Embedded System Application

4190.303C

2010 Spring Semester

CRT, LCD, OLED and display systems

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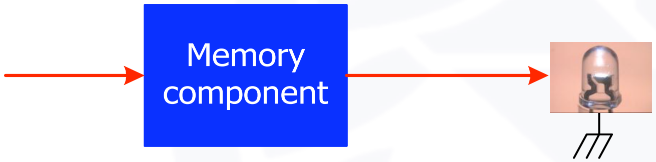
ELPL Embedded Low-Power Laboratory

Display Devices

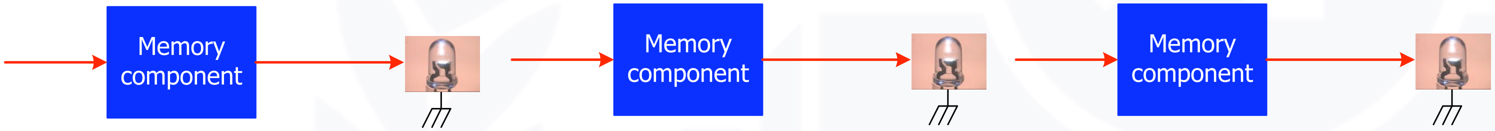
- Bulbs
- Nixie tube (Numeric Indicator eXperimental-1) - The first electronic digital readout
- Vacuum fluorescent display
- Light emitting diode
- LCD
- OLED

Display System Architecture

- Principle of operation
  - Single display



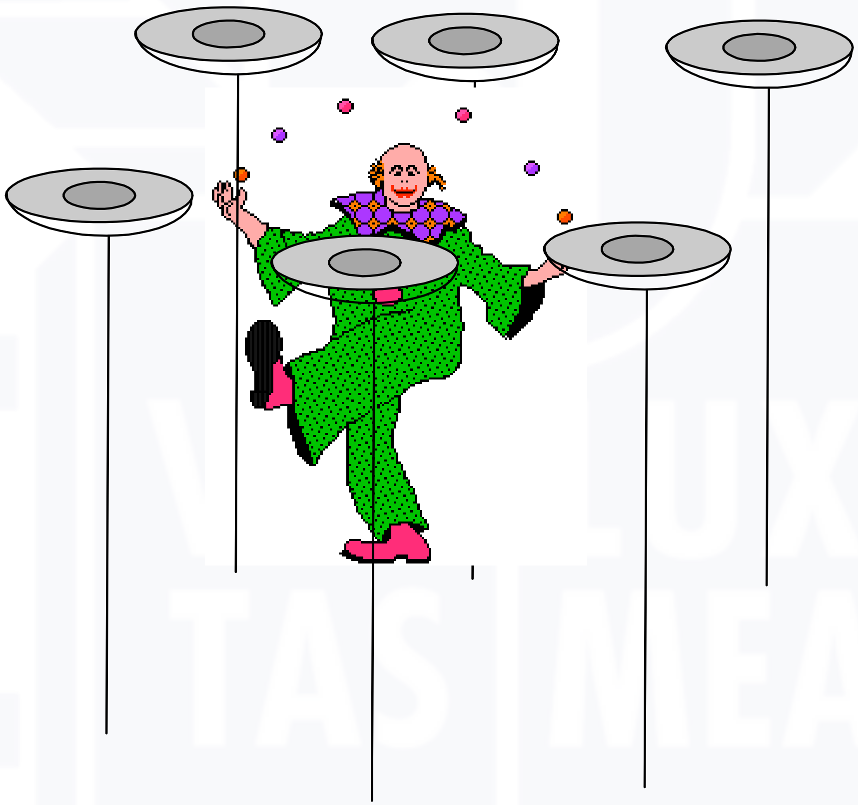
  - Group display



  - Massive display
    - More efficient method is required

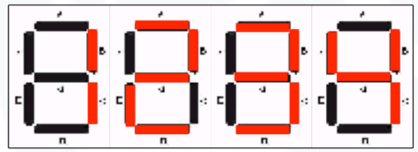
Dynamic Display

- Spinning dishes
  - Static spinning
    - Spin one dish per hand
  - Dynamic spinning
    - Spine several dishes per hand
    - Use of inertia
- Static display
  - Display the device the same information at all times
- Dynamic display
  - Use of human perception
  - Pulse display for illusion
  - For group and massive display

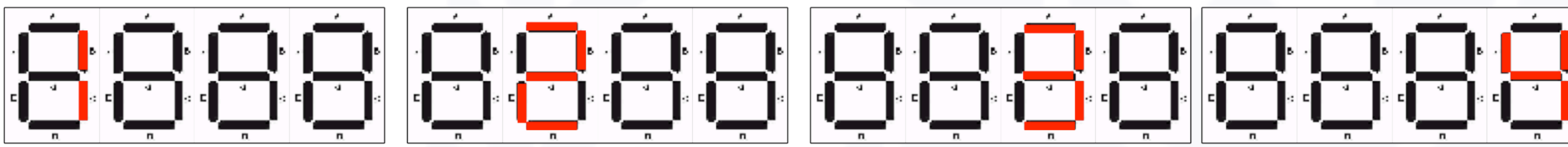


Dynamic Display

- Human eyes cannot perceive a light source that is blinking faster than 30Hz



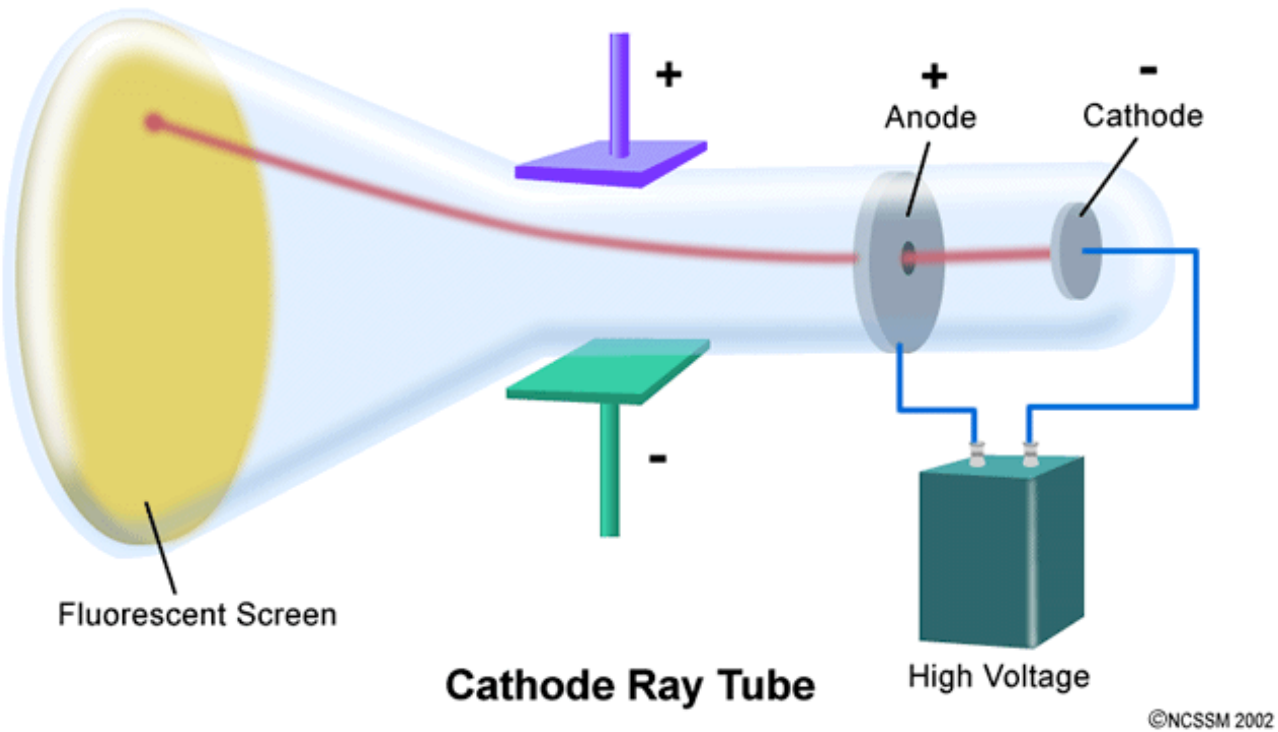
Static display



Dynamic display

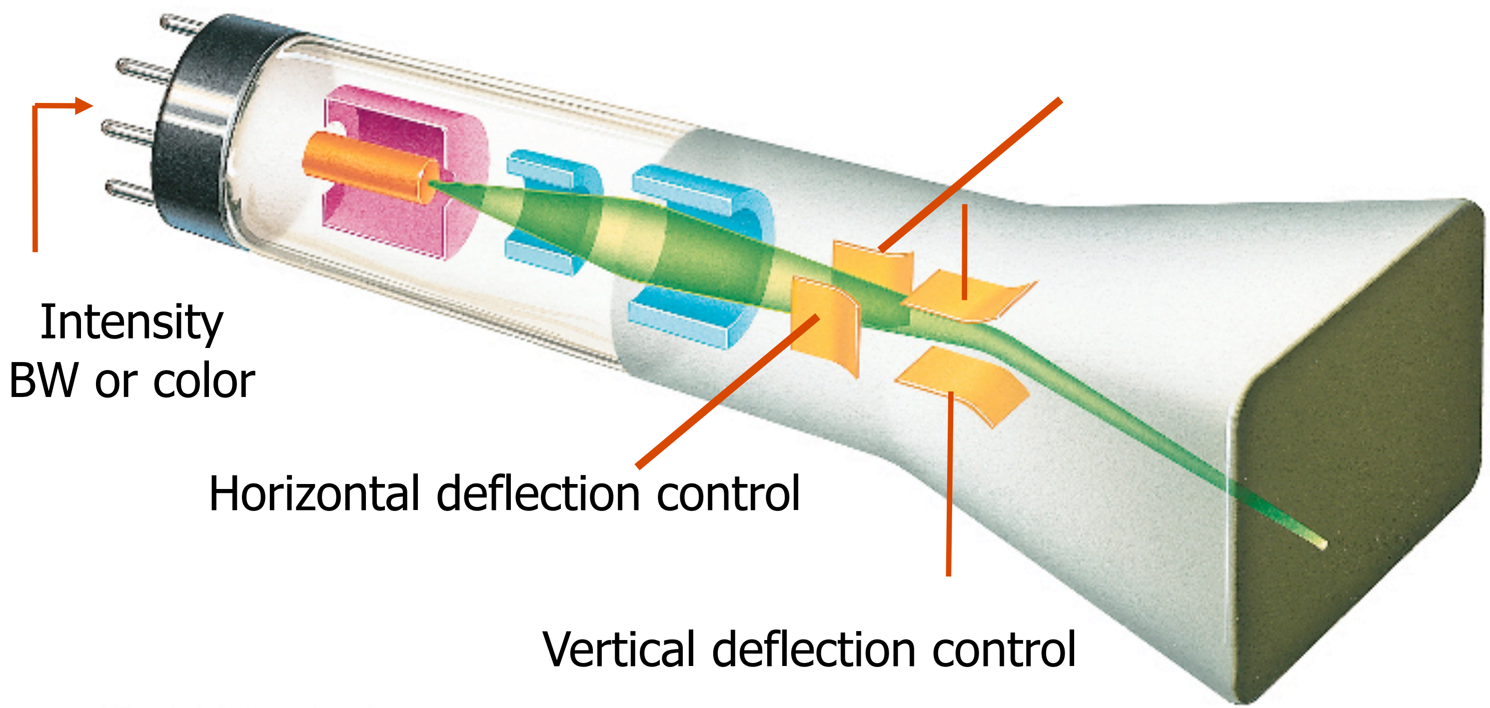
CRT Display

- Cathode Ray Tube (CRT)



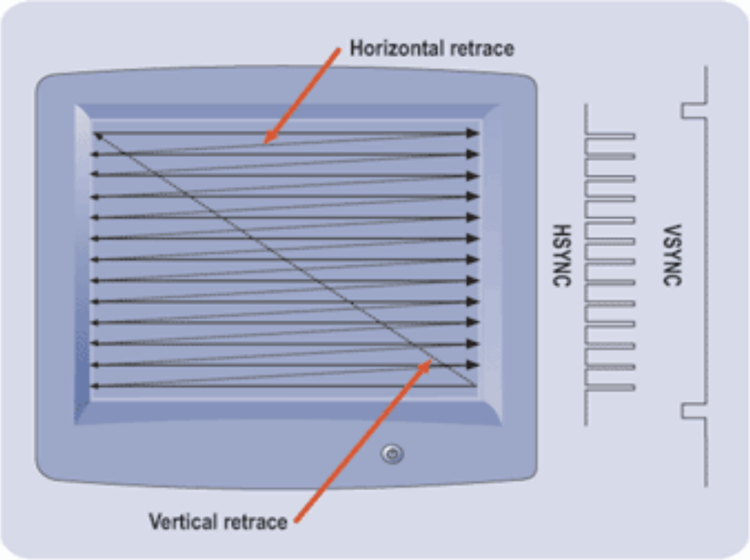
CRT Display

- Horizontal and vertical deflection



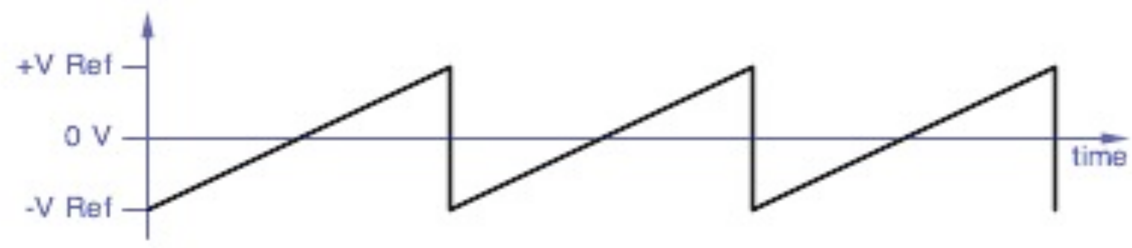
CRT Display

- Raster scan
  - Left to right
  - Top to bottom
  - Rely on afterimage
    - 30Hz or higher refresh rates
- Video timing
  - Hsync signal for horizontal retrace
  - Vsync signal for vertical retrace



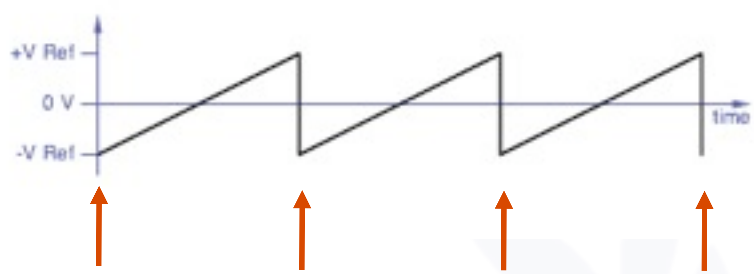
CRT Display

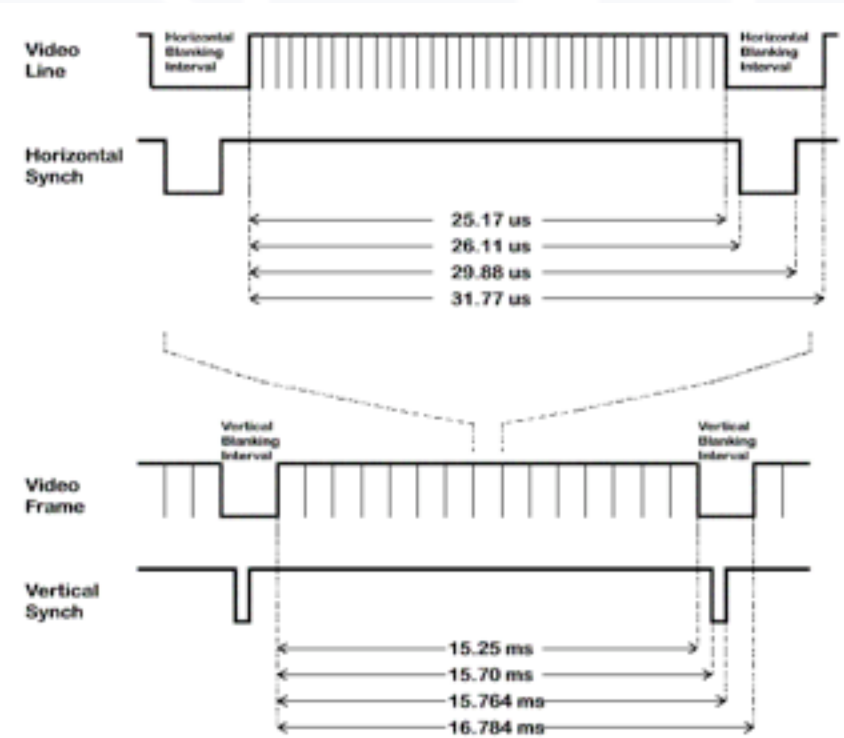
- Sweep signal
  - Saw tooth waveform
  - 15.75KHz saw tooth for the horizontal scan
  - 30Hz saw tooth for the vertical scan



CRT Display

- Video signals
  - RGB – to electric gun
  - Hsync – for horizontal scan
  - Vsync – for vertical scan
- RGB can be digital or analog
- Composite signal
- Sync signals synchronize the saw tooth waveforms



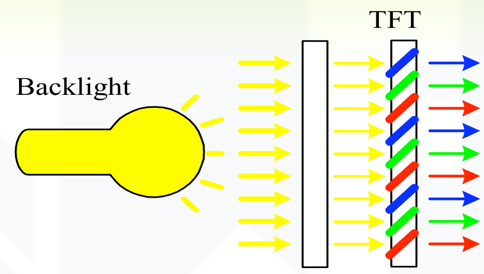


Liquid Crystal Display

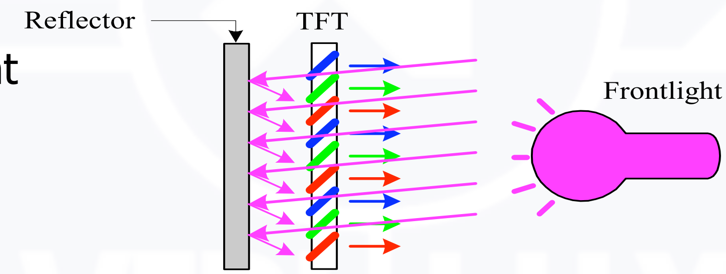
- LCD stands for Liquid Crystal Display
  - Advanced display system
  - "Liquid Crystals" are semi-solid substances that are sensitive to temperature and electricity
- Commonly used in
  - Digital watches, calculators, laptops
- Compared with conventional CRT display systems
  - Advantages
    - Light
    - Thin
    - Low power consumption
  - Disadvantages
    - Expensive for computer display
    - Display size is limited by manufacturing complexities
    - Slow response
    - Non linear color

