CSCI435/CSCI935
Computer Vision: Algorithms and Systems

Image Acquisition – Digital Camera

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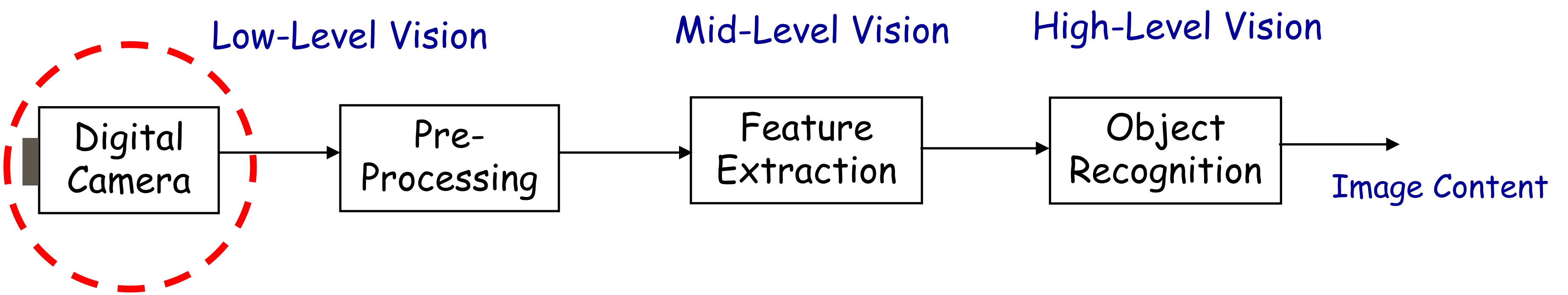
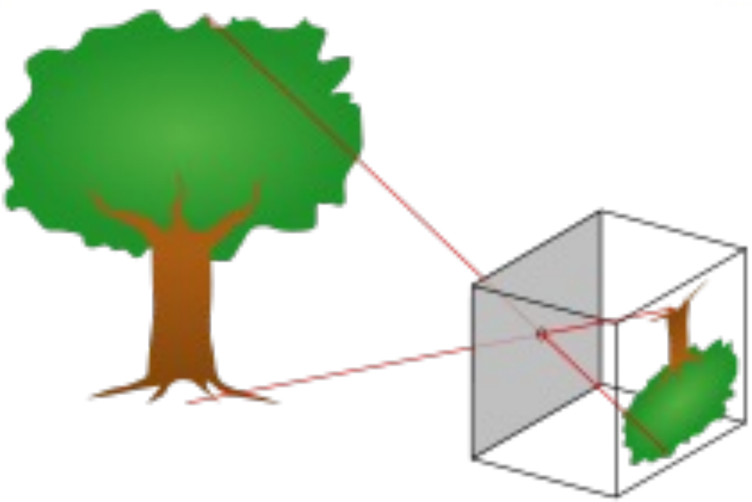
A Computer Vision System (review)

- Key components of a computer vision system



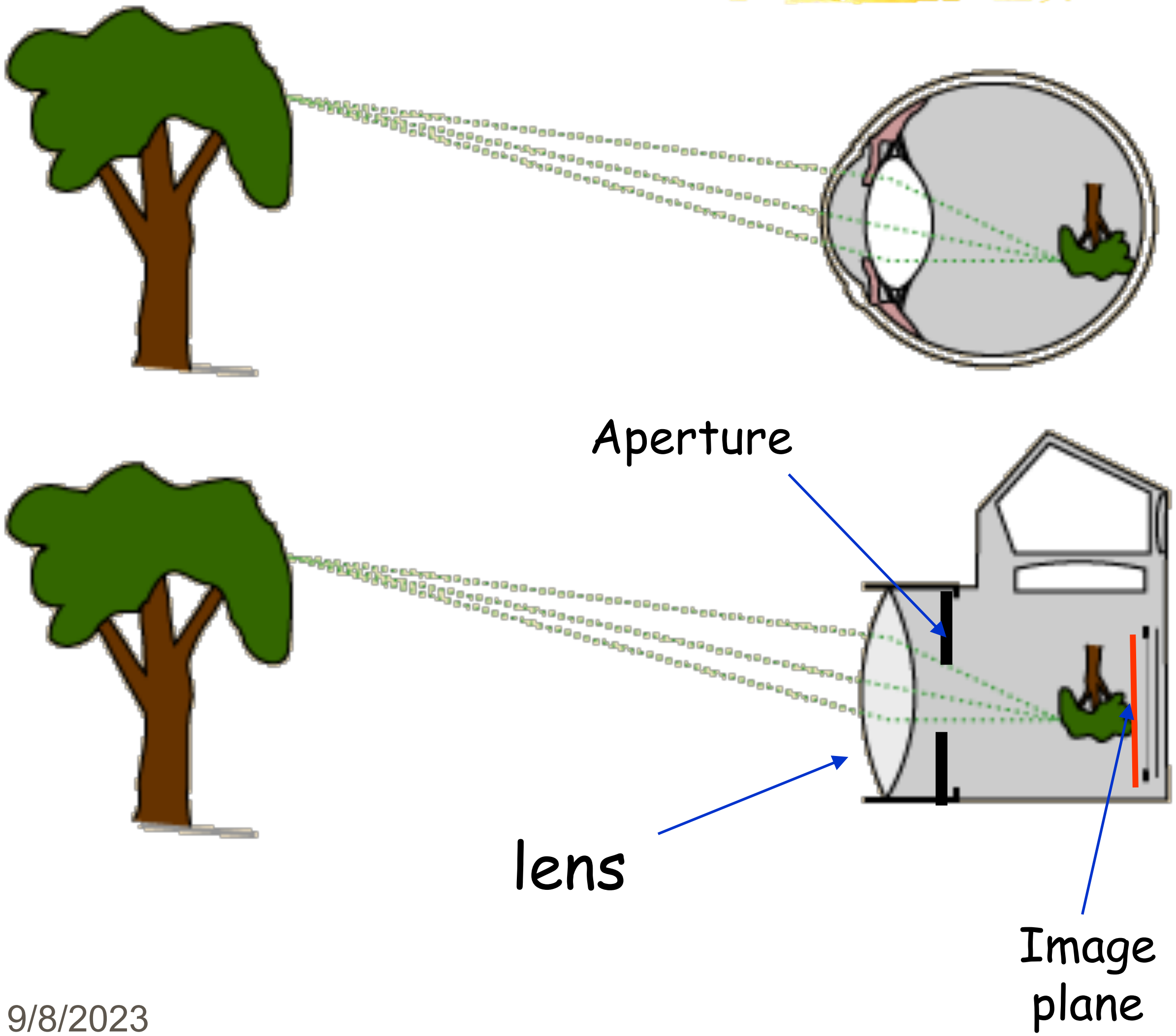
  - The structure and algorithms do not necessarily mimic the actual process of human visual perception, but may utilise some results of biological and cognitive studies

Image Formation - pinhole camera



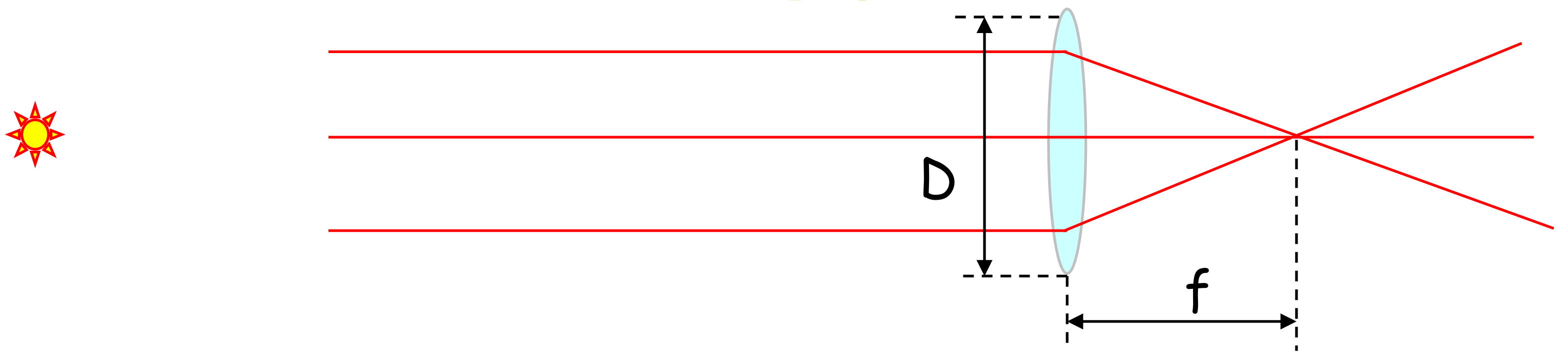
Pinhole camera - http://en.wikipedia.org/wiki/Pinhole_camera

Image Formation - camera with lens

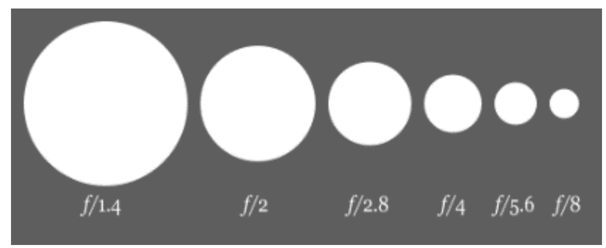


An image is a 2D projection of 3D scenes

Lenses



Major parameters:



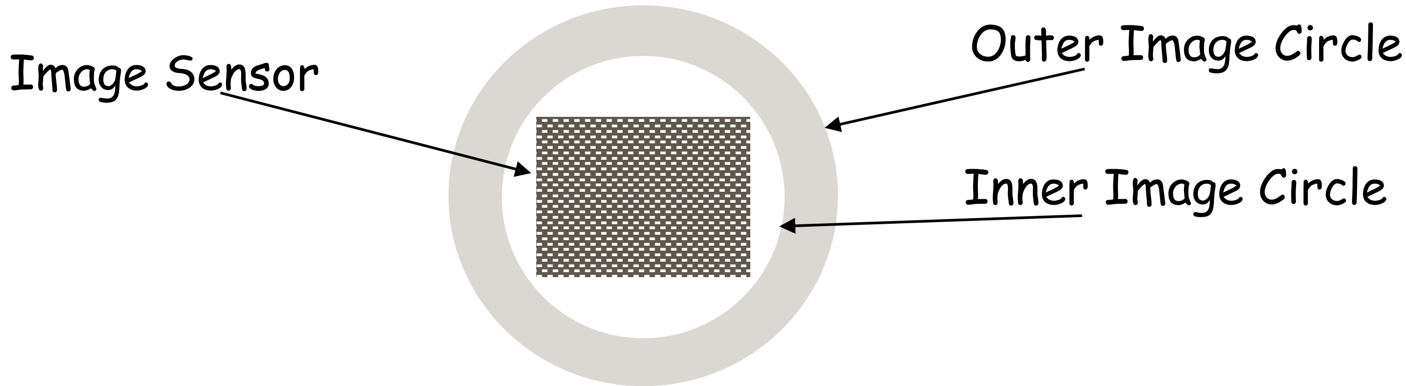
f – focal length

F – F-number

Focal length f is the distance required to focus incoming parallel rays to a single point. It indicates magnification property of a lens

