Image Processing for Single-Sensor Imaging Devices

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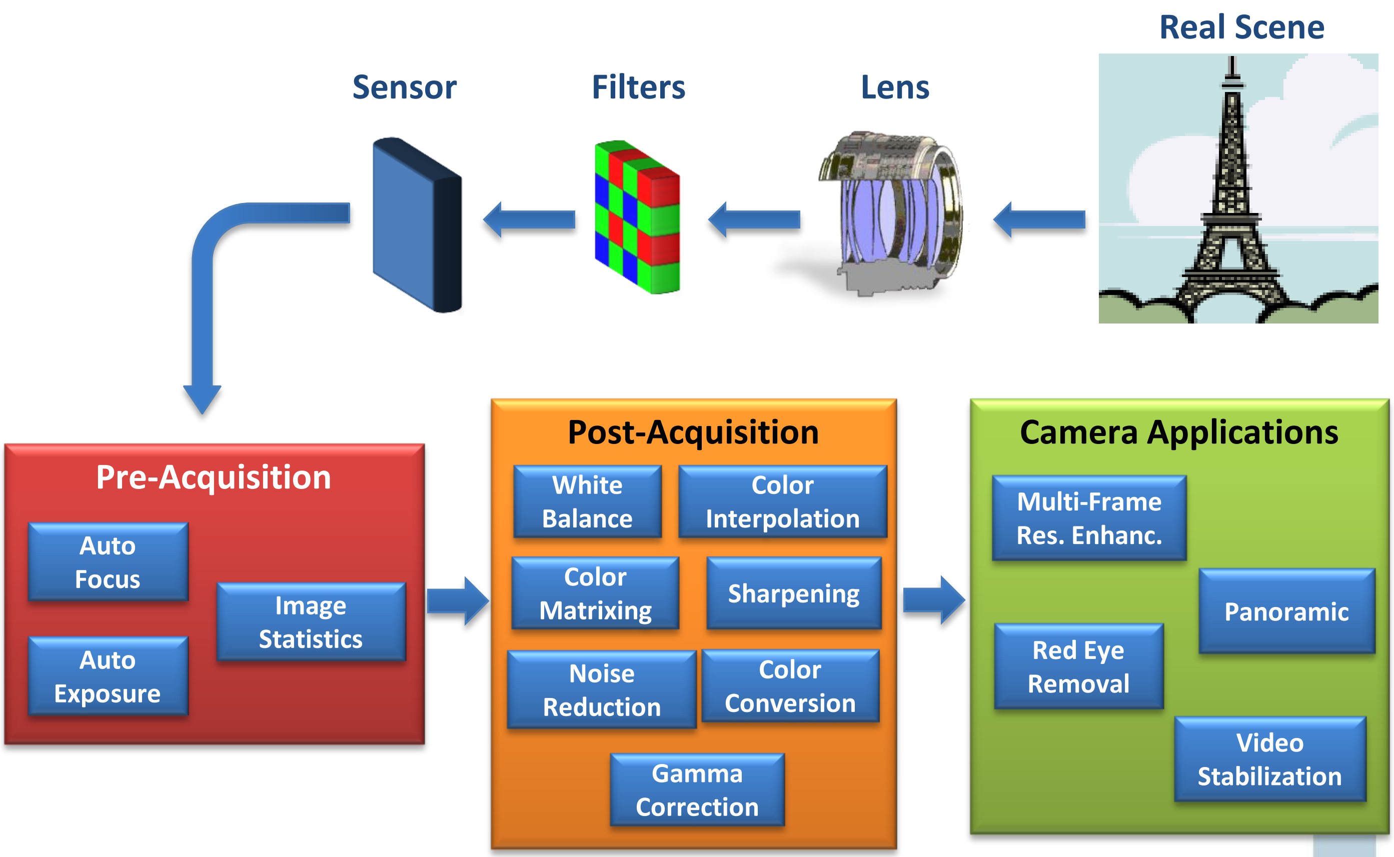
Typical Imaging Pipeline (1)



Data coming from the sensor (in Bayer format) are first analyzed to collect useful statistics for parameters setting (pre-acquisition) and then properly processed in order to obtain, at the end of the process, a compressed RGB image of the acquired scene (post-acquisition and camera applications).

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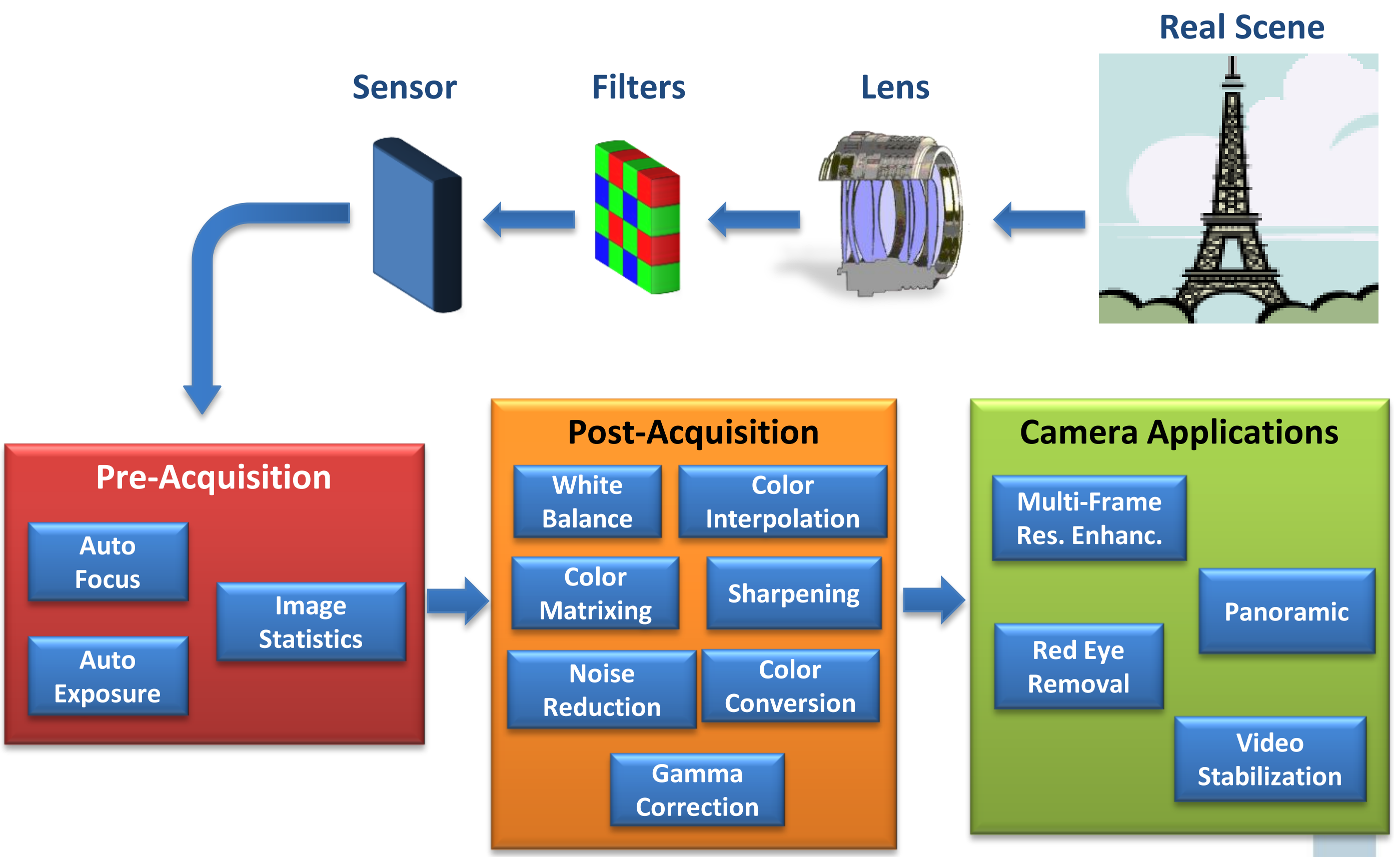
Typical Imaging Pipeline (2)



Camera application functionalities are not mandatory and usually include solution for panoramic, red-eye removal, video stabilization. They can be considered an added value.

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Autofocus

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Autofocus

What is the end-users desire?
To not know that an Auto-Focus algorithm is operating!
Perfect pictures every time at a push of a button

They don’t care!
Often hi-res pictures are viewed later, they do not know the picture is in/out of focus until it is too late.
Latency to snap is the number 1 reason for bad pictures (particularly of children and animals).

They think it is easy (just like their eyes).

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Fixed-focus (1)

- A photographic lens for which the focus is not adjustable is called a fixed-focus lens. The focus is set at the time of manufacture, and remains fixed. It is usually set to the hyperfocal distance, so that the depth of field ranges all the way down from half that distance to infinity, which is acceptable for most cameras used for capturing images of humans or objects larger than a meter.
- In order to reach a short minimal focal distance the aperture and the focal length of the lens are reduced, so that the hyperfocal distance is small. This allows for the depth of field to be extended from infinity to a short distance.
- The disadvantage is the reduction of light that will reach the film through the small aperture. Therefore the lenses are usually not suitable for fast-moving objects which require short exposure times.

Fixed-focus (2)

- Fixed focus can be an inexpensive alternative to autofocus, which requires electronics, moving parts, and power. Since a fixed-focus lens requires no input from the operator, it is suitable for use in cameras designed to be inexpensive, or to operate without electrical power as in disposable cameras, or in low-end 35 mm film cameras.
- Especially suitable are fixed focus lenses for low resolution CCD cameras as found in webcams and mobile phones, because the low resolution of the detector allows a loose focusing on the CCD without noticeable loss of image quality. Therefore the circle of confusion gets bigger and hyperfocal distance smaller.
- Special-purpose cameras are used for situations like aerial photography from aircraft. Because the ground is far from the camera, focus adjustment is not necessary.

Autofocus

- Autofocus (or AF) is a feature of some optical systems that allows them to obtain correct focus on a subject, instead of requiring the operator to adjust focus manually.
- Some AF systems rely on a single sensor, while others use an array of sensors. Most multi-sensor AF cameras allow manual selection of the active sensor, and many offer automatic selection of the sensor using algorithms which attempt to discern the location of the subject.
- Some AF cameras are able to detect if the subject is moving towards or away from the camera, including speed and acceleration data, and keep focus on the subject - a function used mainly in sports and other action photography.
- The data collected from AF sensors is used to control an electromechanical system that adjusts the focus of the optical system.

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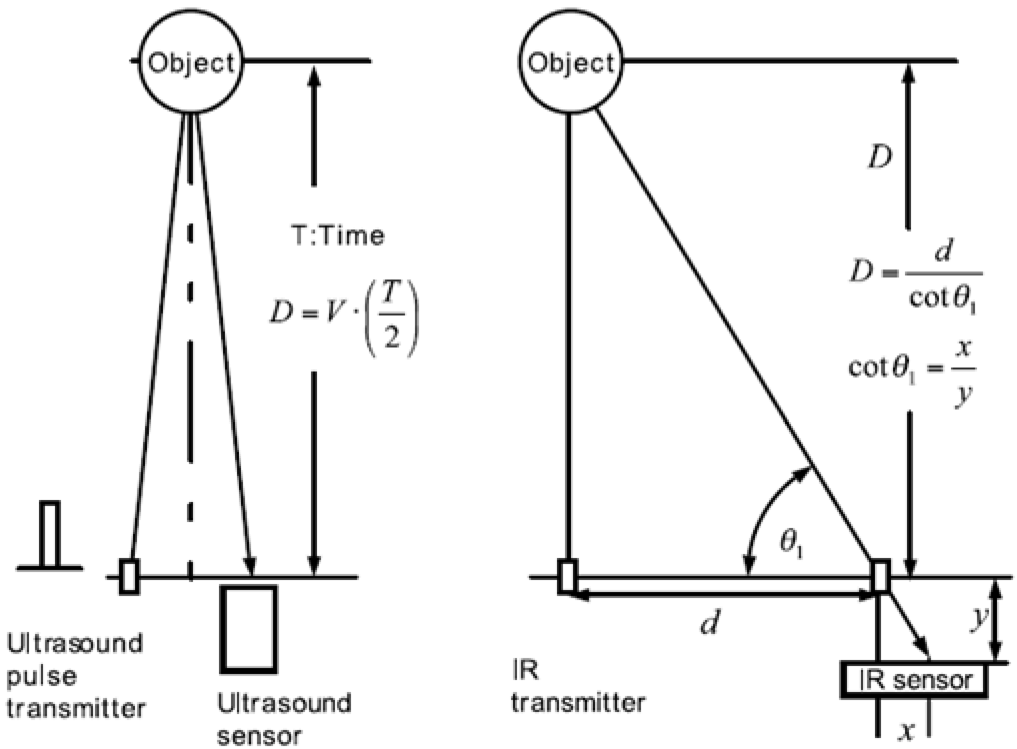
Active Autofocus (1)

- Active AF systems measure distance to the subject independently of the optical system, and subsequently adjust the optical system for correct focus.
- There are various ways to measure distance, including ultrasonic sound waves and infrared light.
- In the first case, sound waves are emitted from the camera, and by measuring the delay in their reflection, distance to the subject is calculated. Polaroid cameras including the Spectra and SX-70 were known for successfully applying this system.
- In the latter case, infrared light is usually used to triangulate the distance to the subject. Compact cameras including the Nikon 35TiQD and 28TiQD, the Canon AF35M, and the Contax T2 and T3, as well as early video cameras, used this system.

Active Autofocus (2)



(a) Ultrasonic method (b) Infrared method

Passive Autofocus

- Passive AF systems determine correct focus by performing passive analysis of the image that is entering the optical system. They generally do not direct any energy, such as ultrasonic sound or infrared light waves, toward the subject.
- However, an autofocus assist beam is required when there is not enough light to take passive measurements.
- Passive autofocusing can be achieved by phase detection or contrast measurement.

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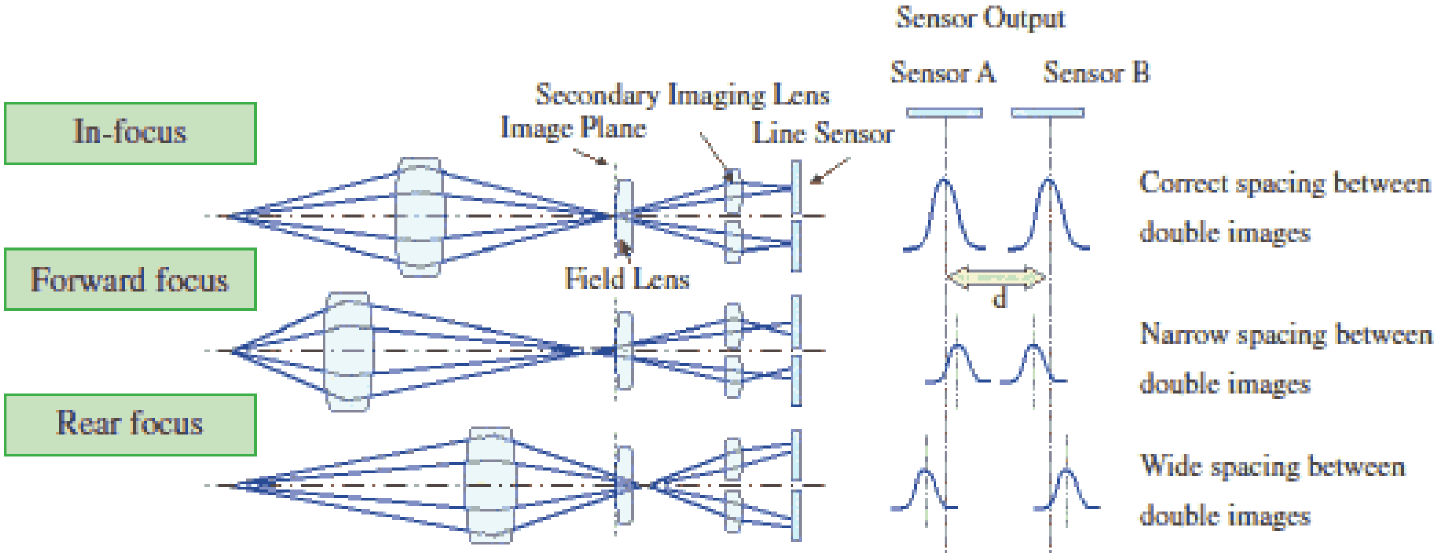
Phase detection (1)

- Most single-lens reflex cameras use an autofocus method called the "phase detection system." Using a separator lens in autofocus module, this system produces two images from the image information of the subject captured through the lens. It then measures the distance between those two images using a line sensor, and detects defocus amount.
- Although AF sensors are typically one-dimensional photosensitive strips (only a few pixels high and a few dozen wide), some modern cameras (Canon EOS-1V, Canon EOS-1D, Nikon D2X) feature Area SIR sensors that are rectangular so as to provide two-dimensional intensity patterns. Cross-type (CT) focus points have a pair of sensors oriented at 90° to one another.

