What is a Display? An Introduction to Visual Displays and Display Systems

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Abstract

Display technologies have become an indispensable element of modern life, forming the primary communications and information portal for day to day life as well as for industry, entertainment, commerce, health, and security. As such, we are all familiar with the concept and use of a "display," but the question of what exactly constitutes a display is a question that is not straightforward to address. The *Handbook of Visual Display Technology* provides a comprehensive reference resource covering all aspects of this technological field, and as an introduction and overview, this chapter presents a summary of the many different aspects of electronic displays: from pixels through device technologies and electronic driving methods to systems engineering. Displays are highly complex systems requiring input from researchers and innovators in material science, manufacturing, electronics, and software as well as optics, vision science, and

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user interface design. This introduction consequently provides a broad overview of the field for beginners and experienced display professionals and references the other sections of the handbook for those wanting to explore specific topics in more detail.

List of Abbreviations

3D	Three dimensional
AM	Active matrix
ARM	Advanced risk machines (microprocessor)
CE	Consumer electronics
ChLCD	Cholesteric LCD
CRT	Cathode ray tube
DMD	Digital mirror device
ECO	Engineering change order notification
EL	Electroluminescent
E-Paper	Electronic paper
FHD	Full high-definition resolution (1,920 × 1,080)
FLCD	Ferroelectric LCD
FPD	Flat panel display
HD	Hard disk
IF	(Electronic) interface
ITO	Indium tin oxide
LCD	Liquid crystal display
LED	Light-emitting diode
Lib	Software library
LTB	Last-/lifetime buy notification
MEMS	Micro electromechanical system
MOSFET	Metal oxide field effect transistor
MUX	Multiplex drive
OLED	Organic LED
OS	Operating system
PC	Personal computer
PDLC	Polymer-dispersed LCD
PDP	Plasma display panel
PM	Passive matrix
PPI	Pixel per inch
RAM	Random access memory
Seg	Segment of a display
STN	Super twisted nematic LCD
TCON	Timing controller
TFT	Thin film transistor
VFD	Vacuum fluorescent display

Introduction

We live in an age of mobile information technology which relies heavily on the visualization of multimedia data and user input. These tasks are often performed by high-resolution electronic displays equipped with a touch screen. There is no better way to present a large amount of information than by using an electronic display. Compared to audio, for example, the data rate of high-definition video content is orders of magnitude higher and can reach gigabits per second.

Over the past few decades, the performance of displays has continuously improved, with resolution increasing from a few thousand to millions of pixels, from black and white displays through multiple gray levels to vivid full-color reproduction. The evolution of electronic displays started with vacuum-based cathode-ray tubes (CRTs) around 1900 (Blankenbach et al. 2008) (see chapter "► Cathode Ray Tubes (CRTs)"). For about 100 years CRTs dominated the display market. However, this story came to an end with the development of flat panel displays (FPDs) starting with segmented LCDs at around 1975 for mass markets. Within a few years, character and low-resolution passive matrix (PM) LCDs were introduced. The merits of these early LCDs were characteristics such as low power consumption and slim form factor with light weight, which improved existing products such as watches and calculators. These portable electronic devices had been dominated by LEDs and VFDs (a vacuum-based technology), but the much lower power consumption of LCDs led to the rapid migration to LC-based displays in this sector. For non-portable TV and entertainment displays, another vacuum-based technology, the flat plasma display panel (PDP), paved the road to TV screen sizes beyond 30″, the realization of wall-mounted TVs. Further developments of LCD technologies in terms of image quality and screen size also began to penetrate the applications and markets that had been dominated by CRTs, with the result that in the early 1990s, monochrome (and within a few year color) PM LCDs were available with VGA resolution. This paved the way for the development of laptop computers and mobile computing.

At around the end of the 1990s, the realization of mass-produced active matrix (AM) LCDs based on thin film transistor (TFT) technology provided higher resolution and better image quality compared to passive matrix LCDs. The first mass market for AM LCDs was for laptops where this technology pushed PM LCDs out of the market within a few years. Soon after this AM LCD technology reached the levels of maturity and pricing to also address the desktop monitor market. A 17″ CRT monitor had a depth of around 50 cm and an active area equivalent to that of a 15″ flat panel. Hence, the slim form factor, low weight, and competitive pricing at below $500 for 15″ AM LCD were attractive enough to rise AM LCD monitor sales nearly exponentially.

Soon after this, the LCD industry was able to produce larger panels suitable for TV applications, starting at 27″ and reaching sizes of over 100″ within a few years, during which there was a rapid decline in the market for CRTs. The success of LCD

TV sets due to synergies and mass production of various sizes also caused a decline of PDPs after 2010, which forced many manufacturers to quit this technology.

Another area of rapid development in recent years has been the handheld display market, following the introduction of Apple's first iPhone and later the iPad, along with the growth in smartphone and tablet devices more broadly. However, the dominance of LCD technologies has been challenged in recent years, since ~ 2012, by the introduction of one of the newest display technologies utilizing organic electroluminescence, in the form of organic light-emitting diode or "OLED" technologies. OLEDs can exhibit high image quality at lower thicknesses than competitive LCDs and are now becoming a robust alternative to LCD in both portable and large area TV markets.

In recent years, another FPD technology entered mass production: reflective bistable e-paper displays with outstanding features such as sunlight readability (since it is a reflective technology), lowest power consumption, and high resolution. These are typically monochrome displays, with low switching speed not suitable for video information rates, but ideal for text and gray scale image display.

The examples provided above refer mostly to consumer electronic (CE) products, which have driven the large-scale manufacturing innovations for the various technologies. Another important aspect of the development and use of light-emitting and light-modulating technologies for display applications is in the area of professional displays, including industrial, e-signage, automotive, aerospace, and medical. The volumes in these sectors are significantly smaller than those of CE displays; thus, the professional displays follow CE trends. However, a main difference is that CE products are mostly developed for a lifetime of a few years with a few hours per day, while many professional displays are operated 24/7 for a decade and longer. Another difference is that the value chain of most CE devices is located in Asia, whereas professional displays, which are mostly produced in Asia, are implemented into electronic systems worldwide (providing added value).

What is a Display?