Liquid Crystal Display

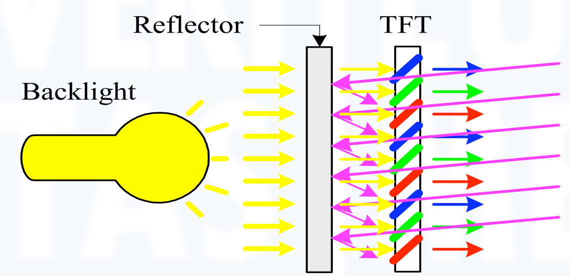
- Transmissive mode
  - Illuminated from behind using a backlight lamp
  - Powerful backlight source due to the low transmittance (less than 10%)
  - High image contrast (typically 300:1)
- Reflective mode
  - Illuminated from the front using an ambient light or a frontlight lamp
  - Very low power consumption with the frontlight turned off
  - Low image contrast (typically 10:1) due to the low reflectance (3 to 5%)
- Transflective mode
  - Partially transmissive and reflective



Transmissive mode



Reflective mode



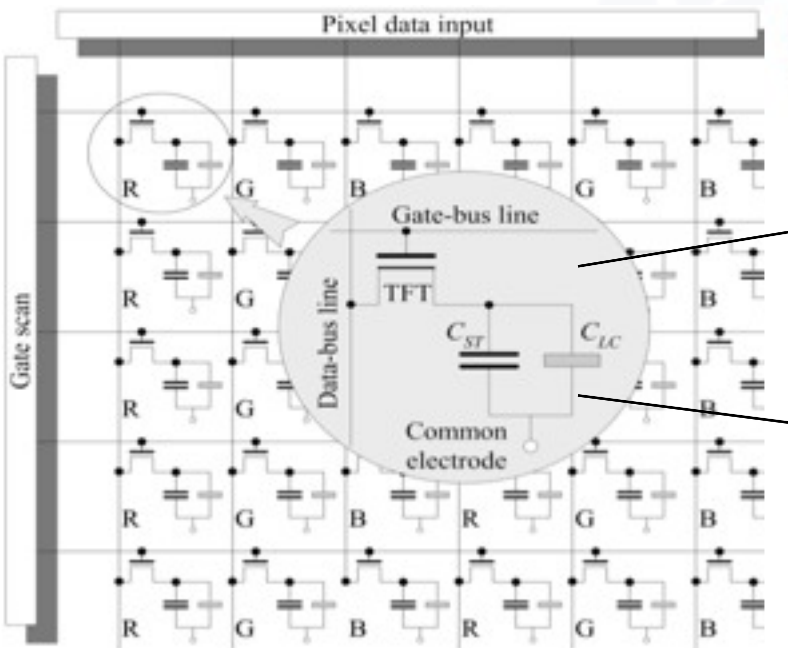
Transflective mode

Passive Matrix LCD

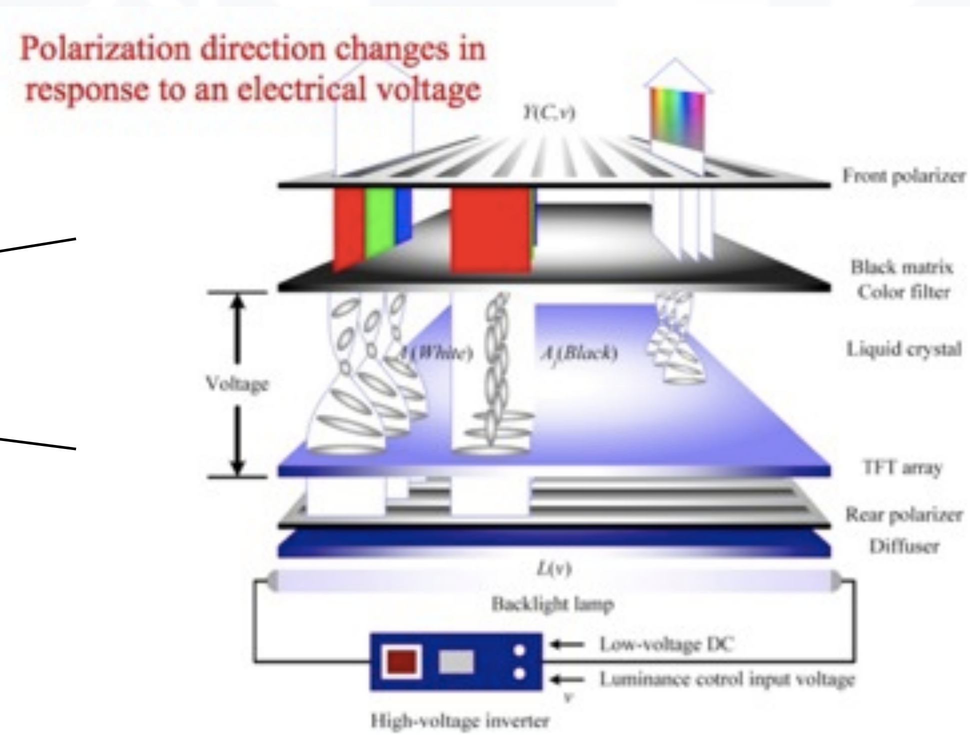
- Advantages
  - Very simple design
  - Inexpensive
  - Reduced number of electrodes
    - rows + columns electrodes for rows X columns pixels
- Disadvantages
  - It has a slow response time
    - This implies slow image refreshment rate and hence lower quality of changing display
  - It has inherent imprecise voltage control
    - That causes pixels around the required pixel to be partially activated and thus affecting the quality

Active Matrix LCD

- TFT LCD panel



TFT-array substrates (C_{ST}: a storage capacitor and C_{LC}: an equivalent capacitor for a liquid crystal cell)



Structure of a transmissive LCD panel

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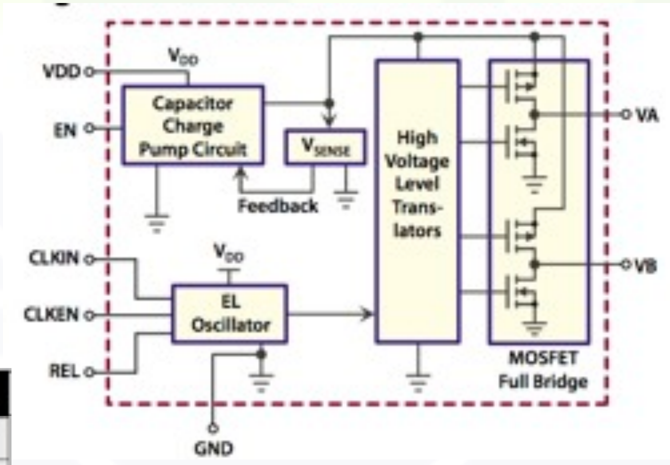
Active Matrix LCD

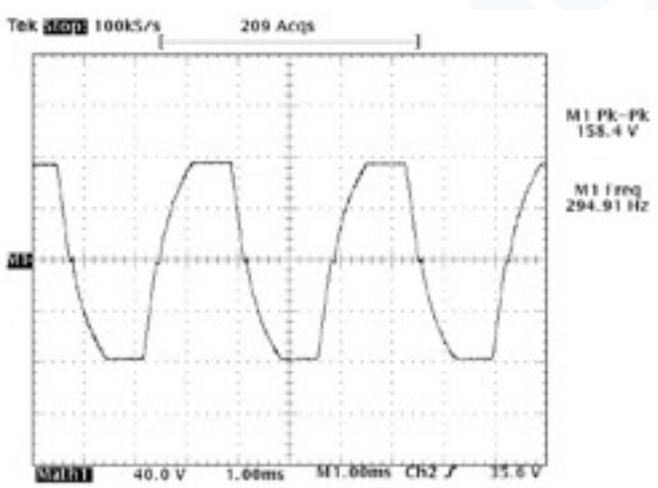
- LCD driver circuit
  - LDIs
    - LCD driver integrated circuits
    - Alternate voltage generation to prevent any deterioration of image quality resulting from the DC stress of liquid crystals
      - Modulation of the voltage to control the transmittance of liquid crystals
    - Analog LDIs
      - Capable of producing a continuous voltage signal
    - Digital LDIs
      - Capable of producing discrete voltage amplitudes
      - n-bit LDI → 2n transmittance levels for each sub pixel → 23n colors

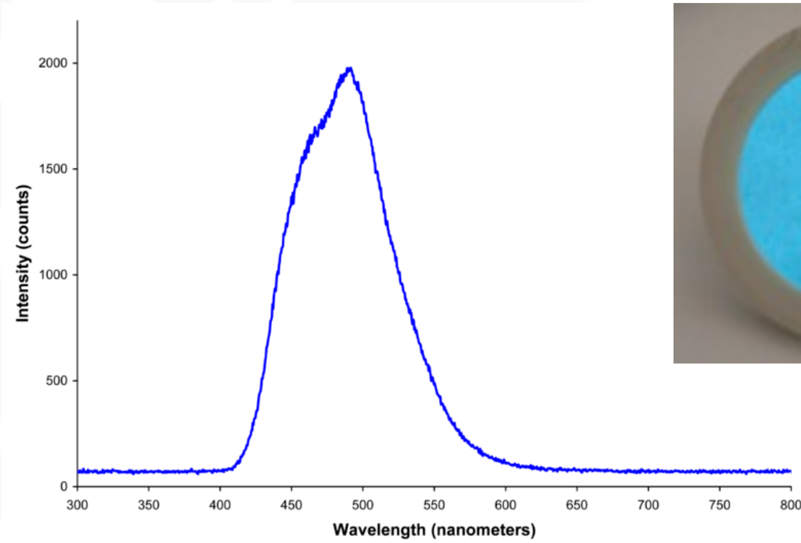
LCD Backlight Systems

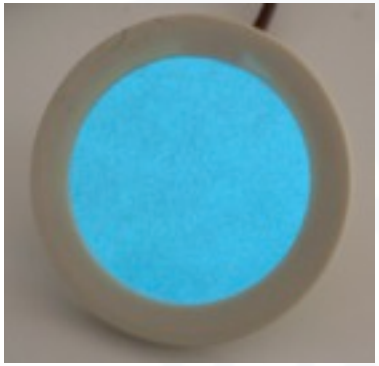
- EL (Electroluminescence)
  - Colored backlight
    - Not applicable to color LCDs
  - Thin and planar
    - No need of a diffuser
  - High AC voltage is required for EL driving



Sym	Parameter	Min	Typ	Max	Units
V_A-V_B	Peak to peak output voltage	136	160	184	V
f_{EL}	EL lamp frequency	240	280	320	Hz





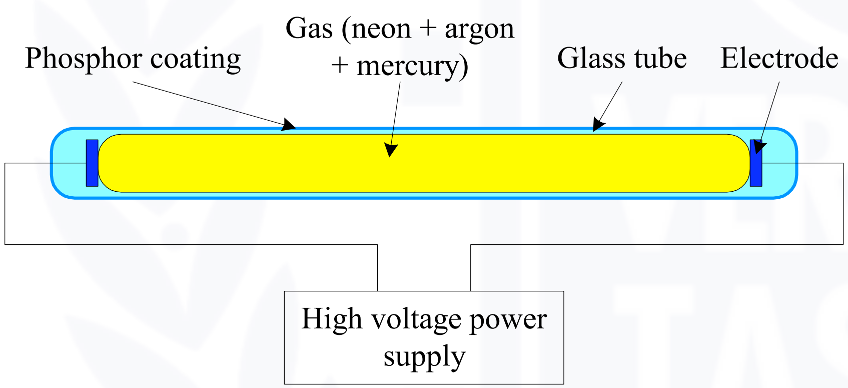


LCD Backlight Systems

- Colored LED
  - Low cost
  - Colored backlight
    - Not applicable to color LCDs
  - Easy low-voltage DC driving
  - Need of a diffuser

LCD Backlight Systems

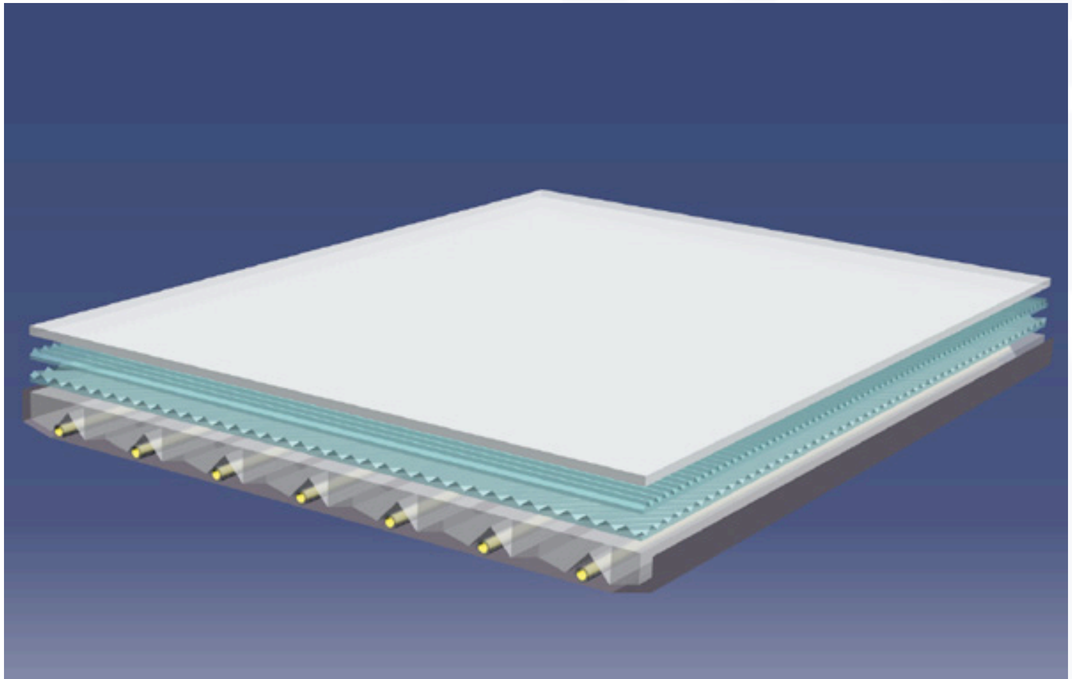
- Backlight system
  - Principle of operation for CCFT
    - Electrically excited mercury → Ultraviolet light radiation → Phosphor coating reaction → Visible light
    - High-voltage inverter
      - Kick-off voltage: 1000+V AC
      - Nominal voltage: 400 to 450 V AC



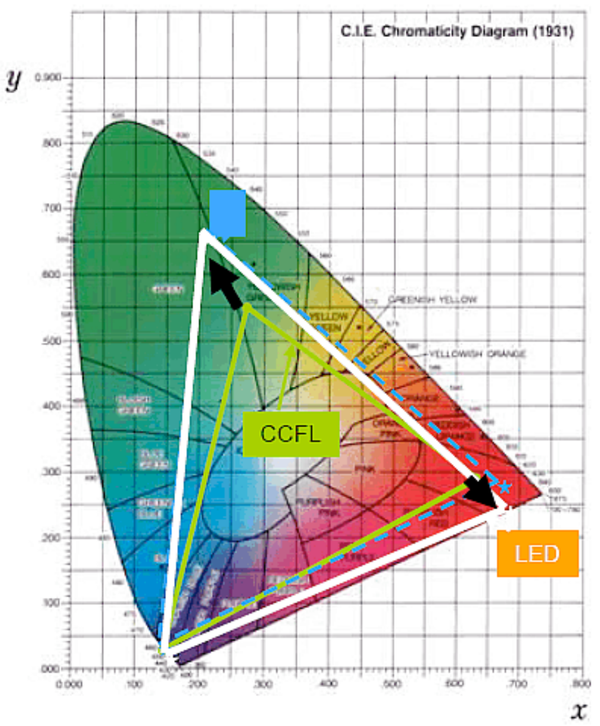
Structure of a cold cathode fluorescent tube

LCD Backlight Systems

- White LED backlight
  - High luminance
  - Low power
  - Longer life



Direct-type backlight unit



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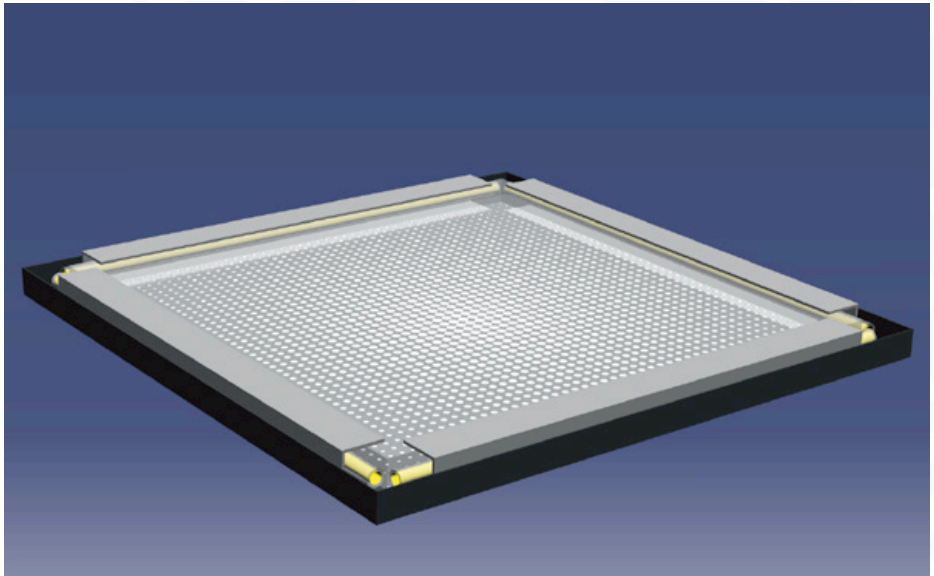
LCD Backlight Systems

