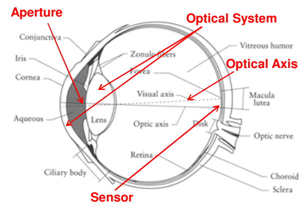
Computational Photography

Lecture 03

The Anatomy of Digital Cameras

Elements of an Imaging Device

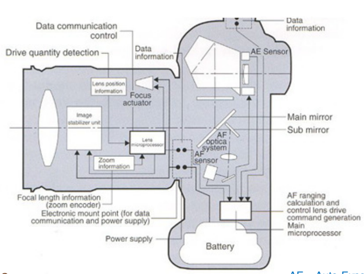


Base image from *Principles of Digital Image Synthesis*, Vol. 1, page 6, by Andrew Glassner, Morgan Kaufmann Publishers, Inc.

Digital Single Lens Reflex (DSLR) Cameras

DSLR Internal Components

DSLR Internal Components



Canon

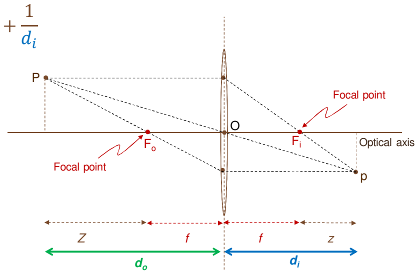
AE – Auto Exposure
AF – Auto Focus

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

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

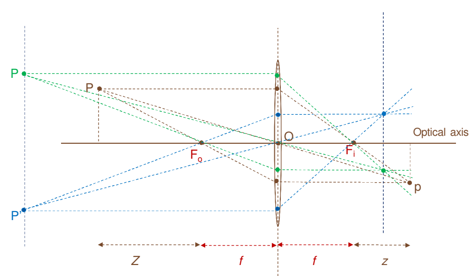


Applet (1): http://www.phy.ntnu.edu.tw/ntnujava/index.php?topic=48
Applet (2): http://graphics.stanford.edu/courses/cs178/applets/gaussian.html

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 optical the axis on the other side

Geometric Optics of a Thin Lens



DSLR Camera Settings

Focal Length and Aperture

- 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

Aperture: f stops

f-stops are a sequence of standard f-numbers (f1.4, f2.0, f2.8, ..., f16) , one f-stop step duplicates the diaphragm area: $f_i = \sqrt{2} f_{i-1}$

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

Aperture and Depth of Field

Image source: Wikipedia.org

Aperture and Depth of Field

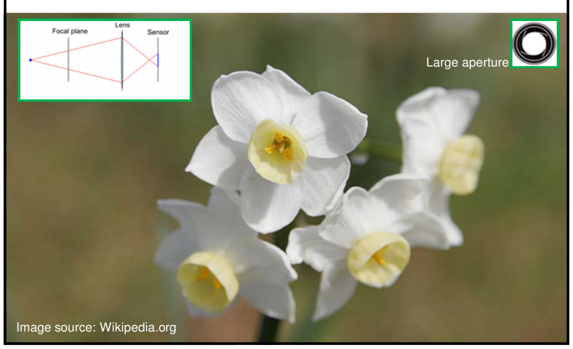
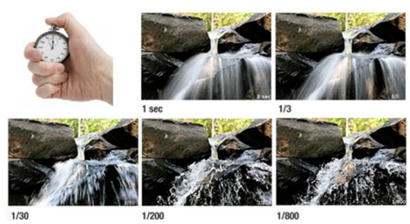


Image source: Wikipedia.org

Shutter Speed or Exposure Time

Length of time the "shutter" allows light onto the CCD



Exposure = Aperture + Shutter Speed

The amount of light that reaches the sensor, depends on aperture and shutter speed

From Photography, London et al.

