Image Acquisition
Basic Principle of Image Acquisition

Lens
- Projects the real-world scene onto the image plane
- Field of view & depth of field

Image sensor
- Converts analog irradiance pattern into image samples

Image processor
- Analog-to-digital conversion
- Demosaicing
- Gamma encoding / tone mapping
- White balancing
- Color space conversion
- Denoising, sharpening, etc.
- Compression
Image sensor in digital cameras

- Array of light-sensitive photocells (photocell = sample)
- Photocells employ photoelectric effect
- Irradiance is converted into electric signal
- Filter: Remove unwanted wavelengths
- Two types of sensors: CCD & CMOS
- Exposure-voltage function approximately linear (below saturation level)
Sensor Noise

Predominant noise: **Photon shot noise**
- Number of photon that arrive during exposure time is random
- Poisson distribution ($\sigma^2 = \mu$)
- SNR increases with exposure
- SNR increases with sensor size

Other noise sources
- Dark current noise (charges created by thermal vibration)
- Read noise (thermal noise in readout circuitry)
- Reset noise (some charges remain after resetting photocells)
- Fixed pattern noise (manufacturing variations)
ISO Speed and Signal-to-Noise Ratio

**ISO Speed** for digital cameras
- Introduced for analog films as measure of light sensitivity
- Determines the signal amplification before analog-to-digital conversion
- Doubling the ISO doubles the amplification factor (halves required exposure)
Capturing of Color Images

Basic approach

- Filter incoming light using three (or more) different color filters
- Capture filtered color components
- Convert into signals for color primaries of representation format
Cameras with three image sensors

- Light is split into three color components using a trichroic prism assembly (coatings for which reflection/transmission depends on wavelength)
- Three image sensors: One for each color component
- Main advantage: High light sensitivity (all photons are used)
- Disadvantage: Expensive, large, heavy
**Sensors with Color Filter Arrays**

**Bayer pattern**

**Single sensor cameras**
- Separate color filter on top of each photocell
- Photocells have different spectral responses
- Requires **demosaicing** (interpolation of unknown sample values)
- Lower resolution / demosaicing artifacts

**Bayer pattern**
- Most common type of color filter array
- Twice as many green than red/blue samples
  (humans more sensitive to middle wavelengths)
Bayer Image Demosaicing — Illustration

- Raw image data (as recorded by sensor)
- Demosaicing / interpolation
- Gamma encoding
- Color balancing
- Generated color image (3 components)

Note: The processing order can differ
Demosaicing Artifacts

- Only one color component is captured per pixel
- 67% of the samples have to be interpolated
- Interpolation can cause visible artifacts: Moiré patterns
- Interpolation artifacts can be reduced by optical low-pass filter
- Optical low-pass filter also reduces sharpness

Bayer sensor  full-color sensor
Alternative Color Filter Arrays

- **Bayer pattern** (most common)
- **Fuji X-Trans** (e.g., Fujifilm X-Pro 1)
- **RGB+E pattern** (e.g., Sony DSC-F 828)
- **CYM pattern**
- **CYGM pattern** (e.g., Canon PowerShot S10)
- **RGB+W pattern** (Kodak Truesense)
The Image Processor

Converts obtained sensor signal into representation format

- Demosaicing (for sensors with color filter arrays)
- White balancing
- Conversion into RGB space of representation format
- Gamma encoding of linear color components
- Transform into Y’CbCr format (if desired)
- Final quantization of sample values

Additional processing steps

- Algorithms for improving image quality
  - Denoising
  - Sharpening
  - Reduction of artifacts caused by lens aberrations / distortion
- Compression (e.g. JPEG or H.264 | MPEG-4 AVC)
Part Summary

Structure of cameras
- Lens, image sensor and image processor

Image sensor
- Matrix of light-sensitive photocells
- Linear transfer characteristic (photons to electrons)

Sensor noise
- Predominant noise: Photon shot noise (Poisson distribution)
- Signal-to-noise ratio increases with exposure and sensor size

Capturing of color images
- Three-chip sensors
- Sensors with color filter arrays (demosaicing)

Image processor
- Conversion of captured data into representation format
- Denoising, sharpening, lens correction, data compression
Display of Images and Video
Electron guns produce electron beams
Electrons that hit the phosphor-coated screen cause the emission of photons
Direction of electron beams is controlled by magnetic coils
Electron beam is linewise swept over the screen (50/60 times per second)
Color CRTs: Three electron guns and three types of phosphors
Liquid crystals are placed between glass plates with transparent electrodes.