$F = f/D$ indicates light collection property. The smaller F, the more light is collected

Image Circle



- Image quality produced by a lens is the best at the centre of the image plane with gradual degradation towards the outer image circle

  - geometric distortions
  - blur
  - chromatic aberrations (refractive index $n = \lambda_i / \lambda_{rf}$ is wavelength dependent)

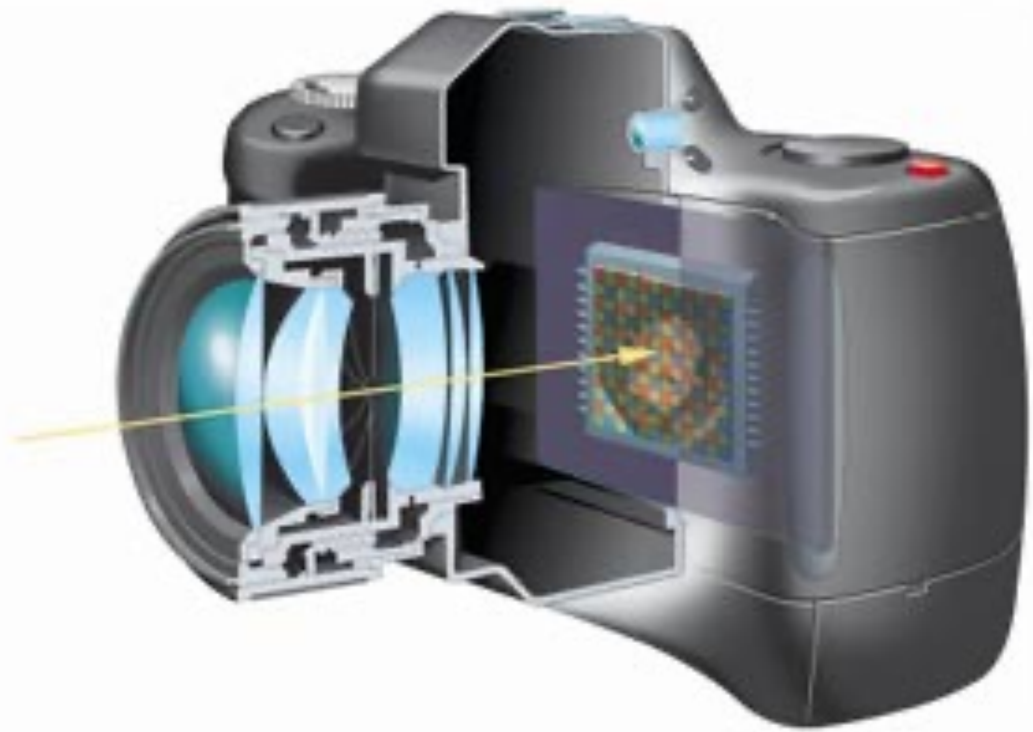
- Outside Inner Image Circle image quality is not guaranteed

Digital Camera Image Sensors

1. Light goes through lens and hits image sensor plane.

2. Image sensor plane is a checker board pattern of color.

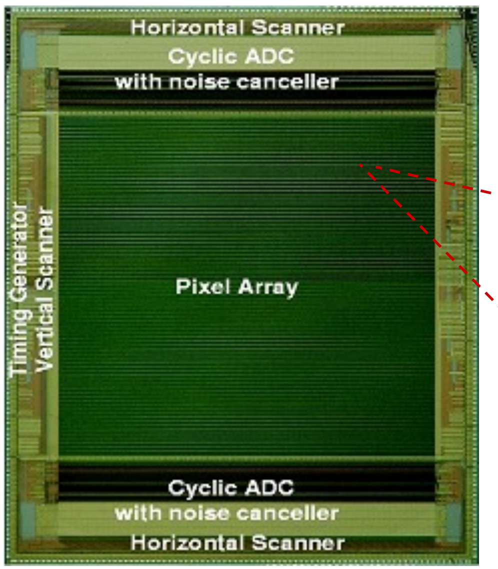
3. Camera estimates image color from checker board pattern.

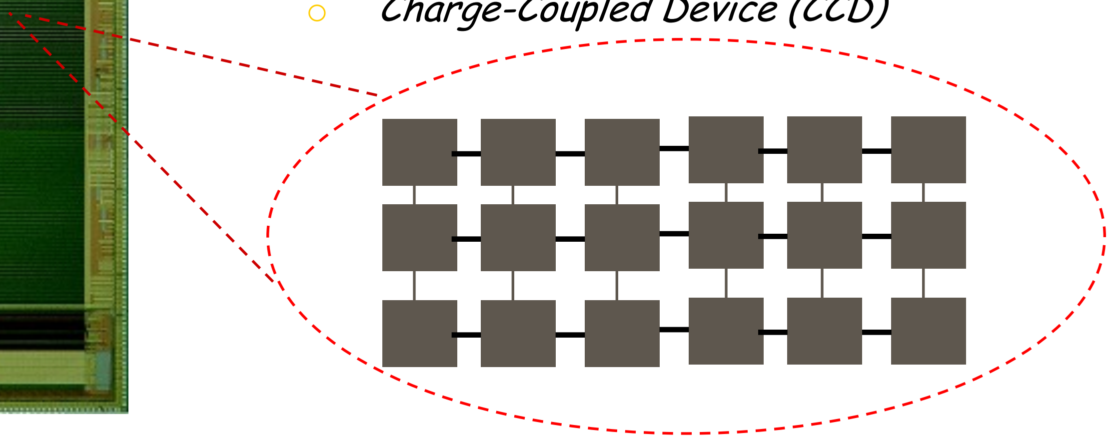


FOVEON

Image Sensor

- Image Sensor is semiconductor component with a photosensitive region
  - *Complementary metal-oxide-semiconductor* (*CMOS*)
  - *Charge-Coupled Device (CCD)*

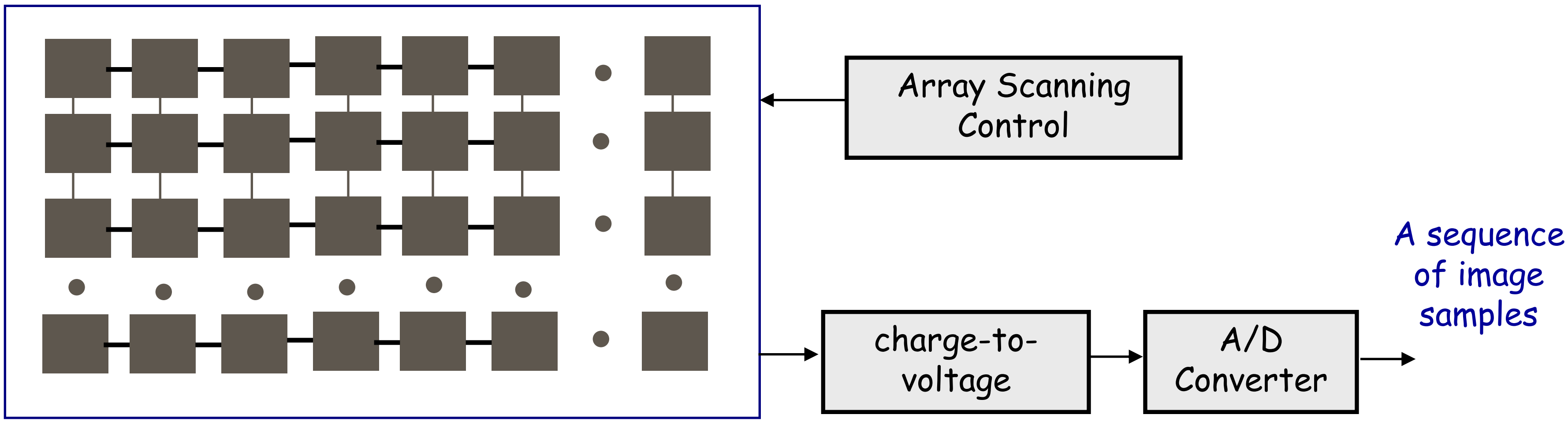




- Photosensitive region is a 2D array of photosensitive elements that accumulate electric charges `q(i,j)` proportional to the illuminance `E(i,j)` and exposure time `t`

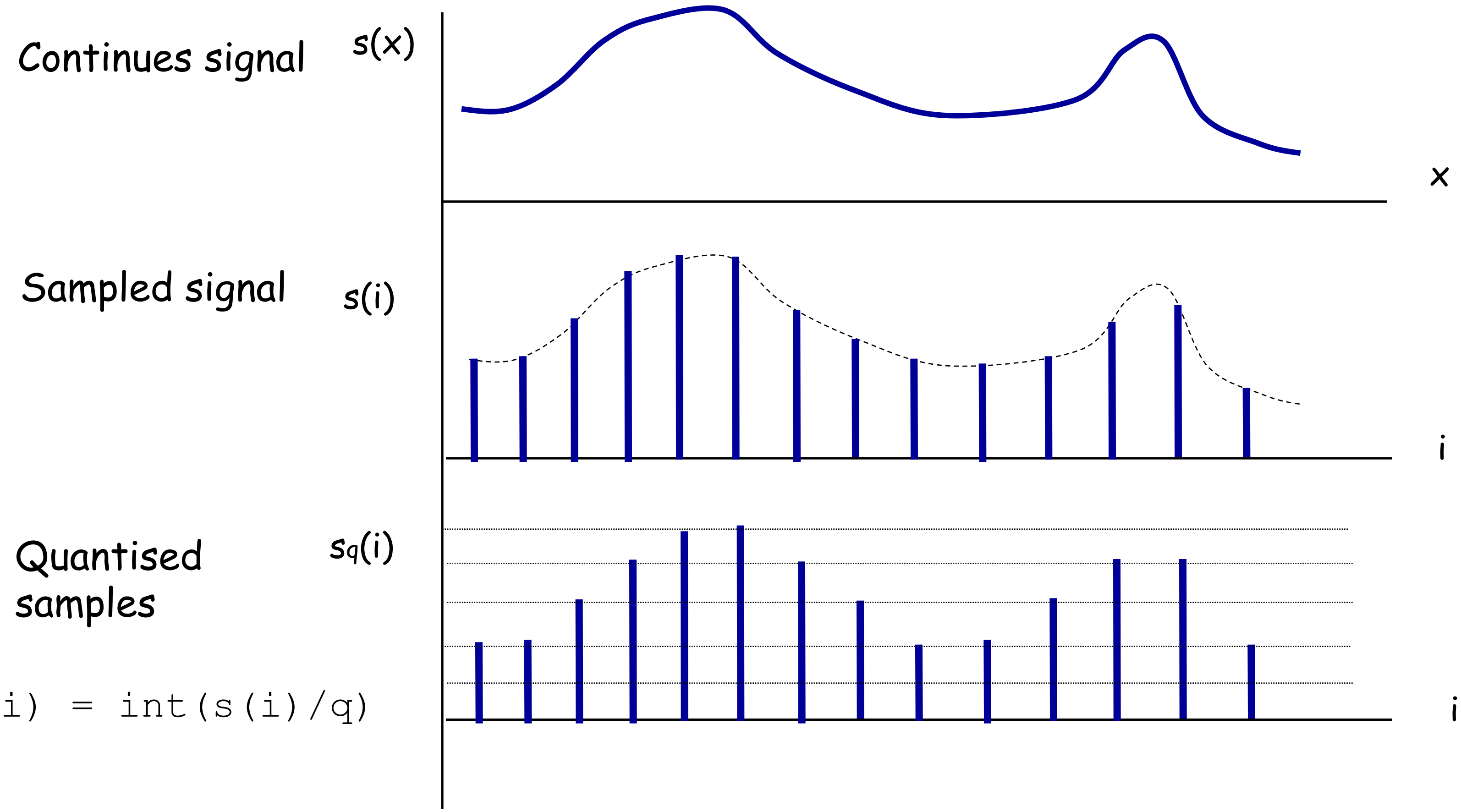
$$q(i,j) = k*E(i,j)*t$$

Image Sensor



- Accumulated charges `q(i,j)` are sequentially scanned row-by-row
- Electric charges are converted to voltages `v(i,j)` and digitised
- The sensor output is a sequence of **digitised** image samples