The answer to the question of what actually constitutes a "display" is one that is not as straightforward as one would imagine, given the familiarity we all have with the use of displays though our interaction with TVs, automotive information panels, mobile phones, computers, tablets, etc. Answers to the question would include:

- A transducer to convert digital or analogue information to be processable by the human brain
- An electro-optic effect in a many materials
- Conversion of electrons to photons
- An electronic device which consists of hardware and software including an interface to a data source providing visual information
- The primary human interface to a system such as a computer
- A device which presents visual information and accepts user inputs

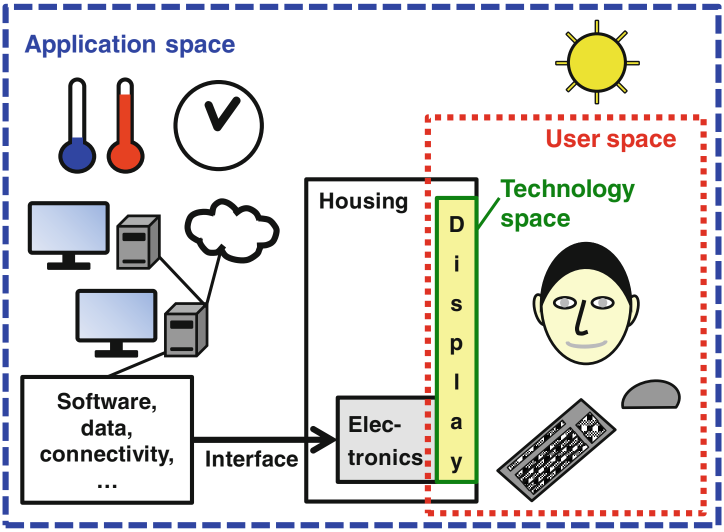


Fig. 1 A display within a system of hard- and software providing data (out) to a user and reacts to its input

All of the above answers pinpoint different aspects of displays and systems equipped with a display. An important topic is that a display presents visual data for its user, and user inputs can change the data to be presented. The systems aspect is illustrated in Fig. 1. This system point of view helps to understand the nature of display subassemblies, components, and materials. Each of these elements needs to be optimized for a dedicated display system including the hardware and software with respect to user needs.

Figure 1 provides the three perspectives of a display:

- **Application space**: the environment in which the display system (MacDonald 2012) (see, e.g., chapters "▶ Flexible Displays: Attributes, Technologies Compatible with Flexible Substrates, and Applications," "▶ LED Display Applications and Design Considerations," Parts 45, "Projection Systems," and 51, "Advanced Display Measurement Procedures") is operated. Consideration of the specific environment to be used results in user and specification requirements. The application space is independent of the display technology. This space is highly influenced by markets, economics, and trends (see Sect. 12, "Display Markets and Economics") or, e.g., the intended application (e.g., mobile devices, see Part 43, "Mobile Displays").
- **User space**: Screen size, resolution, and color for human perception (see chapter "▶ Geometric Optics") and inputs of data and commands to the system, e.g., via touch (see Part 21, "Touchscreen Technologies"), keyboard, and mouse.
- **Technology space**: Selecting, manufacturing (e.g., Part 34, "LCD Production"), and improving a display (transducer technology) which fulfills the requirements

of the user and application's space (Lee et al. 2008) (optical parameters see Sect. 11, "Display Metrology").

The user space should be taken into account first when developing a new product with a display (user-centered design). For example, it would not be sensible to build in a FHD display in a calculator or indeed an 8-Segment display in a smartphone. Both approaches would, to a certain extent, fulfill some of the requirements but would fail to achieve all: A FHD calculator provides high-resolution figures but with low battery operating time and at high cost. An 8-Segment smartphone display can show the numbers dialed, is sunlight readable and has low power consumption, but is impossible to visualize contact names or any form of information and media-rich content.

Display Technologies Overview

There are many different technologies used to build a display. These technologies are typically known by the acronym that refers to the primary electro-optical effect that is used to emit and/or modulate visible light at a pixelated level, e.g., CRT, LCD, and OLED. This may be further divided into technologies which generate their own light, emissive, or those that modulate light generated separately (e.g., via a backlight) – *reflective* or *transmissive*. Displays are also referred to as being direct view, virtual, or projected, to describe the manner in which the image is viewed by the user. These categories are used in Fig. 2 to provide an overview of the major technologies:

- Direct view displays (the user looks direct onto a display)
- Projection displays (the user sees the image of a microdisplay projected onto a reflective screen, Part 45, "Projection Systems")
- Microdisplays (the user look to a display which is typically near its eye, Parts 44, "Microdisplay Technologies," and 46, "Head-Worn Displays (HWDs)")
- 3D displays (displays which can produce three-dimensional images, Sect. 9, "3D Displays")

The different characteristics of emissive, transmissive, and reflective displays are presented in (Fig. 4):

- Emissive displays (Sect. 6, "Emissive Displays") generate light by converting electrical power to (visible) photons.
- Reflective displays (Sect. 8, "Paper-Like and Low Power Displays") modulate their reflectance, typically via a voltage-controlled effect.
- LCDs (Sect. 7, "Liquid Crystal Displays" and (Wu and Yang 2014)) are labeled as both reflective (e.g., 8-Segment display as used in a watch) and transmissive (AM LCD with light generating backlight) (den Boer). Confusion can occur

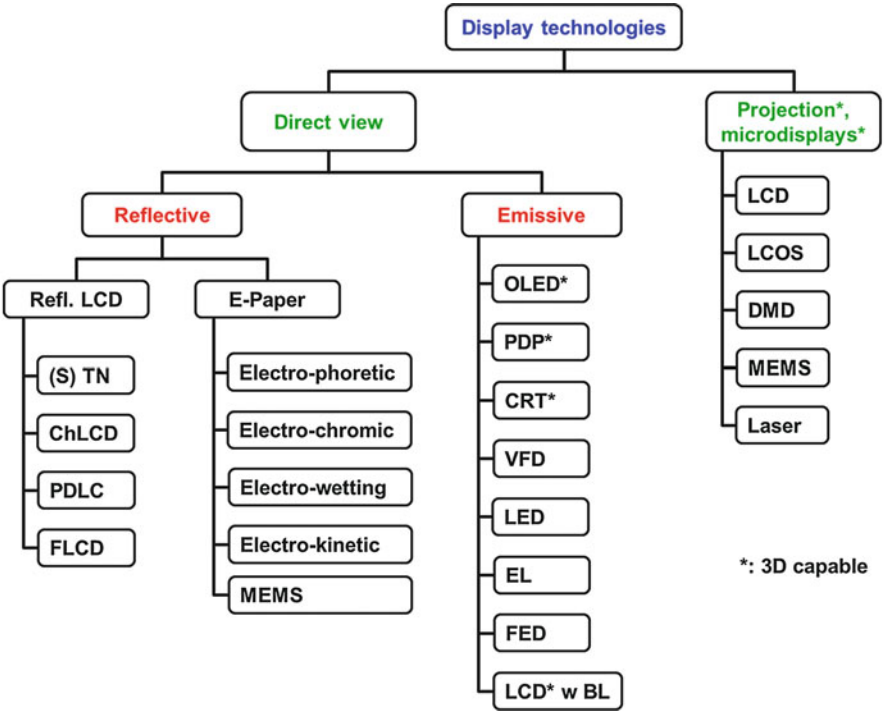


Fig. 2 Overview of major display technologies

when a complete system is considered; hence, an LED-AM LCD backlight and modulator combination could be referred to as an emissive display.