All these combinations of aperture and shutter speed give the same **exposure**

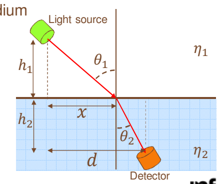
Field of View / Zoom

Sensitivity (ISO number)

- 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)

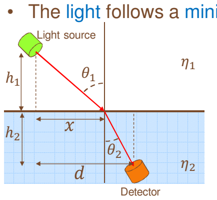
Optical Path Length

- The speed of light in a medium with refractive index η is c/η
- The length of the optical path of a light beam is given by $\sum_{i=1}^{n} \eta_i L_i$
  - η_i is the refractive index of the *i-th* medium
  - L_i is the path length in the i-th medium



Minimal Optical Path Length

- The light follows a minimal optical-path length: $\sum_{i=1}^{n} \eta_i L_i$



$$P(x) = \eta_1\left(\sqrt{h_1^2 + x^2}\right) + \eta_2\left(\sqrt{h_2^2 + (d-x)^2}\right)$$

$\frac{d}{dx}P(x) = 0$ (apply the chain rule: $\frac{df}{dx} = \frac{df}{dg}\frac{dg}{dx}$)

$$\eta_1\left(\frac{1}{2}\frac{2x}{\left(\sqrt{h_1^2 + x^2}\right)}\right) + \eta_2\left(\frac{1}{2}\frac{(2x-2d)}{\sqrt{h_2^2 + (d-x)^2}}\right) = 0$$

$$\eta_1\left(\frac{x}{\left(\sqrt{h_1^2 + x^2}\right)}\right) + \eta_2\left(\frac{(x-d)}{\sqrt{h_2^2 + (d-x)^2}}\right) = 0$$

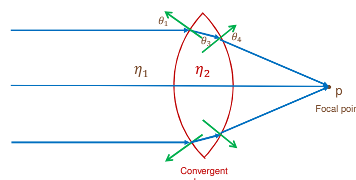
$$\eta_1\left(\frac{x}{\left(\sqrt{h_1^2 + x^2}\right)}\right) = \eta_2\left(\frac{(d-x)}{\sqrt{h_2^2 + (d-x)^2}}\right)$$

$\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$ (Snell's Law!)

Lens Design and Snell's Law

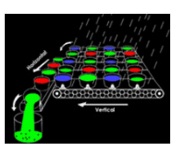
- Controlling surface normal vectors, given the ratio $^{\eta_1}/_{\eta_2}$

$$\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$$



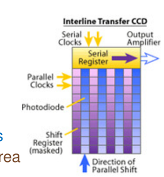
CCD Arrays

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



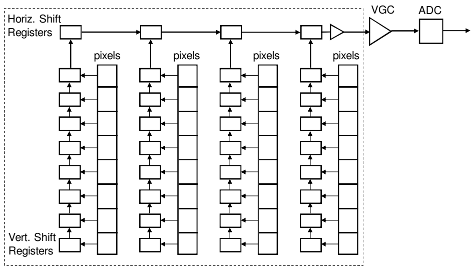
Interline Transfer Sensors

- 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%



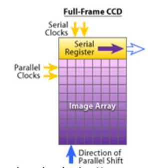
Interline Transfer Sensors (Cont.)

- CCD Sensor Architecture



Full Frame Sensors

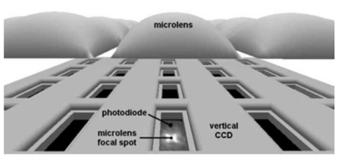
- Used in professional cameras (high image quality)
- Do not use shift registers, requires mechanical shutter
- Fill factor: ~70%
- High sensitivity
- High dynamic range
- No need for microlenses
- Disadvantages
  - Top shutter speed constrained by mechanical shutter

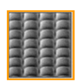


CCD Arrays

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

CCD chip (IBM)





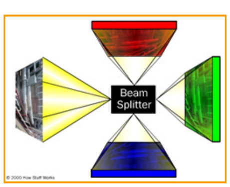
Microlens

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)