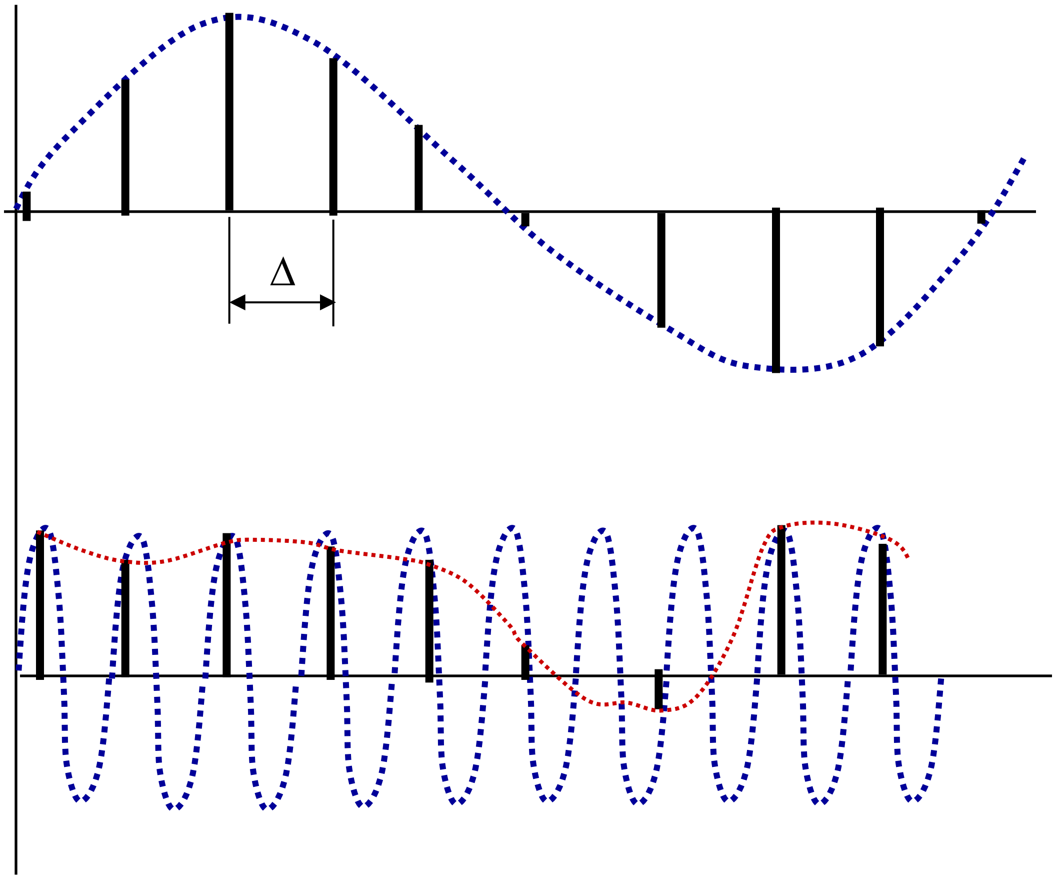
Digitization



$s_q(i) = int(s(i)/q)$

Aliasing

A continues signal can be perfectly reconstructed from its samples, providing the sampling rate is correct



If the sampling interval Δ is not at least half of the period of highest frequency F_{max}, correct reconstruction is not possible

The Sampling Theorem:

$\Delta \leq 1/(2 * F_{max})$

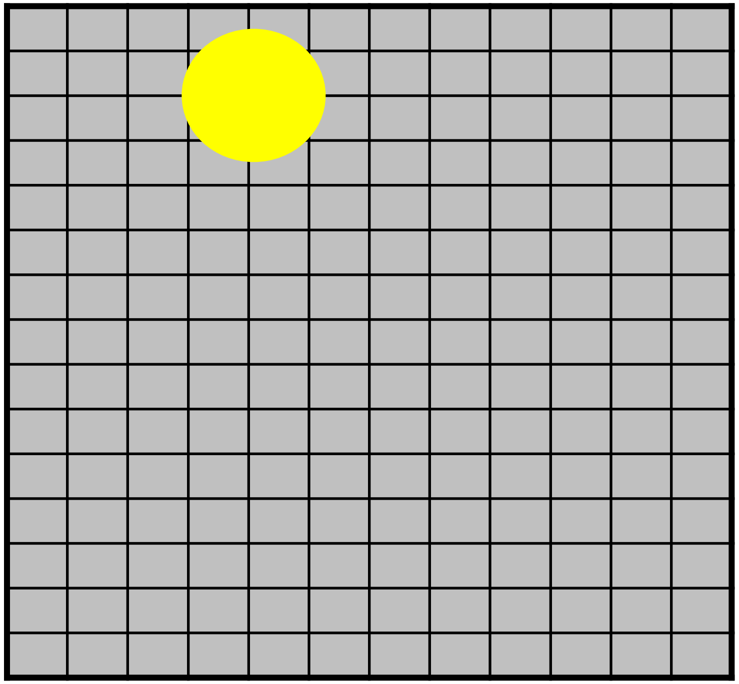
Digitization of Images

A properly sampled image

An under sampled image

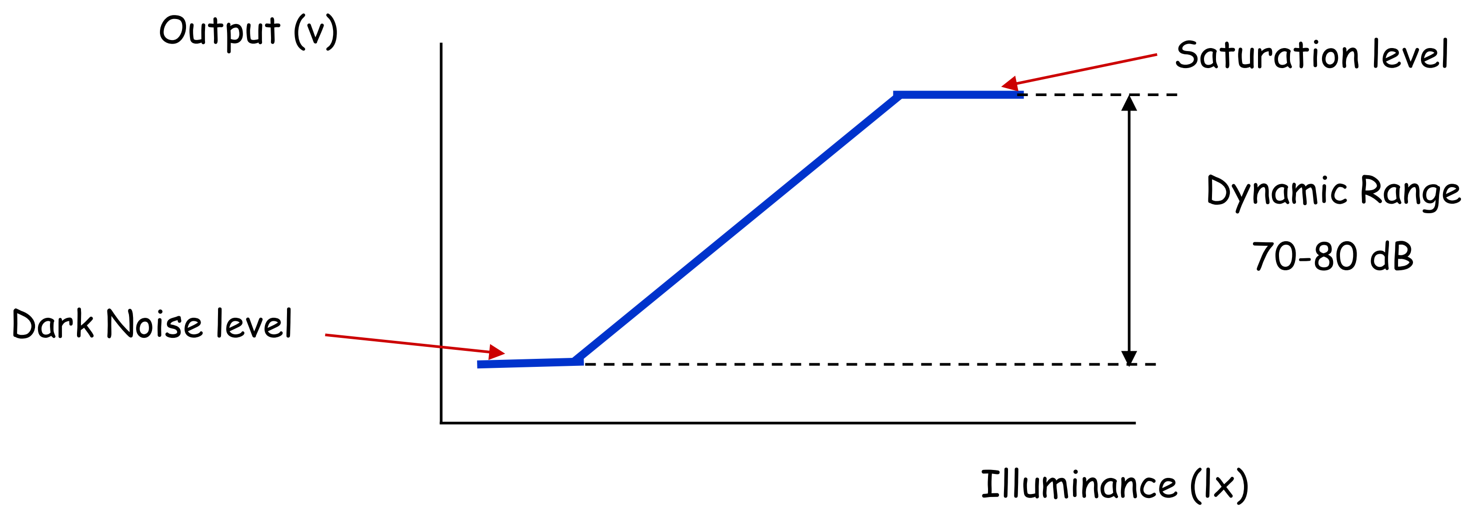
Quiz

The image sensor is an array of photosensitive elements 5x5μm each. What should be the smallest size of the ray of light produced by a lens to avoid aliasing?