The typical cross section of a FPD glass is provided in Fig. 3. The major components are designated as the front plane, electro-optical layer, and back plane. Sub elements, or layers, of these provide the different functions required. For example:

- The substrate provides mechanical stability and protection against environmental impact, e.g., moisture. Most of the displays use glass (Part 15, "TFTs and Materials for Displays and Touchscreens: Display Glass") as substrate; however, much effort is directed at the use of flexible substrates (Part 20, "Flexible Displays") made of plastic or thin glass.
- Additional layers added to the substrate can include a polarizer (front plane for LCDs and OLEDs, backplane LCD), touch screen (see Part 21, "Touchscreen Technologies"), or with color displays such as AM LCDs (and some OLEDs), also use red, green, and blue (RGB) filters for separation of subpixel color modulation in order to achieve a full-color image capability (Part 3, "Color Science").

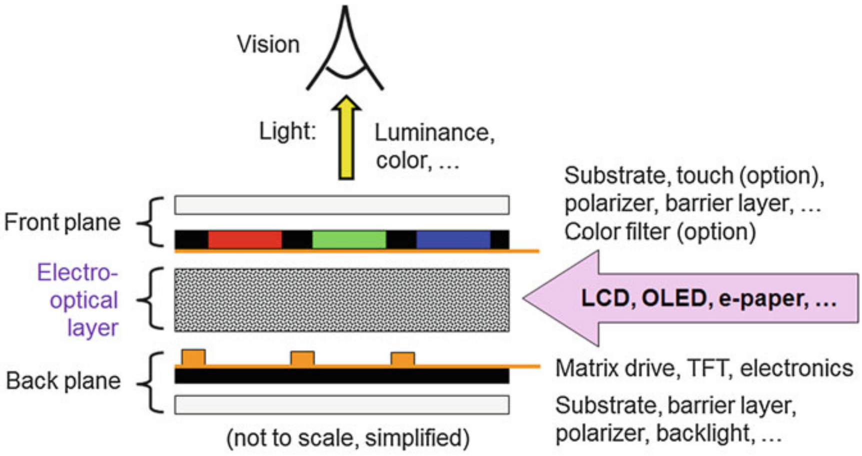


Fig. 3 Simplified cross section of a basic flat panel active matrix (color) display glass

- Driving of pixels (and RGB subpixels) is achieved via electronic structures (electrodes and devices) on both the front and back plane. The front plane electrode is typically unstructured for most active matrix displays and consists of ITO (Part 18, "Transparent Conductors: ITO and ITO Replacements") for LCDs and metal for OLEDs. Row and column electrodes (metal) and TFTs (Parts 16, "Inorganic Semiconductor TFT Technology," and 17, "Emerging TFT Technologies") are on the back plane of active matrix displays. Passive matrix displays usually have crossed electrode stripes where the intersections form the pixel. Some more details are presented in section "Display Driving Principles".
- The electro-optical layer is responsible for the light generation or modulation mechanism that facilitates the visual display of information: light is either reflected (reflective displays such as e-paper, see Sect. 8, "Paper-Like and Low Power Displays"), generated by current (emissive displays, e.g., OLED Part 28, "Organic Electroluminescent Displays," PDP Part 25, "Plasma Display Panels"), or transmitted through the display from a backlight, (e.g., LCD, see Part 33, "LCD Backlights and Films"). More details are described below.
- LCDs have either a reflector (reflective) or a backlight (Part 33, "LCD Backlights and Films") attached to the back plane.

A successful display systems design is consequently one that considers optics (Sect. 1, "Fundamentals of Optics for Displays"), photometry, and human vision (Sect. 2, "Human Vision and Perception"), the core display transducer technology utilized (Sects. 6, "Emissive Displays," and 7, "Liquid Crystal Displays") drive electronics (Sect. 4, "Driving Displays"), as well as physical display characteristics and measurements in order to compare and evaluate display performance (Sect. 11, "Display Metrology").

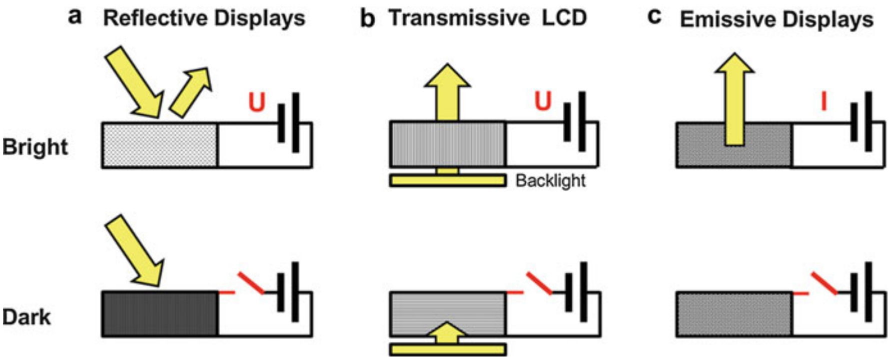


Fig. 4 Visualization of fundamental electric-to-optic conversion for major FPD technologies

Table 1 Typical display features depending on technology

Topic	Reflective	Emissive/transmissive
Examples	Segmented LCD PM LCD E-paper	OLED PDP VFD AM Color LCD with backlight
Typical merits	Low power Sunlight readable	Multimedia Supply chain of AM LCDs
Typical shortcomings	Nor or limited color Some with slow response time	Bright light performance High power consumption

The three fundamental electro-optic principles of reflective, transmissive, and emissive displays are shown in Fig. 4. As simplification, the principles are only visualized for black and white, with a summary of the corresponding display features in Table 1.