Phase detection (2)



http://www.canon.com/bctv/faq/aft.html

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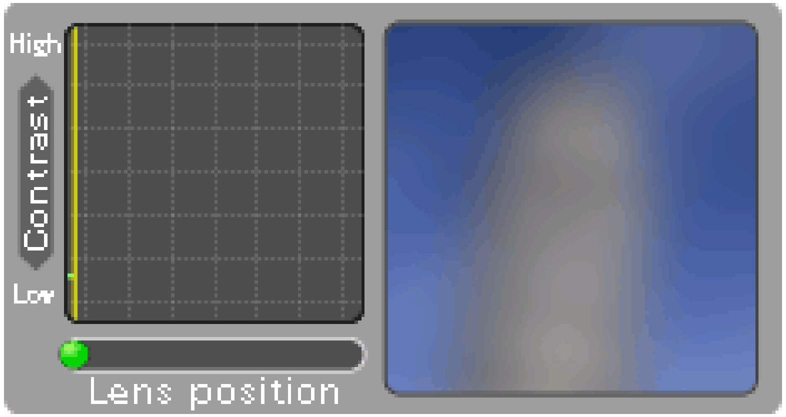
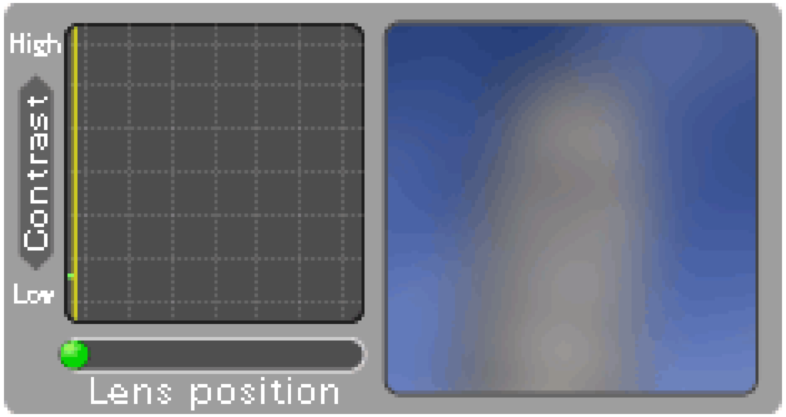
Contrast measurement (1)



Many DSCs use a digital integration method for auto focus that uses the acquired image from the sensor and a digital band-pass filter because the algorithm is simple and easy to implement in a digital signal-processing block. The digital integration focus method works on the assumption that high-frequency (HF) components of the target image will increase when in focus.

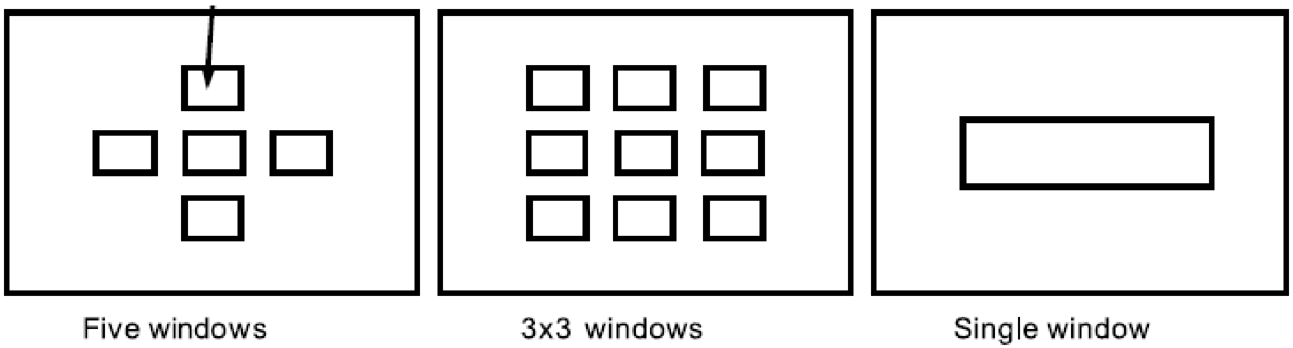
The focus calculation block is composed of a band-pass filter and an absolute value integration of the output from the filter.

Contrast measurement (2)



Based on the principle that "**in focus = highest contrast**" this system analyzes the image information of the subject obtained by an image sensor.
The host processor of the camera uses the Autofocus output value and adjusts the lens to get peak output from the autofocus block.
Then, by moving the lens, this system seeks the lens position where the image contrast is highest.

Window Layout



The AF block receives horizontal pixel data and calculates the filter output. Then it accumulates the absolute values of the AF filter outputs. It is desirable to calculate in vertical and horizontal directions in each window. From the viewpoint of hardware implementation, horizontal line scan is easy but vertical line scan requires some amount of line buffer memory.

Statistics Examples

Classical Laplacian:

$$\text{SquareLaplaceMeasure} = \sum_{x}^{n} \sum_{y}^{m} \mathrm{L}(x, y)^2$$

$$\text{AbsoluteLaplaceMeasure} = \sum_{x}^{n} \sum_{y}^{m} \left|\mathrm{L}(x, y)\right|$$

0	-1	0
-1	4	-1
0	-1	0

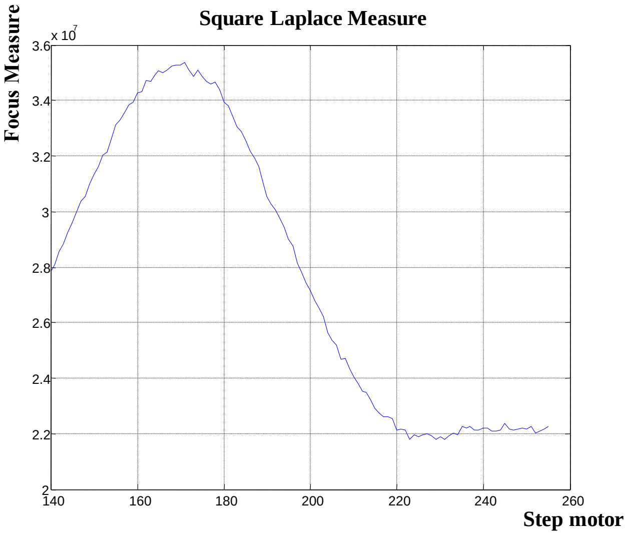
Diagonal Laplacian

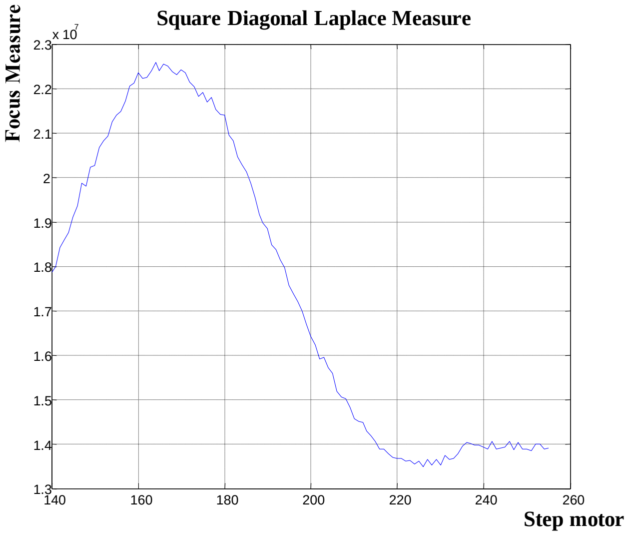
$$\text{SquareDiagonalLaplaceMeasure} = \sum_{x}^{n} \sum_{y}^{m} \mathrm{L}(x, y)^2$$

$$\text{AbsoluteDiagonalLaplaceMeasure} = \sum_{x}^{n} \sum_{y}^{m} \left|\mathrm{L}(x, y)\right|$$

-1	0	-1
0	4	0
-1	0	-1

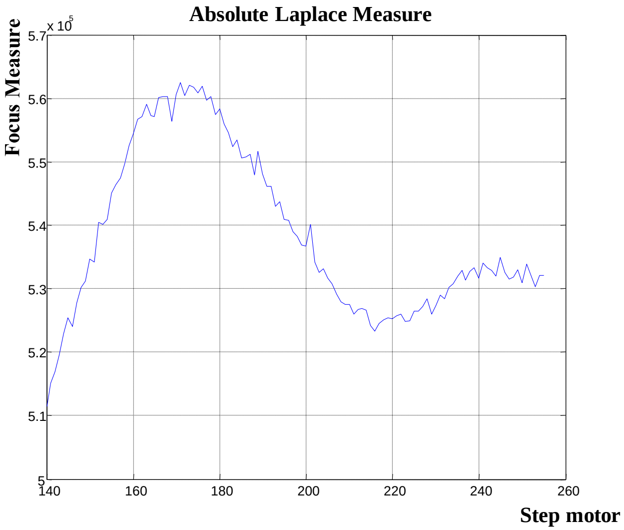
Focus Measure

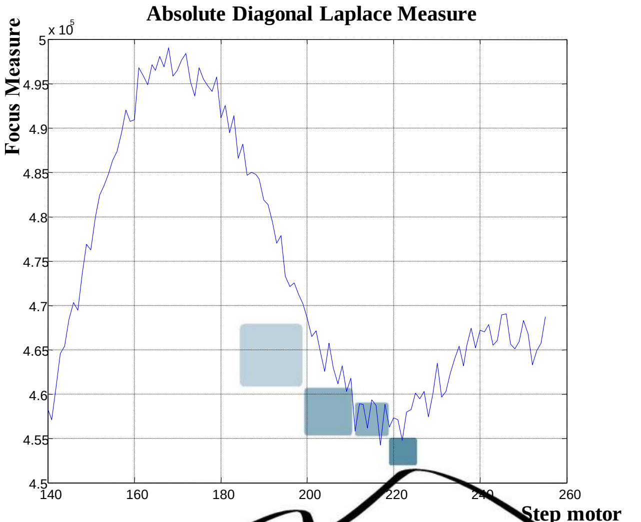




Measure window

Motor Steps





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Comparison of active and passive systems

- Active systems will typically not focus through windows, since sound waves and infrared light are reflected by the glass. With passive systems this will generally not be a problem. Accuracy is often considerably less than passive systems.
- Active systems may also fail to focus a subject that is very close to the camera (e.g., macro photography).
- Passive systems may not find focus when the contrast is low, notably on large single-coloured surfaces (walls, blue sky, etc.) or in low-light conditions.
- Passive systems are dependent on a certain degree of illumination to the subject (whether natural or otherwise), while active systems may focus correctly even in total darkness when necessary. Some external flash units have a special low-level illumination mode (usually orange/red light) which can be activated during auto-focus operation to allow the camera to focus.

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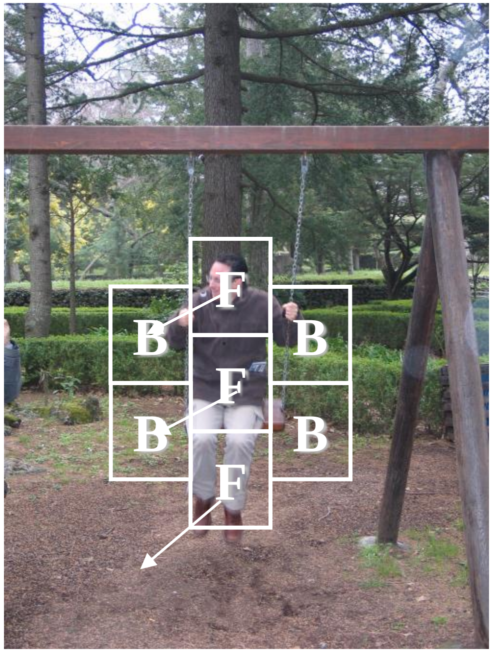
Advanced AF

- Multi-zone analysis
- Tracking
- Object detection & Motion Analysis



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Actuator Review

Available Technologies For electro-mechanical Micro Actuation:

1. **Electromagnetic Actuators**
    1. Stepper Motors
    2. Simple Solenoids
    3. Voice Coil Solenoids
2. **Piezoelectric Actuators**
    1. Stacked Piezo Devices
    2. Bimorphs
    3. Disk Translators
    4. Moonie Motors
    5. Helimorphs
    6. Oscillating Bimorphs
    7. Inch Worms
    8. Ultrasonic disk motors
3. **Electrostatic Actuators**
4. **Electrostrictive Actuators**
5. **Magnetostrictive Actuators**
6. **Shape memory alloys**
7. **MEMS Actuators**

References

Image Sensors and Signal Processing for Digital Still Cameras -J. Nakamura –CRC Press, 2006;

http://en.wikipedia.org/wiki/Autofocus

http://www.cambridgeincolour.com/tutorials/camera-autofocus.htm

http://www.dmi.unict.it/~battiato/EI_MOBILE0708/EI_MOBILE0708.htm

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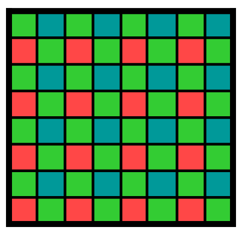
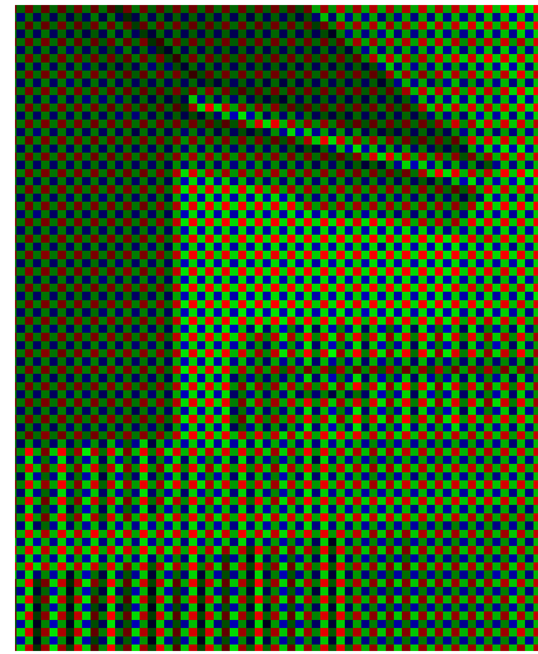
Demosaicing