Dynamic Range

- Accumulated charge: `q(i,j) = k*E(i,j)*t`



- Dynamic range $20*\log_{10}(V_{max}/V_{min})$

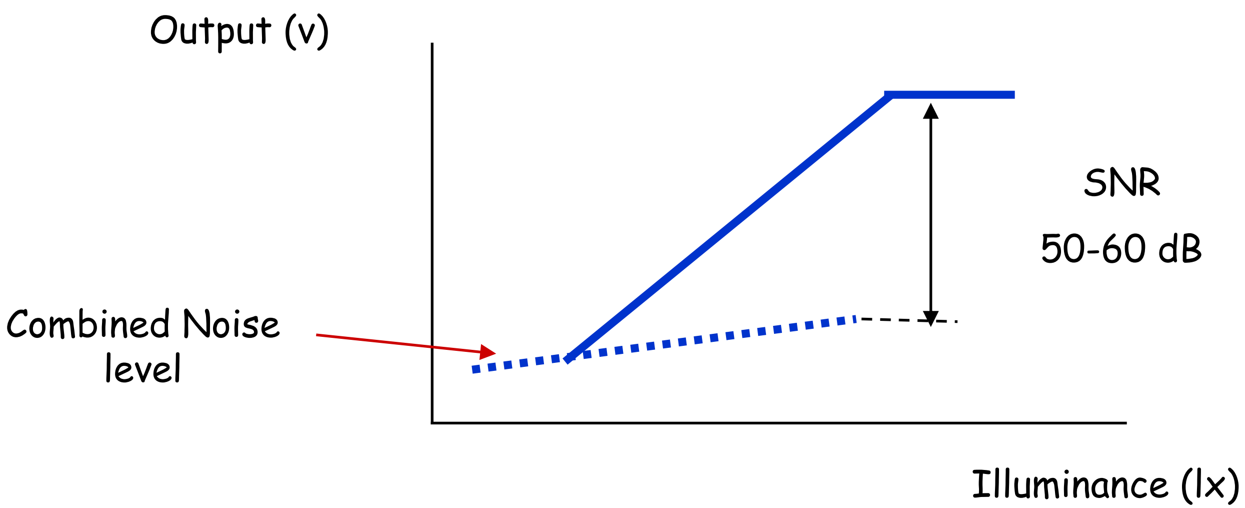
100 times = 40db

1000 times = 60db

10000 times = 80db

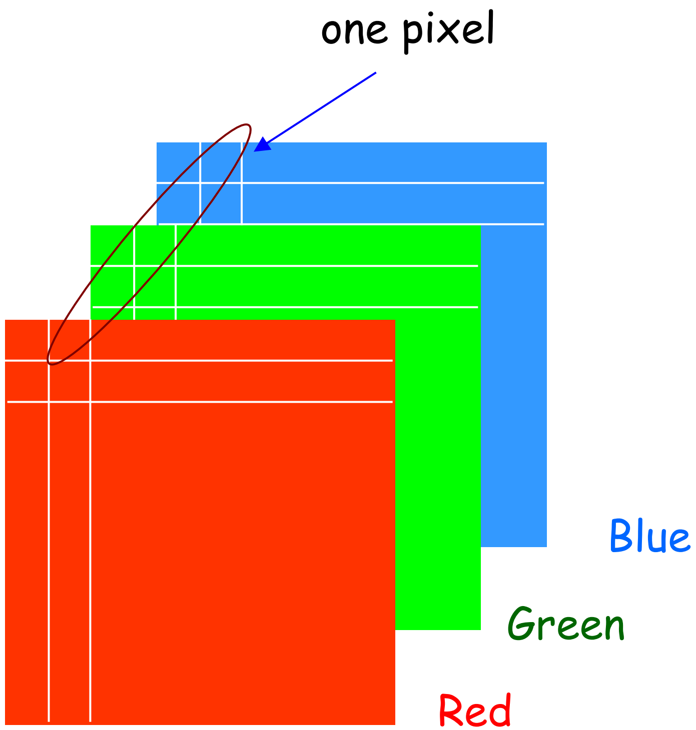
Signal-to-Noise Ratio (SNR)

- Besides the dark current noise, there are other sources of noise. Cumulative noise depends on Illuminance



- SNR $20 * \log_{10}(V_{max} / V_{noise})$

Colour Images



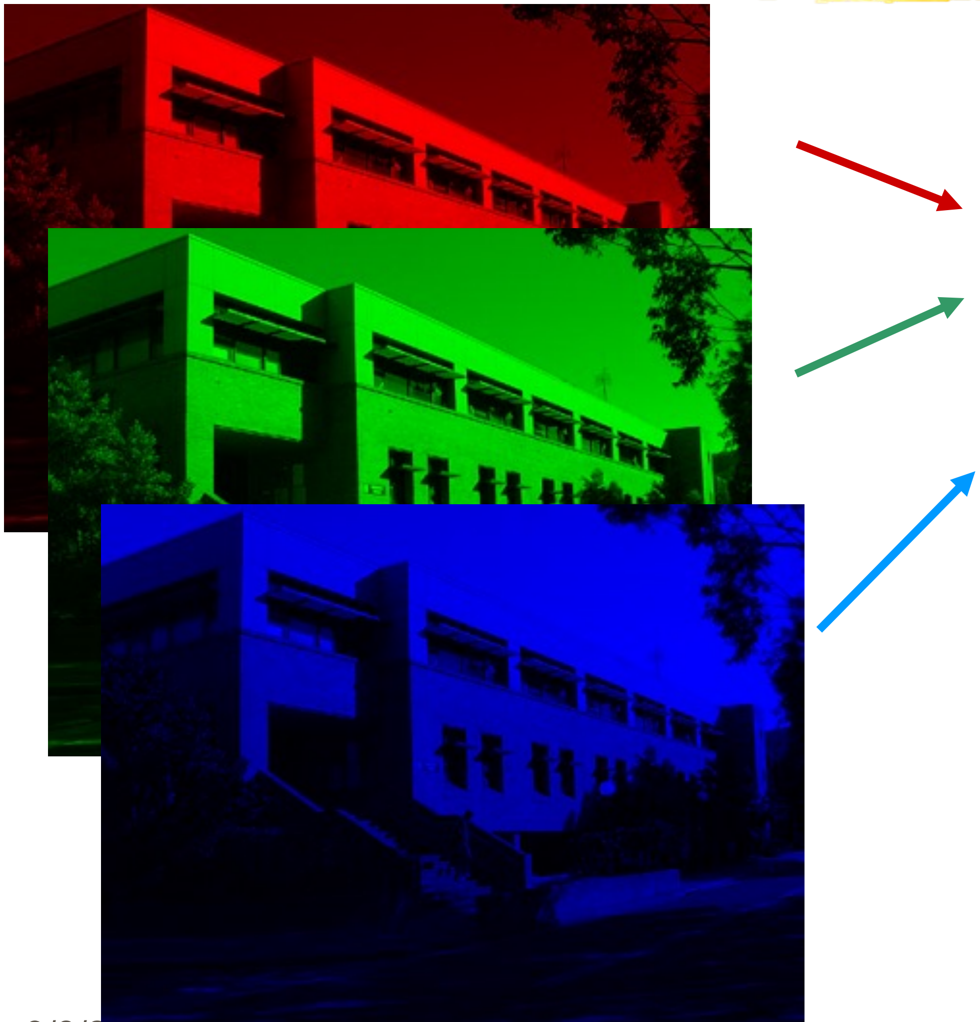
Color Image

- To preserve information about colours, colour images must contain intensities for three colour channels for every picture element (pixel)

Explain why three colour channels are sufficient to represent real world images ?

- Each individual channel can be considered as a monochrom image captured in a limited band of spectrum (400-500nm, ..., etc)

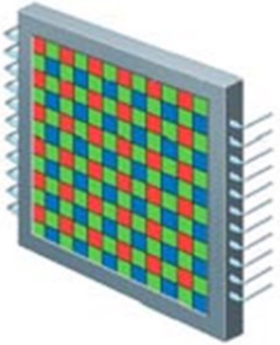
Colour Images

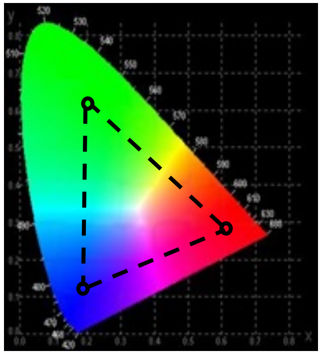


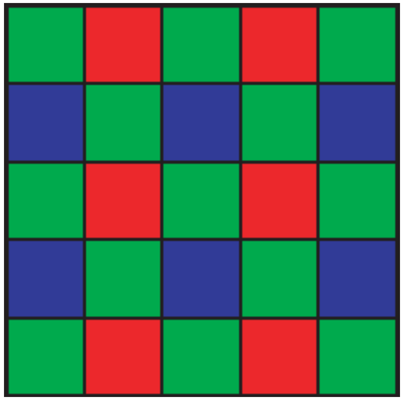
Visual representation

Single Sensor Digital Cameras

- Each photosensitive element is covered by a transparent colour filter that passes only one colour band
- Colour filter parameters determine the gamut of captured images
- The filters are arranged into a colour filter array (CFA) with the pattern that optimises efficiency