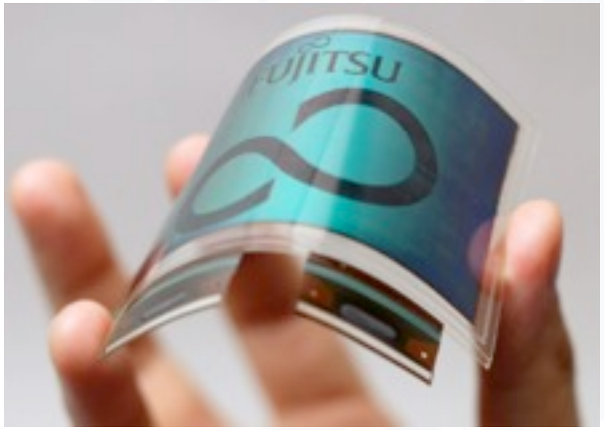
- White LED backlight
  - High luminance
  - Low power
  - Longer life

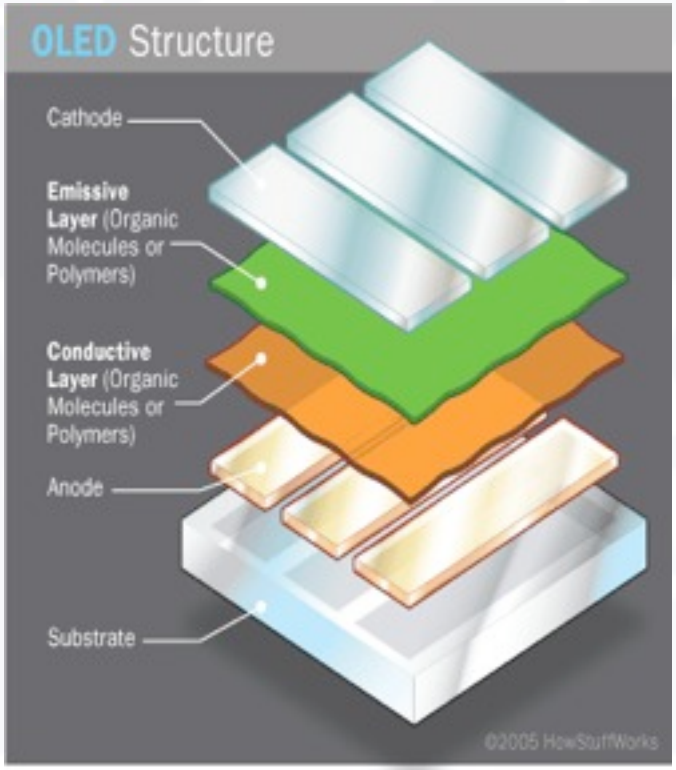


Sidelight-type backlight unit

Organic Light Emitting Diode

- OLED stands for Organic Light Emitting Diode
  - An OLED is an electronic device made by placing a series of organic thin films between two conductors. When electrical current is applied, a bright light is emitted
  - A device that is 100 to 500 nanometers thick or about 200 times smaller than a human hair
- Types of OLEDs
  - Passive-matrix OLED
  - Active-matrix OLED
  - Transparent OLED
  - Top-emitting OLED
  - Flexible OLED
  - White OLED



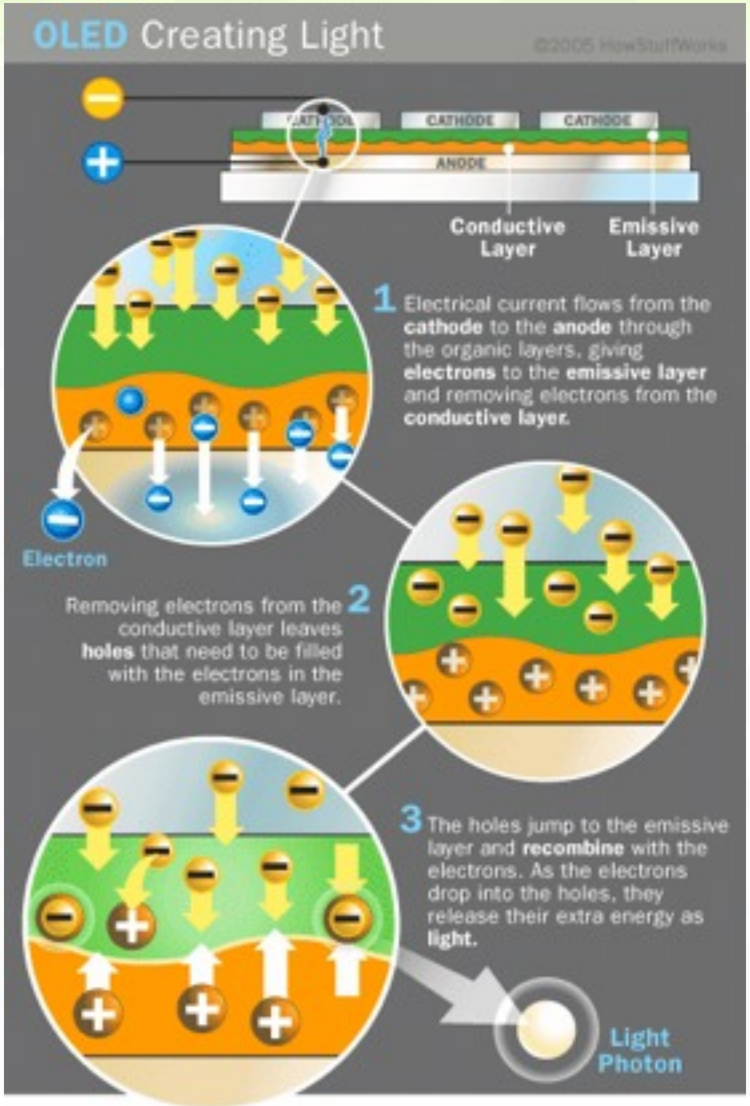


Organic Light Emitting Diode

- Compared with LED and LCD
  - Advantages
    - Thinner, lighter and more flexible
    - Plastic substrates rather then glass
    - High resolution (< 5 µm pixel size) and fast switching (1-10um)
    - Do not require backlight, light generated
    - Low voltage, low power and emissive source
    - Robust Design (Plastic Substrate)
    - Larger sized displays
    - Brighter - good daylight visibility
    - Larger viewing angles -170º
  - Disadvantages
    - Lifetime
      - White, Red, Green: 46,000-230,000 hours → about 5-25 years
      - Blue: 14,000 hour → about 1.6 years
    - Expensive
    - Susceptible to water
    - Overcome multi-billion dollar LCD market

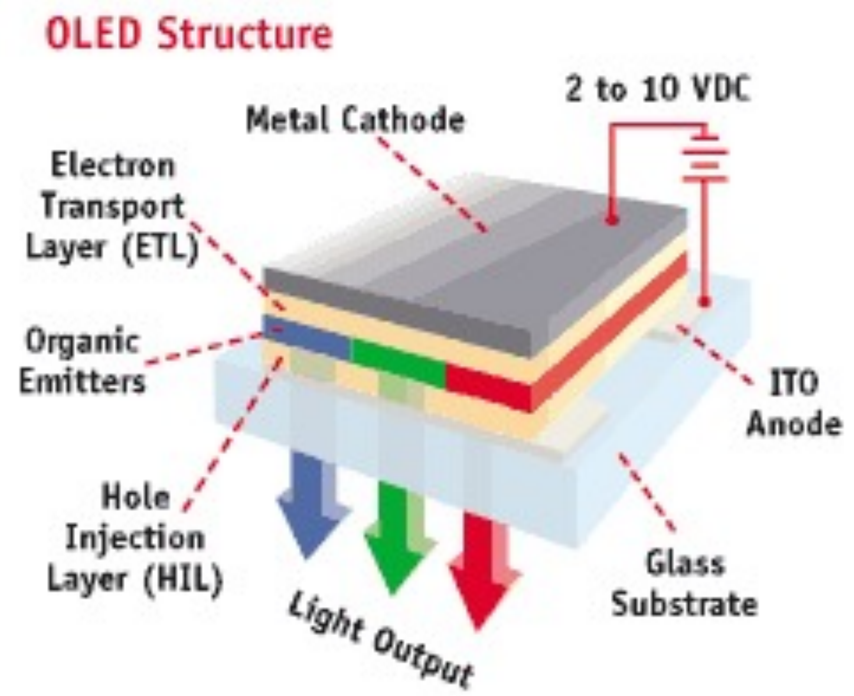
Organic Light Emitting Diode

- How OLED works
  - Voltage applied across Cathode and Anode
    - Typically 2V-10V
  - Current flows from cathode to anode
    - Electrons flow to emissive layer
    - Electrons removed from conductive layer leaving holes
    - Holes jump into emissive layer
  - Electron and hole combine and light emitted



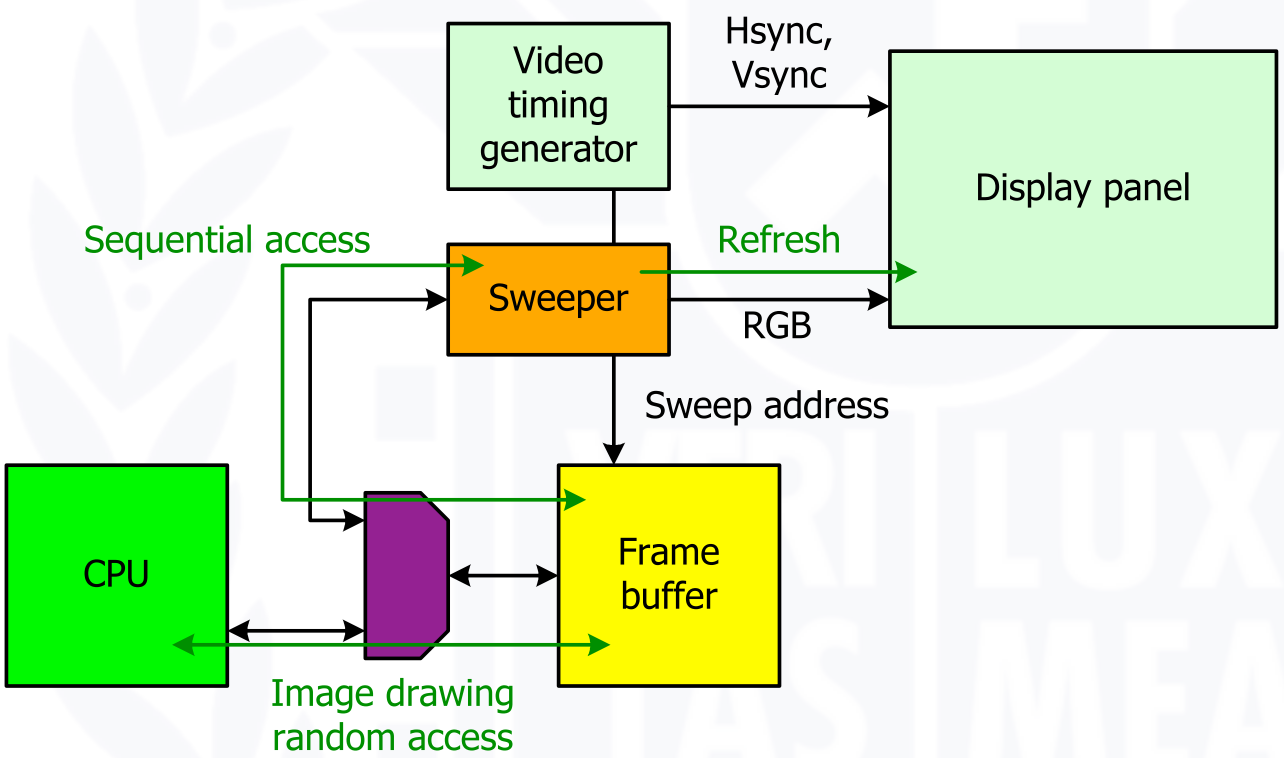
Organic Light Emitting Diode

- How OLED works
  - Different Colors
    - Type of organic molecule in the emissive layer
    - 3 molecules used -RGB
  - Intensity/brightness
    - Amount of current



Display System Architecture

- Character display
  - Frame buffer
  - Font ROM
  - Sweeper
- Graphic display
  - Frame buffer
  - Sweeper



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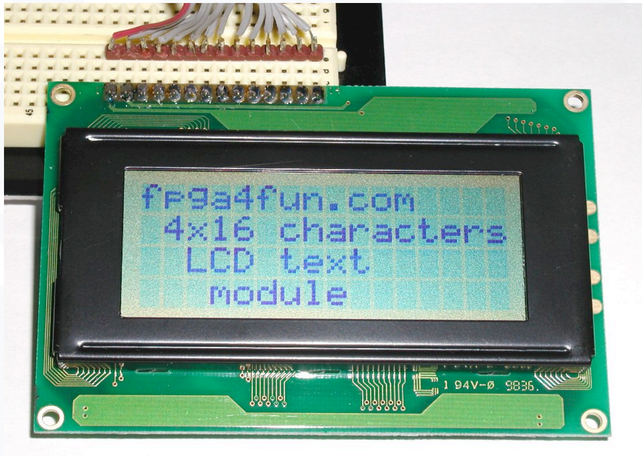
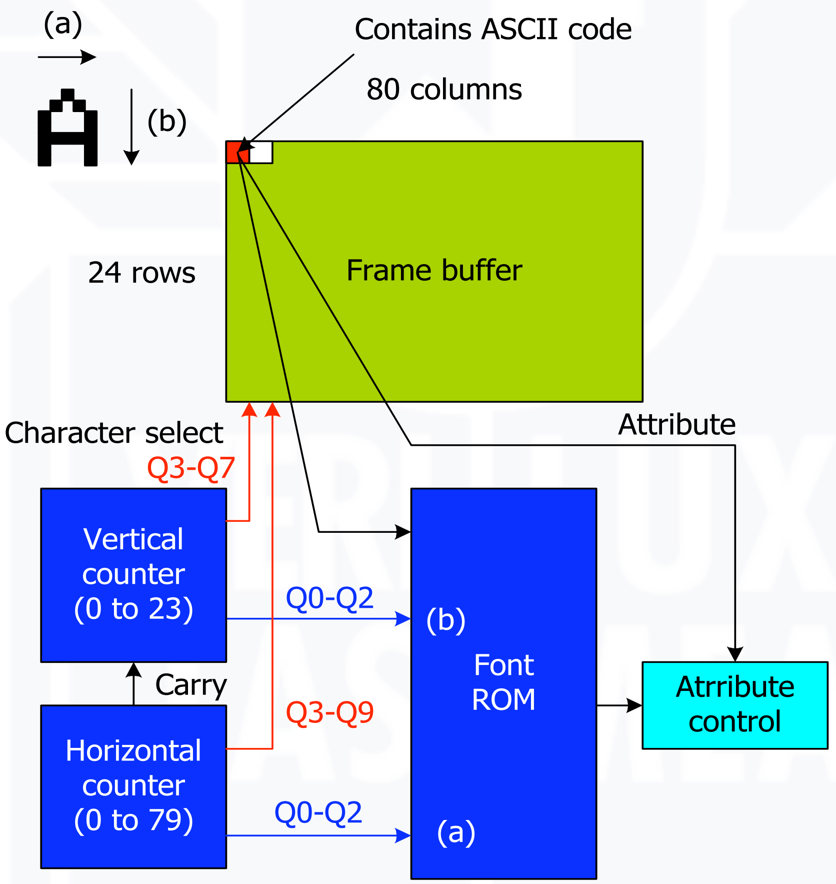
Graphics and Text Display

- Text display
  - Display device can only display text
  - Display hardware is designed to display text only
  - Simple control logic
- Graphic display
  - Dot matrix
  - Small pixels
  - Display hardware is designed to display anything



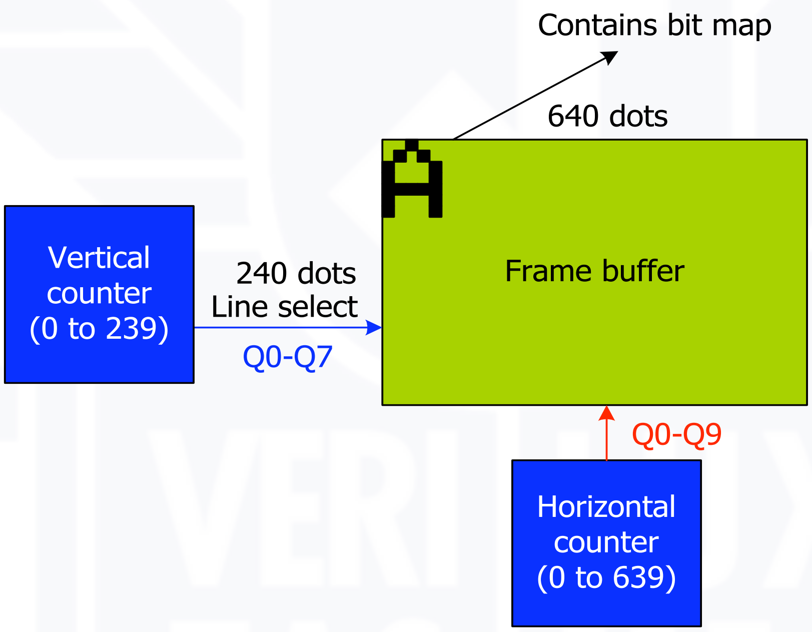
Character Display

- Character only display
- Frame buffer contains only column * row * ASCII + attribute (8 or 16 bit)
- Attributes
  - Bold, underline, blinking, etc.
- Font ROM contains bit-map fonts
- Scroll
  - Rewrite the frame buffer
  - Move a pointer
  - Smooth scroll increments the vertical counter
- Poor CPU and frame buffer performance may result in wave scroll or whites on the screen
- Graphics characters



Graphics Display

- Frame buffer contains bit map data: pixel
- Attributes are emulated by changing the frame buffer contents
  - E.g. blinking → repeat write and erase a character
- General architecture
- Requires higher performance



Graphics Display Definitions

- Pixel
  - Picture element, the basic building block on a computer display/image i.e. computer image consists of many pixels
- Bits Per Pixel (bpp)
  - The number of bits assigned per pixel to describe the brightness and color information of that pixel.
  - Also called: Bit depth (more the number of bpp, better the quality of image)
- Monochrome panels
  - Only one color is possible
  - If 1 bpp, black-and-white mode, or in 2 bpp and 4 bpp for shades of gray
- Color panels
  - 4 bpp and higher (4, 8,12,16,24 bpp etc)
  - Different bits used to hold RGB info, the primary colors
  - Ex: Usual spec for white in 24 bit is 255, 255 ,255 means Red value = 255, Green value = 255 and Blue value = 255 (8 bits each)