- The reflection characteristic of reflective (non-emissive) displays is controlled by a voltage (U, low current, Fig. 4a) switching between black (absorption, low reflectance) and white (high reflectance). These displays are therefore readable in bright light but must be illuminated when dark. As ambient light is utilized, the power consumption is extremely low ("green displays"). Examples are segmented monochrome LCDs (Sect. 7, "Liquid Crystal Displays") and e-paper displays (Sect. 8, "Paper-Like and Low Power Displays"). The latter ones are mostly bistable, which means that electrical power is only needed when a pixel should change its status. This is very significant in terms of power consumption, which facilitates very long battery life for e-readers based on this technology.
- Transmissive display (Fig. 4b) is the term used for color LCDs (mostly active matrix) which are equipped with a bright backlight. A voltage changes the transmission between a low (black) and a high value (white) of the liquid crystal

layer (cell) to modulate the light from the backlight subsystem. So the power consumption of the basic LC cell is low but that of the display is high due to the necessary backlight. Because of the reliance upon an integrated light sources, transmissive LCDs can also be referred to as emissive displays, and even as "LED" displays, which actually only refers to the backlight.

- Emissive displays (Fig. 4c, Sect. 6, "Emissive Displays") generate light by converting electrical power into to visible light. Note that "I" is used as the current symbol here, since these are often current driven, and, relative to reflective technologies, higher powers are typically required. For emissive display, the power consumption also depends on the actual data shown; hence, a black background is preferable in this context. Examples are OLED, PDP, CRT, VFD, FED, EL, and LED.
- Transmissive and emissive displays typically provide a high-quality optical performance under indoor ambient conditions, but their outdoor use is limited due to the need for a very high luminance to provide sufficient contrast. This requires higher power consumption, hence reducing battery life and impacting on longevity of the display system due to heat generation.

It is evident that no single display technology exists which is suitable for all applications. A key decision point is the choice between low-power monochrome displays and multimedia screens consuming a relatively large amount of power.

What is a Pixel?

In a similar manner to the complexities associated with the question of what constitutes a display, the issue of what is a pixel, or picture element, is also one that requires some consideration. The primary factors associated with an answer to this question are:

- A pixel is the very basic switchable unit of a visual display (see Fig. 5a).
- A display consists of a small number (e.g., 8-Segment displays to millions of pixels (e.g., FHD, see Fig. 5b)).
- The electro-optical function of a pixel is to control the light output (emissive, transmissive) or reflectivity (reflective) by the application of an electrical waveform according the gray level to be reproduced. This parameter is based on the electro-optical characteristic and is called gamma value (see chapter "▶ Luminance, Contrast Ratio, and Gray Scale") which adapts the luminance output to vision (see chapter "▶ Light Detection and Sensitivity").
- A color pixel usually consists of three subpixels (red, green, and blue, RGB, see Fig. 5).
- If all subpixels of a pixel have the same gray level, the pixel appears black (minimum) value, gray (intermediate values), or white (maximum value).

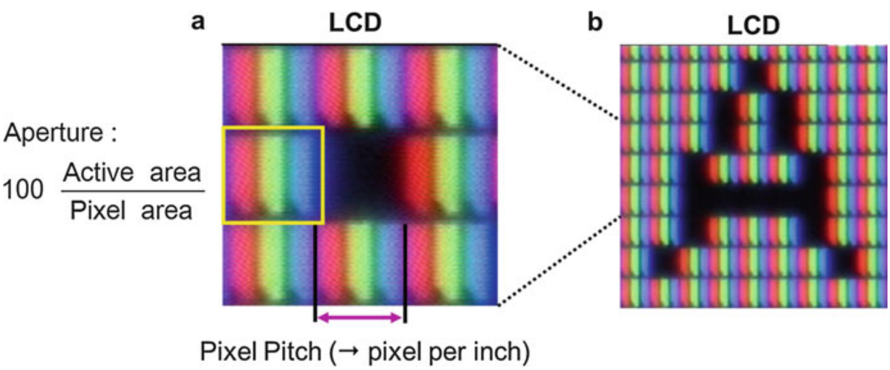


Fig. 5 Visualization of color AM LCD pixels. (**a**): 3 by 3 pixels (8 *white*, 1 *black*). (**b**): "A" is displayed by 7 × 7 pixels

This effect is caused by vision and the pixel size must then be in the range of the human eye resolution. As the color pixels in Fig. 5 are too large for the typical reading distance of a figure; a distance of about 10 m would be needed here for merging and the result is a perceived as a darker gray square.

- The shape of a matrix pixel is typically a square or rectangle, whereas segmented pixels (typically called a segment not a pixel) can have any shape as in 8-Segment numeric displays or even bespoke icons (e.g., petrol pump icon on an automotive console display).
- The size of a pixel should be appropriate for the specific application-related observer distance to the display.
- If not otherwise specified, five defects per million pixels (5 ppm) are allowed for standard applications (details see ISO 13406,2).

Three selected topics of the above list are now discussed more in detail – pixel size, gray scale, and color generation.

The human eye resolution is about 1′ (1 min of arc) which corresponds to about 0.15 mm or 170 ppi (pixels per inch) for an observer distance of 1 m. As there is a linear relationship, the ppi value increases for lower observer distance and rises for larger one. A reasonable value is 100 ppi/m (0.25 mm pixel size per meter observer distance). Examples are Apple's retina display in iPhones with 326 ppi (78 μm) intended for 30 cm observer distance (about 100 ppi per meter distance) and the iPad 3 with 264 ppi for 0.5 m. For a TV set of 55″, the screen width is about 120 cm which results in a pixel size of about 0.6 mm or 40 ppi. This results in about 2.5 m recommended observer distance for visual matching. The ppi value for billboards or video walls with 10 m and more observer distance is about 10 resulting in a pixel size of about 2.5 mm which is achievable with individual LEDs; however, most LED displays for these applications have 8+ mm pixel pitch due to cost. Another important topic is aperture, the ratio of the active pixel area divided by the total pixel area (inset Fig. 5a). This ratio is lower than 1 (or 100 %) as the area separating the rows and columns is "lost"; the small dark area in Fig. 5a at the bottom left side of a subpixel is the TFT. All non-used area of a pixel is usually covered black.