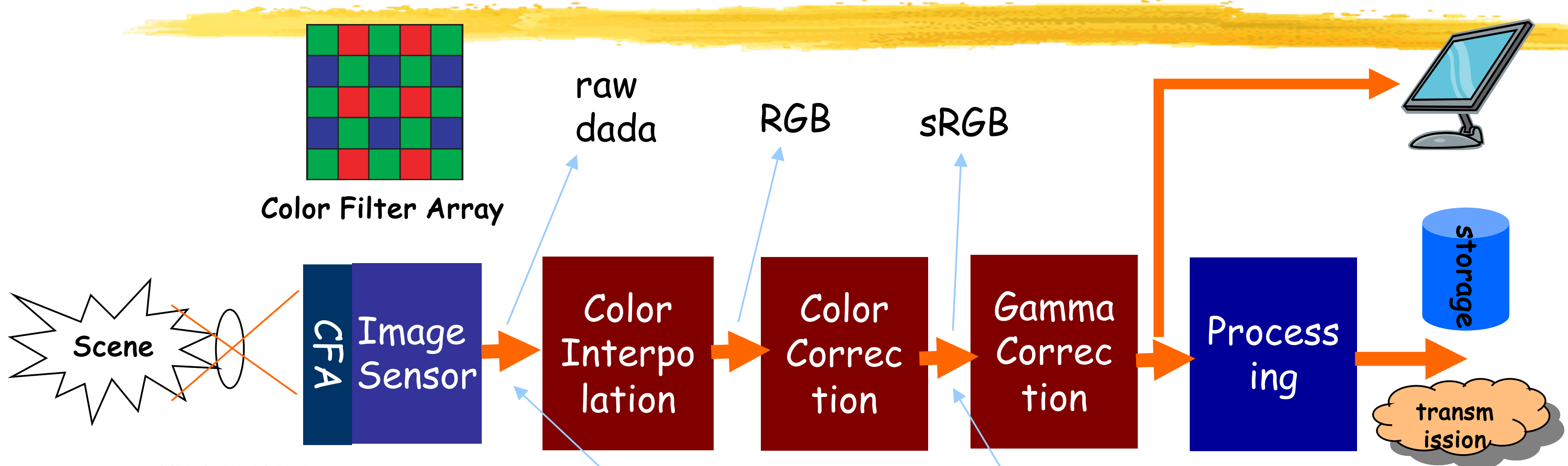


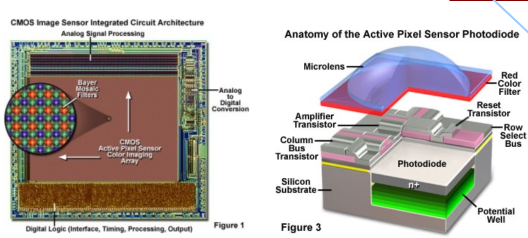


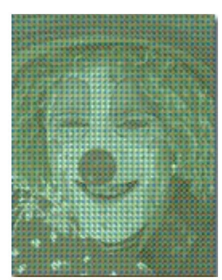


CFA - Bayer pattern

Single Sensor Digital Cameras







CCD - Charge-coupled devices
CMOS - Complementary
metal-oxide semiconductor

Color Interpolation

- Reconstructs RGB colour samples for each pixel from Bayer colour samples

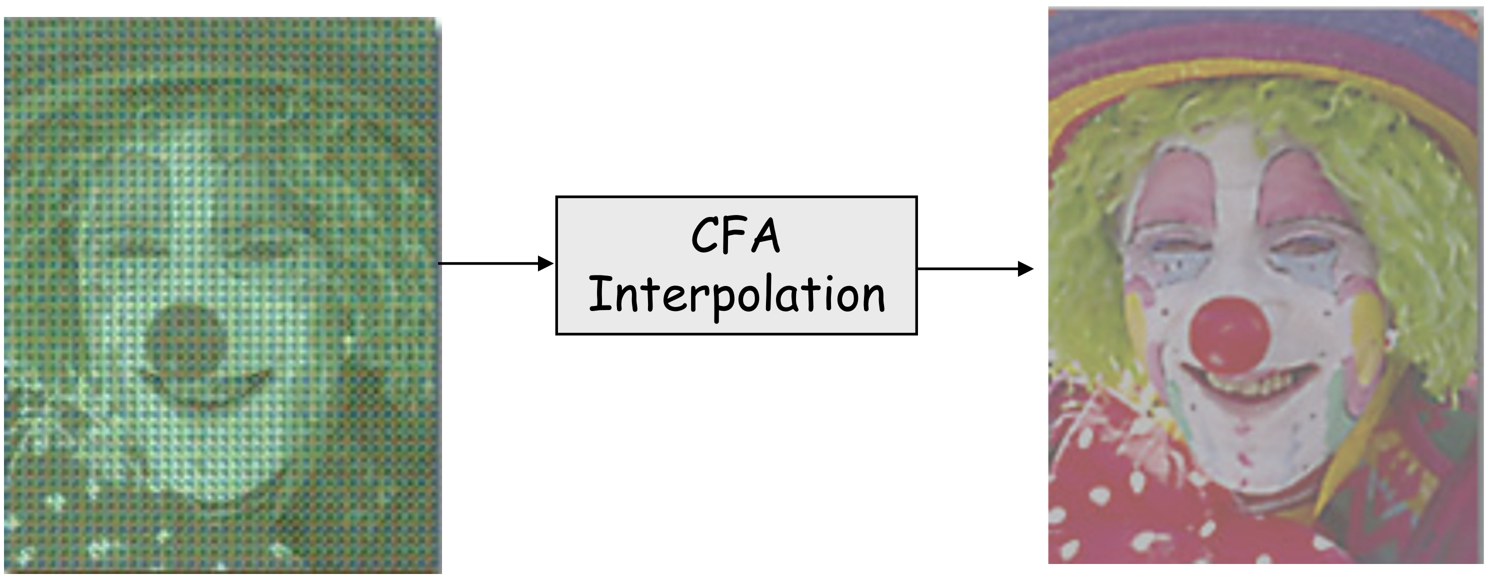


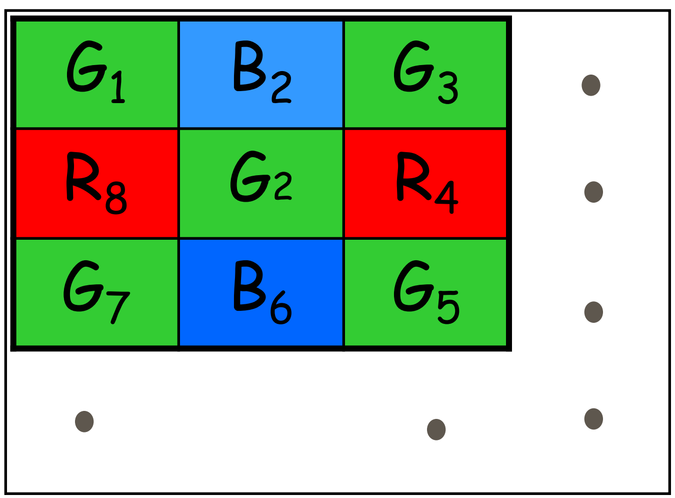
Image captured by a sensor

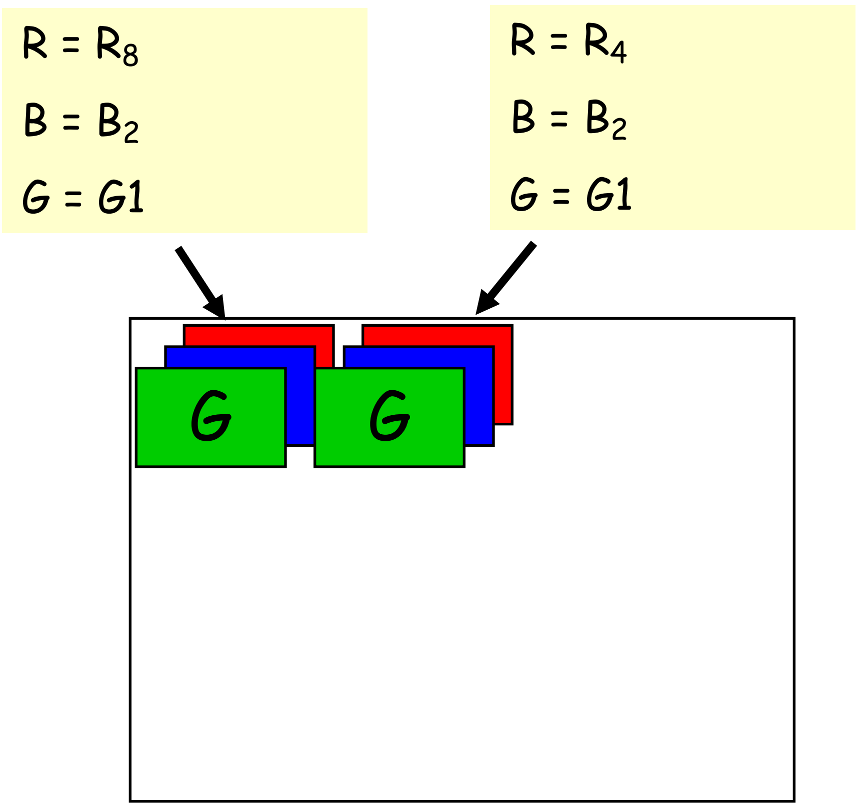
True colour image

Color Interpolation

Nearest Neighbor

- Replicate the corresponding values of the nearest neighbor pixel





CFA Interpolation

Bilinear

- Interpolate missing colour samples as an average of the neighbor pixels

$G = G_2$

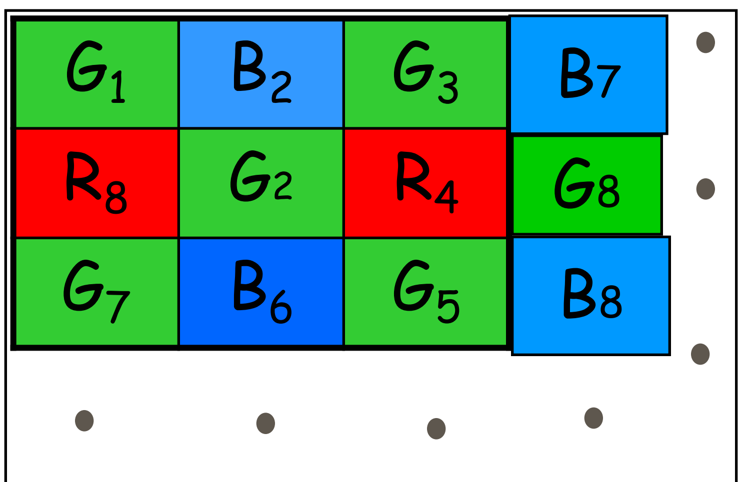
$B = (B_2 + B_6)/2$

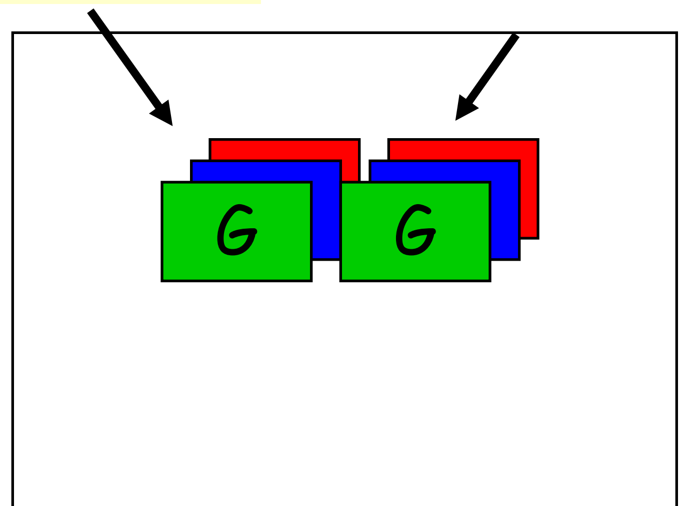
$R = (R_8 + R_4)/2$

$G = (G_2 + G_3 + G_5 + G_8)/4$

$R = R_4$

$B = (B_2 + B_6 + B_7 + B_8)/4$





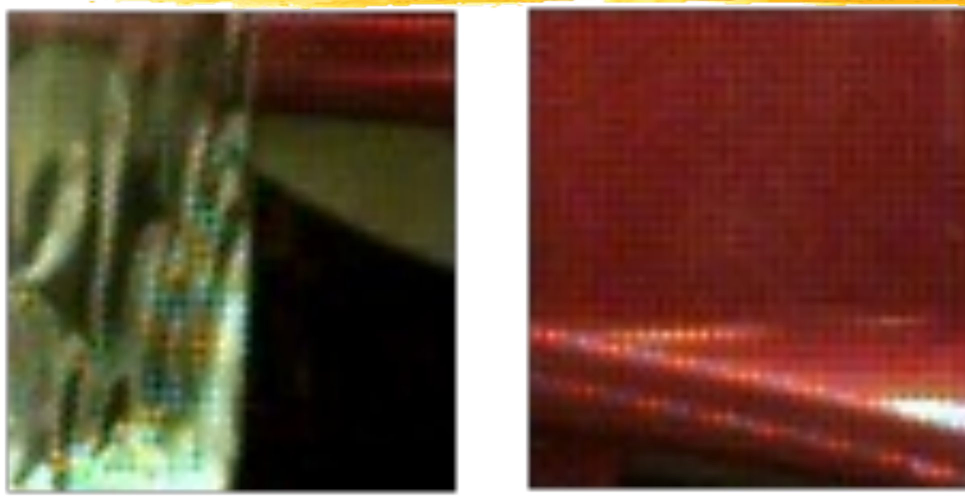
Quiz

- What could be the potential problems associated with
  - Nearest Neighbour interpolation method,
  - Bilinear interpolation method

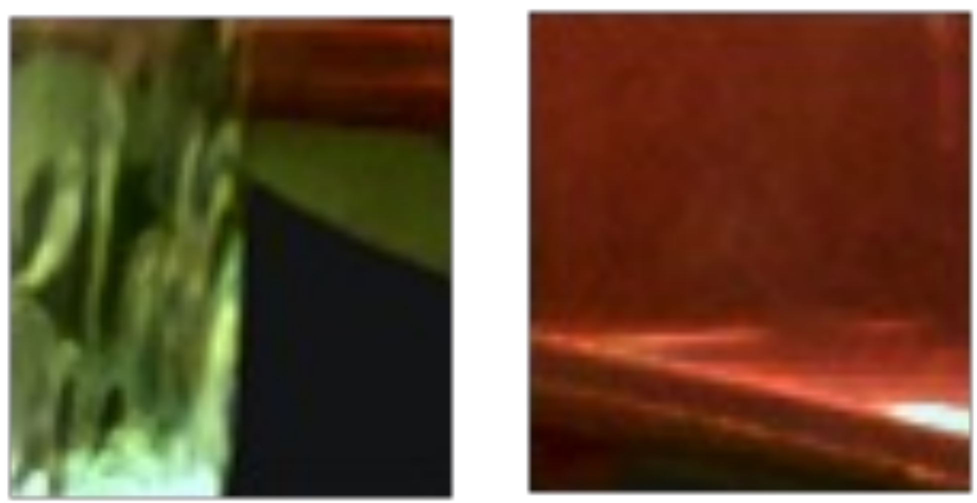
  considering that there is noise from image sensors and fine edges (details) in the image ?