CFA



Bayer CFA

CFA image



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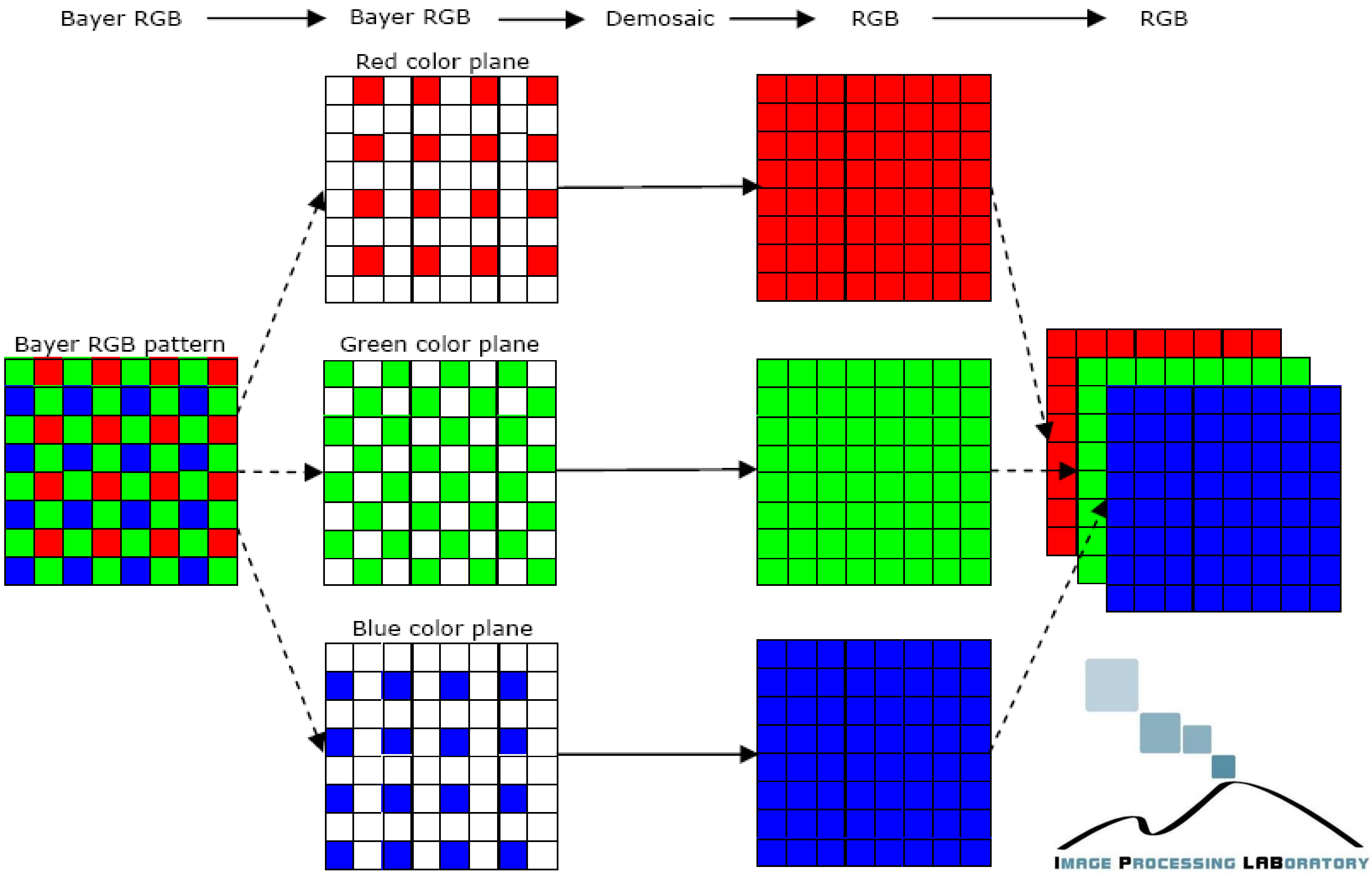
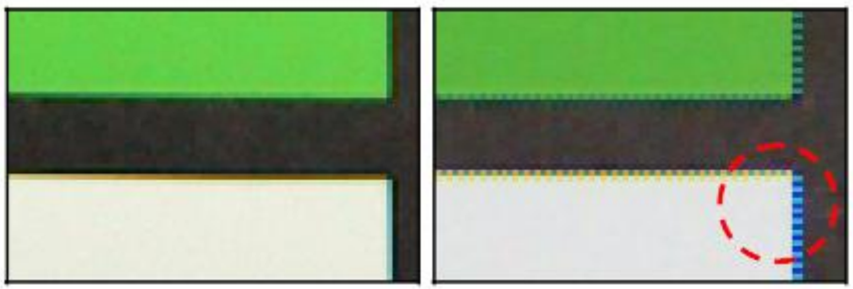
Demosaicing

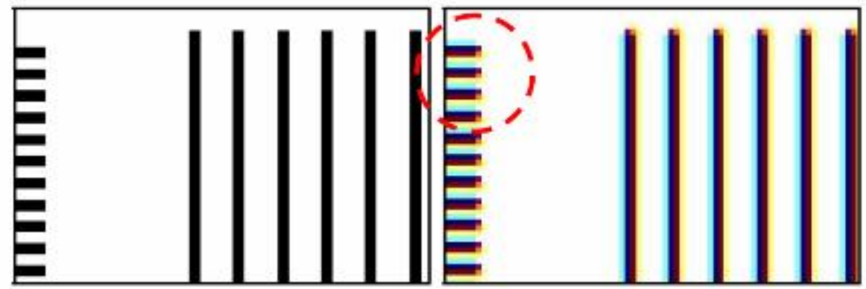


Color Artifacts

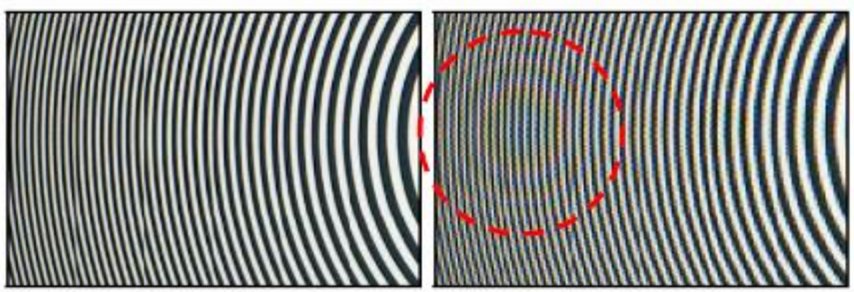
- Common artifacts
  - Most visual artifacts appear at edges and areas of high frequency



Zipper effect



False color

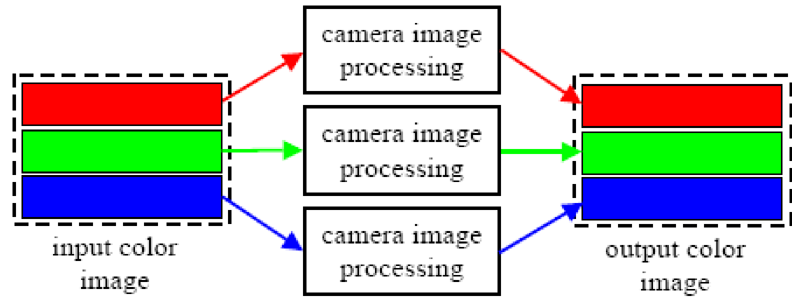


Aliasing

Blurring

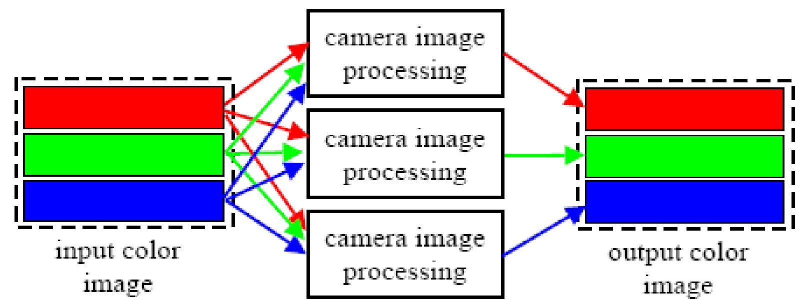
Processing

Component-wise processing



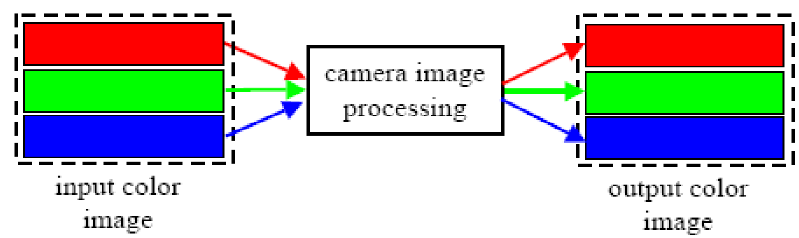
- each color plane processed separately
- omission of the spectral information results in color shifts and artifacts

Spectral model based processing



- essential spectral information utilized during processing
- computationally very efficient - most widely used in camera image processing

Vector processing



- image pixels are processed as vectors
- computationally expensive

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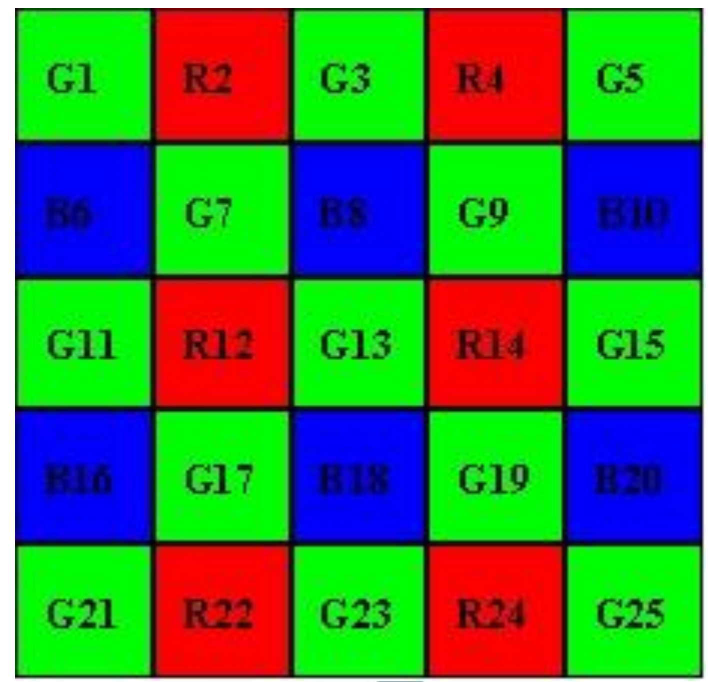
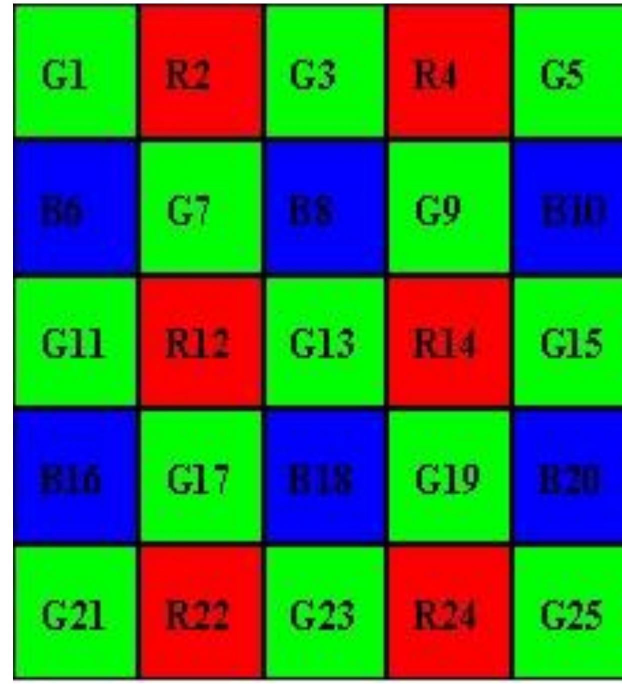
Color Interpolation - Bilinear Interpolation (1)

- Interpolation of green pixels
  - The average of the upper, lower, left and right pixel values is assigned as the G value of the interpolated pixel
  - G8 = (G3+G7+G9+G13) / 4
- Interpolation of a red/blue pixel at a green position
  - The average of two adjacent pixel values in corresponding color is assigned to the interpolated pixel.
  - B7 = (B6+B8) / 2
  - R7 = (R2+R12) / 2



Color Interpolation - Bilinear Interpolation (2)

- Interpolation of a red/blue pixel at a blue/red position
  - The average of four adjacent diagonal pixel values is assigned to the interpolated pixel
  - R8 = (R2+R4+R12+R14) / 4
  - B12 = (B6+B8+B16+B18) / 4



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Bilinear

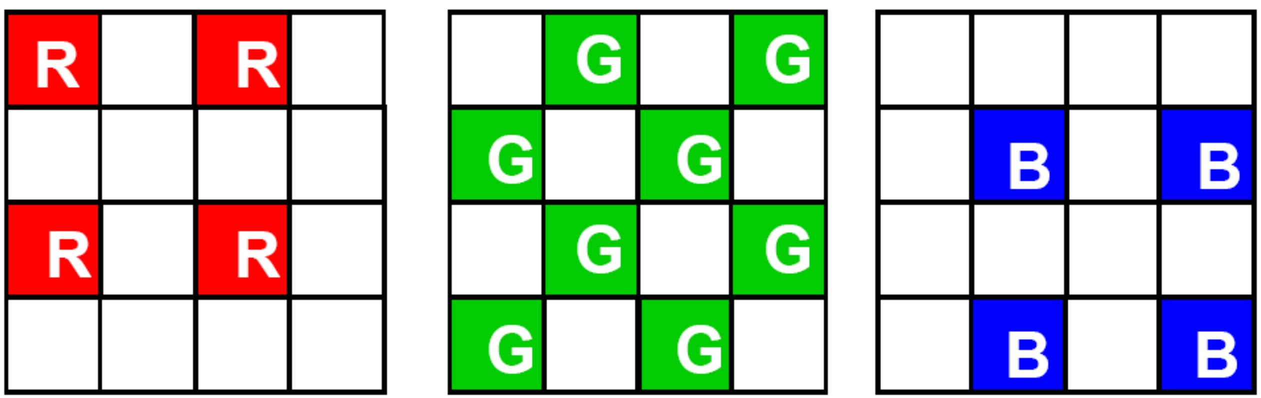
- **Simple realization with *3 by 3* filter kernels**

$$R_F(n_1,n_2) = \mathbf{F}_R \otimes M_R(n_1,n_2)$$

$$G_F(n_1,n_2) = \mathbf{F}_G \otimes M_G(n_1,n_2)$$

$$B_F(n_1,n_2) = \mathbf{F}_B \otimes M_B(n_1,n_2)$$

$$\mathbf{F}_R = \mathbf{F}_B = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} \Big/ 4 \quad , \quad \mathbf{F}_G = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} \Big/ 4$$



$M_R(n_1,n_2)$ $\qquad$ $M_G(n_1,n_2)$ $\qquad$ $M_B(n_1,n_2)$

Lighthouse
original

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Lighthouse
Interpolated color
image (bilinear)

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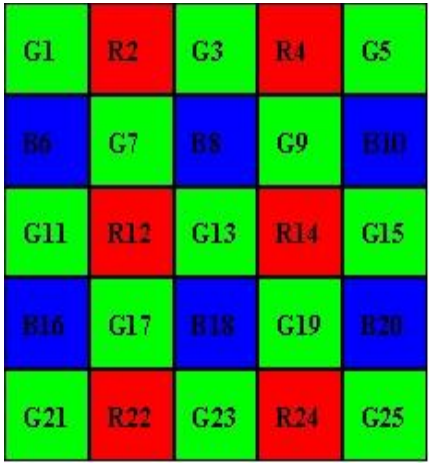
Edge-Directed Interpolation

Interpolation of green pixels :

First, define two gradients, one in horizontal direction, the other in vertical direction, for each blue/red position. For instance, consider B8 : define two gradients as

$$\Delta H = |G7 - G9| \text{ and } \Delta V = |G3 - G13|$$



Define some threshold value T

The algorithm then can be described as:

$$\begin{array}{l}
\text{If } \Delta H < T \text{ AND } \Delta V > T, \\
\qquad G8 = (G7 + G9) / 2; \\
\text{Else if } \Delta H > T \text{ AND } \Delta V < T, \\
\qquad G8 = (G3 + G13) / 2; \\
\text{Else} \\
\qquad G8 = (G3 + G7 + G9 + G13) / 4 \\
\text{End}
\end{array}$$

The choice of T depends on the images and can have different optimum values from different neighborhoods. A particular choice of T is $T = (\Delta H + \Delta V) / 2$

$$\begin{array}{l}
\text{If } \Delta H < \Delta V, \\
\qquad G8 = (G7 + G9) / 2; \\
\text{Else if } \Delta H > \Delta V, \\
\qquad G8 = (G3 + G13) / 2; \\
\text{Else} \\
\qquad G8 = (G3 + G7 + G9 + G13) / 4 \\
\text{End}
\end{array}$$

Adaptive Interpolation (1)

Using Laplacian For Enhancement: Use the second-order gradients of red/blue channels to enhance green channel.