As most of the explanations and examples above refer to black ↔ white transitions, gray level reproduction will be introduced here in brief, with more details are presented in the chapters of each specific display technology (Sects. 6, "Emissive Displays," and 7, "Liquid Crystal Displays"). The gray-level-to-luminance relation must be nonlinear ($L \sim GL^{\gamma}$) due to vision characteristics. The relevant parameter is gamma (γ) and is typically 2.3; the measurement procedure is provided in chapter "▶ Luminance, Contrast Ratio, and Gray Scale." The gray level (or luminance) can be controlled in two different ways:

- Analogue: The light output level is a function of voltage (LCD) or current (OLED).
- Digital: The light output level is constant but switches between zero and "constant" in time (pulse width modulation PWM, examples include PDP, LED, and DMD) or area (as in digital printing and some e-paper technologies).

Fundamentally there are two principles for color reproduction by electronic displays:

- "Side by side" as shown in Fig. 5, where vision merges the subpixels to the intended color of the pixel. This principle is used by most direct view display technologies.
- "Field sequential" shows the primaries one after each other at tripled frame rate (e.g., 180 Hz for three colors compared to 60 Hz for "side by side"). At this high frame rate, the sequential primaries (with their dedicated gray levels) are merged by vision to the intended color. This principle is used in single-panel DMD projectors – see Sect. 10, "Mobile Displays, Microdisplays, Projection, and Headworn Displays" – and LCD demonstrators with "blinking" RGB backlight (saving color filter and 2/3 of the TFTs, see chapter "▶ LCD Backlights").

Most of today's color displays are based on three primary colors – red (R), green (G), and blue (B); they form as subpixels a color pixel within the pixel area (RGB subpixel, Fig. 5). Their color coordinates span a triangle (see chapters "▶ The CIE System" and "▶ Color") called the (color) gamut. Colors within this triangle can be reproduced by variations of the primary's gray levels (resulting in different luminance). The number of possible colors depends on the gray level resolution: In modern displays, the gray level depth per color is 8 bit which equals 256 gray levels incl. black. For three primary RGB this results in 16.7 million (256^3) different colors. However, due to non-ideal display characteristics, ambient light reflections, and limits of vision, this full gamut is not perceived by an observer.

Display Driving Principles

After introducing pixels, the next step toward understanding how a display works is to consider how the pixels are electrically driven, e.g., setting a gray level or switching between gray levels (the simplest case is black ↔ white). The two fundamental approaches (see chapter "▶ Direct Drive, Multiplex, and Passive Matrix") are shown in Fig. 6 – direct drive (a) and matrix drive (b). For direct drive all segments (typically used instead of "pixel" for this case) are directly connected to the driving electronics. So there is full control over the voltage and the waveform of any segment. The arrangement and the shape of the segments can be individually designed for the application to be, for example, bars or icons, with the geometry defined by electrode structuring.

However, it is obvious that this principle might only be effective for low numbers of segments, but not for addressing thousands or millions of pixels. One reason is the (wasted) area needed for the wiring and another is the cost for the electronics. Therefore, matrix addressing is applied for high-resolution displays (Fig. 6b): All pixels are in pre-defined positions in a matrix at the cross points of rows and columns which define the pixel structure (usually RGB rectangles resulting in a square). The pixels are not addressed here at the same time as with direct drive. The most common principle is "row-at-a-time" addressing. Row after row is selected (scanning), and the gray level data (voltages) of each row are set in parallel by the column drivers. In other words, when a row is selected, the gray levels for all pixels of this row are "present" at the individual column lines. A frame starts at the first row, and after the last row was selected, the next frame starts with the first row (again). The refresh frequency needed for such a scan is typically 60 Hz which equals a frame time of 16.7 ms. For a FHD display with 1,080 rows, every row is selected for only 15 μs. During that time, all gray level data of 5,760 subpixels (1,920 × 3) for the next row must be transmitted.

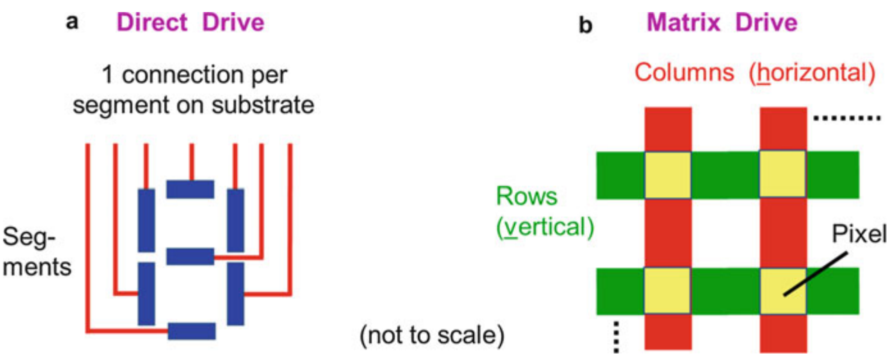


Fig. 6 Fundamental driving principles of pixels: Direct (**a**) and matrix (**b**) drive

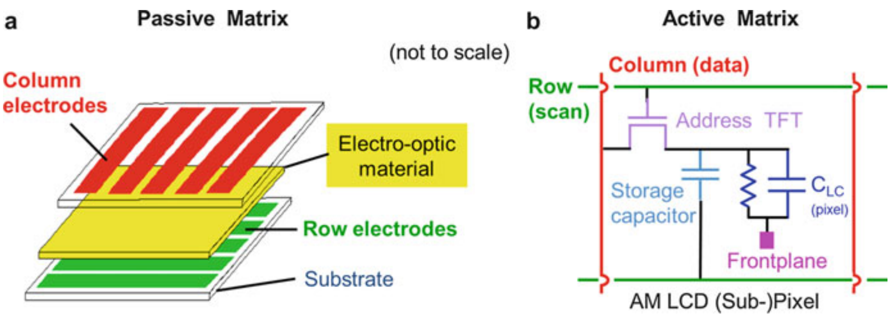


Fig. 7 Schematic drawing of passive (**a**) and active (**b**) matrix driving

The most simple matrix driving is called passive matrix (PM, Fig. 7a): Electrodes are structured as parallel stripes of conductive material (mostly ITO) on the front- and backplane; the pattern of front- and back plane is arranged orthogonal. Between the electrodes is the electro-optic material. However, this approach with only rows and columns has a fundamental drawback: the voltage of a column is "present" at every pixel of that column no matter if a row is selected. Consider the following example: A selected row has a voltage of −5 V; a non-selected row has a voltage of 0 V. The column voltage swings between 0 (black) and +5 V (white). A selected row has now −5 V and the column electrode of a black pixel 0 V. This results in a pixel voltage of |5| V. For a white pixel in a selected row, the effective voltage is |10| V. But all other pixels in this column are exposed to +5 V and 0 V by the row electrode resulting (again) in |5| V. Pixels in "black" columns and non-selected rows have 0 V. So it is obvious that passive matrix drive can only work when the electro-optic material has a threshold (here > 5 V) and a steep electro-optical curve. This can be achieved for LCDs by STN technology (see chapter "▶ Twisted Nematic and Supertwisted Nematic LCDs"). Therefore, the resolution of PM LCDs and PM OLEDs (peak luminance) are limited. On the other hand, all commercial PDPs have been passive matrix (but in a special mode called memory mode, see Part 25, "Plasma Display Panels").