Artefacts - Moire Patterns

NN or Bilinear

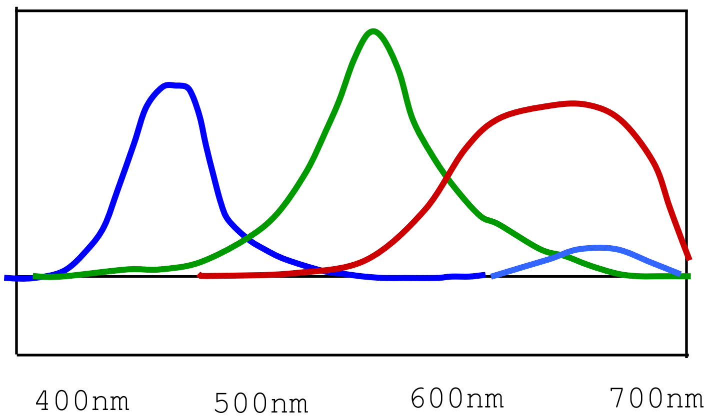


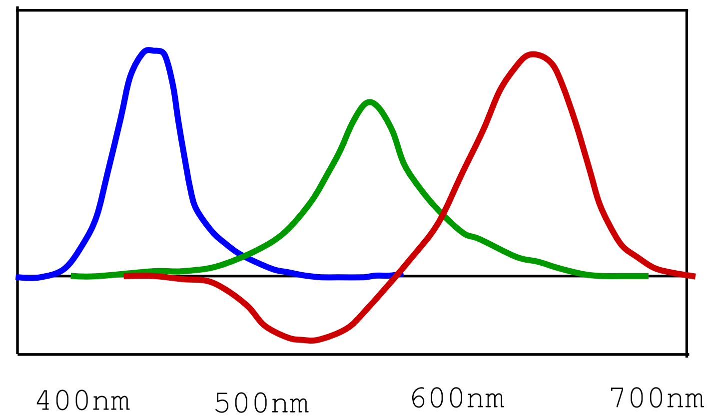
Edge Preserving



Colour Correction

- Spectral sensitivities of colour filters have significant deviation from CIE Colour Matching Functions

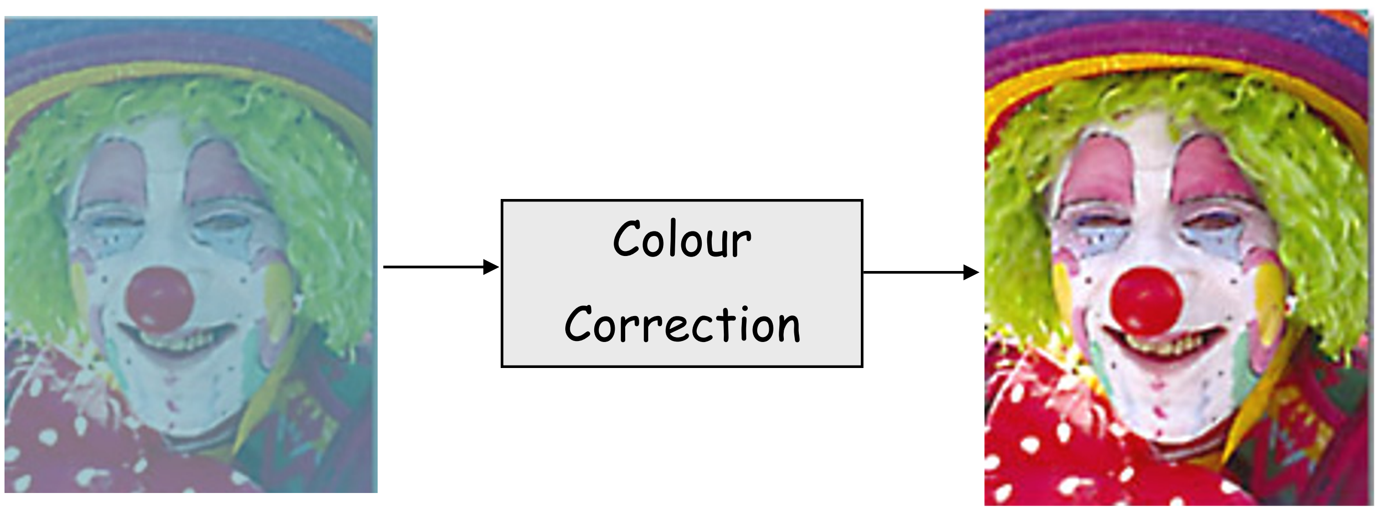




- Due to mismatch between colour sensitivities, CFA interpolated images have poor colour reproduction

Colour Correction

- Colour Correction digitally compensates deviation of spectral sensitivities of CFA to bring them closer to CIE Colour Matching Functions



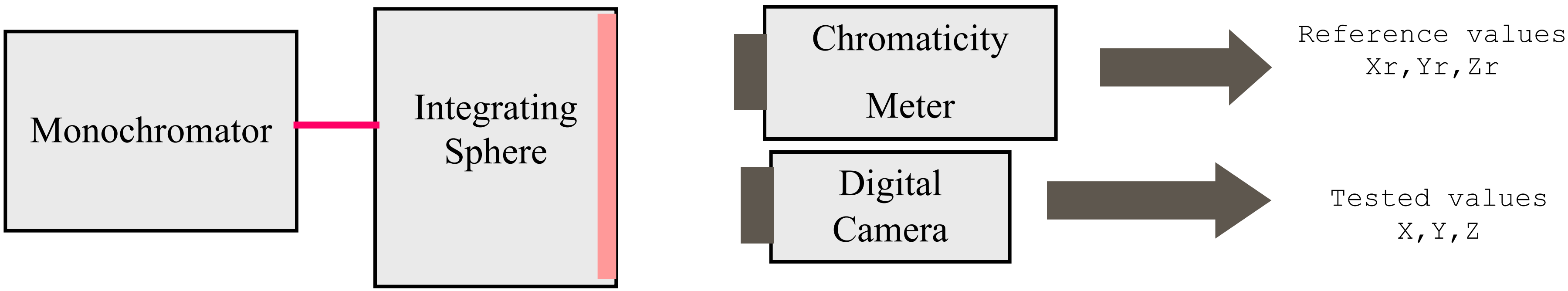
Colour Correction

- Transforms RGB values produced at CFA Interpolation stage into colour corrected RGB values

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = T_C \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- T_C is a 3 x 3 color correction matrix, obtained through optimisation to maximise colour fidelity.
- Each colour correction matrix is device dependent and may not be optimal for other sensors

Colour Calibration Equipment



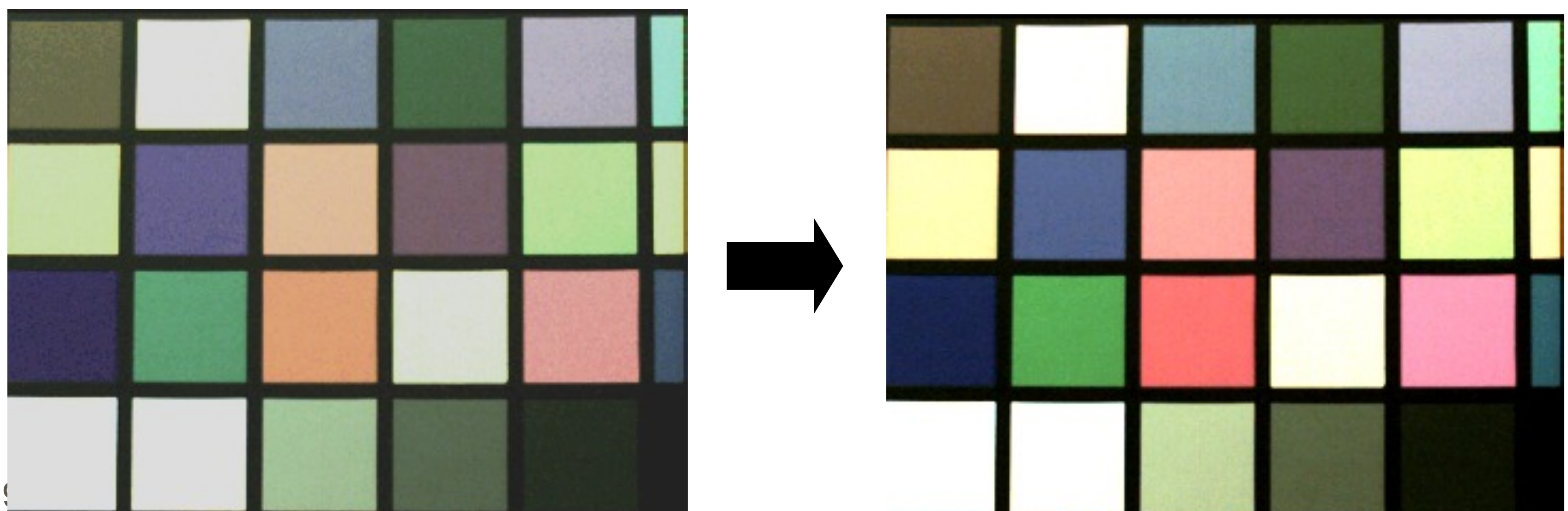
- A monochromator creates a narrow spectrum light ray
- An integrating sphere creates a uniformly illuminated surface from the ray
- A chromaticity meter produces CIE chromaticity values that are used as a reference for camera colour calibration
- The colour correction matrix is optimised to minimise the error between the sets of reference values and tested values

$$Er = \sqrt{\frac{1}{n}\sum\left((X_r - X_t)^2 + (Y_r - Y_t)^2 + (Z_r - Z_t)^2\right)}$$