<u>Step 1:</u> Edge-directed interpolation for the *G* channel

For interpolating a missing *G* value at the *R* pixel, *R5*,

(1) Compute magnitude sums of first-order derivatives and second-order derivatives.

$$\boxed{\begin{aligned}\alpha &= |R_3 - 2\cdot R_5 + R_7| + |G_6 - G_4| \\ \beta &= |R_1 - 2\cdot R_5 + R_9| + |G_8 - G_2|\end{aligned}}$$

(2) Classify the direction and existence of an edge around a red center pixel R_5 into three cases.

(3) Select a proper directional interpolation scheme.

$$\boxed{\begin{aligned}G_5 &= \frac{G_4 + G_6}{2} - \frac{R_3 - 2\cdot R_5 + R_7}{2} \quad , if\ \alpha < \beta \\ G_5 &= \frac{G_2 + G_8}{2} - \frac{R_1 - 2\cdot R_5 + R_9}{2} \quad , if\ \alpha > \beta \\ G_5 &= \frac{G_2 + G_4 + G_6 + G_8}{4} - \frac{R_1 + R_3 - 4\cdot R_5 + R_7 + R_9}{4} \quad , if\ \alpha = \beta\end{aligned}}$$

		R_1		
		G_2		
R_3	G_4	R_5	G_6	R_7
		G_8		
		R_9		

Adaptive Interpolation (2)

Step 2: Edge-directed interpolation for the *R* and *B* channels

In the case of the R-channel interpolation

$$R_2 = \frac{R_1 + R_3}{2} - \frac{G_1 - 2G_2 + G_3}{2}$$

$$R_4 = \frac{R_1 + R_7}{2} - \frac{G_1 - 2G_4 + G_7}{2}$$

R_1	G_2	R_3
G_4	B_5	G_6
R_7	G_8	R_9

$$R_5 = \frac{R_3 + R_7}{2} - \frac{G_3 - 2 \cdot G_5 + G_7}{2} \quad , \ if \ \alpha < \beta$$

$$R_5 = \frac{R_1 + R_9}{2} - \frac{G_1 - 2 \cdot G_5 + G_9}{2} \quad , \ if \ \alpha > \beta$$

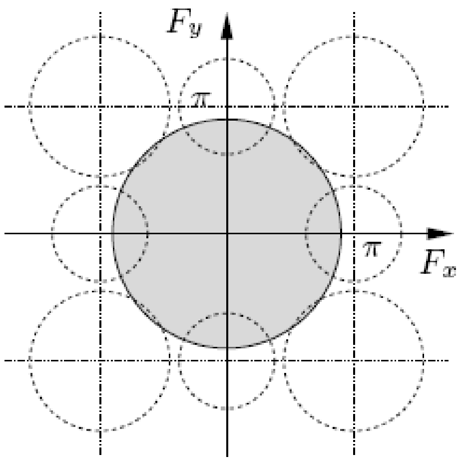
$$R_5 = \frac{R_1 + R_3 + R_7 + R_9}{4} - \frac{G_1 + G_3 - 4 \cdot G_5 + G_7 + G_9}{4} \quad , \ if \ \alpha = \beta$$

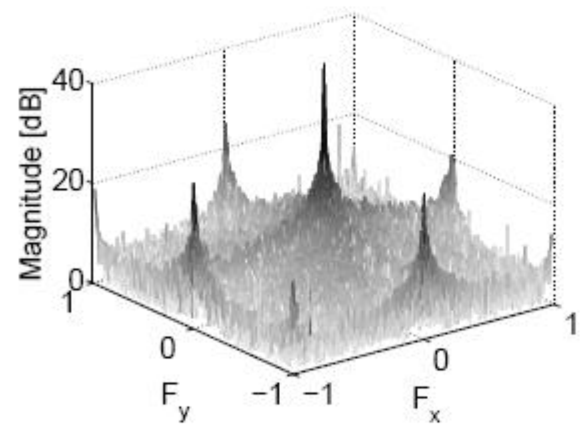
$$\alpha = abs(G_3 - 2 \cdot G_5 + G_7) + abs(R_7 - R_3)$$

$$\beta = abs(G_1 - 2 \cdot G_5 + G_9) + abs(R_9 - R_1)$$

Frequency Domain Approaches (1)

$$
\begin{aligned}
R_s(\omega_1,\omega_2) &= \frac{1}{4}[R(\omega_1,\omega_2) - R(\omega_1-\pi,\omega_2-\pi) + R(\omega_1-\pi,\omega_2) - R(\omega_1,\omega_2-\pi)] \\
G_s(\omega_1,\omega_2) &= \frac{1}{2}[G(\omega_1,\omega_2) + G(\omega_1-\pi,\omega_2-\pi)] \\
B_s(\omega_1,\omega_2) &= \frac{1}{4}[B(\omega_1,\omega_2) - B(\omega_1-\pi,\omega_2-\pi) + B(\omega_1-\pi,\omega_2) - B(\omega_1,\omega_2-\pi)]
\end{aligned}
$$





$$
I_s(\omega_1,\omega_2) = L(\omega_1,\omega_2) + C_1(\omega_1-\pi,\omega_2-\pi) + C_2(\omega_1-\pi,\omega_2) - C_2(\omega_1,\omega_2-\pi)
$$

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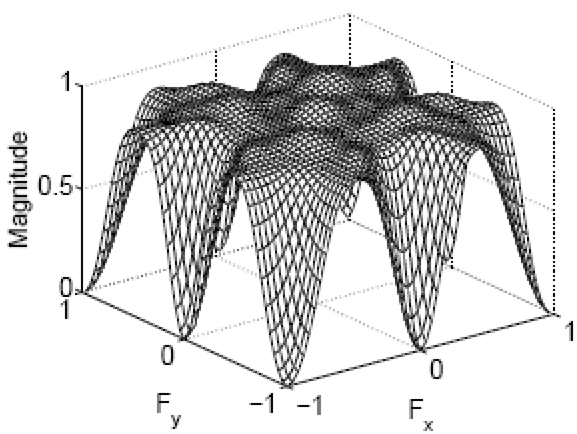
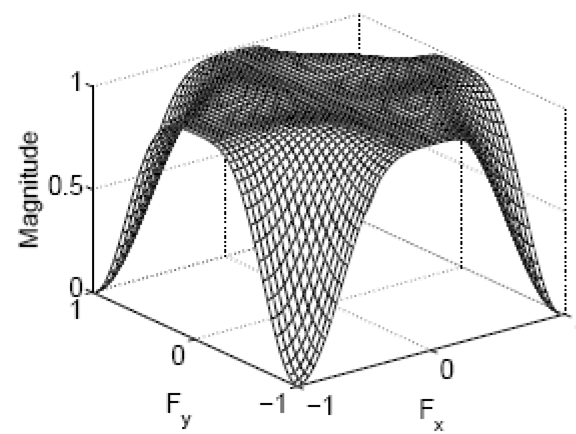
Frequency Domain Approaches (2)

$$I_s(\omega_1, \omega_2) = L(\omega_1, \omega_2) + C_1(\omega_1 - \pi, \omega_2 - \pi) + C_2(\omega_1 - \pi, \omega_2) - C_2(\omega_1, \omega_2 - \pi)$$

$$\begin{aligned}
L(\omega_1, \omega_2) &= \frac{R(\omega_1, \omega_2) + 2G(\omega_1, \omega_2) + B(\omega_1, \omega_2)}{4} \\
C_1(\omega_1, \omega_2) &= \frac{-R(\omega_1, \omega_2) + 2G(\omega_1, \omega_2) - B(\omega_1, \omega_2)}{4} \\
C_2(\omega_1, \omega_2) &= \frac{-R(\omega_1, \omega_2) + B(\omega_1, \omega_2)}{4}.
\end{aligned}$$





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References

http://www.site.uottawa.ca/~edubois/courses/CEG4311/slides/InterpolationRGBcomponents.ppt

J.E. Adams and J.F. Hamilton Jr., **Adaptive color plane interpolation in single sensor color electronic camera**, U.S.Patent 5,629,734

B.K. Gunturk, J. Glotzbach, Y. Altunbasak, R.W. Schafer, R. M. Mersereau, **Demosaicking: Color Filter Array Interpolation**, IEEE Signal Processing Magazine, 22(1): pp. 44-54, 2005.

S. Battiato, M. Guarnera, G. Messina, V. Tomaselli, **Recent patents on color demosaicing**, Recent Patents on Computer Science, Bentham Science Publishers Ltd, 1(2), pp. 194-207, 2008.

D. Menon, S. Andriani, G. Calvagno, **Demosaicing with Directional Filtering and a Posteriori Decision**, IEEE Transactions on Image Processing, 16(1), pp. 132-141, 2007.

M. Guarnera, G. Messina, V. Tomaselli, **Adaptive color demosaicing and false color removal**, Journal of Electronic Imaging, 19(2), 2010.

Colour theory

THE HUMAN VISUAL SYSTEM

- The human eye has three types of light receptors: L (long), M (middle), and S (short) cones. Humans recognize color after processing the light information from the cones through nerves to the brain.
- The stimuli from the cones are converted into luminance, red–green, and yellow–blue signals. These signals are transmitted to the brain for recognition as another set of color attributes, such as lightness, chroma, and hue.
- In addition to the cones, an eye has another type of receptor, which is called rod. Because it is deactivated in a bright environment, it does not contribute to the recognition of color.
- It is only active in a dark environment during which the three cones are deactivated. A single receptor does not give spectral information, so color is not sensed in such a dark environment.

THE HUMAN VISUAL SYSTEM (2)

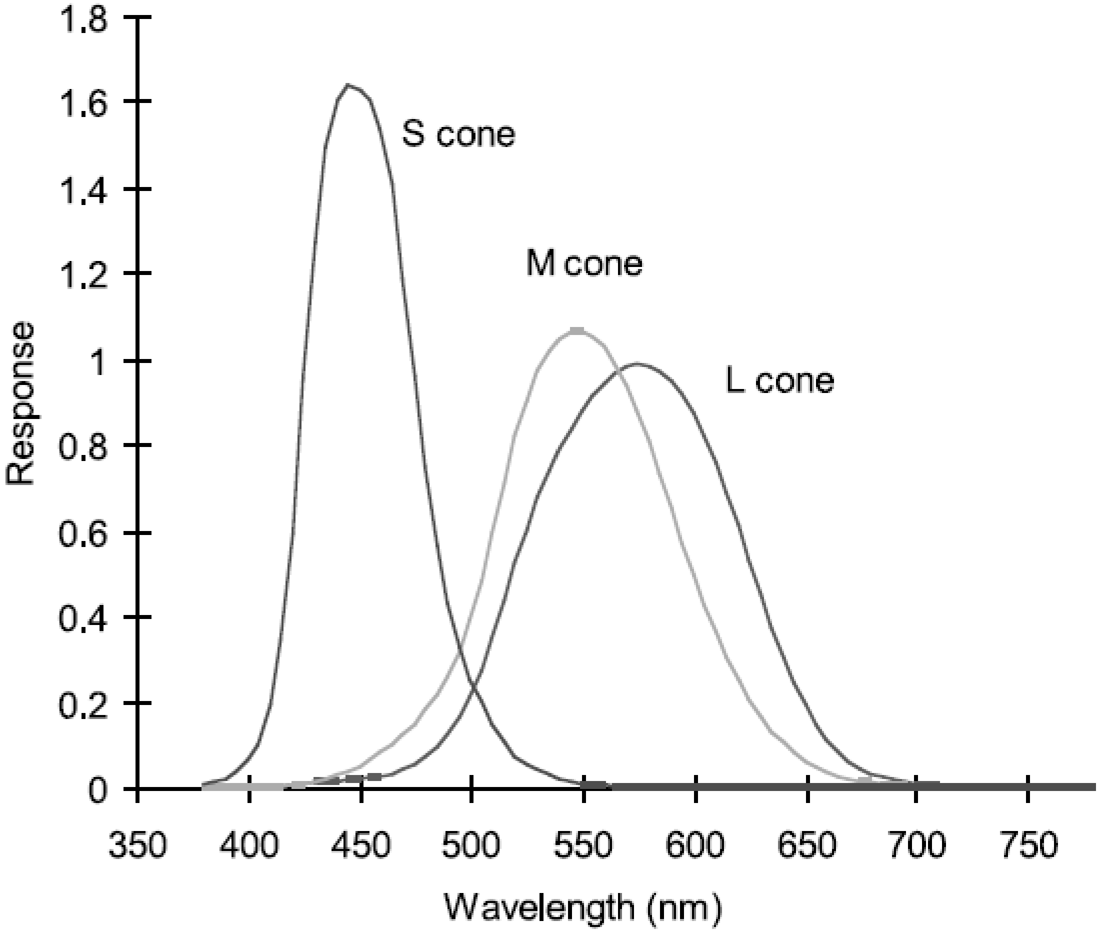
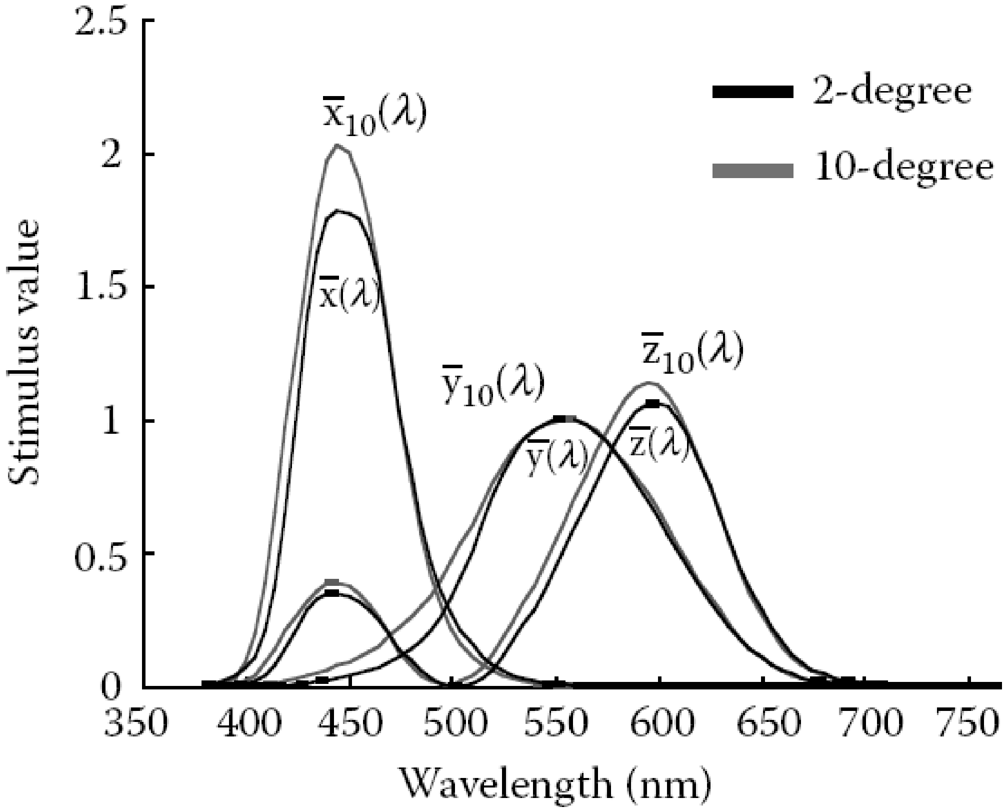


Image Processing LABoratory

COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (1)

- In industrial use, it is desired that color information be quantified and exchangeable. CIE (International Commission on Illumination) specifies the methodology, which is called colorimetry.
- It essentially traces the process in the human visual system with some modifications, approximations, and simplification for easy use in industry.
- Instead of the cone sensitivities, a set of equivalent sensitivity curves is defined as a linear transformation of the set of cone sensitivities. The sensitivity curves, are called the CIE color-matching functions.

COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (2)



These functions are noted as x(λ), y(λ), z(λ), where y(λ) is adjusted to represent luminance to fulfill industrial demands.

COLOR-MATCHING FUNCTIONS AND TRISTIMULUS VALUES (3)

When an arbitrary object with spectral reflectance, $R(\lambda)$, is illuminated by a light source with spectral radiance, $L(\lambda)$, tristimulus values, which are also a linear transformation of the cone sensitivities, can be obtained as follows:

$$X = \int L(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int L(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int L(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda$$

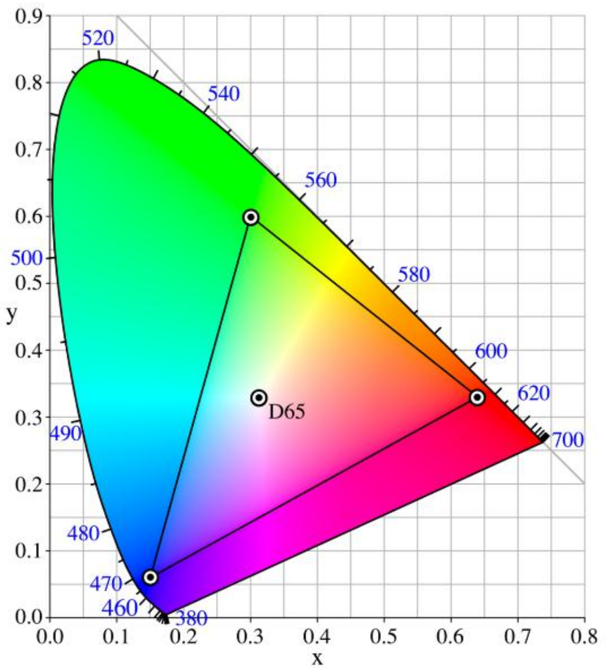
This is called the CIE 1931 (1964) standard colorimetric system. Here, the *Y* value provides luminance and the *X* and *Z* values physically have no meaning.

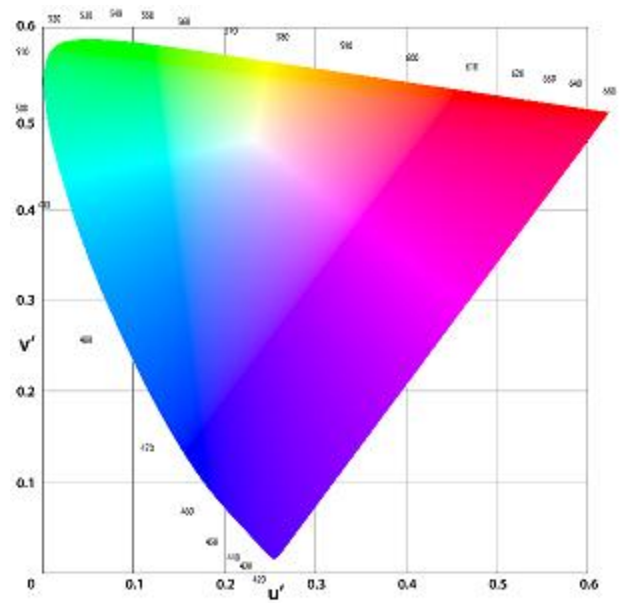
IMAGE PROCESSING LABORATORY

CHROMATICITY AND UNIFORM COLOR SPACE (1)

- Two forms of representing color have become prevalent: chromaticity coordinates and uniform color spaces.
- The former is a simplified way of ignoring the luminance axis and may be easily understood by a two-dimensional representation.
- The latter attempts to imitate human color recognition in three dimensions.

CHROMATICITY AND UNIFORM COLOR SPACE (2)





$$x = \frac{X}{X+Y+Z}, \; y = \frac{Y}{X+Y+Z}$$

$$u' = \frac{4X}{X+15Y+3Z}, \; v' = \frac{9Y}{X+15Y+3Z}$$

IMAGE PROCESSING LABORATORY

CHROMATICITY AND UNIFORM COLOR SPACE (3)

- For uniform color spaces, the CIE 1976 *L*a*b** color space and the CIE 1976 *L*u*v** color space recommended by CIE in 1976 are widely used. These are designed to simulate color recognition.
- These equations require the tristimulus values of the white point for normalization.
- It should be noted that the color spaces were developed for a specific observing condition (a color patch with a neutral gray background (*L**= 50)). If the background does not match the condition, the uniformity of the color spaces is not guaranteed.

CHROMATICITY AND UNIFORM COLOR SPACE (4)

$$X_n = \begin{cases} \left(\dfrac{X}{X_0}\right)^{\frac{1}{3}} & \dfrac{X}{X_0} > 0.008856 \\ 7.787\left(\dfrac{X}{X_0}\right) + \dfrac{16}{116} & \dfrac{X}{X_0} \le 0.008856 \end{cases}$$

$$Y_n = \begin{cases} \left(\dfrac{Y}{Y_0}\right)^{\frac{1}{3}} & \dfrac{Y}{Y_0} > 0.008856 \\ 7.787\left(\dfrac{Y}{Y_0}\right) + \dfrac{16}{116} & \dfrac{Y}{Y_0} \le 0.008856 \end{cases}$$

$$Z_n = \begin{cases} \left(\dfrac{Z}{Z_0}\right)^{\frac{1}{3}} & \dfrac{Z}{Z_0} > 0.008856 \\ 7.787\left(\dfrac{Z}{Z_0}\right) + \dfrac{16}{116} & \dfrac{Z}{Z_0} \le 0.008856 \end{cases}$$

$$L^* = \begin{cases} 116\left(\dfrac{Y}{Y_0}\right)^{\frac{1}{3}} - 16 & \dfrac{Y}{Y_0} > 0.008856 \\ 903.29\left(\dfrac{Y}{Y_0}\right) & \dfrac{Y}{Y_0} \le 0.008856 \end{cases}$$

$$a^* = 500(X_n - Y_n)$$

$$b^* = 200(Y_n - Z_n)$$

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COLOR DIFFERENCE

The geometrical difference of two colors in a uniform color space should be proportional to the apparent, or perceived, color difference. The color difference is denoted by ΔE^* (delta E). In the $L^*a^*b^*$ color space, ΔE is written as ΔE^*_{ab} and is computed as follows:

$$\Delta E^*_{ab} = \left[\left(L^*_1 - L^*_2 \right)^2 + \left(a^*_1 - a^*_2 \right)^2 + \left(b^*_1 - b^*_2 \right)^2 \right]^{\frac{1}{2}}$$

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CHARACTERIZATION OF A CAMERA (1)

A typical methodology to characterize a camera with a linear matrix colorimetrically is to use test patches whose spectral responses are similar to those of real objects. Suppose that the target tristimulus values for color targets are given by:

$$T = \begin{bmatrix} X_1 & \cdots & X_i & \cdots & X_n \\ Y_1 & \cdots & Y_i & \cdots & Y_n \\ Z_1 & \cdots & Z_i & \cdots & Z_n \end{bmatrix}$$

and the estimated tristimulus values are given by:

$$\hat{T} = \begin{bmatrix} \hat{X}_1 & \cdots & \hat{X}_i & \cdots & \hat{X}_n \\ \hat{Y}_1 & \cdots & \hat{Y}_i & \cdots & \hat{Y}_n \\ \hat{Z}_1 & \cdots & \hat{Z}_i & \cdots & \hat{Z}_n \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \cdot \begin{bmatrix} r_1 & \cdots & r_i & \cdots & r_n \\ g_1 & \cdots & g_i & \cdots & g_n \\ b_1 & \cdots & b_i & \cdots & b_n \end{bmatrix} = A \cdot S$$

where matrix *S* is measurement data through the camera. To obtain 3 X 3 matrix A, simple linear optimization or recursive nonlinear optimization can be applied.

IMAGE PROCESSING LABORATORY

CHARACTERIZATION OF A CAMERA (2)

The coefficients are to be retrieved for each device.

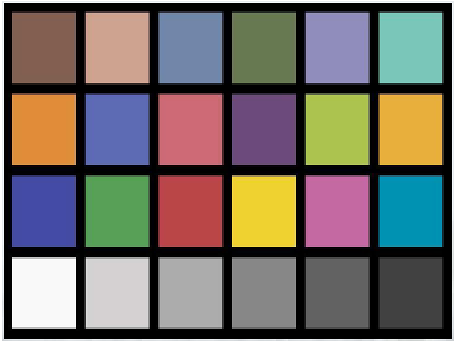
Usually a statistical retrieving phase is used with the Macbeth chart:

– Several image acquisitions of the chart (without dominant colours);

– Mean (to reduce the noise effects);

– Linear regression obtaining the a_{ij} *values.*

$$A = T \cdot S^T \cdot (S \cdot S^T)^{-1}$$

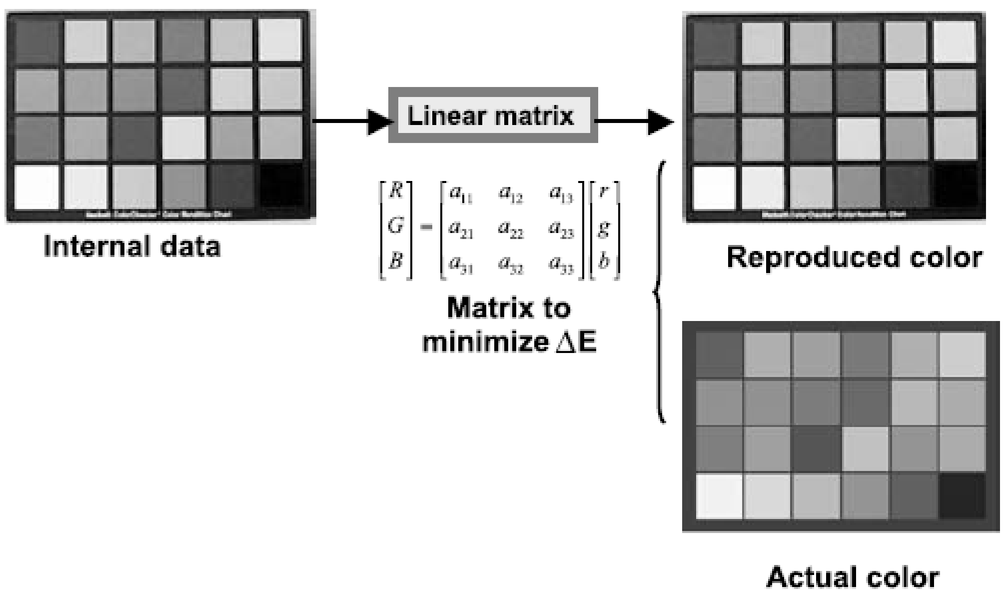


CHARACTERIZATION OF A CAMERA (3)

An alternate method minimizes the total visual color difference, *J,* using a recursive conversion technique. ΔE may be calculated in a CIE uniform color space:

$$J = \sum_{i=1}^{n} w_i \Delta E(X_i, Y_i, Z_i, \hat{X}_i, \hat{Y}_i, \hat{Z}_i)$$

where w_i is a weight coefficient.



White Balance (1)

- One of the most challenging processes in a digital camera is to find an appropriate white point and to adjust color.
- Real scenes contain many light sources. In such a situation, the human visual system adapts to the circumstances and recognizes the objects as if they were observed in typical lighting conditions, while a camera's sensor still outputs raw signals.
- For instance, they recognize white paper as white in the shadow of a clear sky even though its tristimulus values give a bluish color because the paper is illuminated by sky blue.
- It is known that the major adjustment is performed in the retina by adjusting each cone's sensitivity. This process is called chromatic adaptation.

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White Balance (2)

Incorrect white balance

Correct white balance

http://www.cambridgeincolour.com/tutorials/white-balance.htm

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White Balance (3)

- Color correction is based on the (Von Kries) diagonal hypothesis
- It states that a color balancing can be obtained by a different gain application on each color channel.
- On a RGB image representation a diagonal transform is performed as follows:

$$\begin{bmatrix} R_b \\ G_b \\ B_b \end{bmatrix} = \begin{bmatrix} k_r & 0 & 0 \\ 0 & k_g & 0 \\ 0 & 0 & k_b \end{bmatrix} \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix}$$

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Typical approaches

- They are based on strong assumption in the scene content.

- Two classical methods are used:
  - Gray world approach (GW)
  - White patch approach (WP)

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Gray World approach

- It assumes that the average of all surface reflactance in a scene is gray. Each deviation is due to the illuminant.
- The algorithm works as follow:
  - Retrieve the mean value for each color channel;
  - Retrieve the k_i coefficients in order to set these value in the mid point.

White Patch approach

- It assumes that a white object is always in the scene (i.e. the maximum values for each channel is to be the maximum allowed).
- The algorithm works as follow:
  - Retrieve the max value for each channel (Rmax, Gmax, Bmax)
  - Retrieve the k_i coefficients in order to set these value in the maximum allowed by the representation.