- Backlight is linearly polarized.
- Polarization direction is modified by liquid crystals.
  - Controlled by voltage (image signal) between electrodes.
- Second polarizer adjusts light intensities depending on polarization direction.
- Color filters for obtaining red, green and blue sub-pixels.
Display consists of cells which are painted with a colored phosphor
- Each cell corresponds to a sub-pixel (3 cells form a pixel)
- The cells contain a noble gas and a small amount of mercury
- When voltage is applied, the noble gas is ionized, forms a plasma and UV photons are emitted
- The UV photons hit the phosphor at the inside of the cell, which cause the phosphors to emit visible light of the corresponding color
- The light intensity is controlled by the applied voltage
Organic light-emitting diode emits light and does not use a backlight
- Composed of a layer of organic materials situated between two electrodes
- Many OLEDs consist of a conductive (electrons) and an emissive (holes) layer
- When voltage is applied, electrons and holes are recombined and form an excited bound state called exciton
- Photons are emitted when electron-hole pairs fall back to base state
- Wavelength of emitted photons depends on band gap of material
Projectors

LCD projectors

- Similar principle as slide projector, but slide is replaced by LCD
- White light is split into red, green and blue component (mirrors or prisms)
- An image for each color component (red, green, blue) is generated by passing the light through an LCD
- The red, green and blue images are combined using dichronic prisms

Digital light processing (DLP) projectors

- Digital micromirror device (DMD):
  One microscopic mirror for each pixel on a chip
- Micromirrors can be rotated to send light through the lens or to a heat sink
- Gray values are obtained by quickly toggling the mirrors
- Color images are generated by sending the light through a rotating color wheel or using 3 DMDs (one for each primary color)
Resolution, Optimal Viewing Distance and Angle of View

Visual acuity of human vision

- Can resolve lines at about 1 minute of arc

Optimal viewing distance

- Display of size $W \times H$ with resolution $N_W \times N_H$
- Viewing distance $v_{\text{opt}}$ (can just resolve two points)

$$v_{\text{opt}} \approx \frac{(W/N_W)}{\sin((1/60)°)} \approx \frac{3400 \, W}{N_W} \approx \frac{3400 \, H}{N_H}$$

Angle of view for optimal viewing distance

- Horizontal angle of view $\theta_W$ for optimal viewing distance $v_{\text{opt}}$ is given by

$$\theta_W = 2 \cdot \arctan \left( \frac{W}{2 \, v_{\text{opt}}} \right) \approx 2 \cdot \arctan \left( \frac{N_W}{6800} \right)$$

- Same consideration for vertical angle of view $\theta_H$
Display Size for Optimal Viewing & Example Calculations

Display size for optimal viewing

- Given viewing distance $v$ and picture aspect ratio $a = W/H$
- Display diagonal $D_{opt}$

\[
D_{opt} = \sqrt{(a \cdot H)^2 + H^2} \\
\approx \frac{N_H \cdot \sqrt{a^2 + 1}}{3400} \cdot v
\]

<table>
<thead>
<tr>
<th>picture format $N_W \times N_H$ (picture aspect ratio)</th>
<th>opt. viewing distance $v_{opt}$</th>
<th>corr. angle of view $\theta_W \times \theta_H$</th>
<th>corr. display size $D_{opt}$ for $v = 2$ m / $v = 3$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDTV: 720 × 576 (4:3)</td>
<td>5.9 · $H$</td>
<td>$12^\circ \times 10^\circ$</td>
<td>28” / 42”</td>
</tr>
<tr>
<td>HDTV: 1920 × 1080 (16:9)</td>
<td>3.1 · $H$</td>
<td>$32^\circ \times 18^\circ$</td>
<td>50” / 75”</td>
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<tr>
<td>UHD-1: 3840 × 2160 (16:9)</td>
<td>1.6 · $H$</td>
<td>$59^\circ \times 35^\circ$</td>
<td>100” / 150”</td>
</tr>
<tr>
<td>UHD-2: 7680 × 4320 (16:9)</td>
<td>0.8 · $H$</td>
<td>$97^\circ \times 65^\circ$</td>
<td>200” / 300”</td>
</tr>
</tbody>
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Part Summary

Display technologies
- Cathode ray tube (CRT) displays
- Liquid crystal displays (LCDs)
- Plasma displays
- Organic light-emitting diode (OLED) displays

Projection technologies
- LCD projectors
- DLP projectors

Display size and resolution, optimal viewing distance, angle of view
- Human vision has a maximum acuity
- Optimal viewing distance depends on display size and resolution
- Angle of view for optimal viewing conditions
- Display size for given viewing distance and optimal viewing