Graphics Display Definitions

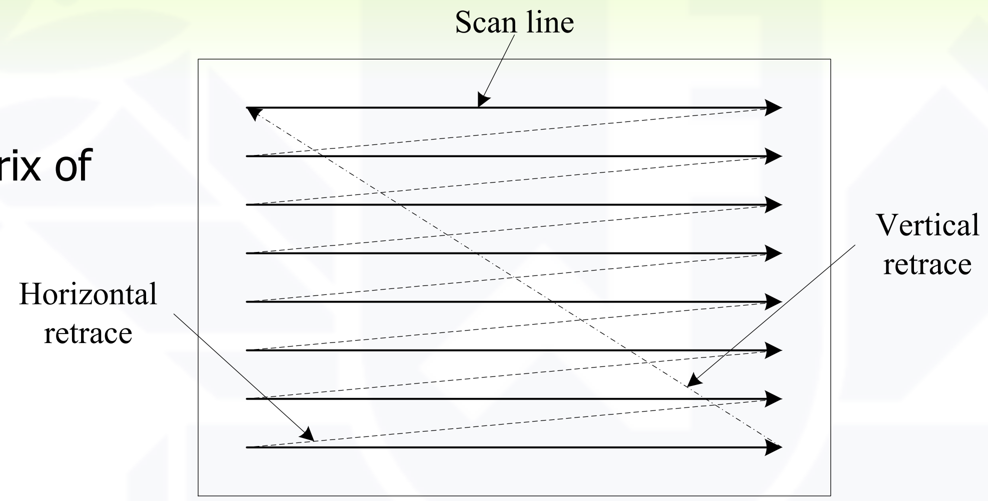
- Resolution
  - It is the number of pixels that the display panel contains
    - CRT display resolution is limited by the horizontal and vertical clock frequencies
    - LCD display resolution is determined by the number of pixels on the panel
  - It is expressed as the number of pixels on the horizontal axis (columns) and the number of pixels on the vertical axis (rows). Total number of pixels is calculated by multiplying the two quantities.
    - E.g.: 320 X 240 TFT panel
      - 320 Columns and 240 rows
      - Total Memory required: 320 X 240 X bpp bits
  - More resolution means better the image quality and sharpness

Graphics Display Definitions

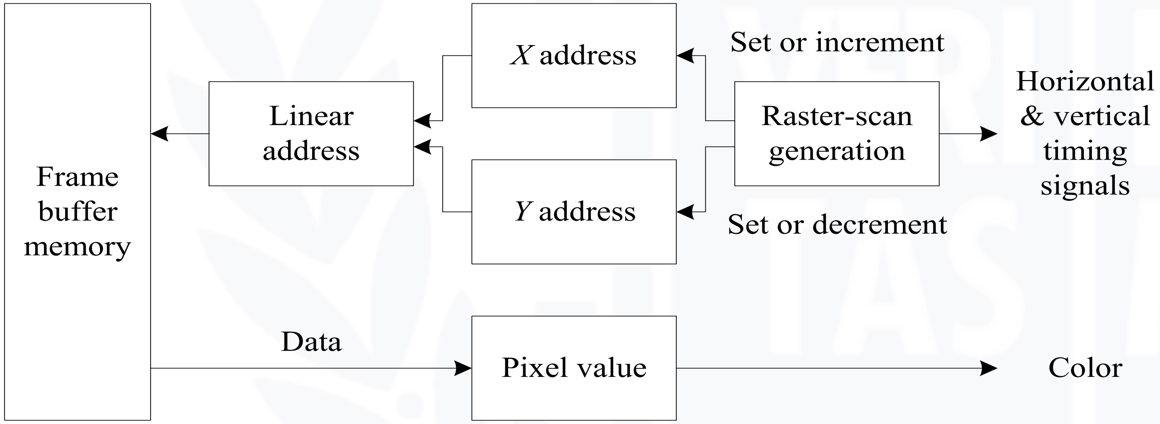
- Frame rate
  - Refresh rate
  - NTSC – 30 frame/sec
    - Human eye can recognize flickering around 30Hz frame rate
  - Computer monitors – over 60Hz
    - 60Hz frame rate is basically flicker free
    - Near 60Hz refresh, however, may interfere with light bulbs
    - 72Hz or higher frame rate is used for quality display

LCD Systems

- Raster-scan displays
  - Raster: a set of horizontal scan lines
  - Image: formed from the raster (matrix of pixels➔pixmap)
  - LCD controller
    - Sweep operation to control the color intensity of each subpixel periodically



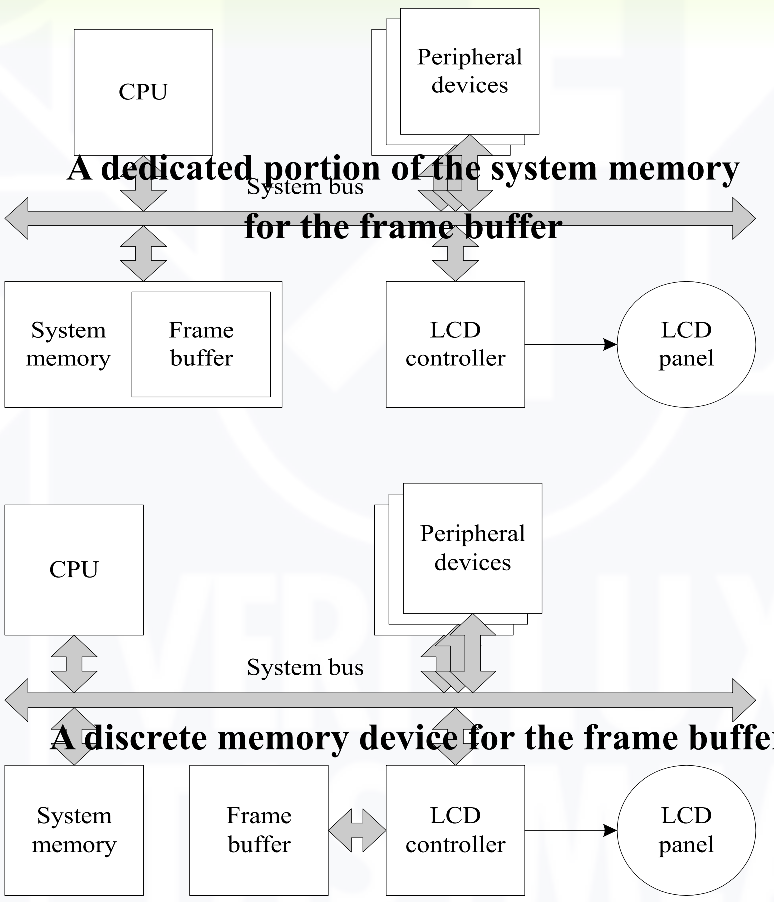
Raster-scan operation



Logical organization of the LCD controller

LCD Systems

- LCD system architectures
  - Simple architecture
    - Shared main and frame buffer memory as a cost-effective solution➔Slowed-down CPU performance
    - Software graphics package for scan conversion ➔ Slow scan conversion procedure
  - High-end architecture
    - Discrete frame buffer memory for high bandwidth and large capacity ➔ No tied-up CPU execution
    - Hardware graphics processor in the LCD controller for scan conversion ➔ Fast scan conversion procedure (optional)



Common LCD system architectures

Graphics Programming

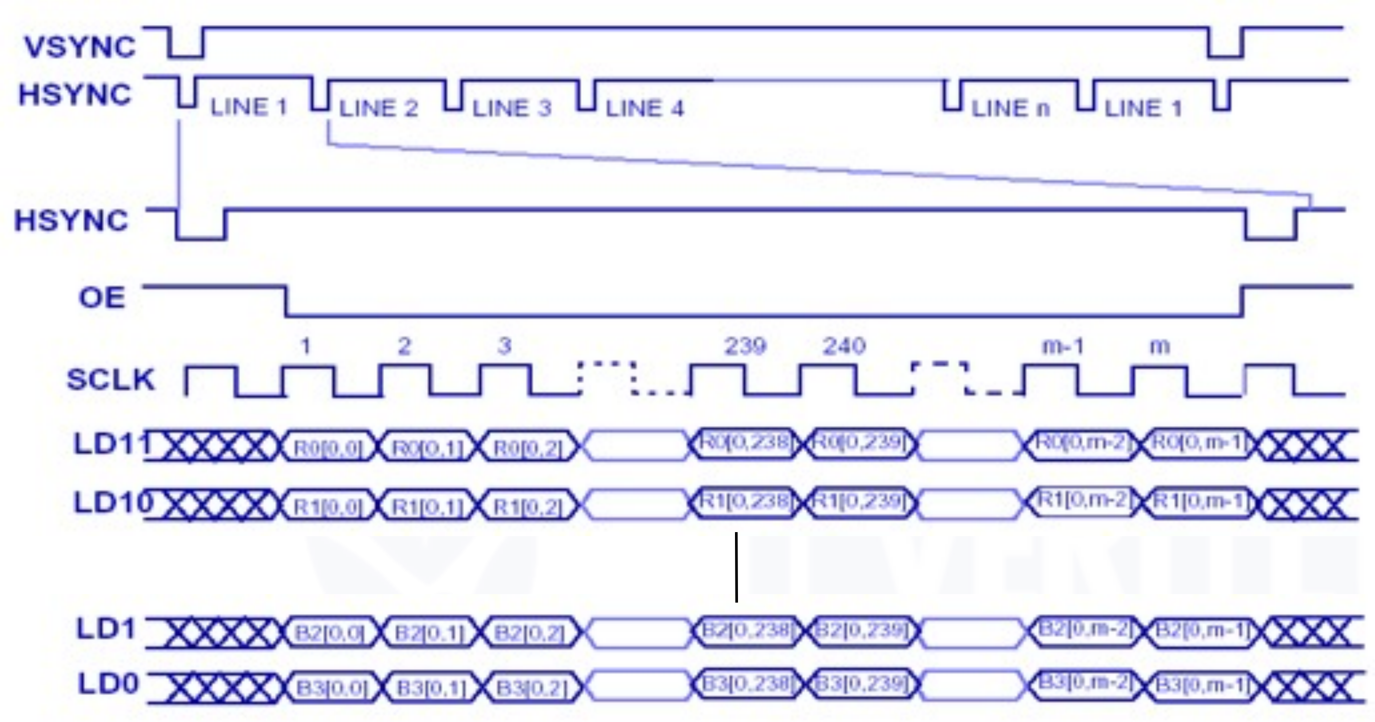
- Text display
  - Bit map font
    - Calculation of the character location
    - Block move font data to the frame buffer
  - Line drawing
    - Dot fill
    - Line drawing algorithms
  - Graphics library
    - 2D graphics
      - 2D objects: line, circle, UI objects, etc.
    - 3D graphics
      - Graphics pipeline
        - Object data ➔ geometry calculation ➔ lighting ➔ rasterization ➔ hidden surface elimination

LCD Interface

- Embedded frame buffer type
  - Same to memory interface (SRAM)
  - Address, data and RD/WR control
  - Additional control inputs
    - Intensity
    - Backlight
    - Display on/off
- VGA compatible interface
  - Same to CRT interface
  - RGB, Hsync and Vsync
  - TTL, LVDS or serial interface
  - Additional control inputs
    - Backlight
    - Display on/off

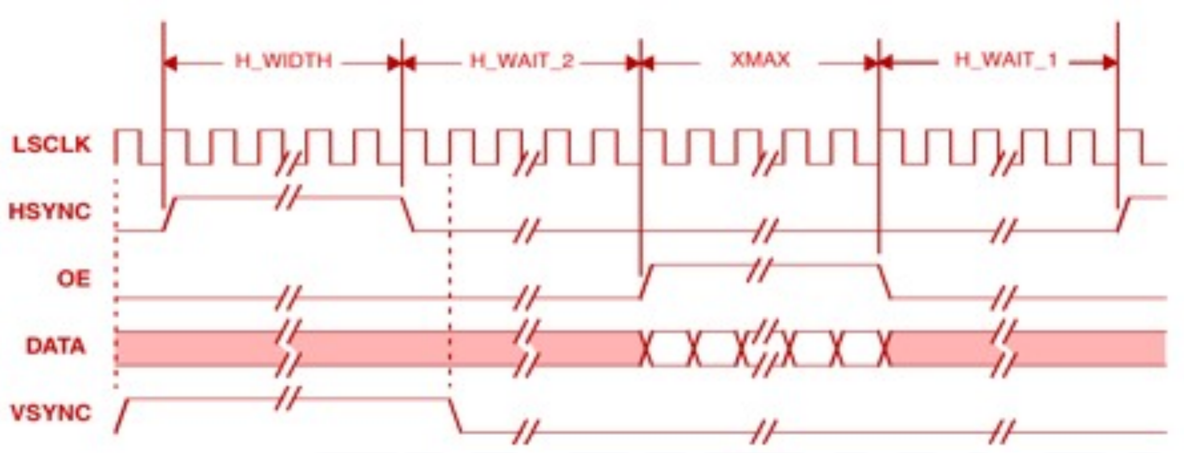
Panel Interface Signals

- Timing diagram



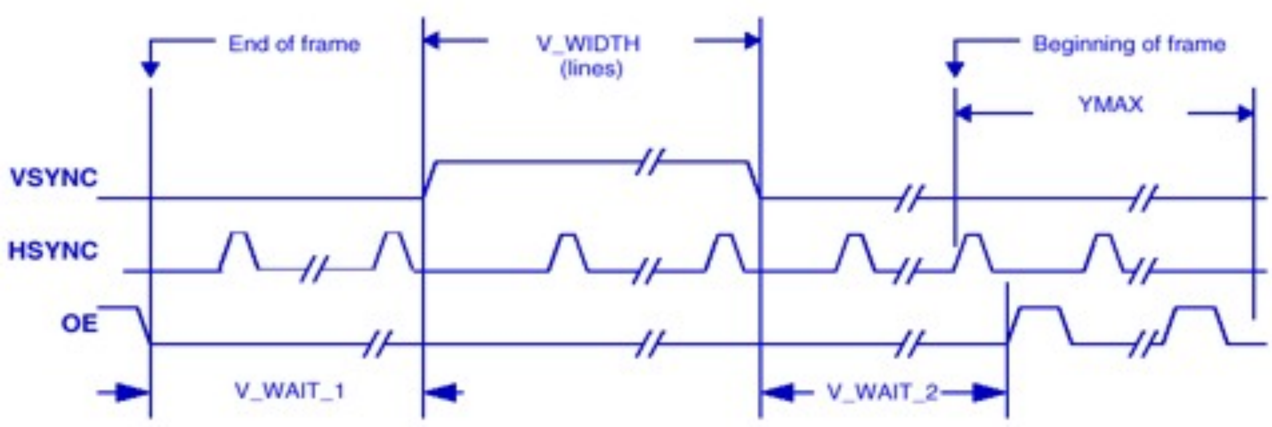
Panel Interface Signals

- Horizontal timing (timing per one line)
  - H_WIDTH: defines the width of the HSYNC pulse (at least 1)
  - H_WAIT_2: defines the delay from the end of HSYNC to the beginning of OE
  - H_WAIT_1: defines the delay from the end of OE to the beginning of the HSYNC pulse
  - XMAX: defines the total number of pixels per line
  - HSYNC width, H_WAIT_2,H_WAIT_1, are all programmable



Panel Interface Signals

- Vertical timing (timing per one frame)
  - V_WAIT_1 is a delay measured in lines. If V_WAIT =1, there is a delay of one HSYNC before VSYNC
  - For V_WIDTH(vertical sync pulse width) =0, VSYNC encloses one HSYNC pulse. For V_WIDTH = 2, VSYNC encloses two HSYNC pulses
  - V_WAIT_2 is a delay measured in lines. For V_WAIT_2 = 1 , there is a delay of one HSYNC after VSYNC.
  - The delay from end of one frame to the beginning of the next is programmable

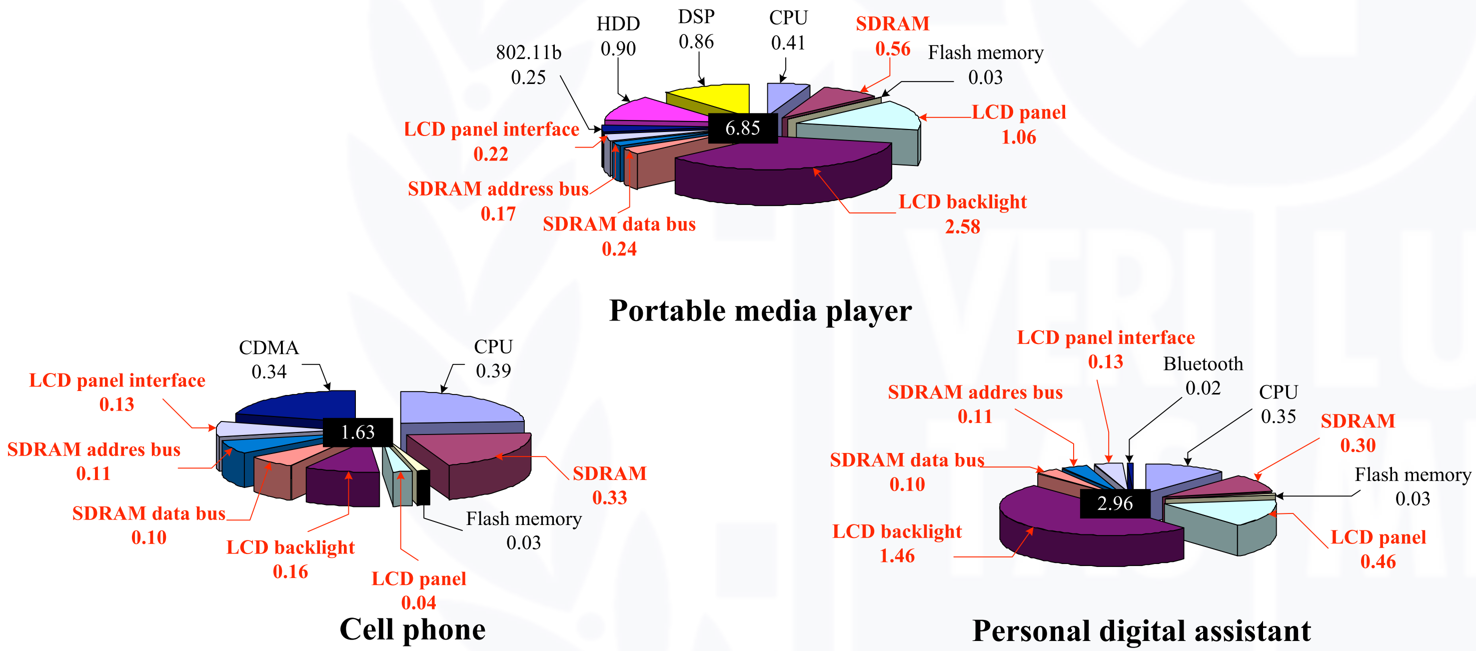


DLS: Motivation

- High power consumption of liquid crystal displays
  - High-resolution, high-color TFT LCDs as the de-facto display standard of portable electronics
    - Small size, light weight, and low power consumption comparing with a CRT (cathode-ray tube)
    - Powerful backlight source and large-capacity frame buffer memory
      - Still high power consumption of the display in portable devices
  - Immature energy-aware display technology
    - Previous research focused on the device level approach
      - Much higher energy efficiency of current LCD panels and backlight tubes than before.
    - No consistent system-level low-power design techniques for LCD systems
      - c.f. DVS (Dynamic Voltage Scaling) for processors
      - c.f. DPM (Dynamic Power Management) for peripherals
      - c.f. Memory energy optimization
      - c.f. Bus encoding for interconnections