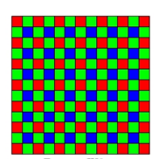
Three-CCD Camera

- 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)

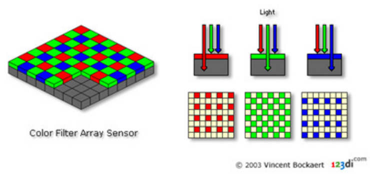
- Bayer filter Pattern
- Human visual system more sensitive to green
  - Luminance: $Y = 0.299*R + 0.587*G + 0.114*B$



Bayer filter

Color Filter Array (CFA)

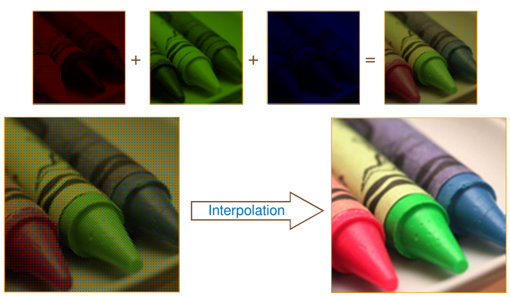
- Bayer filter Pattern
- Human visual system more sensitive to green
  - Luminance: Y = 0.299*R + 0.587*G + 0.114*B



Captured Image is Monochromatic

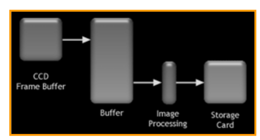
Raw data captured by the CCD

Producing the Final Image



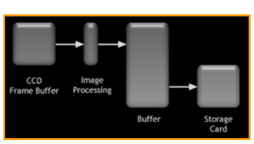
Before-Image-Processing Buffer

- 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

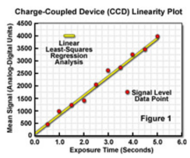
- Images are placed in the buffer in their final output format
- Examples: Canon G1, Nikon Coolpix 990, Canon EOS-D30



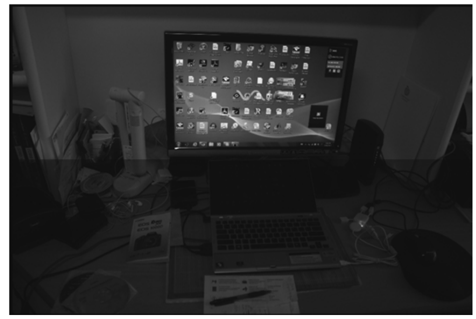
Compression Artifacts

Processing Raw Data on the PC

- Demosaicking (color interpolation)
- White balancing (to compensate for color consistency)
- Gamma compensation (to handle HVS non-linearity)
- Edge sharpening and noise reduction



RAW Image (linear gamma)



RAW image captured by a Canon Rebel XS

Demosaicked Image (linear gamma)

Color Interpolated Image

White Balancing

- Pick a color triple (r_f, g_f, b_f) as reference and sets to (1,1,1)
- Adjusts all other colors according the used scaling factors:

$$(r_{wb}, g_{wb}, b_{wb}) = \left(\frac{1}{r_f}r, \frac{1}{g_f}g, \frac{1}{b_f}b\right)$$

Captured image | After white balance

Image source: Wikipedia.org

White Balancing

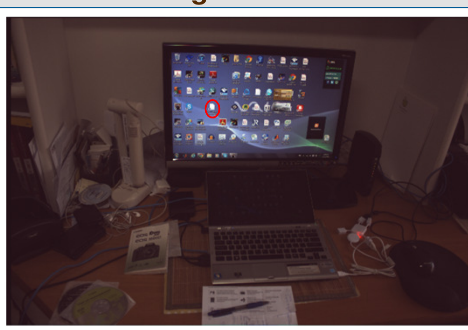


Image after white balance using a bright icon on the screen as reference white

White Balancing

Image after white balance using a piece of paper as reference white

White Balancing

Image after white balance using a piece of plastic as reference white

Demosaicked Image (AWB)

