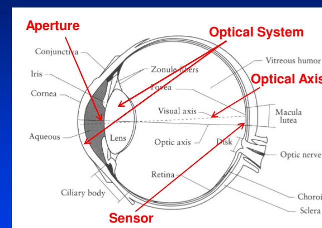
Fundamentals of Image Processing

Lecture 04

The Anatomy of Digital Cameras

Elements of an Imaging Device

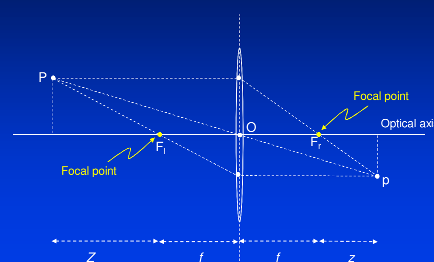


Base image from *Principles of Digital Image Synthesis*, Vol. 1, page 6, by Andrew Glassner, Morgan Kaufmann Publishers, Inc.

Optical Systems

- In practice, optical systems can be very complex
- The fundamental ideas can be understood studying the simplest optical system: the *thin lens*
- Thin lens attributes
  - An optical axis passing through the lens center
  - Two focal points, placed on opposite sides of the optical axis and equidistant from the lens center

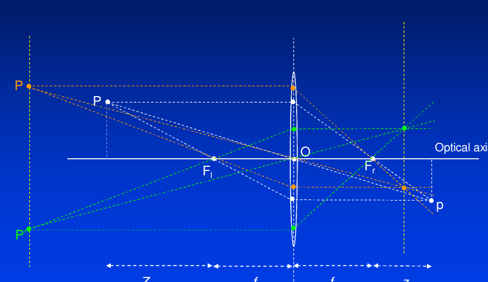
Geometric Optics of a Thin Lens



Thin Lens Properties

- Any ray entering the lens parallel to the optical axis on one side goes through the focal point on the other side
- Any ray entering the lens from the focal point on one side emerges parallel to the axis on the other side

Geometric Optics of a Thin Lens



Some Definitions

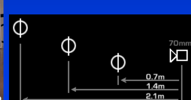
- Focal Length
  - distance (in mm) from the lens to its focal point
- Aperture
  - adjustable diaphragm of over overlapping blades which can be thought of as the iris of the eye
  - The aperture value represents a ratio of the equivalent focal length of a lens to the diameter of its entrance pupil
  - Different notations: f/8, F8, 1:8 (all the same)
  - The larger the f-number the smaller the aperture

Some Definitions

- ISO value
  - in traditional film photography the ISO (ASA) value of a film represents the film's sensitivity
  - a film with lower ISO value requires more light to create the same image than a film with a higher ISO value
  - in a digital camera the sensitivity depends on the sensor
  - a CCD is an analogue device which outputs a certain voltage for a certain amount of light that reaches it
  - when you increase the sensitivity you are really just turning up the amplification of this signal (and of the "dark current" – noise)

Depth of Field (DOF)

- Region in front (1/3 of the DOF) and behind (2/3 of the DOF) the main focus point which remain "sharp"
- Affected by aperture, subject distance and focal length
- The bigger the F number, the larger the DOF



Shutter Speed

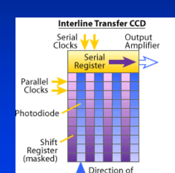
- Length of time the "shutter" allows light onto the CCD
- To "freeze" the action use a shutter speed of 1/250s plus
- To avoid shake use a shutter speed faster than the focal length of the lens (*e.g.*, 300mm lens → 1/300s)

CCD Arrays

- Bucket Analogy
- Collect photons and outputs a voltage reading
- Major types of sensor
  - Interline Transfer sensors
  - Full Frame sensors

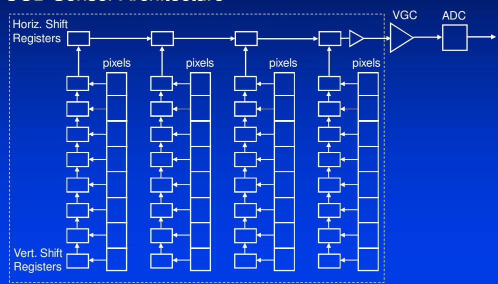
Interline Transfer Sensors

- Used in typical consumer-grade digital cameras
- Transfer values from photodiodes into shift registers
  - Type of photodetector capable of converting light into voltage
- Can produce video feed output
- Extra electronics required around each pixel
  - Fill factor ~ 30% of the pixel area
  - Use of microlenses to capture and focus more light into the smaller photodiode area
    - Improves fill factor to about 70%



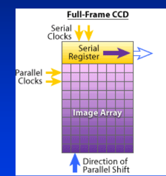
Interline Transfer Sensors (Cont.)

- CCD Sensor Architecture



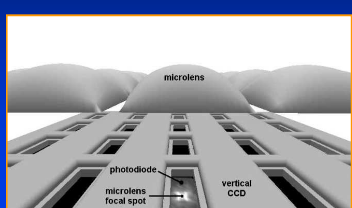
Full Frame Sensors

- Used in professional cameras (high image quality)
- Do not use shift registers, requires mechanical shutter
- Fill factor: ~70%
- High sensitivity
- High dynamic range
- No need for microlenses
- Disadvantages
  - Cannot get video feed out
  - Top shutter speed constrained by mechanical shutter

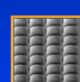


CCD Arrays

- All CCD chips are analog devices
- Requires A/D conversion



CCD chip (IBM)



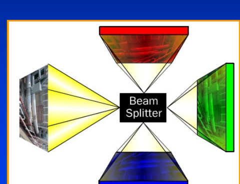
Microlens

Color CCD Cameras

- Photodiodes are monochrome devices
- In order to capture color, we need to use color filters
- Approaches
  - Use three CCDs (one for each of the RGB channels)
  - Use one CCD with a color filter array (CFA)