DLS: Problem Statement

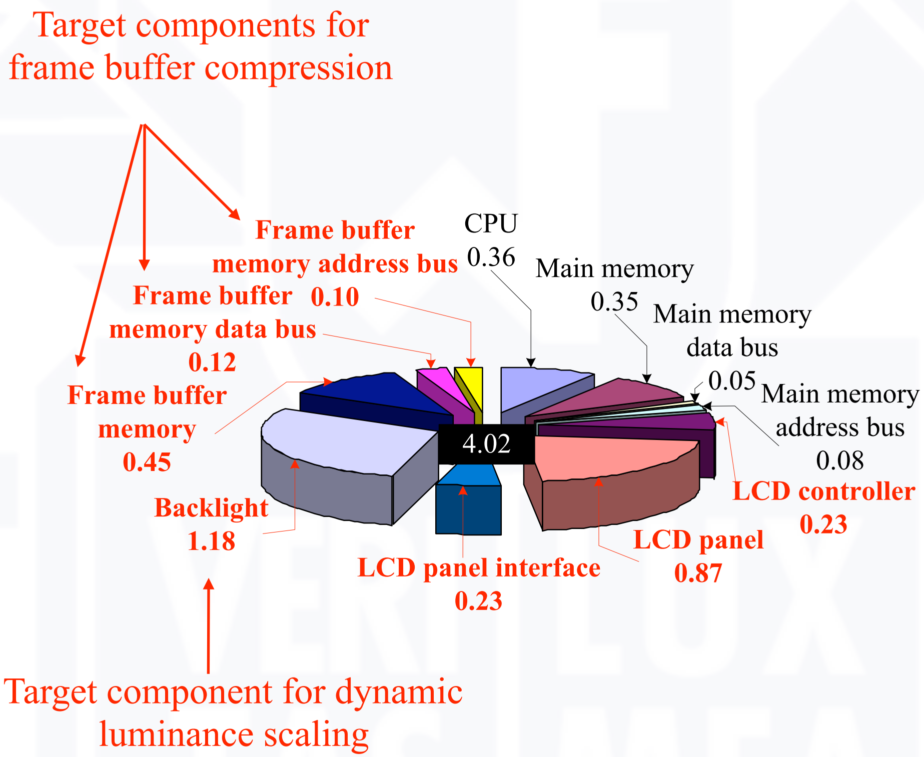
- Energy reduction of the display system at the system level
  - Power reduction of two major display components
    - Backlight system
    - Frame buffer system
  - Lossy approaches, but no appreciable display quality degradation



Power consumption for running a streaming video application (W)

DLS: Research Contributions

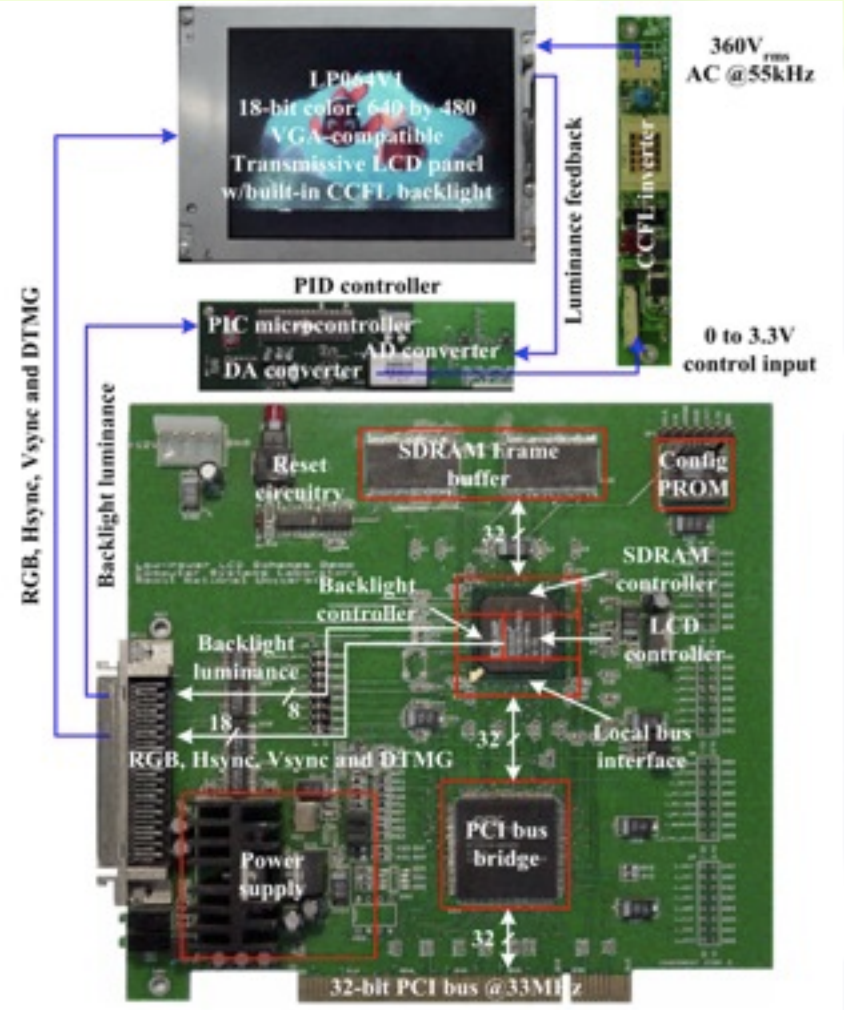
- Energy characterization and analysis of LCD systems
  - Energy characterization of color TFT LCD components by accurate energy measurement
  - System-level energy analysis of LCD systems in portable electronics
- System-level low-power display techniques
  - Dynamic luminance scaling ➔ Energy-efficient backlight system
    - Papers: IEEE Design & Test of Computers 2004, IEEE Transactions on VLSI Systems 2004, ESTIMedia 2004 and ISLPED 2002
  - Frame buffer compression ➔ Low-power frame buffer system
    - Papers: ASP-DAC 2004 and ESTIMedia 2005



System-level power analysis for running a movie player on the reference platform (W)

DLS: Research Contributions

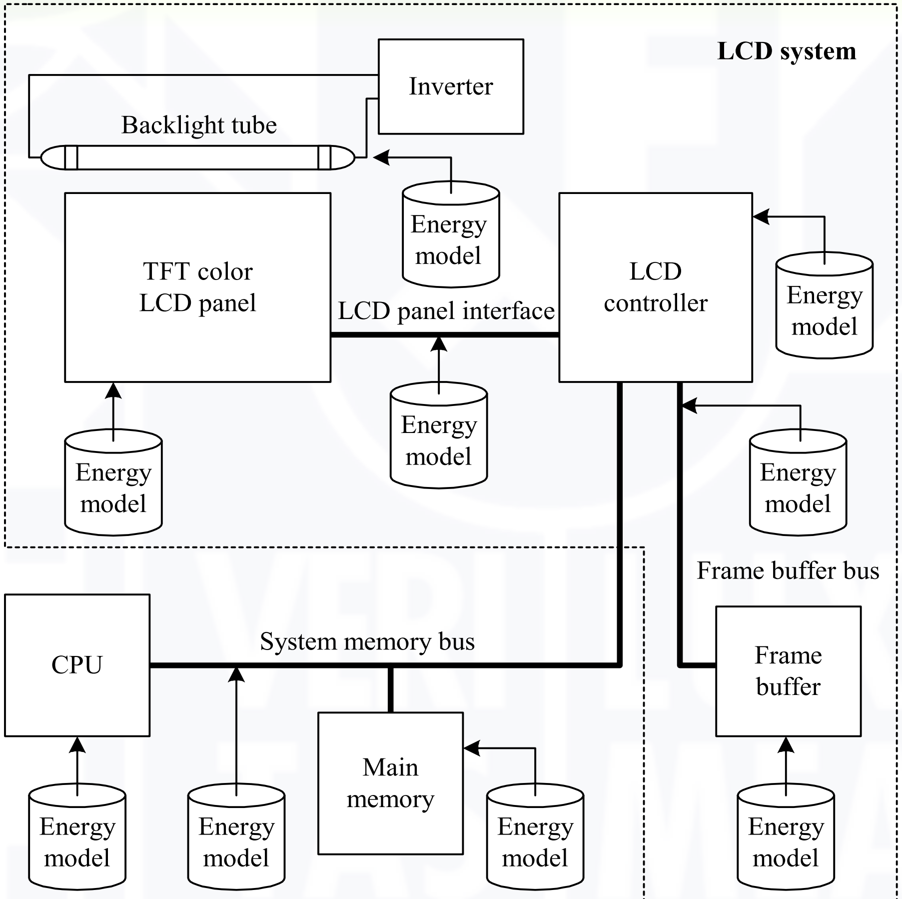
- Working prototype implementation supporting the proposed low-power techniques
  - Validation of the proposed techniques by the measurement of the actual display power consumption
  - Awards: Low-Power Design Contest Award at ISLPED 2002, 2003 and 2004
- Demonstration of the energy reduction in view of the total power consumption of a reference platform
  - Integrated framework to evaluate the power reduction achieved by the proposed techniques on a reference platform



Block diagram of the prototype implementation

DLS: Power Consumption Models

- Reference platform with a high-quality liquid crystal display
  - Energy models associated with dominant power consumers
  - Display components in a dash-lined box
- Total system energy consumption including the computing part
  - Emphasizing the energy reduction in view of the whole system



Energy models for a portable embedded system with a high quality LCD system

DLS: Power Consumption Models

- LCD panel
  - Components
    - Color TFT LCD panel
      - High-color 640x480 LP064V1 from LG-Philips
    - LCD panel interface
      - 4 inch long 4bit control bus and 16bit data bus @25MHz

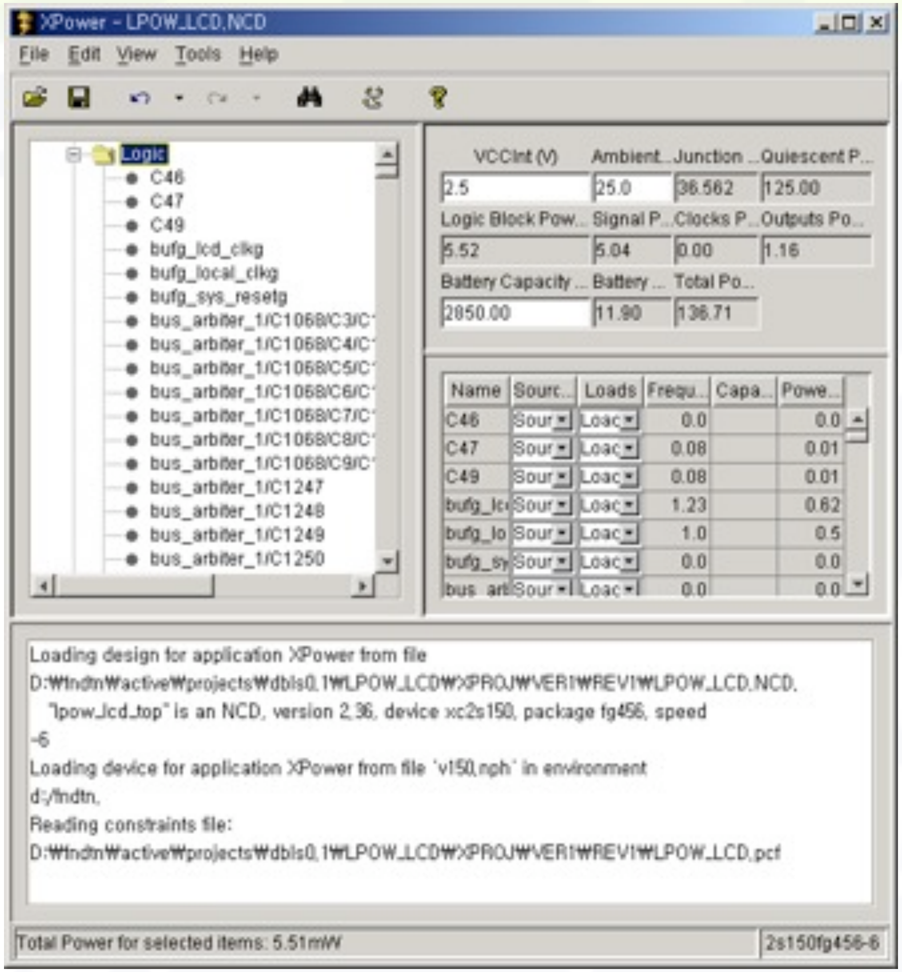
Number of blocked colors	Color	Power (mW)	△Power (mW)
0	Red+Green+Blue	830.5	0.00
1	Red+Green Red+Blue Green+Blue	858.5 857.5 856.0	28.00 27.00 25.50
2	Red Green Blue	885.5 887.0 882.5	55.00 56.50 52.00
3		908.0	77.50

Power consumption of the LCD panel

- Energy model
  - Similar to the energy state machine of memory buses
  - Panel transmittance
    ➔Amount of charge that must be stored in the TFTs
    ➔ Panel power consumption
  - Panel power consumption proportional to the number of blocked colors
  - Energy state machine for the LCD panel interface
    - Similar to the energy state machine of memory buses
    - High power consumption due to the large capacitance of a flat cable comparing with that of memory buses

DLS: Power Consumption Models

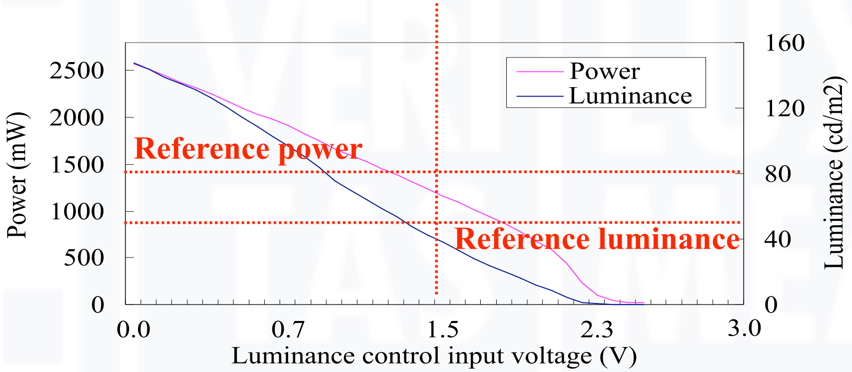
- LCD controller
  - Components
    - Xilinx Spartan-II FPGA XC2S-150FG456 LCD controller
      - 3 GCLKs, 2 GCLKIOBs, 2 DLLs, 182 IOBs, 926 SLICEs
      - 64,656 equivalent gate count
  - Energy model
    - 229.0mW @66MHz reported by Xilinx XPower
      - Power estimation software from Xilinx
      - 2.5V VCCint , 3.3V VCCout



DLS: Power Consumption Models

- Backlight
  - Components
    - CCFL (Cold Cathode Fluorescent Lamp)
      - High-voltage inverter (12V DC ➔ 300V to 550V AC)
      - Superior optical efficiency: 60 to 100 lumens/watt
    - White LED
      - Optical efficiency: 20 lumens/watt
  - Energy model
    - Average power consumption proportional to the backlight luminance
      - Digital multimeter ➔ Power
      - Illuminometer (Minolta LS100) ➔ Luminance

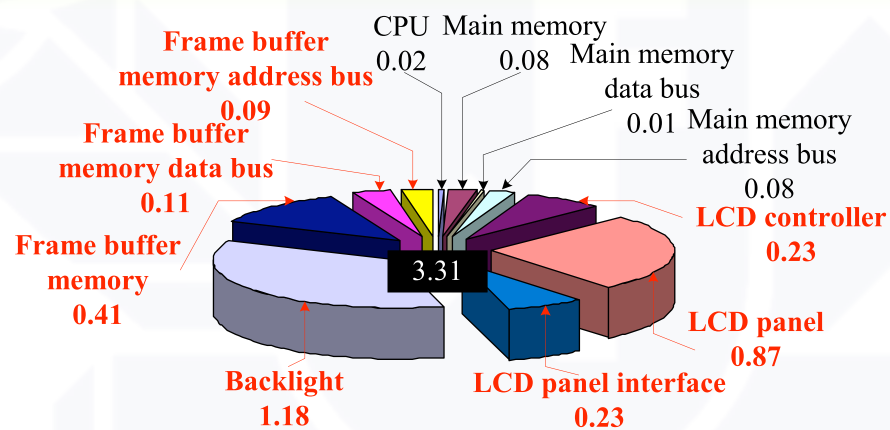
Characterizing the power-luminance relation of the backlight



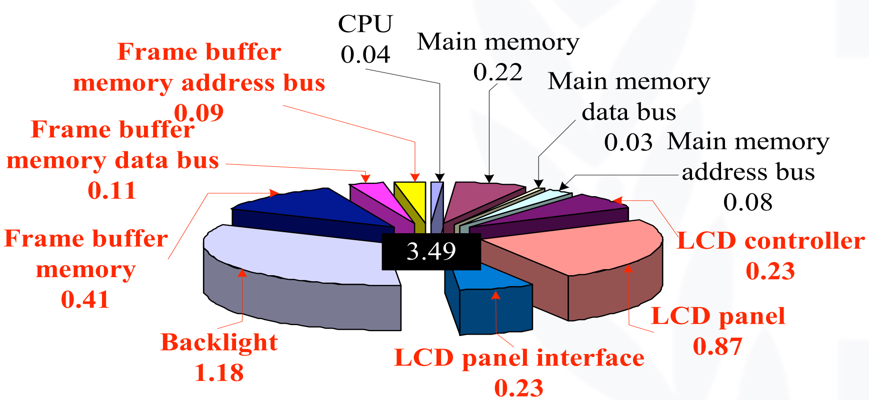
Steady-state luminance and power consumption of the CCFL backlight system