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Gw and WP limits

gray-world hypothesis problem scenary:

- ✓ very simple scenes with few colors.
- ✓ images with a limited range of dominant hues, i.e. underwater images,
- ✓ synthetic graphic…

White-patch hypothesis problem scenary:

- ✓ High contrast scenes: white pixels could be saturated.
- ✓ Noise sensitivity
- ✓ metallic and specular surfaces
- ✓ a real white object could be present on the scene

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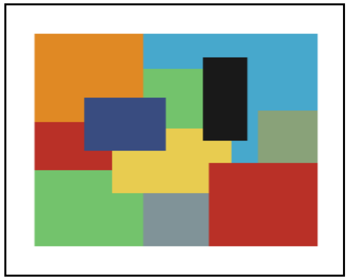
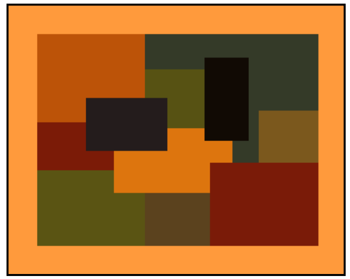
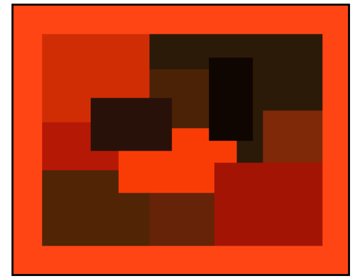
GW and WP critical examples



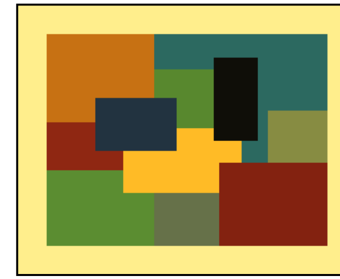
Original image



Neon illuminant

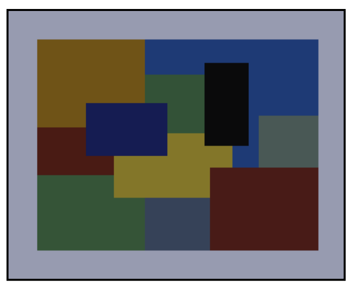


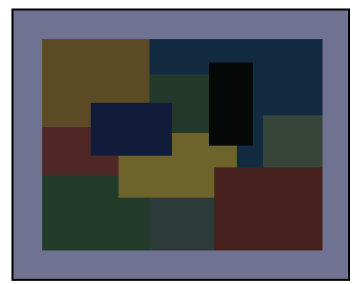
Red

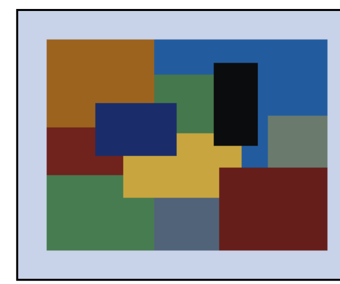


Nitraphot

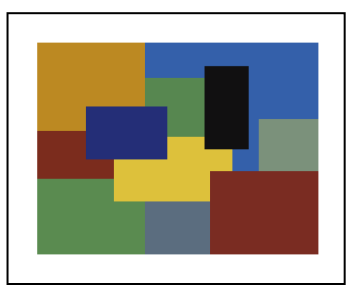
Recovered images under gray world assumption

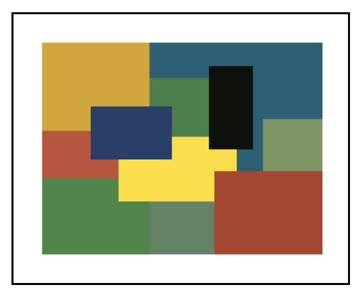


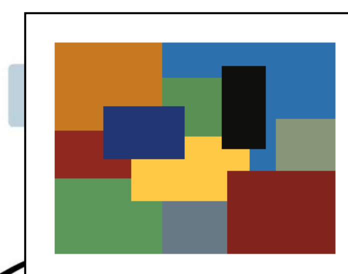




Recovered images under white patch assumption







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Critical examples

Underwater image

AWB Processed image

With constrained approaches, chromatic distortion is introduced when a real dominant hue is present.

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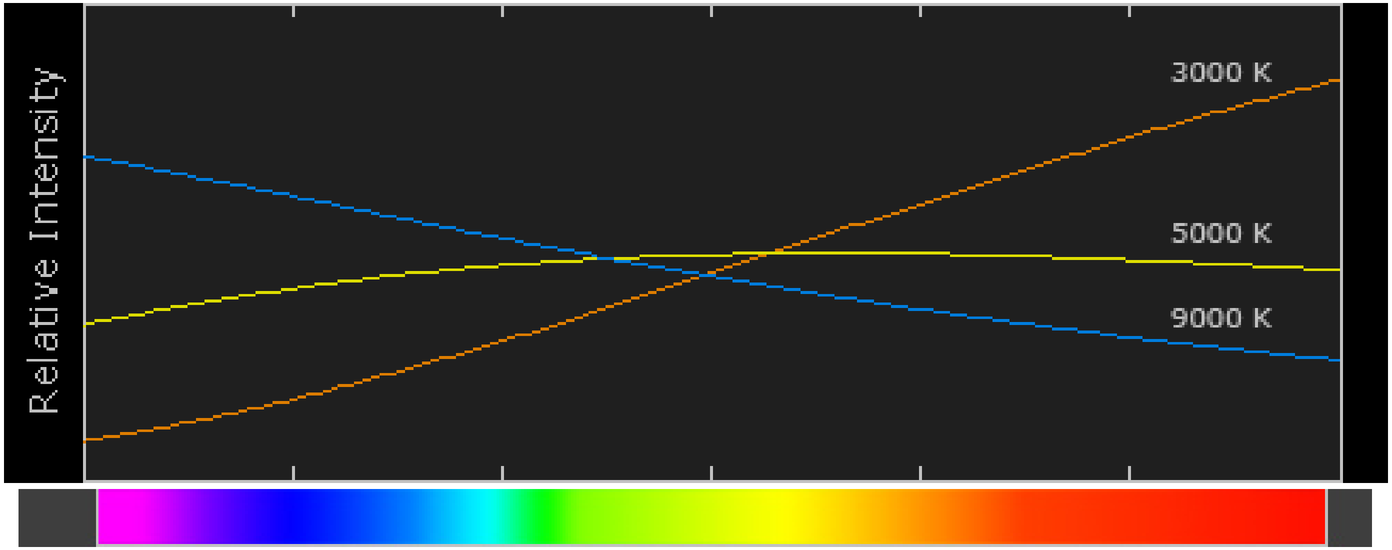
Color Temperature

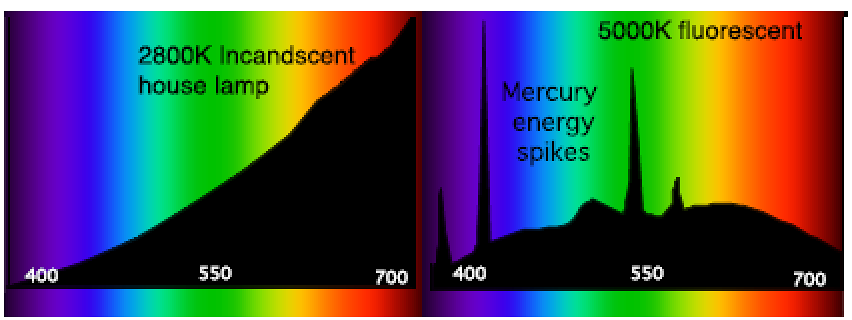
Color temperature describes the spectrum of light which is radiated from a "blackbody" with that surface temperature. A blackbody is an object which absorbs all incident light neither reflecting it nor allowing it to pass through.



Counterintuitively, higher color temperatures (5000 K or more) are "cool" (green–blue) colors, and lower color temperatures (2700–3000 K) "warm" (yellow–red) colors (shorter wavelengths contain light of higher energy).

Color Temperature (2)

Color Temperature	**Light Source**
1000-2000 K	Candlelight
2500-3500 K	Tungsten Bulb (household variety)
3000-4000 K	Sunrise/Sunset (clear sky)
4000-5000 K	Fluorescent Lamps
5000-5500 K	Electronic Flash
5000-6500 K	Daylight with Clear Sky (sun overhead)
6500-8000 K	Moderately Overcast Sky
9000-10000 K	Shade or Heavily Overcast Sky



Light sources such as daylight and tungsten bulbs closely mimic the distribution of light created by blackbodies, although others (e. g. fluorescent) depart from blackbodies significantly.

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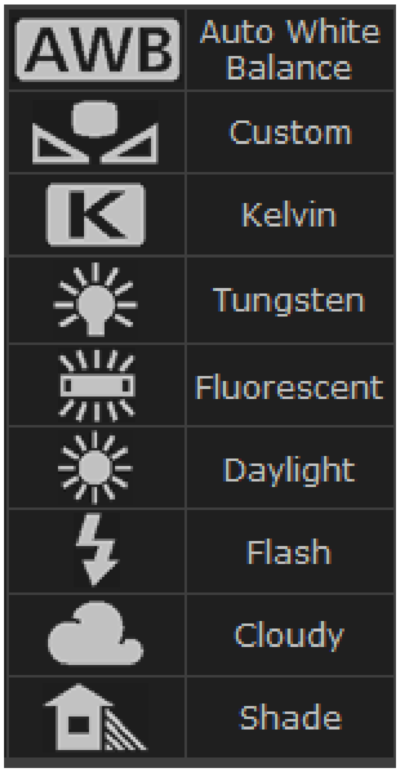
White balance



Most digital cameras contain a variety of preset white balances.

Auto white balance is available in all digital cameras and uses a best guess algorithm within a limited range usually between 3000/4000 K and 7000 K.

Custom white balance allows you to take a picture of a known gray reference under the same lighting, and then set that as the white balance for future photos.

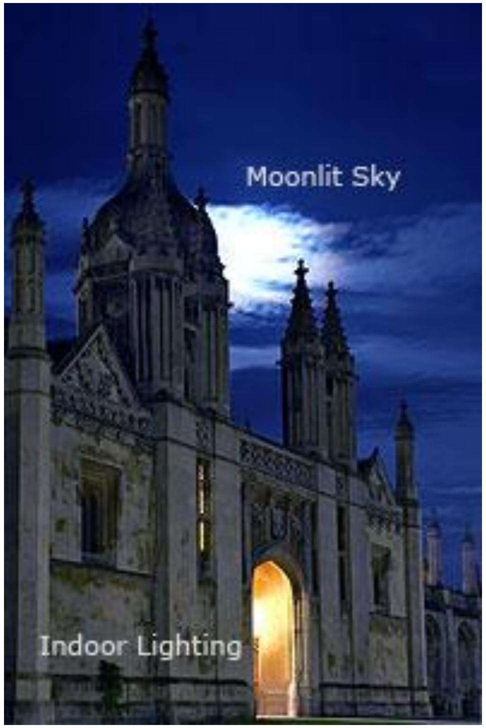
With "Kelvin" you can set the color temperature over a broad range.

Custom white balance

Automatic white balance

Custom white balance

Mixed lighting



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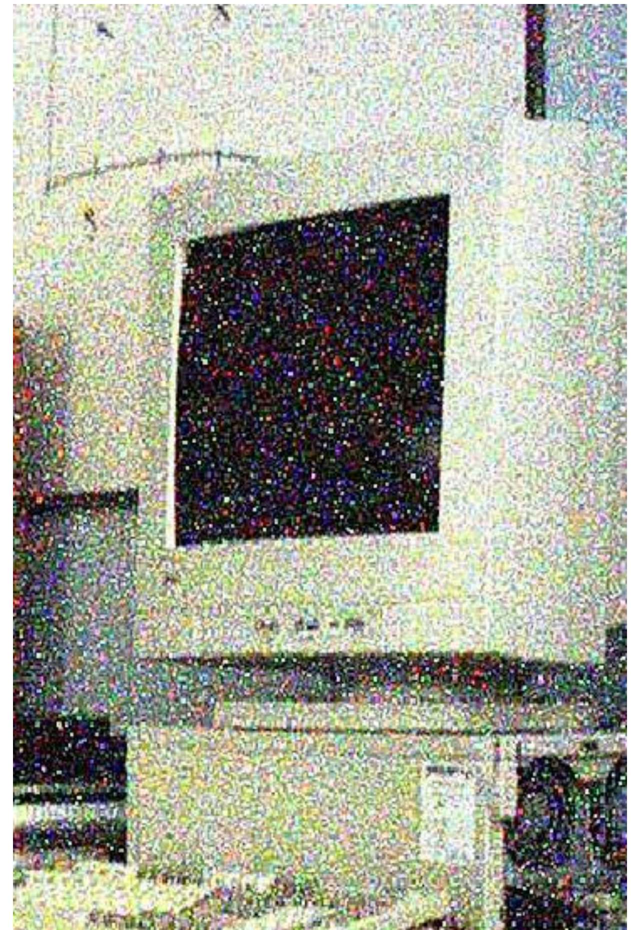
References

- Image Sensors and Signal Processing for Digital Still Cameras -J. Nakamura –CRC Press, 2006;
- http://www.cambridgeincolour.com/tutorials.htm
- http://www.dmi.unict.it/~battiato/EI_MOBILE0708/EI_MOBILE0708.htm

Denoising

Introduction

- Among the many factors contributing to image quality degradation, noise is one of the most recurrent and difficult elements to deal with.
- Smart filters capable to remove noise without affecting the tiny details of a digital image are of primary importance to produce pleasant pictures.



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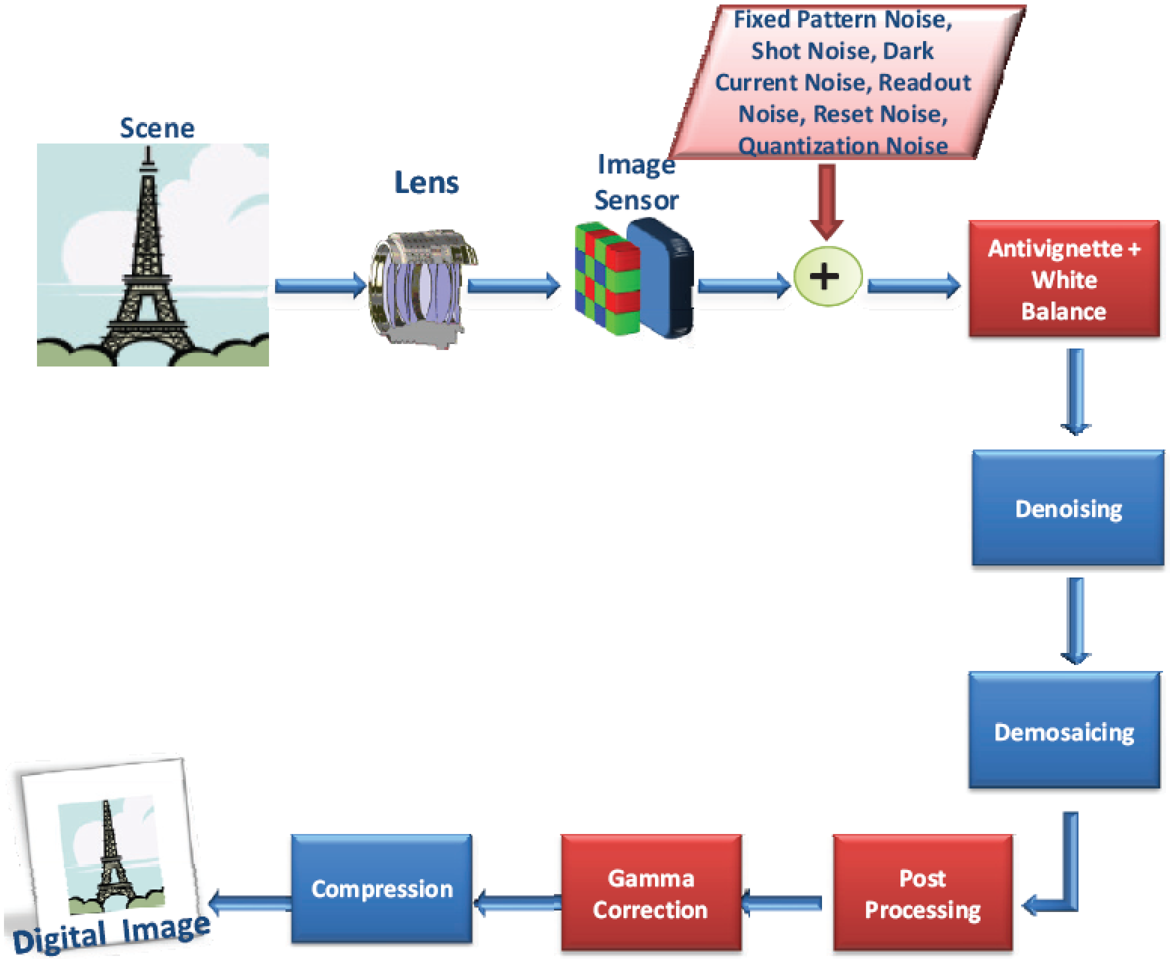
Noise Sources (1)



