images can be produced by a variety of optical configuration
  - simple magnifier

- Virtual images can not be directly viewed on a screen
  - require an additional lens
  - e.g. the eye

- Many optical instruments produce virtual images
  - microscopes, telescopes etc.
Virtual Displays Using LCOS Technology

- Full-color virtual display viewers
  - up to 1280 x 1024 addressability demonstrated
  - color achieved via field-sequential mode
    - typically RGB LED illuminators
  - flexible optical designs in terms of:
    - resolution
    - virtual image distance
    - magnification/field-of-view
  - both hand-held and head-mounted

- Enables many new applications
  - virtual monitors for computers & PDAs
  - high content mobile pagers and fax
  - mobile imagers for police/fire/emergency
  - high quality digital camera viewfinders
  - head-mounted displays for:
    - surgery, repair technicians etc.
E-ink

http://www.eink.com/technology/howitworks.html
Organization of an LCD Pixel

- Color Filter Panel
- Liquid Crystal
- TFT Panel
- Backlight
- Transparent Electrodes
- Polarizing Filter
- Transistor Pixel
Thin Film Transistor LCD
Passive and Active Matrix LCD
Color Array Organization

<table>
<thead>
<tr>
<th></th>
<th>Stripe</th>
<th>Mosaic</th>
<th>Delta</th>
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<tr>
<td>Color Mix</td>
<td>Poor/w. low res.</td>
<td>Good</td>
<td>Best</td>
</tr>
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Pixel comparisons

CRT | LCD-1 | LCD-2
---|---|---
[Image of pixel comparisons]
There Are Lots of CRT Phosphors

(courtesy L. Silverstein)
CRT Phosphors and Gamma

![Graphs showing radiances and luminances vs. wavelength and digital value.](image)
Phosphor Spectral Additivity II
Camera-Display Matching Equation

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
= \begin{pmatrix}
C
\end{pmatrix}
\begin{pmatrix}
D
\end{pmatrix}
\begin{pmatrix}
e_r \\
e_g \\
e_b
\end{pmatrix}
\]

C = CIE functions
D = Display primaries

Linear display intensities

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
= CD
\begin{pmatrix}
e_r \\
e_g \\
e_b
\end{pmatrix}
\]

\[x = CDe\]
\[e = (CD)^{-1}x\]
Spatial distortion examples

Describing geometric distortion

\[(x, y) \rightarrow (x + u(x, y), y + v(x, y))\]

\(u(x, y), v(x, y)\) are the displacement fields
Early handset data from Imageval consulting case
Primaries for a vendor’s handset
Handset primaries at different intensity levels

The shape changes

Wavelength (nm)
Gamut of A Phone Handset Compared with \((x, y)\) of Macbeth Color Checker Under D65

Chromaticity coordinates of an MCC (blue circles) under D65. The display gamut of a handset is shown by the red triangle, and the primaries are shown as red squares.
Reflective color displays

- **Low power**
- **Low volume and weight**
- **Naturally adaptive to changes in ambient illumination**
- **Low cost**
Why current reflective displays don’t provide full color

- Twisted Nematic (TN) is dominant reflective LCD technology
  - Very Low Light Transmission (i.e. poor reflectivity) because
    - Polarizers
    - Absorptive color filters
    - Aperture ratio
    - Spatial color synthesis (RGB same substrate)
    - Color TN AMLCD 4-5% efficiency in transmissive mode and 1-1.5% in reflective mode
**LCD Voltage Control**

Voltage Field Off \((V=0)\)

Voltage Field On \((V>V_{\text{threshold}})\)

- Polarizer
- Glass
- ITO
- Polymer
- Liquid Crystal
- Unpolarized backlight

![Diagram of LCD structure with voltage fields on and off](image)
LCD System

- TFTs
- pixel electrodes
- black matrix
- glass
- liquid crystal layer
- top electrode
- RGB color filter array
- polarizer
- glass substrate
- backlight
SPD of an LCD

Radiance vs. Wavelength (nm)

NEC 2080
OLED Display Structure is Simple

Display

No backlight (low power)
Simple to manufacture (?)
Very fast switching times
Lifetime issues

Very thin: Human hair is 200x times thickness of each layer
Ink jet printing used to deposit material

Ink Jet printing to define and pattern R, G, B emitting subpixels
The phosphors in a plasma display give off colored light when they are excited. Every pixel is made up of three separate subpixel cells, each with different colored phosphors.

“Plasma displays use the same phosphors as CRTs, accounting for the extremely accurate color reproduction.” From Wikipedia. Someone please fix.
• In late 2006, LCDs overtook plasmas, particularly in the 40-inch (1.0 m) and above segment where plasma had previously gained market share. [42]

• Another industry trend is the consolidation of manufacturers of plasma displays, with around fifty brands available but only five manufacturers.

• In the first quarter of 2008 a comparison of worldwide TV sales breaks down to 22.1 million for direct-view CRT, 21.1 million for LCD, 2.8 million for Plasma, and 0.1 million for rear-projection. [43]
Until the early 2000s, plasma displays were the most popular choice for HDTV flat panel display as they had many benefits over LCDs. As well as better blacks, faster response time, greater color spectrum, and wider viewing angle; they were also much bigger than LCDs, and it was believed that LCD technology was suited only to smaller sized televisions.

However, improvements in VLSI fabrication technology have since narrowed the technological gap. The increased size, lower weight, falling prices, and often lower electrical power consumption of LCDs now make them competitive with plasma television sets.