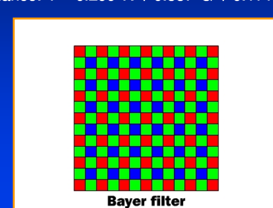
Three-CCD Camera

- A beam splitter is used to project the incident light onto three CCD arrays (RGB)
- Higher quality, but more expensive and bigger cameras



Color Filter Array (CFA)

- Bayer filter Pattern
- Human visual system more sensitive to green
  - Luminance: $Y = 0.299*R + 0.587*G + 0.114*B$



Bayer filter

Color Filter Array (CFA)

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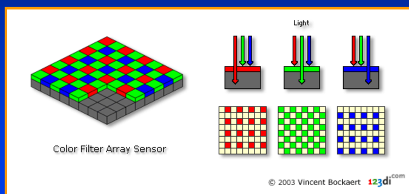
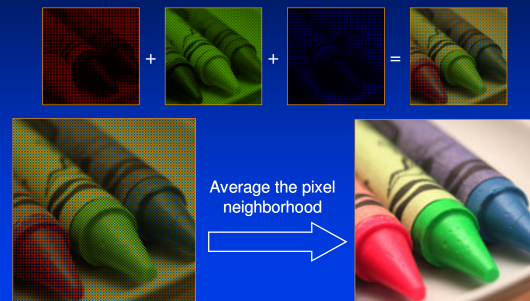
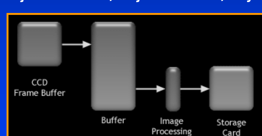


Producing the Final Image



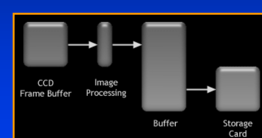
Before-Image-Processing Buffer

- Writing to the storage card takes time
- The raw data from the CCD is placed in the buffer, freeing the CCD for the next picture
- Processing includes color interpolation and compression
- Examples: Fujifilm S1 Pro, Fujifilm 4900Z, Olympus C-3030Z



After-Image-Processing Buffer

- Images are placed in the buffer in their final output format
- Examples: Canon G1, Nikon Coolpix 990, Canon EOS-D30



Processing Raw Data in the PC

- Example of image sharpening

Digital Image Noise

- Image sensors are electronic devices
  - Have inherent uncertainties, inefficiencies and inaccuracies These can result in unwanted artifacts or noise
- The most significant source of noise is *dark current*
  - Unwanted signal that is measured by reading the image that would be captured in the dark when there is no illumination
  - It has a big impact on the camera's dynamic range
- Heat build-up also leads to dark noise (with the noise doubling for every 6 to 8 degrees Celsius)
- Crosstalks are other sources of noise

Digital Image Noise (Cont.)

- Sensor size relative to the number of pixels affects noise
- Smaller pixels have a greater probability of electronic interference which creates noise
- Smaller pixels
  - Smaller photon count per pixel → more sensitivity to noise
  - Reduces dynamic range
- Larger sensors → larger pixels
  - Preferred for higher quality digital cameras
  - More expensive

Noise Reduction

- Noise due to dark current can be eliminated by: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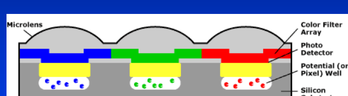
Original image | Black image | Resulting image

Optical Crosstalk

- If a photon intersects a filter element at an angle it may enter the adjacent pixel's photodetector
- This can lead to contamination of the adjacent pixel's charge packet



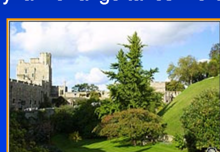
- Correction requires adding barriers between pixels

Electrical Crosstalk

- How deep photons travel into silicon before releasing electrons varies with wavelength
- The shorter the wavelength, the greater the photon energy, and the sooner it excites silicon's electrons
- Photons passing through the red filter can travel further into the silicon before generating electrons

Sensor's Dynamic Range

- Measurement of the sensor's ability to capture image detail across a range of dark to light areas in the image
- The darker the darks and brighter the light areas that can be captured, the higher or better the dynamic range
- Representation of higher dynamic range takes more bits

Sensor's Dynamic Range (Cont.)

- Affected by noise
- Photon count in dark areas may be significantly different (relatively speaking)

Signal-to-Noise Ratio

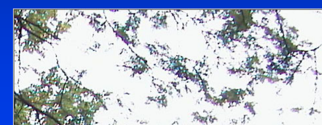
- The true test of a CCD camera's detection ability
- Equivalent to the sensor's dynamic range
- Expresses the maximum number of gray values represented with the CCD
- Computed as the ratio between all stored electrons and the noise electrons

$$SNR = Dynamic\ Range = \frac{Full\ Well\ Electrons}{Noise\ Electrons} = Max.\ Gray\ Scales\ from\ CCD$$

$$CCD\ Camera\ Bit\ Depth = \log_2(Max.\ Gray\ Scales\ from\ CCD)$$

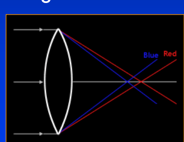
Blooming

- Pixels (photodiodes) have a limit on how much charge they can hold (fill factor)
- For sufficiently strong light, electrons will overflow and contaminate adjacent pixels
- Solution: create overflow wells (takes space!)



Chromatic Aberration (CA)

- Optical problem: camera's lens focuses different wavelengths onto different focal planes
- Amount of CA depends on the dispersion of the glass
- In digital cameras its effects are amplified by the blooming effect



Reducing Chromatic Aberration

- Use of lens systems using two or more pieces of glass
- Not perfect