Colour Calibration using Macbeth Colour Checker

- If colour calibration equipment is not available, Macbeth Colour Checker illuminated by D65 standard light source can be utilised
- An example of Colour Correction Matrix optimised for a CMOS sensor using 24 reference colours

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} 1.28 & -0.11 & -0.12 \\ -0.12 & 1.41 & -0.13 \\ -0.14 & -0.15 & 1.36 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



Gamma Correction

- Each of 2^{10} = 1024 digital levels represents a corresponding level of illuminance

0 - 1023

- According to Webber's law the noticeable contrast threshold is $k = \Delta I/I \approx 2\%$

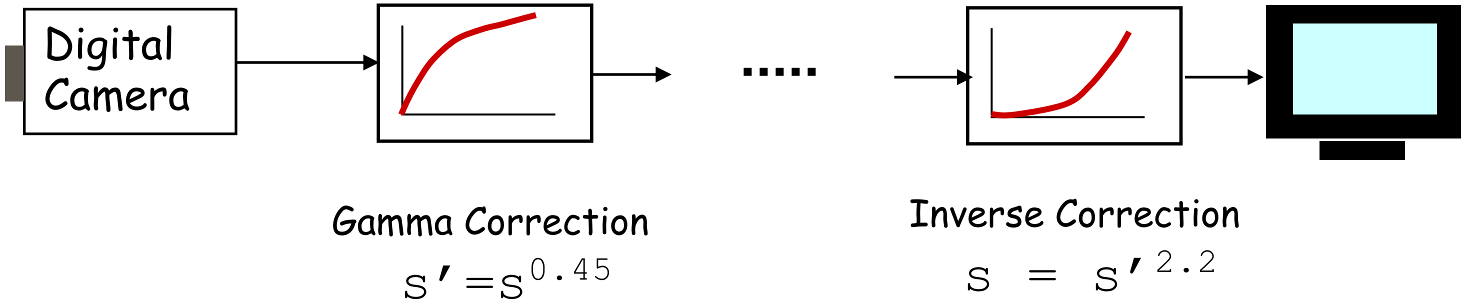
Example: $I_1 = 2$, $I_2 = 3$ => $k = \Delta I/I_1 = 50\%$ over the threshold

$I_1 = 1000$, $I_2 = 1001$ => $k = \Delta I/I_1 = 0.1\%$ below the threshold

1024 quantisation levels are not fully utilised

Gamma Correction

- To map quantised samples into the perceptually uniform domain the samples are Gamma corrected
  $s' = s^{\gamma}$ with $\gamma = 0.4 - 0.5$
- Experiments indicate that after gamma correction 8bit/sample precision provides perceptually uniform quantisation



- To restore linearity, an inverse Gamma Correction is applied in monitors and TVs

Gamma Correction

Example:

- A monochrome gamma corrected image stored with a different number of quantisation levels

2 levels | 4 levels | 256 levels

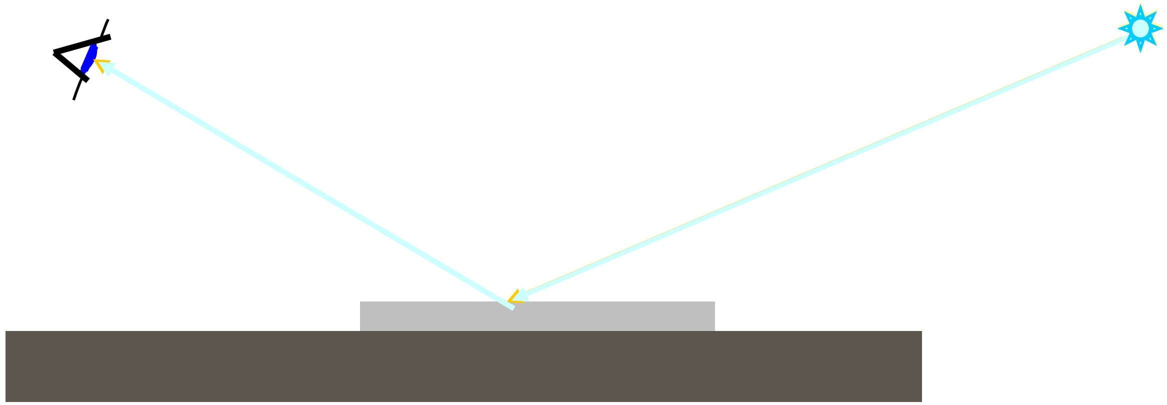
Impl. of Gamma Correction

- Real-time implementation of Gamma Correction using the equation $s' = s^{\gamma}$ is not efficient
- A commonly used approach is a Look Up Table

```
/* LUT with precomputed values for every 10-bit sample */
unsigned char LUT[1024] = {0, . . . , 255};
unsigned short sInput;          /* 10-bit input sample */
unsigned char aGcorrected;      /*  8-bit corrected sample */
.  .   .   .
   sInput = getNextSample();
   sGcorrected = LUT[sInput];    /* gamma correction */
   storeSample( sGcorrected );
.  .   .   .
```

Note: Gamma Correction is a processing stage used in all consumed digital cameras, but it may not be helpful for computer vision applications

Colour Constancy (review)



$$r_1 = \int S_1(\lambda)\,\overline{r}(\lambda)\,d\lambda$$
$$g_1 = \int S_1(\lambda)\,\overline{g}(\lambda)\,d\lambda$$
$$b_1 = \int S_1(\lambda)\,\overline{b}(\lambda)\,d\lambda$$

$$r_2 = \int S_2(\lambda)\,\overline{r}(\lambda)\,d\lambda$$
$$g_2 = \int S_2(\lambda)\,\overline{g}(\lambda)\,d\lambda$$
$$b_2 = \int S_2(\lambda)\,\overline{b}(\lambda)\,d\lambda$$

According to the formulas, if two sources of light have different spectrums, a white object should change its colour

However. the **perceived** color of objects remains relatively constant under varying illumination conditions

The mechanism of adaptation of the human vision to illumination conditions is still not fully understood

White Balancing

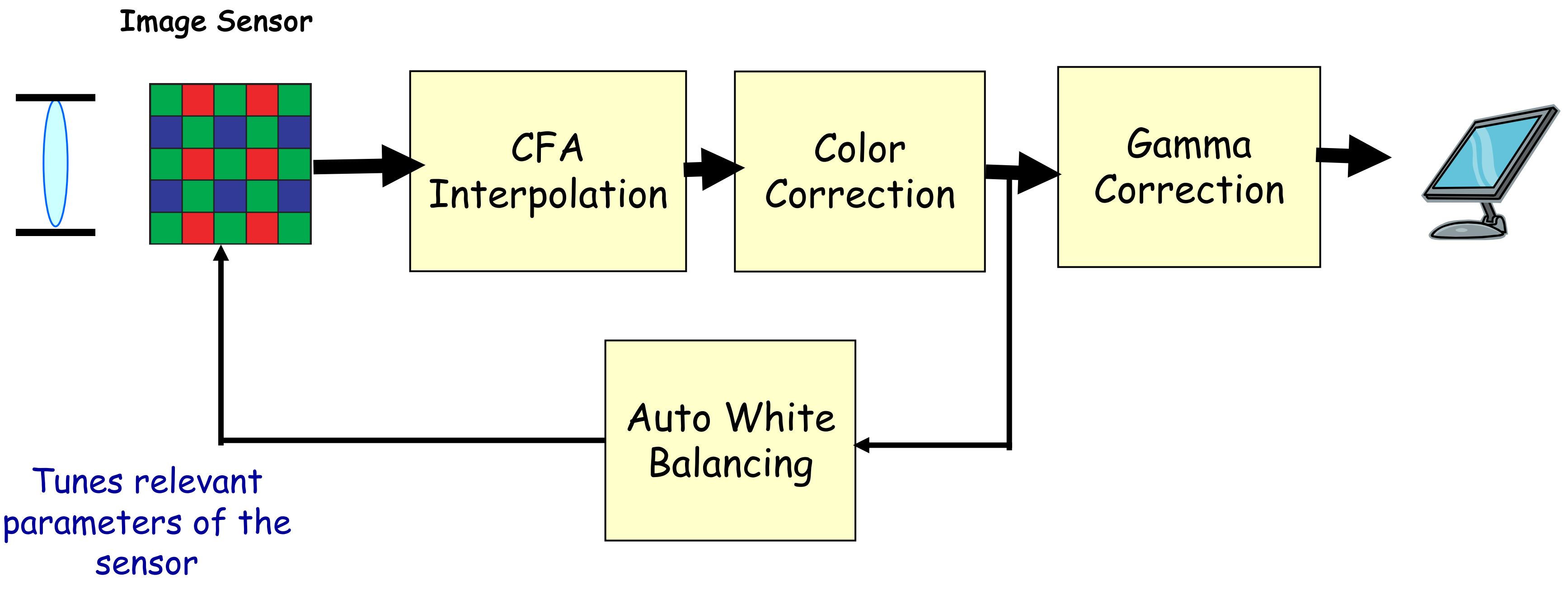
- If the same image is captured at different lighting conditions by a digital camera that does not provide colour constancy, they may have very different gamut

At midday

Before the sunset

Automatic White Balancing

- Every digital camera is equipped with a processing module that provides colour constancy

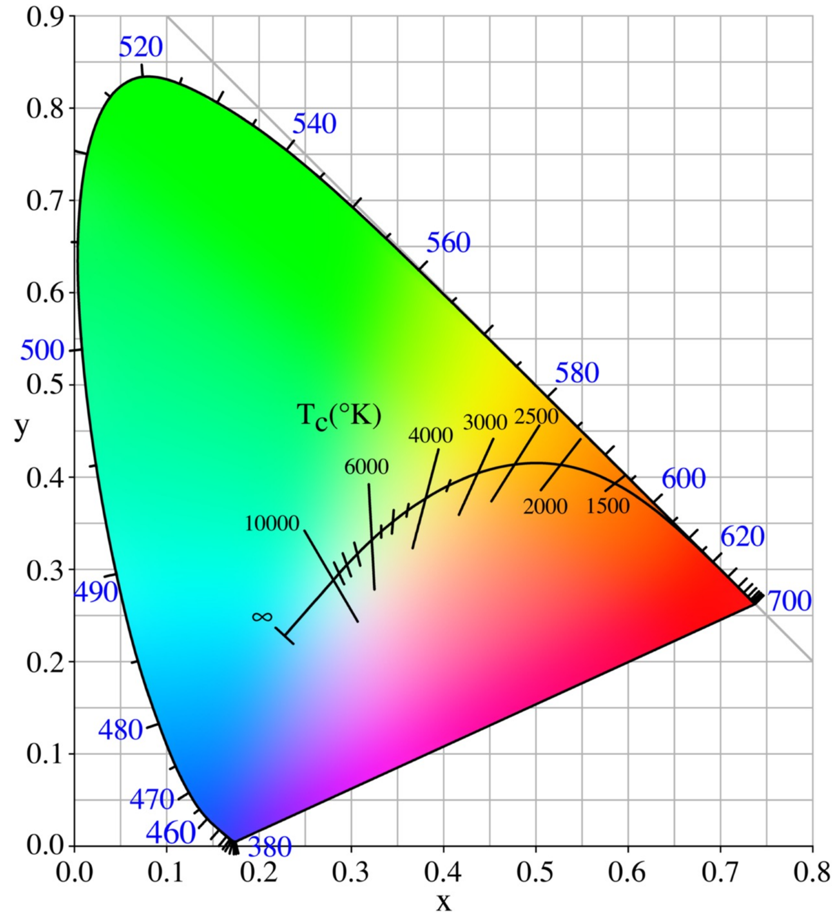


Automatic White Balance

- Try to adjust the gain of each color channel such that the recorded the color is close to the "true color"
  - Predefined approach
    - Daylight, Shade, Cloudy, Tungsten, White Fluorescent Light, Flash, Custom WB setting, user-set Color Temperature (2,500~10,000K)
  - Automatic
    - Grey-world assumption