DLS: Reference Platform

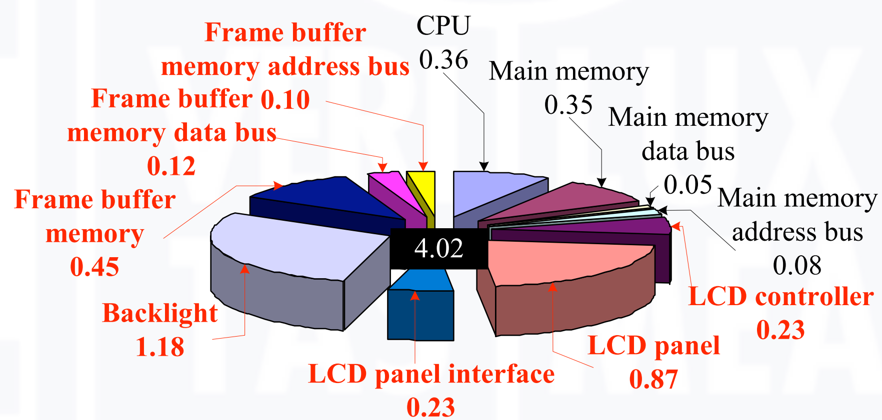
- Significant display power
  - Document viewer (interactive)
    - CPU ➔ Sleeping
    - Memory ➔ Power-down state
  - Spread sheet (memory intensive)
  - Movie player (computing intensive)
    - Still minor computing power



Document viewer



Spread sheet



Movie player

Power consumption of the reference platform (W)

DLS: Related Work

- Device power analysis
  - LCD panel
    - TFT power modeled by a quadratic function of the pixel value
  - CCFL backlight
    - Piece-wise linear function of the luminance
    - Considering the saturation effect of the optical efficiency
- System level power analysis
  - Energy characterization of GUI platforms
    - Hardware, software, and application perspectives
    - Insights for improving the energy efficiency of GUI platforms

DLS: Image Reproduction

- Additive color reproduction system
  - Qualitative match of a color (C)

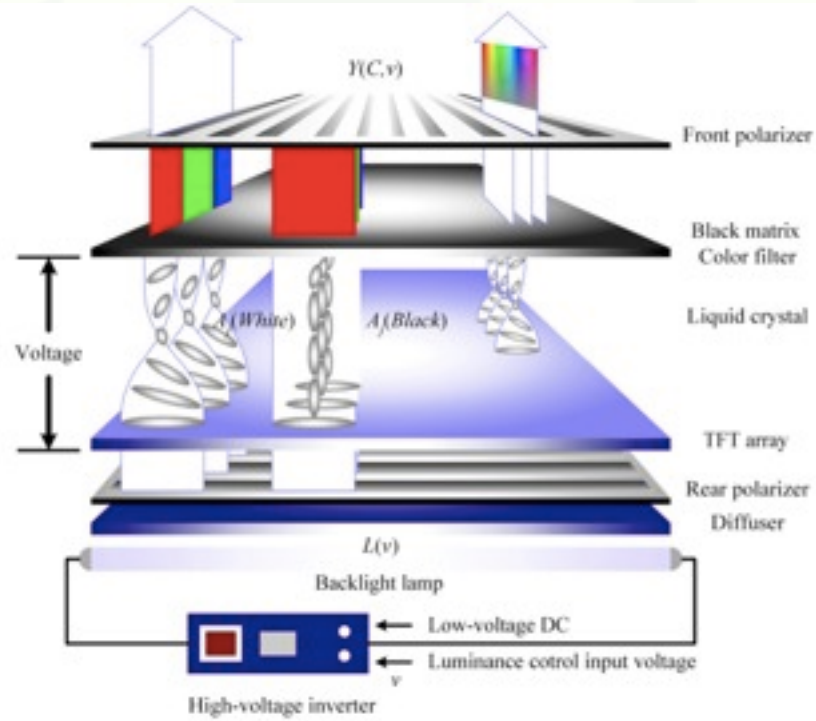
$$C \equiv A_1 R + A_2 G + A_3 B$$

  - Backlight luminance (L(v))

$$L(v) = \sum_{j=1}^{3} \int_{\lambda} W_j P_j(v, \lambda) V(\lambda)\, d\lambda$$

  - Luminance of a pixel (Y(C,v))

$$Y(C, v) = \gamma L(v) \sum_{j=1}^{3} \rho_j A_j(C)$$

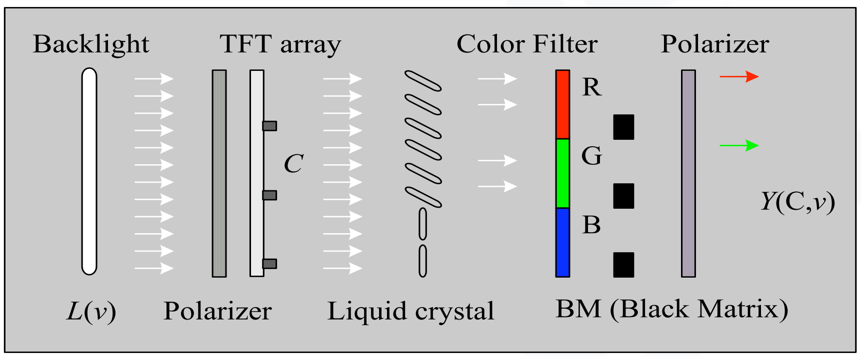


Structure of a transmissive LCD panel

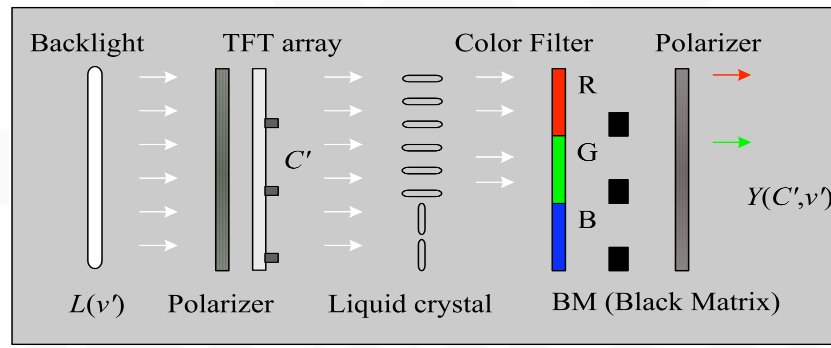
R, *G* and *B*: primary color values
A_j: matching values for color *C*
W_j: matching values for a backlight (typically white)
v: control input voltage of an high-voltage inverter
  : wavelength of a backlight
$P_j(v,\ )$: spectral energy distribution of the primary colors
V( ): relative luminous efficiency
  : product of the aperture ratio (around 2/3) and the transmittance of the two polarizers (around 1/3)
  : transmittance values of the three color filters (typically 50%)
$A_j(C)$: normalized primary color values

DLS: Image Compensation Algorithms

- Principle of DLS (Dynamic Luminance Scaling)
  - Backlight dimming for power saving
    - L(v) ➔ L(v′) such that L(v′) < L(v)
  - Restoring brightness/contrast by appropriate image compensations
    - C ➔ C′ to maintain the same intensity perceived by human eyes



Original



Backlight dimming with appropriate image compensation

DLS: Image Compensation Algorithms

- Brightness compensation
  - i-th image (**C**i)

$$\mathbf{C}_i = \begin{pmatrix} C_{i(1,1)} & \cdots & C_{i(1,H)} \\ \vdots & \ddots & \vdots \\ C_{i(V,1)} & \cdots & C_{i(V,H)} \end{pmatrix}$$

$$v \leq v' \rightarrow L(v) \geq L(v')$$

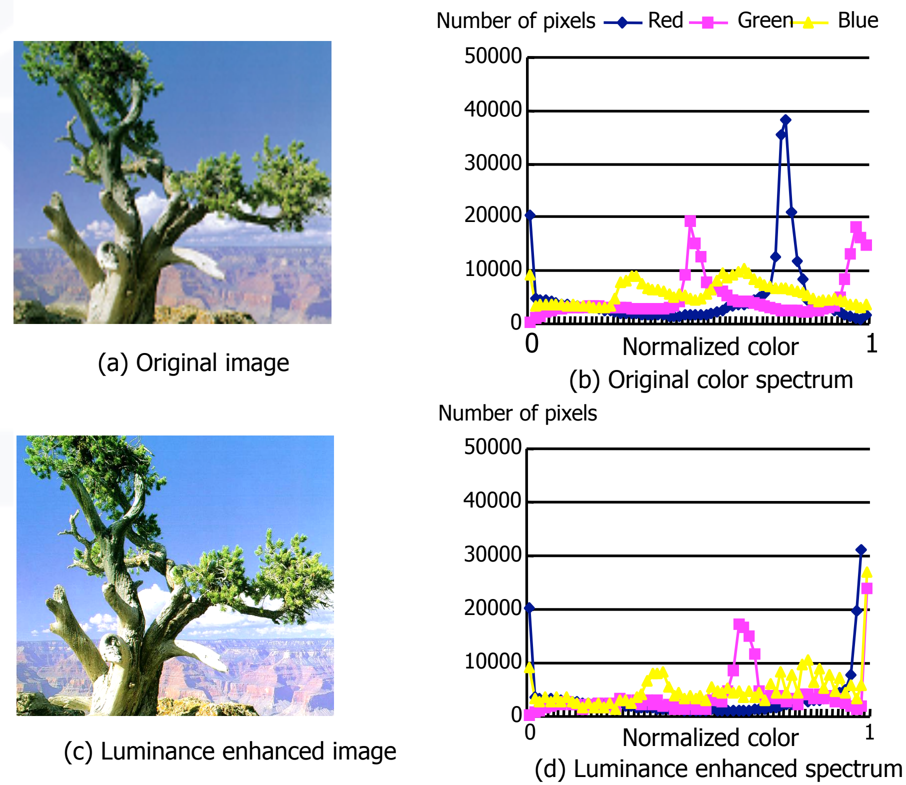
  - Backlight dimming

$$Y(\mathbf{C}_i, v) \approx Y(\mathbf{C'}_i, v')$$

  - Brightness compensation

$$A_j(\mathbf{C'}_i) \approx \frac{A_j(\mathbf{C}_i)L(v)}{L(v')}$$

H: horizontal resolution
V: vertical resolution



(a) Original image
(b) Original color spectrum
(c) Luminance enhanced image
(d) Luminance enhanced spectrum

Example of brightness compensation

DLS: Image Compensation Algorithms

- Distortion ratio (Di)

$$D_i = \frac{\sum_{j=T_H}^{2^n-1} H_j(\mathbf{M}_i)}{\sum_{j=0}^{2^n-1} H_j(\mathbf{M}_i)}$$

  - RGB color space

$$M_{i(k,l)} = 2^n \max(A_1(C_{i(k,l)}), A_2(C_{i(k,l)}), A_3(C_{i(k,l)}))$$

  - YUV color space

$$M_{i(k,l)} = 2^n Y(C_{i(k,l)})$$

  - HSV color space

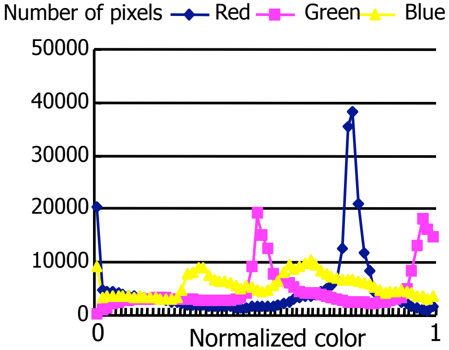
$$M_{i(k,l)} = 2^n V(C_{i(k,l)})$$

- Color transformation function (Tbc(c))

$$T_{bc}(c) = \min(2^n - 1, \frac{2^n - 1}{T_H} c)$$

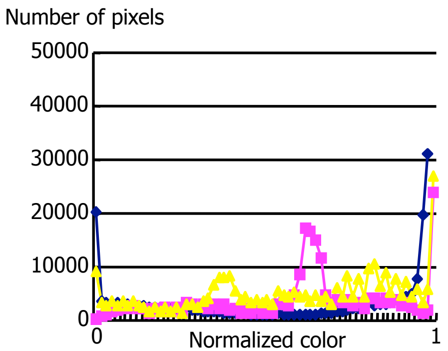
$H(\mathbf{M}_i)$: histogram function

(a) Original image



(b) Original color spectrum

(c) Luminance enhanced image



(d) Luminance enhanced spectrum

Example of brightness compensation

DLS: Image Compensation Algorithms

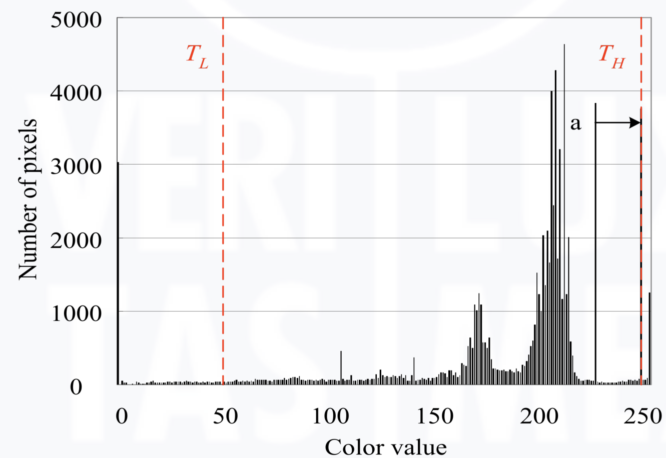
- Histogram stretching
  (image enhancement #1)
  - Extension of brightness compensation
    - Histogram stretching with respect to the low threshold TL as well as the high threshold TH
      ➔ Contrast stretching
  - Color transformation function (Ths(c))

$$T_{hs}(c) = \min(2^n - 1, \frac{2^n - 1}{T_H - T_L} \max(0, (c - T_L)))$$

  - Distortion ratio (Di)

$$D_i^H = \frac{\sum_{j=T_H}^{2^n-1} H_j(\mathrm{M}_i)}{\sum_{j=0}^{2^n-1} H_j(\mathrm{M}_i)}, \qquad D_i^L = \frac{\sum_{j=0}^{T_L} H_j(\mathrm{M}_i)}{\sum_{j=0}^{2^n-1} H_j(\mathrm{M}_i)}$$

GUI components
➔ Brightest area dominates the image
➔ Histograms skewed to bright areas



Example of image enhancement

DLS: Image Compensation Algorithms

- Histogram equalization (image enhancement #2)
  - Maximum readability
    - Wider-spanning color histogram of the image ➔ Better readability than histogram stretching
      - Applicable to objects, whose colors are not important (such as text-based screens)
    - Color change of most pixels ➔ Worse color tonality than histogram stretching
      - Not applicable to streaming images due to the inter-frame color inconsistency
  - Color transformation function (The(c))

$$T_{he}(c) = 2^n \frac{\sum_{j=0}^{c} H_j(\mathrm{M}_i)}{\sum_{j=0}^{2^n-1} H_j(\mathrm{M}_i)}$$

Embedded Low-Power Laboratory

DLS: Image Compensation Algorithms

- Context processing
  - Preventing small foreground objects from having similar colors to their background
    - No correlation between the number of pixels and their importance (e.g. text)
    - Color merge of some minor colors into their background colors after histogram equalization No longer distinguishable
    - Re-stretching of foreground and background colors to maximize the color difference with context information of applications
  - Color transformation function (Tcp(c))

$$T_{cp}(c) = 2^n - b(c) - 1$$

$b(c)$: background color of an object whose color is c

DLS: Image Compensation Algorithms

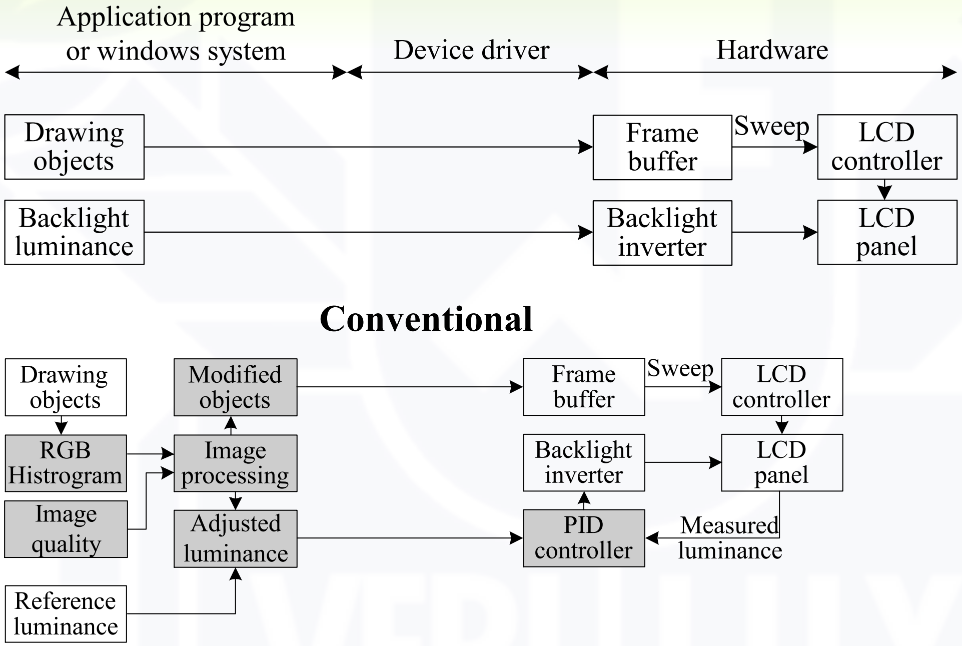
- Computational complexity
  - Construction of the transformation function
    - Histogram construction
    - Determining threshold TH and TL
  - Transformation of the pixel color value
    - Approach #1: addition, subtraction, multiplication, division and comparison for each pixel
    - Approach #2: table lookup (desirable for a high-resolution screen)

DLS: Implementation Layers

- Design considerations
  - Energy consumption
    - Energy reduction from backlight dimming
    - Energy overhead incurred by the image compensation process
  - Performance penalty
  - Application transparency
  - Hardware-software partitioning
- Four different implementation layers
  - Application program
  - Windows system
  - Frame buffer device driver
  - LCD controller hardware