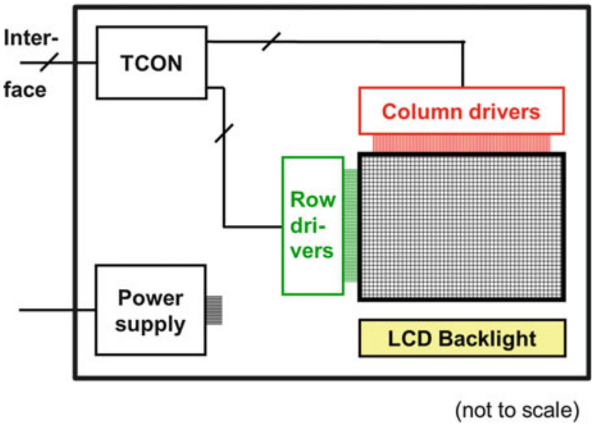
Active matrix driving (Fig. 7b, chapter "▶ Active Matrix Driving"; examples for LCD see Part 32, "LCD Addressing," AMOLED see chapter "▶ Active Matrix for OLED Displays") refers to a matrix display which contains a so-called active (electronic) element for each pixel on its back plane (Fig. 3). The vast majority uses thin film transistors (TFTs). These transistors with the electronic functionality of a MOSFET (called address TFT for AM LCDs) act like switches between the display columns and the pixels. The gate of a TFT is connected to its row (scan); if this row is activated by a voltage, the gate "opens" and let the column voltage (gray level data voltage) passes to the pixel. So a pixel is only exposed to its individual voltage and not, as for PM, to the voltage of the other rows during a frame time. So the TFT "isolates" pixels from the rest of the matrix when not selected by its row. A storage capacitor "holds" the gray level voltage (to compensate that small but nonzero conductivity of liquid crystals) until the corresponding row is selected at the next frame (16.7 ms for 60 Hz). This paves the road toward high resolution and high image quality. The key advantage of active matrix compared to passive matrix drive is that it allows accurate control of the data (usually in the form of a voltage) loaded onto each pixel. TFTs can be produced in different types such as a-Si (amorphous silicon, chapter "▶ Hydrogenated Amorphous Silicon Thin-Film Transistors (a-Si:H TFTs)"), p-Si (polycrystalline silicon, chapter "▶ Polycrystalline Silicon Thin Film Transistors (Poly-Si TFTs)") or oxide (chapter "▶ Oxide TFTs"), and organic (chapter "▶ Organic TFTs: Polymers") material.

What Are a Display Module and Display System?

In this section, we consider more of the full system from which a display is composed. A display consists not only of a pure substrate (Fig. 3) or matrix electrodes and TFTs (Fig. 7) but also the drive electronics and embedded software which determine the gray level data for each subpixel and the selection of rows. A device consisting of display glass, interface (IF), electronics, power supply, and a backlight for LCDs is called "display module" (see block diagram Fig. 8). Each of the subassemblies shown in this figure has dedicated tasks to perform:

- The module itself provides housing for all subassemblies and the mechanical fixture. Its dimensions are relevant for mechanical integration.
- The power supply (Part 14, "Power Supply") delivers all necessary voltages with their maximum current, which are needed within the display module. Some modules have no power supply built-in, so that every voltage has to be provided from outside. This is relevant for the electronic design of the display system.
- The interface (Part 11, "Panel Interfaces") transfers data from a data source (e.g., display or graphics controller, see below) to the timing controller (TCON). Power supply is mostly done as well via the interface connector. The selection

Fig. 8 Block diagram of a high-resolution matrix display module, backlight only for LCDs



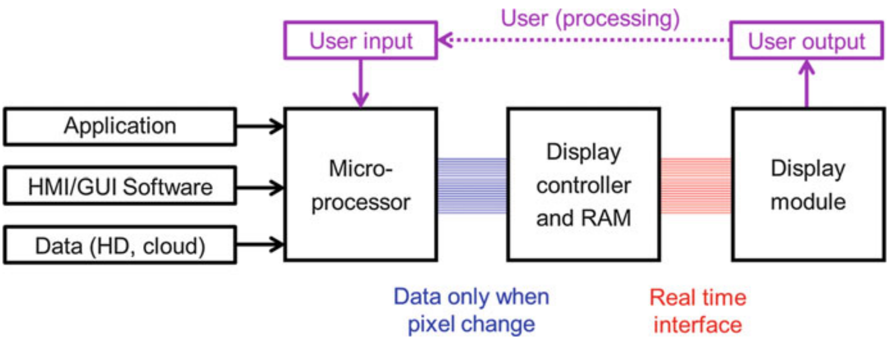


Fig. 9 A display module within a complete electronic system with user interaction

of the electronic interface (see Part 11, "Panel Interfaces") depends mostly on the display resolution – the more pixels the higher the data rate to be transferred.
- The timing controller (TCON) modifies the input interface data to a format which is needed for the row and column drivers, including gray level transfer function (see chapter "▶ Luminance, Contrast Ratio, and Gray Scale") for the electro-optic display technology used.
- Row drivers select subsequentially each row so that gray level data can be transferred to the pixel of the selected activated row (line) by the column drivers.
- Column drivers deliver the gray level voltage waveform for the actual selected row.
- Backlight for color LCDs (chapter "▶ Intelligent Control of LED LCD Backlights," Part 33, "LCD Backlights and Films") or front light for reflective e-paper.

So, finally, a display module is a device for converting input data into a viewable form. This means that the input image data must be adapted to the driving principle and the electro-optical characteristics of the display technology used. Another important topic for judging display materials (such as emitters of emissive displays, see Sect. 6, "Emissive Displays") and subassemblies (such as LCD backlights and films, see Part 33, "LCD Backlights and Films") and systems with a display is efficiency. This is defined as luminance output divided by the total power consumption, multiplied by the active area size (see chapter "▶ Spatial Effects" section "Efficiency"). It is clear that the efficiency should be maximized, especially for mobile and wearable display systems (see Sect. 10, "Mobile Displays, Microdisplays, Projection, and Headworn Displays"). For PC monitors and TV sets, legal requirements, such as EC No 642/2009 in the EU and labels such as Energy Star in the US, exist, forcing display manufacturers to reduce power consumption toward "green displays" (which includes also production, recycling, and disposal).