Colour Temperature (review)

- Color temperature is a characteristic of visible light, a simple way to measure the spectral (hue) of the light.
  - 2700-3600 are recommended for most general indoor lighting



Gray-world Assumption

- What Gray World Assumption states that
  - given an image with sufficient amount of color variations, the average value of the RED, GREEN, and BLUE channels of the image should be same or should average out to a common gray value, i.e.

$$\frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} I_R(i,j) = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} I_G(i,j) = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} I_B(i,j)$$

Gray-world Assumption…

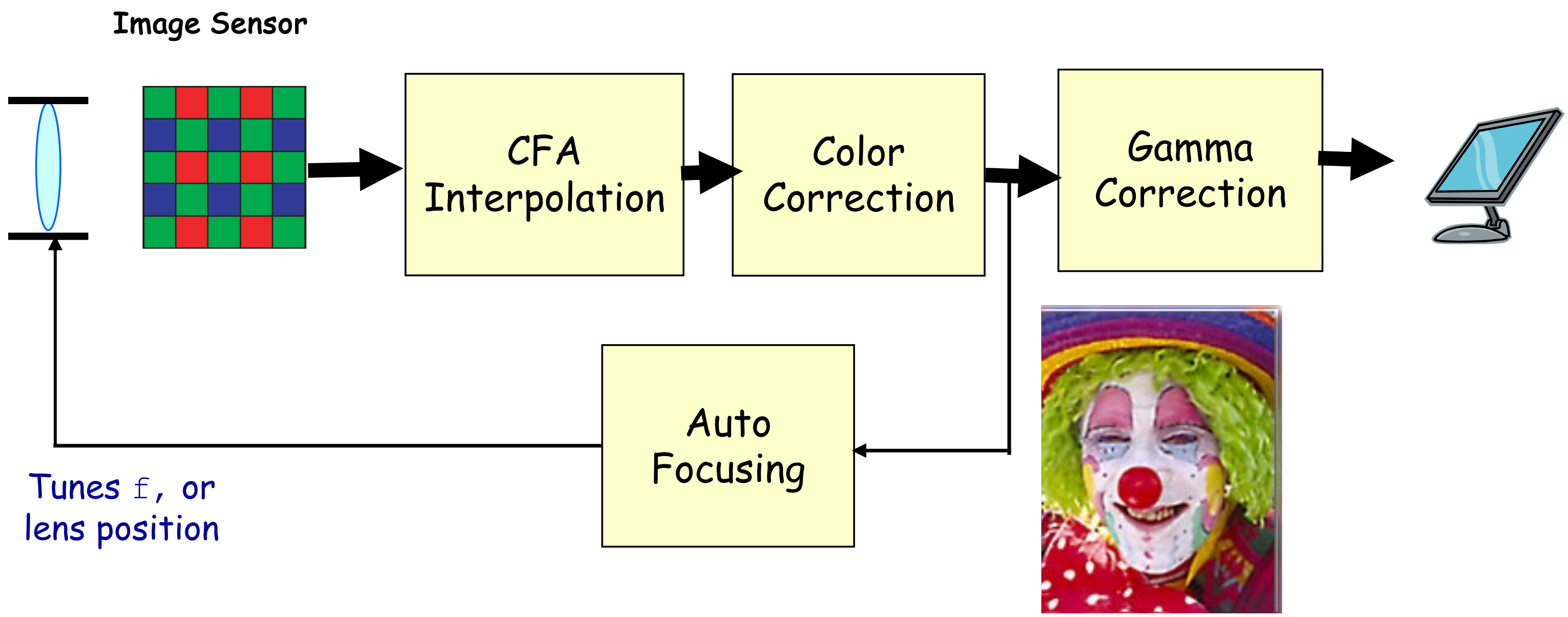
GW enforced

http://scien.stanford.edu/pages/labsite/1999/psych221/projects/99/jchiang/intro2.html

http://web.media.mit.edu/~wad/color/exp1/newgray/

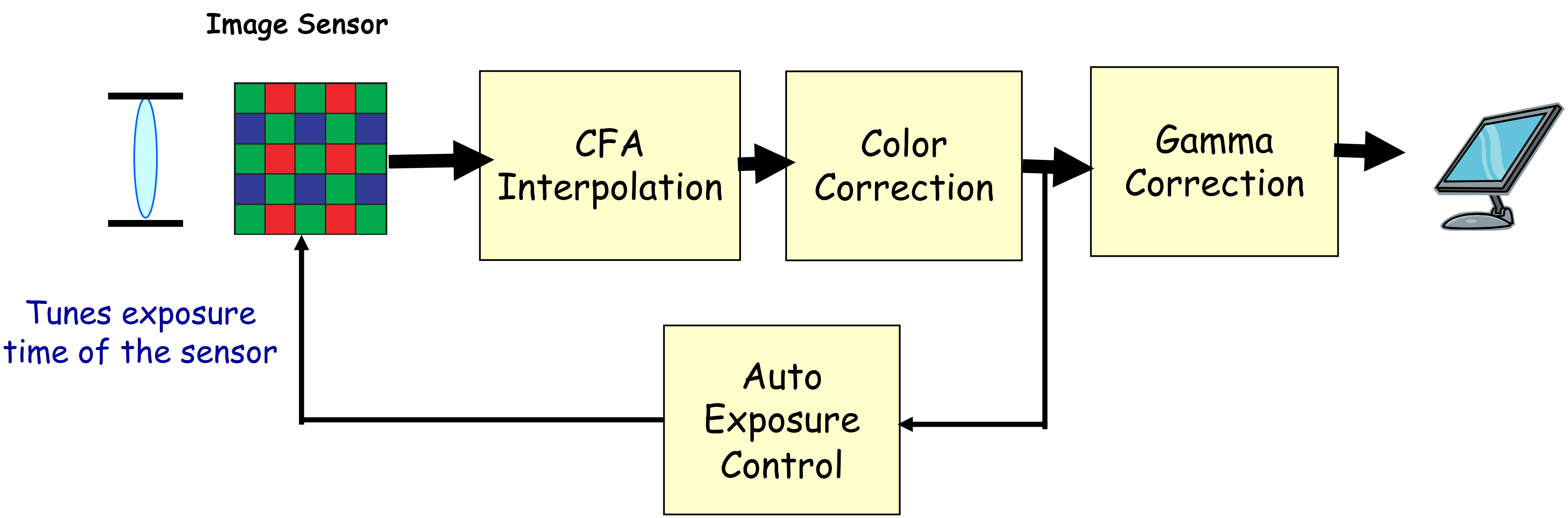
Automatic Focusing

- Auto focusing tunes relevant parameters of the lens to maximise image sharpness



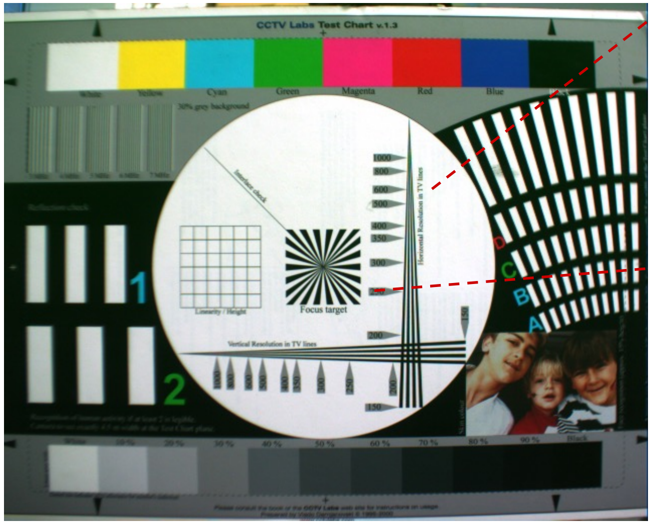
Automatic Exposure

- Every digital camera is equipped with a processing module that controls exposure time
  - dynamic range of sensors is 70-80db
  - dynamic range of Illuminance: 160 – 170db
    from 0.001lx (at night) . . . 100 000 lx (direct sun)

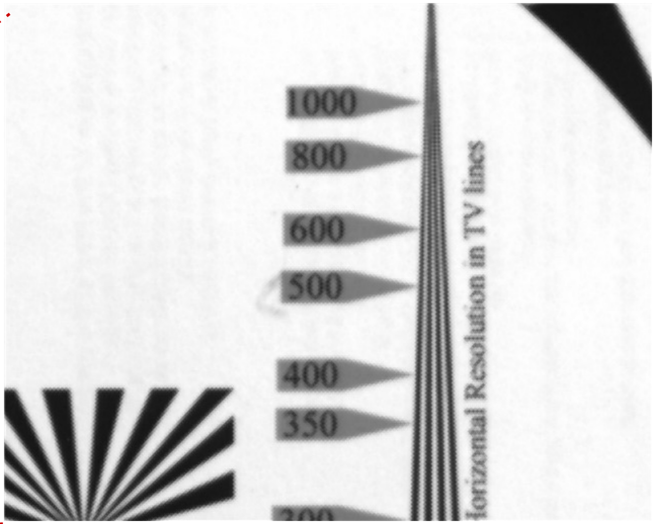


Resolution

- The amount of detail that the camera can capture
- Resolution depends on:
  - sensor resolution
  - optical resolution
  - sharpness of focus
  - CFA interpolation



Test Chart



Suggested Reading

- D Forsyth, Computer Vision. A Modern Approach
  - Chapters 1, 4.4

OpenCV 4.6.0 - References

- Core Operations
  - https://docs.opencv.org/4.6.0/d7/d16/tutorial_py_table_of_contents_core.html
- Changing Colour Spaces
  - https://docs.opencv.org/4.6.0/df/d9d/tutorial_py_colorspaces.html
- OpenCV Course- Full Tutorial with Python
  - https://www.youtube.com/watch?v=oXlwWbU8l2o