DLS: Implementation Layers

- Application program
  - Pros.
    - Application-specific optimization using the application context
      - e.g. approximate histogram in a compressed (10x) domain for an MPEG decoder ➔ Reduced histogram construction overhead
  - Cons.
    - Full-screen application only
      - Backlight as a shared resource
    - Heavy porting burden
      - No standard interface between the application and the DLS function
      - Application's proprietary structure ➔ ad-hoc approach

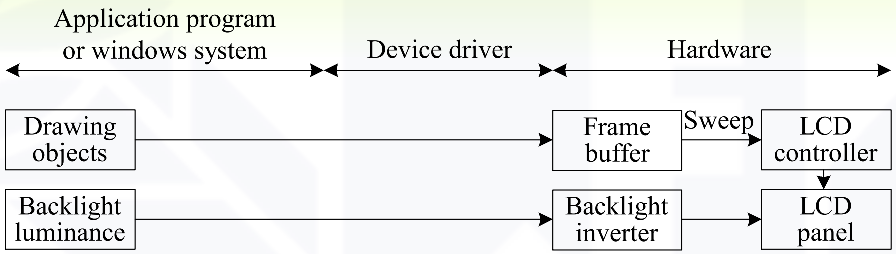


Application embedded or windows system embedded

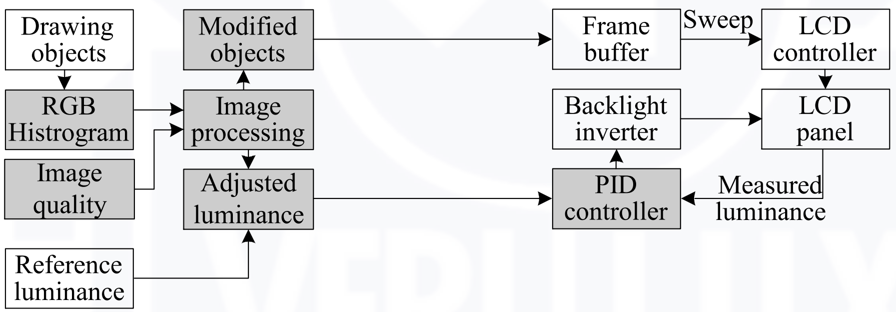
Paper
- IEEE Transactions on VLSI Systems 2004
- ISLPED 2002
Demonstration
- SIGDA University Booth of DAC 2002
- Low-Power Design Contest of ISLPED 2002

DLS: Implementation Layers

- Windows system
  - Pros.
    - Energy benefit of applications without their core modifications
    - Systematic porting procedure
  - Cons.
    - Source code modification of the windows system and applications
    - Performance degradation comparing with the application-embedded approach



Conventional

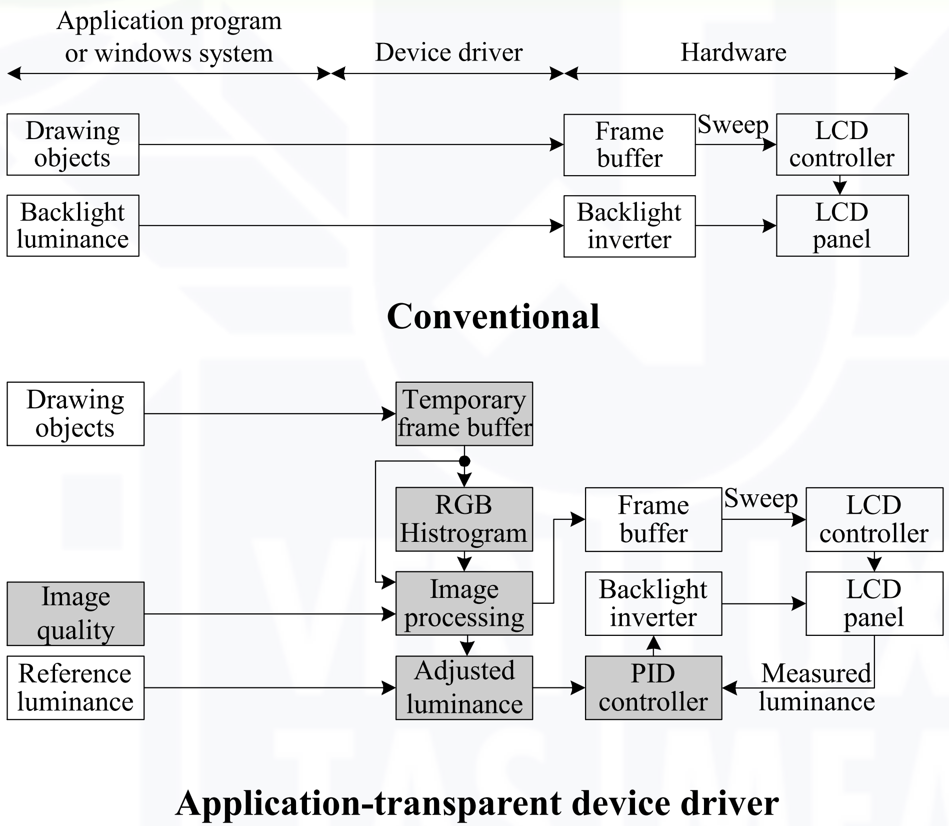


Application embedded or windows system embedded

Paper
- IEEE Transactions on VLSI Systems 2004
Demonstration
- SIGDA University Booth of DAC 2003

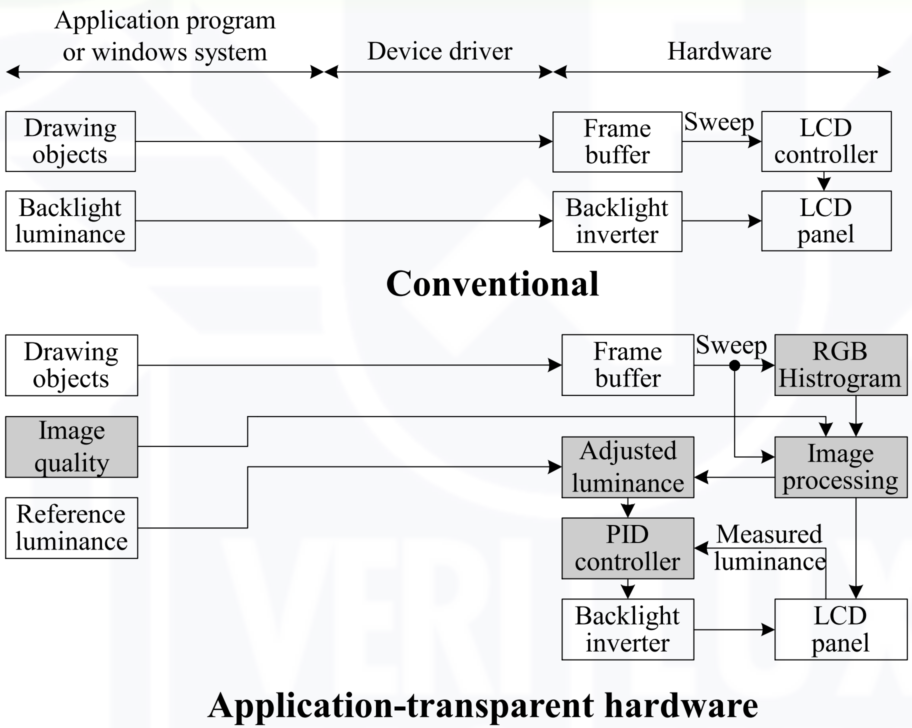
DLS: Implementation Layers

- Frame buffer device driver
  - Pros.
    - Application transparency
      - No need to modify applications or windows system
  - Cons.
    - Very high energy overhead for histogram construction due to synchronization (typically @60Hz)
    - Improper synchronization between the application and the DLS functional blocks in the driver ➔ Visual artifacts
    - No context information ➔ Rebuilding of the transformation function caused by only a slight change of the frame buffer



DLS: Implementation Layers

- LCD controller hardware
  - Pros.
    - Application transparency
      - No need to modify applications or windows system
    - No synchronization problem
    - No additional frame buffer accesses for histogram construction or color transformation
      - Performed on-the-fly during a sweep operation (typically @60Hz)
  - Cons.
    - Additional silicon area and energy overhead incurred by 2n comparators and counters for histogram construction ➔ Not a feasible implementation as it is

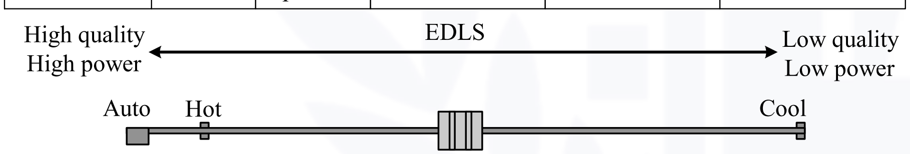


Paper
- IEEE Design and Test of Computers 2004
Demonstration
- Low-Power Design Contest of ISLPED 2004

DLS: Backlight Management Framework

- Input:
  - Simple slider knob for user preferences
    - Backlight luminance
    - Image quality
    - Power budget
- Output:
  - Harmonious combination of brightness compensation and image enhancement across panel modes for transflective LCDs

<table>
<tr><td>Panel mode</td><td colspan="4">Transmissive mode</td><td>Reflective mode</td></tr>
<tr><td rowspan="2">Backlight</td><td>Full backlight</td><td>Medium backlight</td><td colspan="2">Dimmed backlight</td><td rowspan="2">No backlight</td></tr>
<tr><td colspan="2">Constant backlight luminance</td><td colspan="2">Variable backlight luminance</td></tr>
<tr><td rowspan="2">Image</td><td colspan="2">Original image</td><td>Brightness compensation</td><td>Image enhancement</td><td>Image enhancement</td></tr>
<tr><td colspan="2">No image distortion</td><td colspan="2">Fixed-ratio image distortion</td><td>Variable-ratio image distortion</td></tr>
<tr><td>Power source</td><td>External power source</td><td>Rich battery power</td><td>Moderate battery power</td><td>Poor battery power</td><td>Very poor battery power</td></tr>
</table>



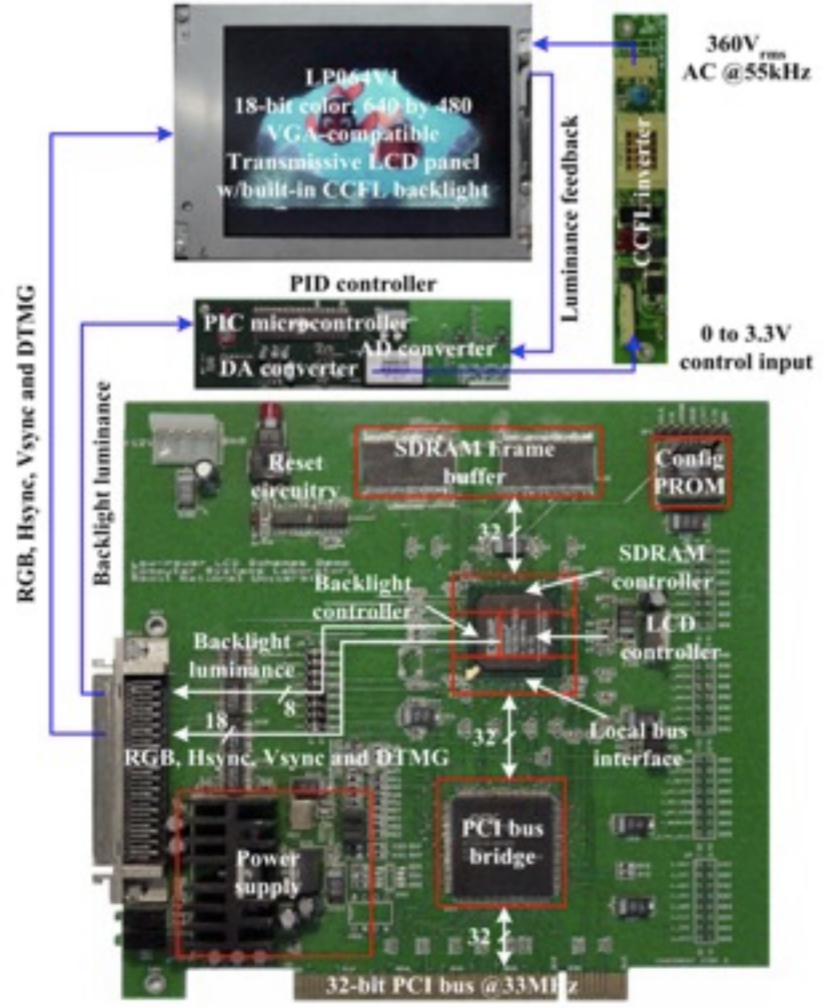
The EDLS slider

The EDLS framework

Paper
- IEEE Design and Test of Computers 2004

DLS: Implementation

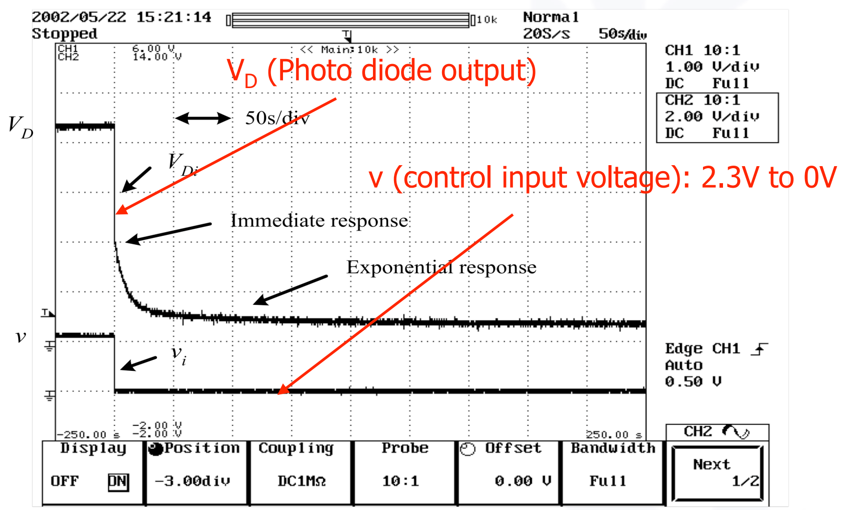
- Prototype specification
  - LG-Philips LP064V1 6.4" transmissive color TFT LCD panel with a CCFL backlight
  - Xilinx XC2S-150FG456 Spartan-II FPGA LCD controller
  - Samsung K4S641632D SDRAM frame buffer memory
  - PLX PCI9054 PCI bridge
  - Frame buffer device driver for the Linux kernel 2.4.19



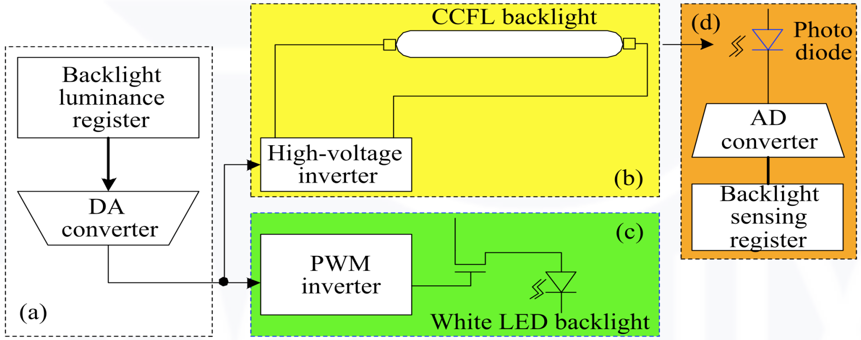
Block diagram of the prototype implementation

DLS: Implementation

- Implementation of a backlight luminance controller
  - CCFL's slow response ➔ Closed-loop control with a feedback input ➔ PID (proportional integral differential) control by sensing the luminance with a photo diode
  - LED's fast response ➔ Open-loop control

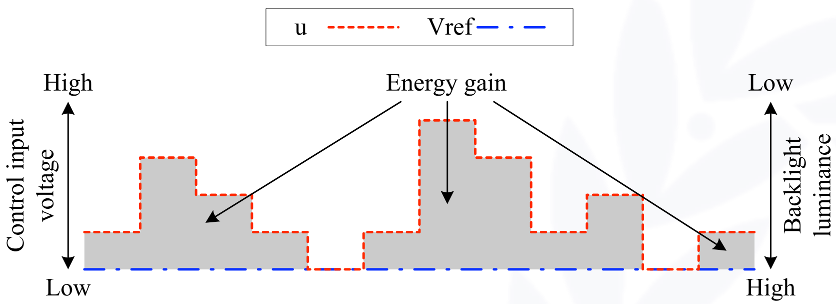


Step response of the CCFL backlight luminance

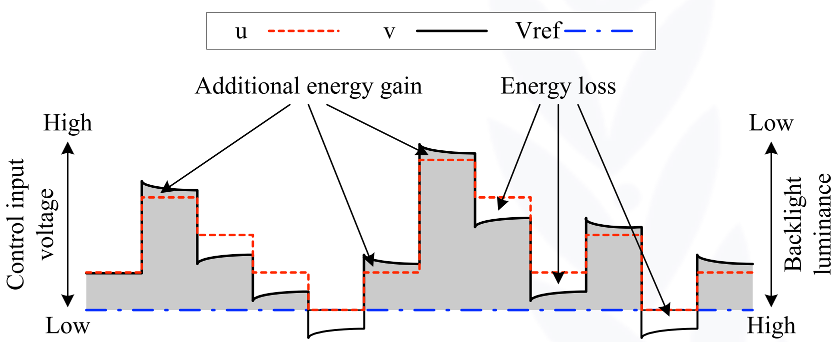


Backlight luminance control circuit:
(a) built-in common circuits for backlight dimming,
(b) a built-in circuit for a CCFL backlight system,
(c) a built-in circuit for a white LED backlight system, and
(d) an add-on circuit to enhance the response time of the CCFL backlight