A whole display system as shown in Fig. 9 combines the following elements and subassemblies:

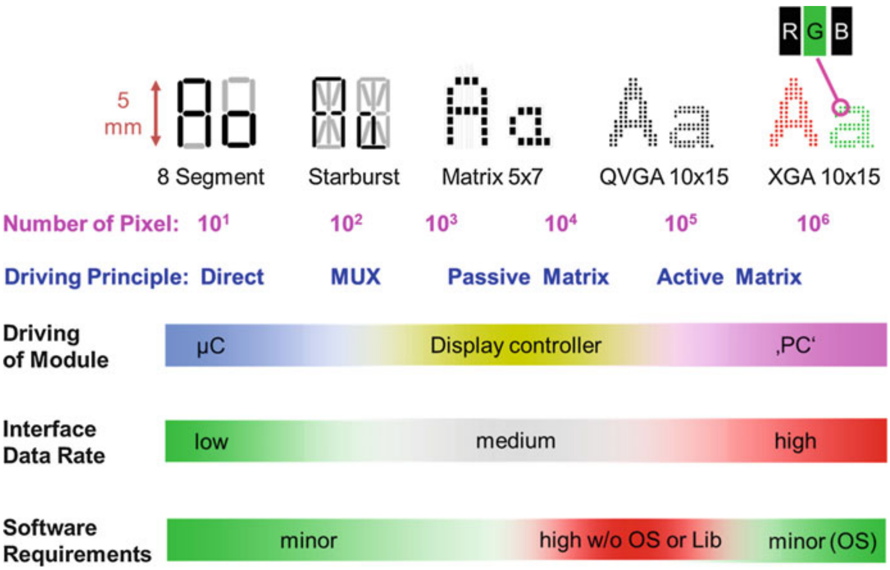


Fig. 10 Overview of character reproduction (for "A" and "a") of displays and its impact on driving principle, display module, interface, and software

- User input via, e.g., keyboard, touch, and mouse.
- Application features like housing and power supply.
- Software for Human Machine Interface (HMI) or Graphical User Interface (GUI); this includes an optional operating system (OS).
- Data source and storage (hard disk, cloud, etc.).
- A microprocessor (includes microcontrollers and processors of PCs) to provide (generate) the content to be shown. The various approaches for micro-controller – display controller – display are presented in Part 12, "Embedded Systems."
- The data generated by the microprocessor are transferred to the display controller and are stored in the display data (or video) RAM. Basically the RAM must be only updated when pixel data change.
- The display controller (graphics adaptor) streams the display RAM data in real time to the display module's interface.
- The display module (see Fig. 8) processes and visualizes these data.
- The user output is mainly provided by the display module but other sources like audio are often used.

It is evident from this introductory discussion that a display is a highly complex system with a vast number of technologies, optimization strategies, and application-specific considerations. Another very important aspects are the associated markets and economics (see Sect. 12, "Display Markets and Economics").

The variety of data representation methods is illustrated in Fig. 10. The simplest displays are named as "8 Segment" (also named often as "Segment 8," "Seg 8," "8 Seg," or "7 Segment") due to their appearance when all segments (pixels) are activated; another explanation refers to 7 segments plus decimal point. Those displays are mostly used for watches and meters such as temperature devices. Their segment count is in the range of tens, and they are therefore addressed by direct drive or low MUX (multiplex, similar to passive matrix). 8-Segment digits can show only a very limited number of characters like A, B, C, E, F, H, L, O, and U. Starburst displays have 4 (diagonal) segments more than 8-Segment displays, enabling the reproduction of numbers and characters, however mostly limited to Latin ones. Furthermore, icons made by electrode structuring are often implemented to provide some "graphics." As the total number of segments lies in the range of 100, these displays are typically MUX driven (chapter "▶ Direct Drive, Multiplex, and Passive Matrix"). Both low-resolution approaches are typically driven by a microcontroller with built-in display controller (see chapter "▶ Direct Drive, Multiplex, and Passive Matrix"). Software development is relatively easy as supported by available C-code subroutines for the microcontroller. Due to low pixel count, the data rate is relatively low. In the future, these segmented displays might gain some volume when integrated in lowest cost systems and smart systems (smart home, Industry 4.0) with rudimentary data visualization and control via wireless interfaces by mobile devices.

Matrix displays range from character displays (typically a few 1,000 s of pixels) to graphics displays with millions of pixels. This type is currently the most widespread for consumer and professional applications. As a consequence of the wide range of pixels, display driving is done by either passive or active matrix (see part 1.4). It is obvious that character reproduction by matrix displays is better and more flexible than on segmented displays, and the facility for color provides further features. The biggest benefit is the visualization of graphics and multimedia content. Passive matrix-driven displays have mostly the display controller built in the display module (low data rate), while active matrix displays are typically a part of PC-like systems or ARM-based devices with the highest data rates up to GBit/s. Without the use of an operating system (OS) or graphics library (Lib), the software effort would be enormous.

Fundamentals of Designing Display Systems Toward Applications

Since the transducer or emitter materials, display subassemblies, or a display module are only a part of a complete electronic system for a dedicated application, a complete approach requires a full system design. Figure 11 provides an overview of such an approach to designing a full system incorporating a display. This approach is illustrated in the logical order with mutual dependencies indicated; yellow boxes are mainly related to displays; cyan symbolizes user and application characteristics:

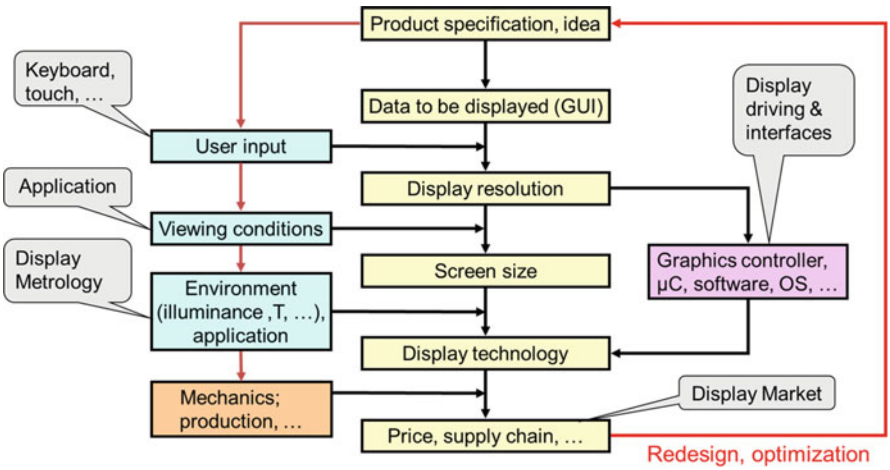


Fig. 11 Typical design flow for a system with a display

- The first step a new product design or a redesign of an existing one is the product specification or an "idea."
- The next step is to define the data to be displayed which are necessary to control or operate the system. The way these data are presented on a display is named as the Graphical User Interface (GUI) or Human Machine Interface (HMI). The latter often refers more to the whole system including the input and output devices.
- Display resolution is defined by the data to be displayed by summing up all text, icon, and graphics elements in terms of pixels.
- The display resolution determines the whole electronic system requirements including the microprocessor and graphics processor (see section "What Are A Display Module and Display System?"). An operating system (OS) and a GUI software are mostly used for high-resolution graphics systems.
- The screen size is set by the observer distance (viewing condition) and related to vision (see section "What Is A Pixel"). If a touch input is used, the touch buttons on the display must also have an appropriate size to match input geometry, typically 2 cm × 1 cm for an OK button.
- The environment of the application including the operating temperature and incident angle of the observer (viewing angle) helps to inform the suitable display technology.
- Other application aspects to be considered are power consumption for battery; vehicle or mains-powered devices; the operating lifetime; ambient lighting conditions such as whether it will be used at night, indoor, sheltered outdoor, outdoor and full sunlight exposure, etc.; and other environmental factors such as humidity and vibration. The optical performance of the resultant system is then determined by display metrology (see Sect. 11, "Display Metrology").

- Finally, the system has to be built, so mechanical construction, procurement, and production issues will need to be considered. In many cases, the display technology or module which would fulfill all requirements is not available (e.g., supply chain for professional products, see below) or the price might be too high. Therefore, redesign and optimization is needed to improve a system.

Supply chain and price are often topics which are underestimated, especially when designing professional displays. As flat panel display production lines are expensive, mass production of a vast number of a display types is the only economical way. Therefore, consumer displays dominate the market with a share of over 90 % (see Sect. 12, "Display Markets and Economics"). All other applications are summarized as professional displays. However, the requirements of consumer electronics and professional displays differ significantly, as summarized in Table 2. Consumer displays are typically produced at high volume for a period of about 1 year due to innovations and trends of, e.g., smartphones. As system's development and lifetime is significantly longer, displays intended for professional use are produced consistently for at least 3 years. The optimization criterion for consumer displays is typically low cost, whereas professional systems must provide a certain performance. As with electronics as a whole, obsolescence is also a critical topic for professional

Table 2 Consumer versus professional displays

	Consumer displays	Professional displays
Minimum order quantity	High	Low
Targeted display production	~1 year	>3 years
Optimization	Typically cost	Typically performance
ECO (Engineering Change Order) notification	Maybe	Yes
LTB (last-/lifetime buy) notification	Maybe	Yes
Requirements	Low	High
Duration per use	Minutes (mobile) to hours (PC, TV)	Several hours to 24/7 use
Lifetime (sum of use time)	1,000–10,000 h	Up to 100,000+ h
Operational time (time in use incl. off time)	Several years	Decade(s)
Location of production	Usually complete value chain located in Asia	Display panels are produced in Asia and value is added in country where the display is integrated into a system.

displays, so communication of producer and customer (ECO and LTB notification) is needed. Professional systems have to fulfill dedicated tasks, so their requirements in terms of system design are significantly higher than, for example, a smartphone where secure operation is not mission critical. Most consumer display systems are operational for periods in the range of hours per day for some years (lifetime), while some professional displays are often continuously operated for years (summing up to 100,000 h of operation) and/or under extreme temperature conditions.

Since around the year 2000, nearly all displays are manufactured in Asia; one reason is that mass production of high-volume consumer devices is located there. As professional systems differ at large extent, manufacturers for professional systems often customize their systems (for added value) by modifying, for example, the housing, power supply, and cover lens for a touch module, toward complex systems for individual needs. However, consumer devices set the major trends and professional displays and then follow these trends. An example is the touch screen: Touch control was used in the industry long before the introduction of Apple's iPhone in 2007. However, soon after that time, touch screens were positively experienced by many people, and so touch screens became a must for many professional display systems as well.

Summary and Directions of Future Research

Displays are the most essential device in the information age as they are the link between user and data visualization. To date, there is no single display technology which fulfills all the different needs of an application. Therefore, many different display technologies have been developed since the invention of the CRT. At the time of writing (2015), LCDs, OLEDs, and reflective e-paper are the dominating technologies, with some other display approaches gaining low volumes as with large LED video walls. Most LCDs and OLEDs are full-color displays capable of presenting multimedia information but with some issues under bright light conditions. Reflective e-paper displays are readable in sunlight but there is very limited color reproduction.

As displays and their resolution set the requirements of a whole system (such as computing and graphics power), it is essential to have a wide knowledge of all aspects of displays – which is the premise of this handbook (and presented as an overview in this section).

Current and future research is focussed on flexible, plastic (unbreakable), and transparent displays to enable new form factors and applications like foldable displays for smartphones as an ideal combination of a small device for making phone calls and browsing the internet with an unfolded screen. The major challenges are bending radius and the number of bendings without noticeable degradation. However, it is clear that "traditional" flat panel displays are here to stay and have a bright future.

Acknowledgment This opening chapter of this revised edition of the *Handbook of Visual Display Technology* is dedicated to Mr Chris Williams, UK. His outstanding networking and enthusiasm for displays brought many of these contributing authors together – this Handbook is the result.

Further Reading

Blankenbach K, Gassler G, Koops HWP (2008) Vacuum displays. In: Eichmeier JA, Thumm MK (eds) Vacuum electronics, components and devices. Springer, Heidelberg, pp 85–125
den Boer W. Active matrix LCDs. Newnes/Elsevier, Amsterdam
Lee J-H, Liu DN, Wu S-T (2008) Introduction to flat panel displays. Wiley, New York
MacDonald LW (2012) Display systems: design and applications. Wiley, Chichester
Wu ST, Yang D-K (2014) Fundamentals of liquid crystal devices. Wiley SID, Chichester