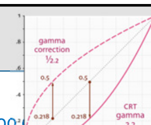
Reconstructed with automatic white balance (Canon Rebel XS)

White Balancing

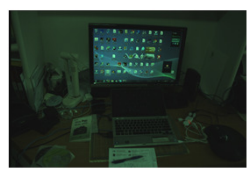
Captured image — Image after white balance

Image source: Wikipedia.org

Gamma Correction



- Linear intensity raw image looks too
- The human visual system (HVS) is more sensitive to darker shades
- Gamma correction: reserves more bits to darker shades



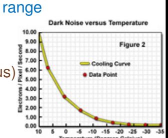
Demosaicked raw image

Image Sharpening

- 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
  - Noise doubles for every 6 to 8 degrees Celsius)
- **Crosstalks** are other sources of noise

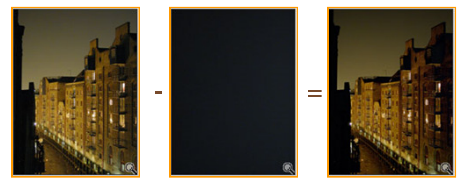


Digital Image Noise (Cont.)

- 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

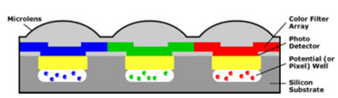
- Noise due to dark current can be reduced by:



Original image   Black image   Resulting image

Optical Crosstalk

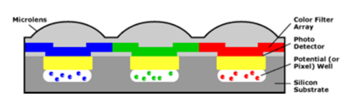
- If a photon intersects a filter element at an angle it may enter the adjacent pixel's photodetector
- This can lead to contamination of the adjacent pixel's charge packet



- Correction requires adding barriers between pixels

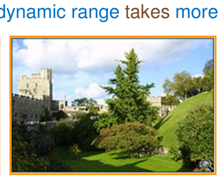
Electrical Crosstalk

- 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 exciting 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

Signal-to-Noise Ratio

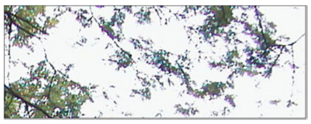
- The true test of a CCD camera's detection ability
- Equivalent to the sensor's dynamic range
- Expresses the maximum number of gray values represented with the CCD
- Computed as the ratio between all stored electrons and the noise electrons

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

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

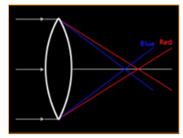
Blooming

- 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!)
    - Control exposure

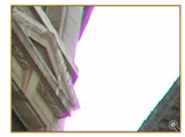


Axial Chromatic Aberration (CA)

- 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

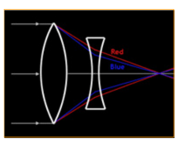


singlet lens



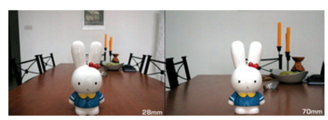
Reducing Chromatic Aberration

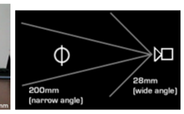
- Use of low-dispersion glass (hybridized glass, often containing fluorite)
- Use of lens systems using two or more pieces of glass
- Not perfect



Perspective Distortion

- Caused by the FOV implied by the focal length
    - changes the way an image looks both in the size of objects and depth of view in the image
    - At wider angles the background appears to be much further away from any subject in the foreground than your eye would normally see (exaggerated perspective)





References

- Phil Askey. Glossary: Digital Photography Review. (http://www.dpreview.com/glossary)
- Sally W. Grotta. Anatomy of a Digital Camera: Image Sensors. (http://www.pcmag.com/article2/0,2817,1156451,00.asp)
- E. Trucco and A. Verri. Introductory Techniques for 3-D Computer Vision. Prentice Hall, 1998.
- UVP Inc. Understanding CCD Cameras. Focal Points – Application Note FP-114.