DLS: Implementation

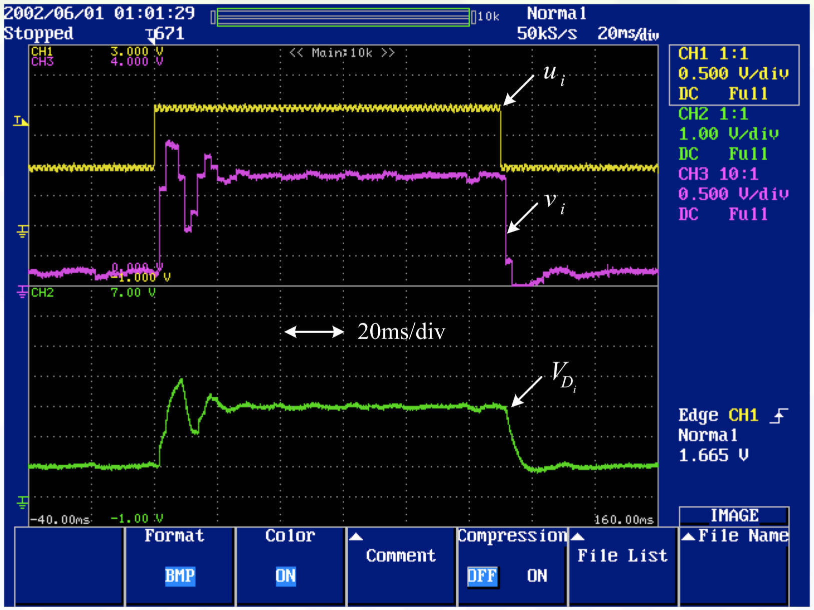


Expected energy gain by DLS



Actual energy gain by DLS with the PID control

Energy overhead by the PID control



Enhanced (2000x) full-scale step response with the PID control

u_i: backlight control command for the target luminance

V_i: backlight control input voltage with the PID control

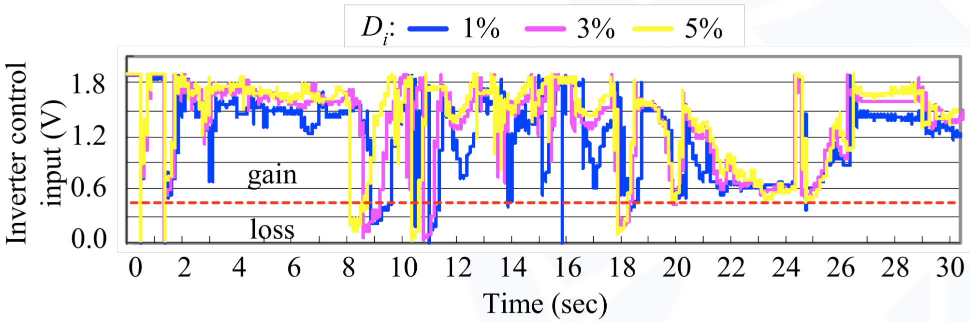
V_{Di}: photo diode output voltage for the feedback input

DLS: Implementation

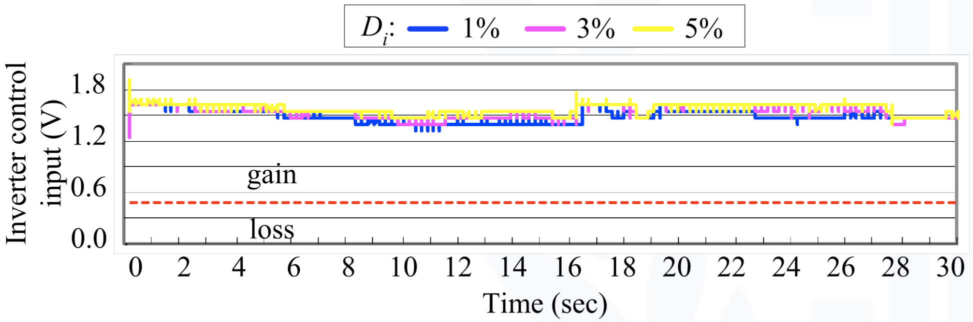
- Implementation of image compensation algorithms
  - MPEG-4 decoder (application)
    - New procedures after the IDCT in a YUV color space
      - Brightness compensation
  - Java 2 Micro Edition Personal Basis Profile (middleware)
    - Additional methods and components in the lightweight Java AWT (Abstract Window Toolkit) (e.g. java.awt.BrightnessController)
      - Brightness compensation
      - Image enhancement: histogram stretching and histogram equalization
      - Context processing
  - LCD controller (hardware)
    - On-the-fly image processing hardware in the LCD controller
      - Brightness compensation
      - Image enhancement: histogram stretching
    - Compact histogram construction logic (e.g. 16bpp → 12bpp) together with the image processing hardware

DLS: Experimental Results

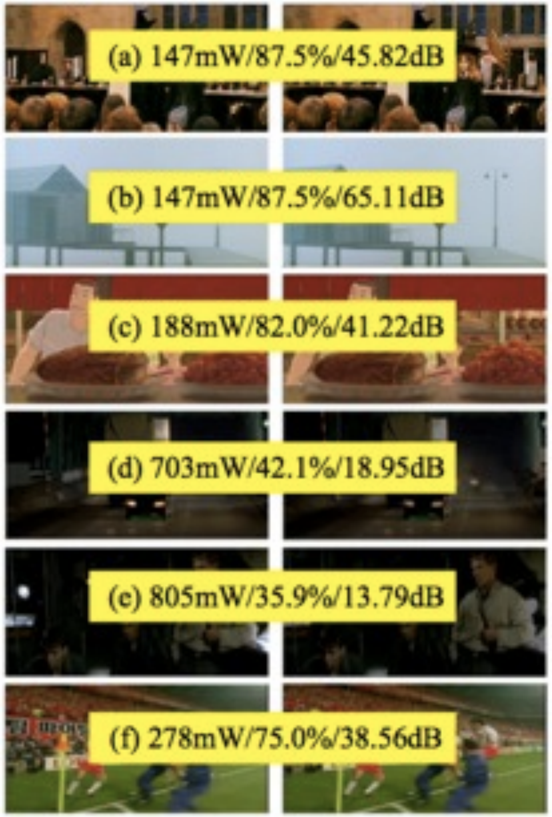
- MPEG-4 decoder (application)



Power saving for a movie stream by DLS



Power saving for a cartoon stream by DLS

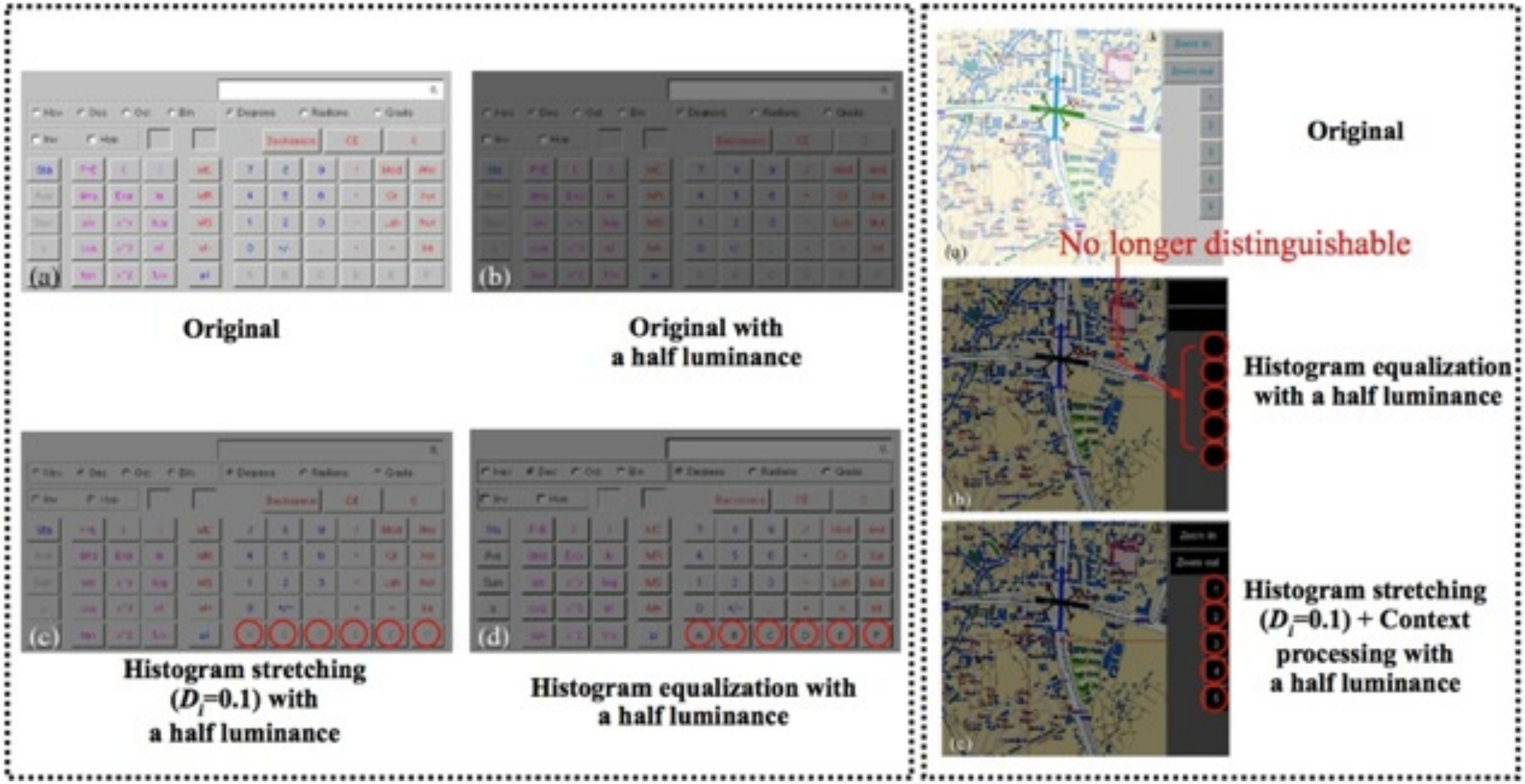


Original **DLS (D_i=0.03)**

Power reduction/Relative backlight luminance/PSNR

DLS: Experimental Results

- Java 2 Micro Edition Personal Basis Profile (middleware)

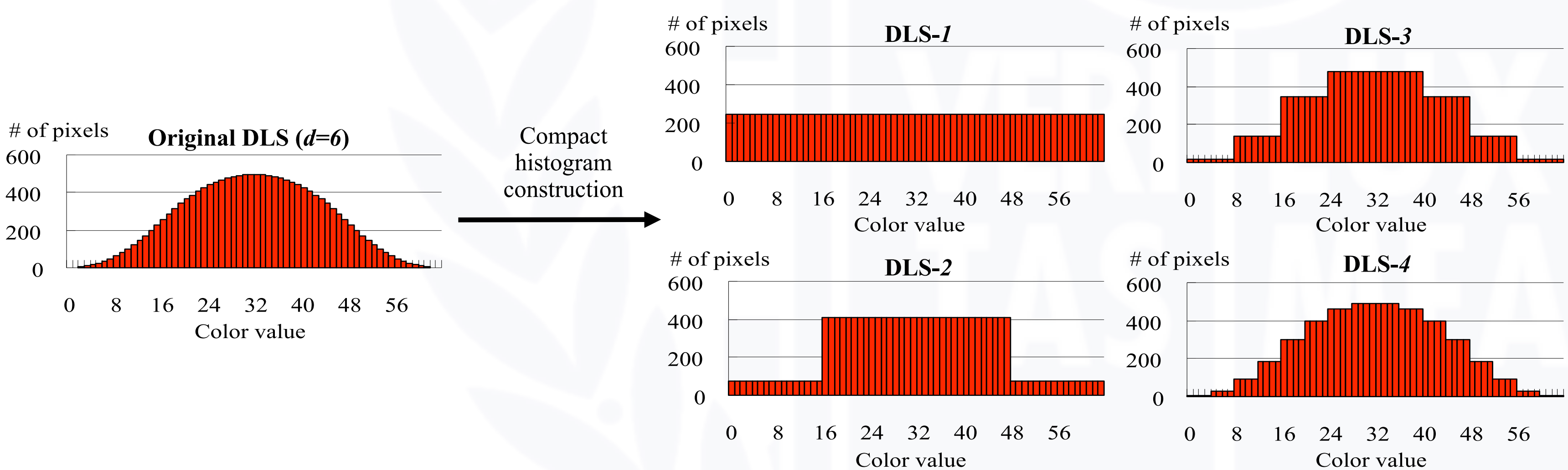


DLS: Experimental Results

- LCD controller (hardware)
  - Relatively small area and power overhead for the image compensation logic such as multipliers and comparators
  - Exponentially increasing area overhead for the histogram construction ➔ Compaction

DLS-*d*	Number of SLICEs	Equivalent gates	Power (mW)	△ Power (mW)
w/o DLS	926	64,656	229	0
DLS-*1*	1,033	66,596	239	10
DLS-*2*	1,121	68,356	248	19
DLS-*3*	1,266	71,372	260	31
DLS-*4*	1,574	77,578	284	55

Power and area overhead of the LCD controller implementation with an FPGA supporting the hardware DLS-*d*



DLS: Experimental Results

- Comparison between the original software DLS and the application-transparent hardware DLS for a movie stream
  - Compact hardware DLS
    - ➔ Approximated version of histogram (step size over 1)
    - ➔ Higher T'H and lower T'L than original TH and TL
    - ➔ Less backlight power reduction, but higher image quality

Power reduction (%)/normalized MSE (%)/PSNR(dB)			
	Distortion ratio		
	1%	3%	5%
Original DLS	23.7/0.01/55.00	29.6/0.07/43.00	32.9/0.19/38.01
Hardware DLS-*4*	18.7/0.00/90.64	24.8/0.01/52.75	31.0/0.11/40.63

Backlight power reduction and objective image quality measures of original DLS and hardware DLS-*4*

DLS: Related Work

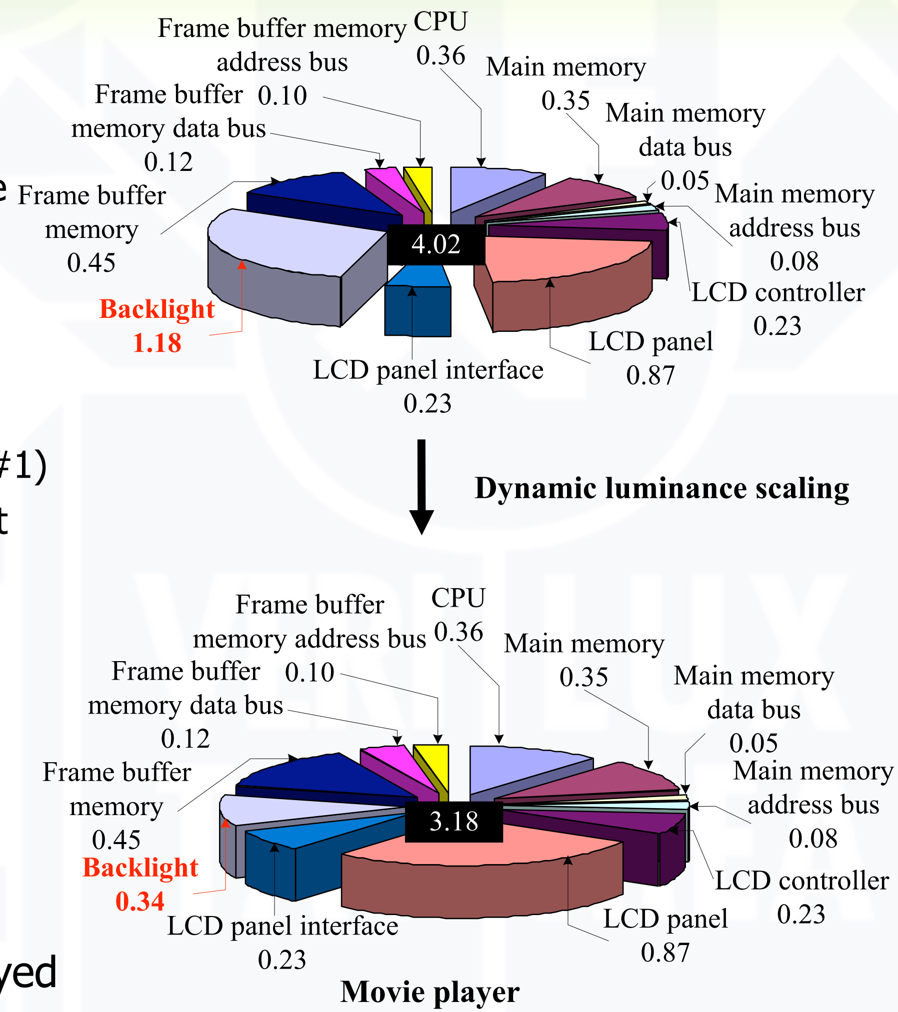
- Backlight luminance scaling
  - Image compensation algorithms
    - CBCS (Concurrent Brightness Contrast Scaling)
    - HEBS (Histogram Equalization for Backlight Scaling)
    - DTM (Dynamic Tone Mapping)
  - Streaming image quality enhancement for backlight luminance scaling
    - QABS (Quality Adapted Backlight Scaling)
  - RGB LED backlight
- Backlight power management
  - Backlight autoregulation
  - Camera-driven display power management

DLS: Conclusions

- Color TFT liquid crystal displays for portable embedded systems
  - Small size and light weight
  - High power consumption of LCD systems
    - Powerful backlight source (30% of total system power)
    - Large-capacity frame buffer memory (17% of total system power)
- Power consumption analysis
  - Device-level power analysis
    - LCD panel and its interface bus
    - Backlight lamp and its high-voltage inverter
    - Frame buffer memory and its associated buses
  - System-level power analysis
    - Reference platform
      - High-performance CPU and memory systems
      - Quality LCD system (VGA resolution, high-color (18-bit))

DLS: Conclusions

- Dynamic luminance scaling
  - Key idea
    - Backlight dimming for power saving
    - Restoring brightness/contrast by appropriate image compensations
  - Four kinds of image compensation algorithms
    - Brightness compensation
    - Histogram stretching (image enhancement #1)
    - Histogram equalization (image enhancement #2)
    - Context processing
  - Three kinds of implementation layers
    - MPEG-4 decoder (application)
    - Java 2 Micro Edition (middleware)
    - LCD controller (hardware)
  - Backlight power saving by up to 71% according to the color histogram of displayed images



Power consumption of the reference platform (W)

DLS: Conclusions

- Future directions
  - Enhancement of the image quality further for video streaming applications
    - Definition of an image quality metrics on the inter-frame brightness distortion considering characteristics of the human visual systems
    - Avoiding the abrupt and frequent backlight luminance changes by examining the color histogram of future picture frames in advance
    - Considering the nonlinear relations between the color value and the liquid crystal transmittance
  - Application-transparent software DLS implementation
    - Utilizing the palette memory in the LCD controller for the color transformation in the low color depth
    - Design of a lightweight histogram construction algorithm in a software