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Noise Sources (2)

Noise in a digital raw image can be classified into two main categories:

- Fixed Pattern Noise (*FPN);*
- Temporal (Random) Noise:
  - Photon Shot Noise
  - Dark Current (Thermal Noise)
  - Readout noise (Bias Noise)
  - KT/C Noise (Reset Noise)
  - Quantization noise

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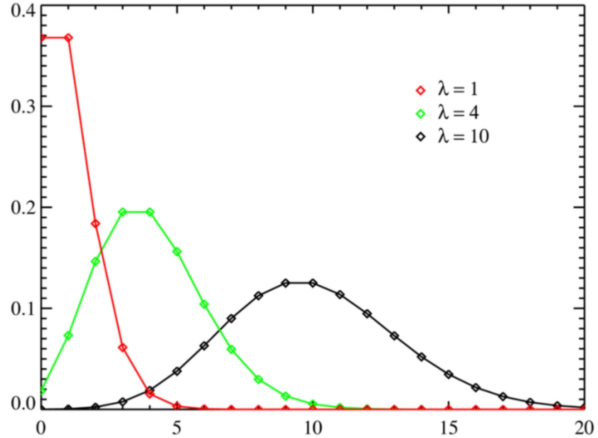
Photon Shot Noise

- During the integration time, the arrival rate of photons at each photosite is not constant; rather, there is an intrinsic uncertainty caused by the oscillations of the number of photons that reach the imager.
- Even in the ideal case of constant and uniform light intensity, each photosite can receive a different number of photons.
- These oscillations can be modeled by Poisson distribution.



$$f(k;\lambda) = \frac{\lambda^k e^{-k}}{k!}$$

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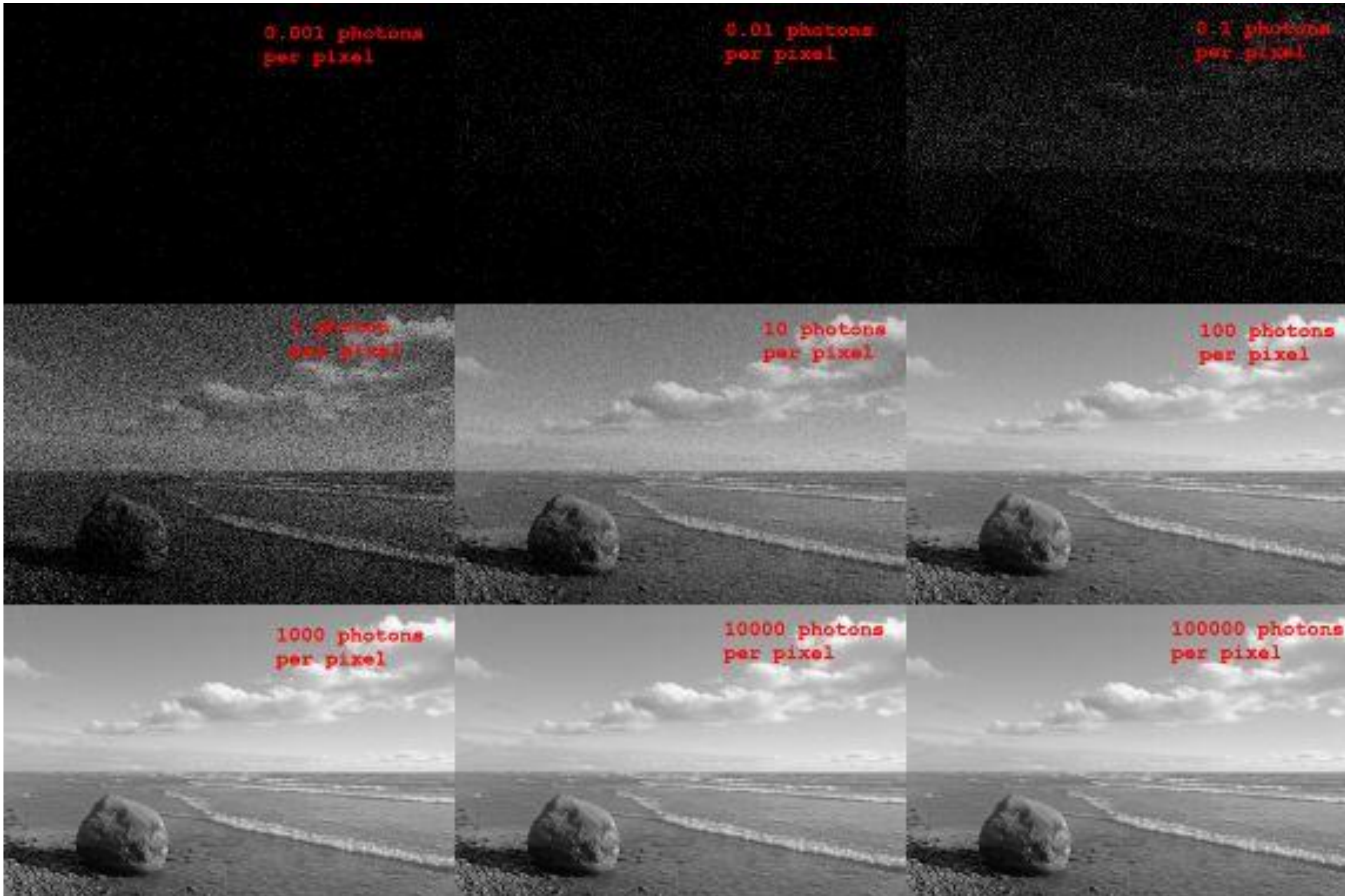
Photon Shot Noise Simulation



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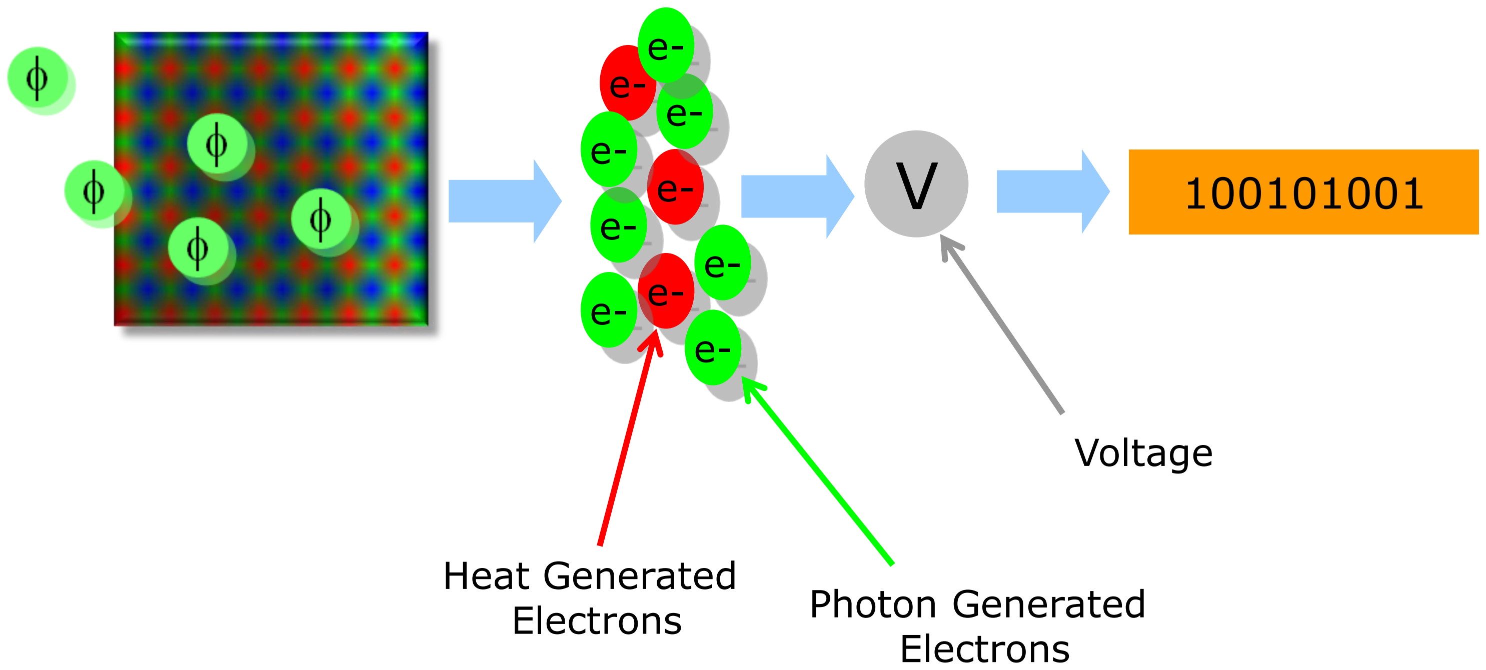
Dark Current



Dark Current Noise exists even when the sensor is not exposed to any incident light, and increases as the temperature of the sensor increases.

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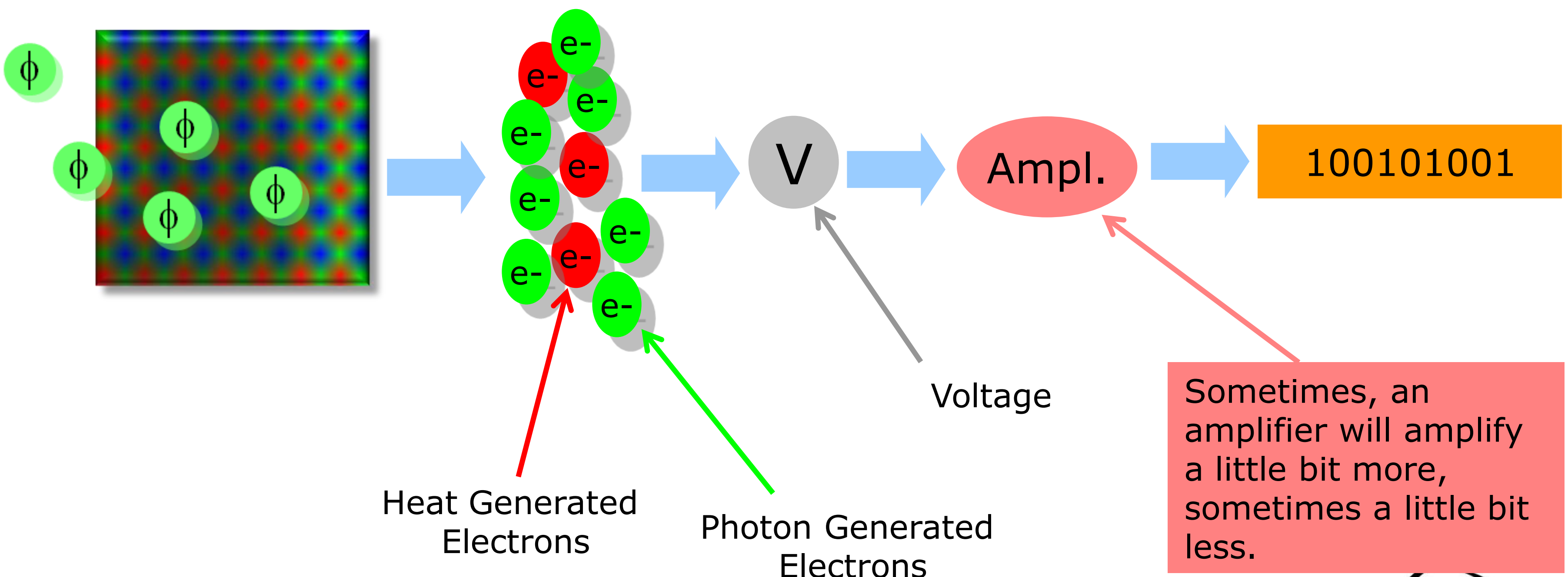
Readout Noise

It is the electronic noise generated during the sensor readout process.



KT/C (Reset) Noise, Quantization Noise

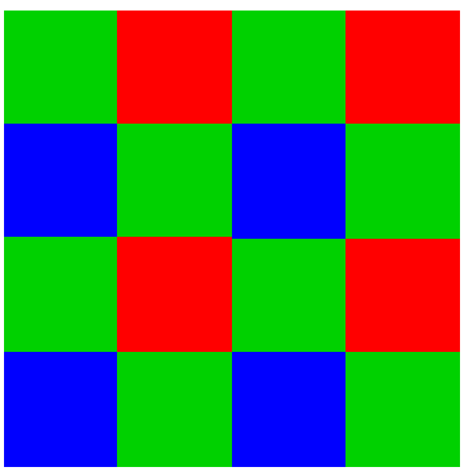
Reset noise: is generated by residual electrons left in sensors capacitor after the reset operation, which is performed before a new scene acquisition occurs.

Quantization noise: is due to conversion of photons into a digital number performed by an A/D converter. In particular, quantization noise significantly affects image quality when the bit-depth of the digital conversion process is small.

Overall Noise

- Considering the presence of many noise sources, it is reasonable to model the overall noise as a zero mean Additive White Gaussian Noise (AWGN), affecting each color component and pixel position independently.

- Noise variance may be different across Bayer color channels.



To obtain better filtering results it is better to estimate the noise level on each Bayer channel separately, producing three different noise estimates per image.

Gaussian Noise Reduction (1)

- Gaussian Noise reduction filter strength must be *adaptive*. Filter strength must scale with the level of noise in the image.
  - High noise level -> High filter strength.
  - Low noise level -> Low filter strength.
- But:
  - Textured areas must be not heavily filtered in order to maintain details;
  - Flat areas can be more heavily filtered to reduce pixel fluctuations.

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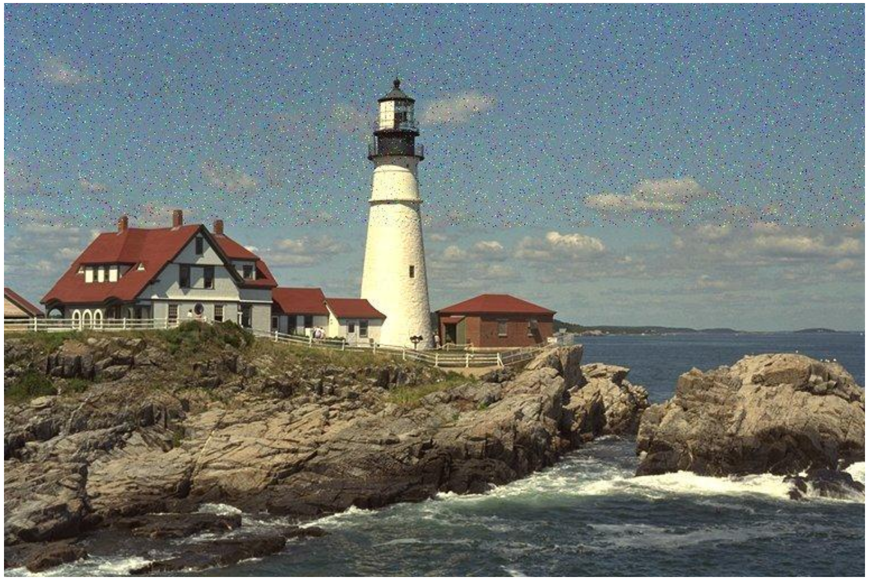
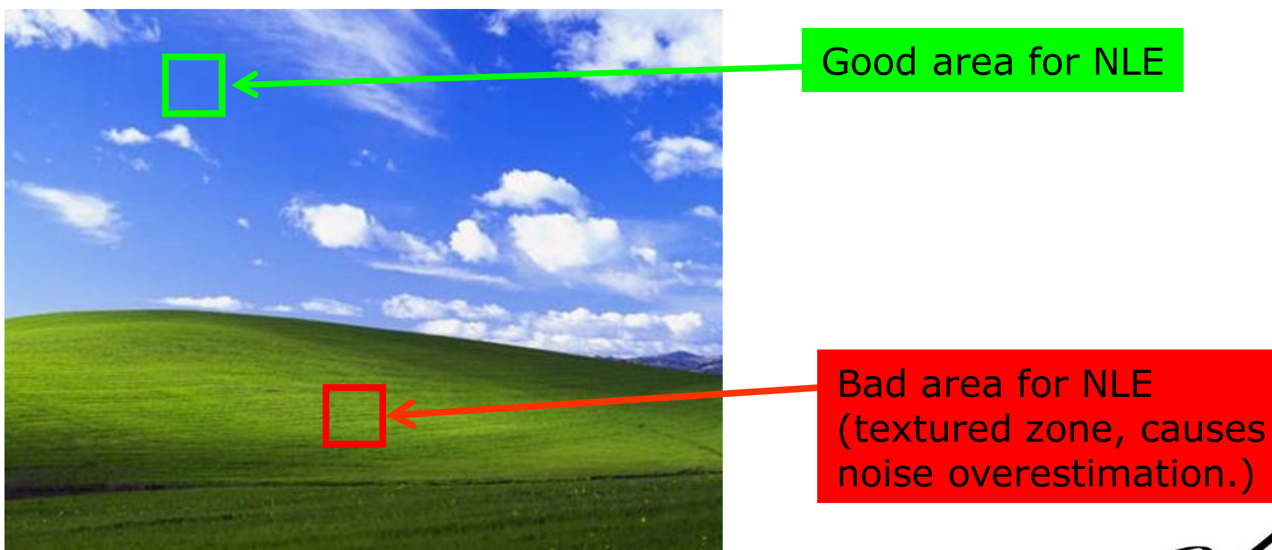
Gaussian Noise Reduction (2)

- Fine texture hides noise (*texture masking*)
- In flat areas pixel fluctuations are supposed to be caused exclusively by random noise: for this reason flat areas are better than textured zone to estimate noise level
- To locate flat areas we can use a *texture detector.*



Noise Level Estimation

- Use a texture detector to locate the flat areas in the image.
- In flat areas, pixel fluctuations are supposed to be caused exclusively by random noise. Hence, flat areas are good for estimating the noise level (i.e. standard deviation of the underlying Gaussian distributed noise).



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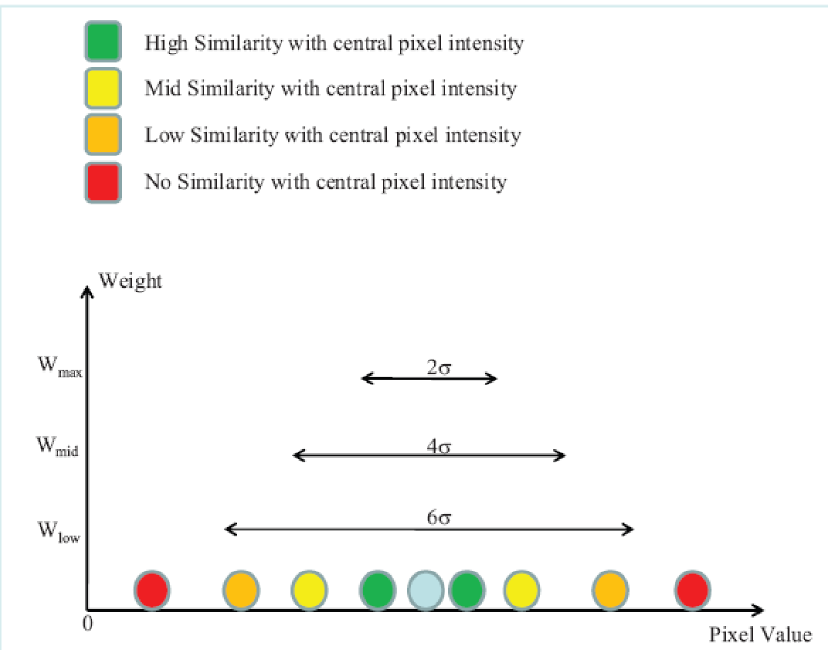
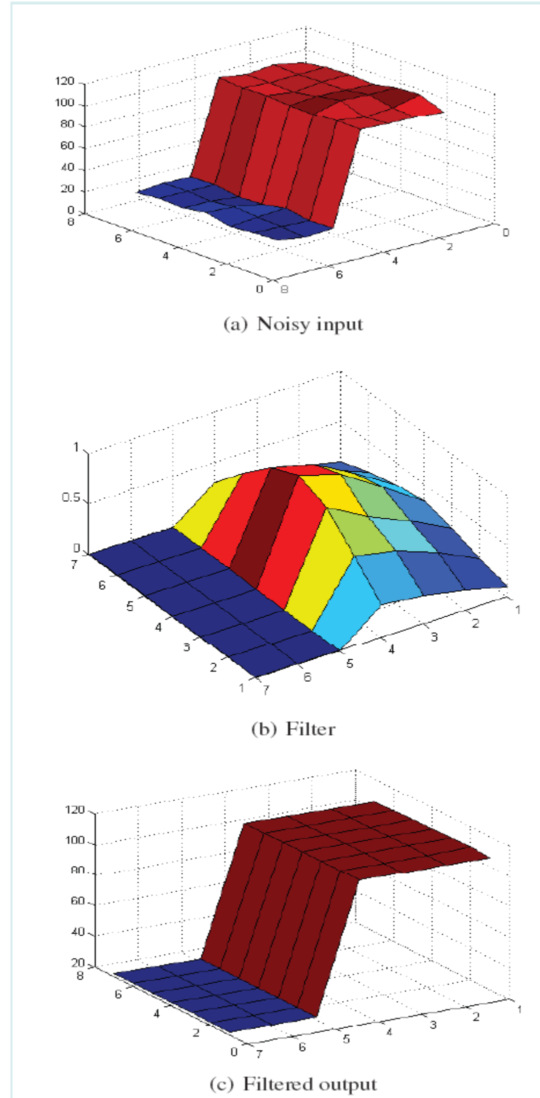
Noise Filtering

Sigma Filter

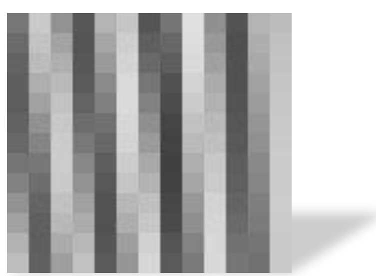


Bilateral Filter

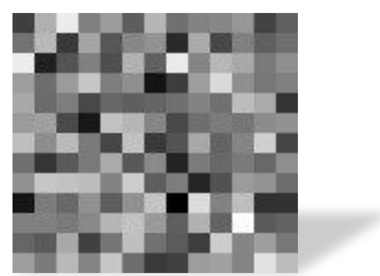


Kim-Lee Algorithm (1)

- "*Image feature and Noise Detection Based on Statistical Hypothesis tests and Their Applications in Noise Reduction*" Y.-H. Kim e J. Lee
- The fundamental idea behind the proposed detection algorithm is based on the observation that there is a strong sample correlation in at least one direction in an image feature area whereas no significant sample correlation appears in a noisy area.



Edge - σ^2=1000



Flat area - σ^2=1000

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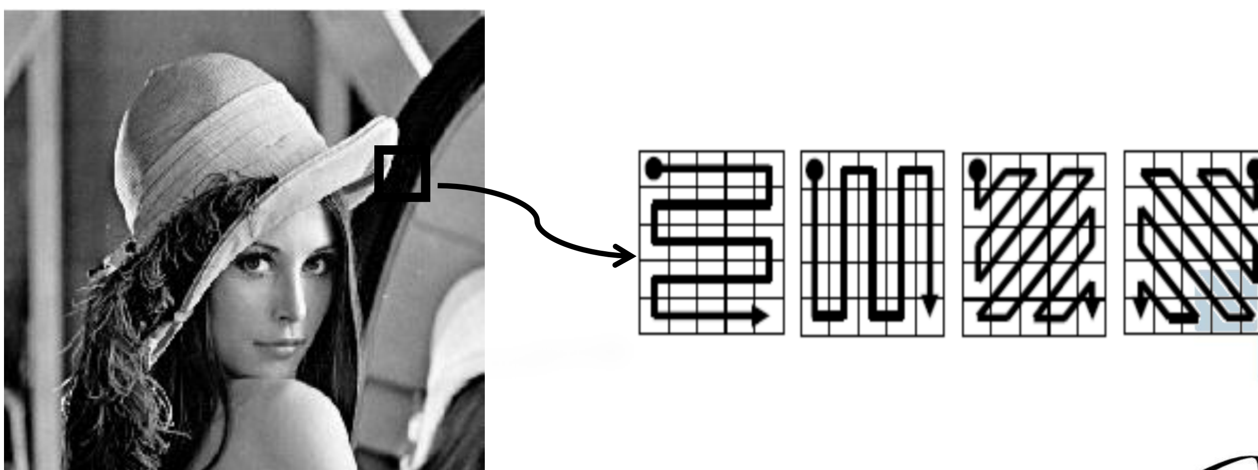
Kim-Lee Algorithm (2)

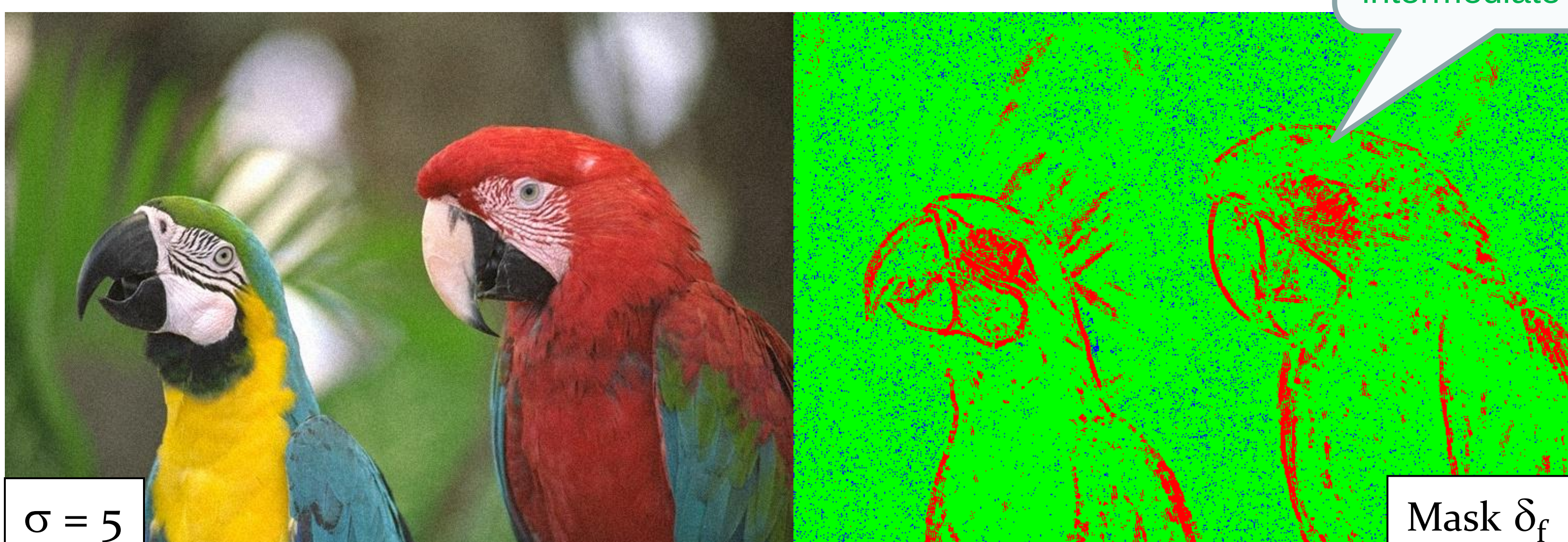
- Kim-Lee algorithm implements a feature and noise detector based on statistical hypotheses and a statistic test.
  - For each pixel x_{ij} the algorithm verifies its spatial correlation with its neighbor samples.
    - If there is a strong sample correlation in at least one direction -> image feature
    - else –> flat area (random noise)



Kim-Lee Algorithm (3)

The degree of feature (denoted as δ_f) for each pixel x_{ij} is introduced. It represents heuristically whether the pixel x_{ij} with its neighborhood forms an image feature, purely random noisy data, or between, as following:

$\delta_f(i,j) = 0$ -> x_{ij} is an image feature
$\delta_f(i,j) = 1$ -> x_{ij} is a random noisy data
$0 < \delta_f(i,j) < 1$ -> image feature with certain degree



Kim-Lee Noise Removal

- Proposed detection algorithm can be used in noise reduction by combining it with a simple average filter.
- Let { y_{ij}^{avg} } be an average filter output for a given input image {x_{ij}}. Then the feature and noise adaptive average filter can be chosen as:

$$y_{ij}^{adapt} = \delta_f \cdot x_{ij} + (1 - \delta_f) \cdot y_{ij}^{avg}$$

- Note that $y_{ij}^{adapt} = x_{ij}$ *when* $\delta_f = 1$ *(feature) and* $y_{ij}^{adapt} = y_{ij}^{avg}$ when $\delta_f = 0$ *(noise).* Depending on the detection of the feature and noise, the output is adaptively adjusted so that the feature can be preserved whereas noise can be smoothed.

IMAGE PROCESSING LABORATORY

Clean image

Noisy image ($\sigma=7$)

Mean filtered image

Kim-Lee algorithm


Mean filtered image


Kim-Lee algorithm

References

A. Bosco, A. Bruna, G. Spampinato, and G. Messina, **Fast method for noise level estimation and integrated noise reduction**, IEEE Transactions on Consumer Electronics, 51(3), pp. 1028–1033, 2005.

A. Bosco, S. Battiato, A. Bruna, and R. Rizzo, **Noise reduction for CFA image sensors exploiting HVS behaviour**, Sensors, 9(3), pp. 1692–1713, 2009.

Y.-H. Kim, J. Lee, **Image feature and noise detection based on statistical hypothesis tests and their applications in noise reduction**, IEEE Transactions on Consumer Electronics, 51(4), pp.1367–1378, 2005.

K. Hirakawa, P.J. Wolfe, **Efficient Multivariate Skellam Shrinkage for Denoising Photon-Limited Image Data: An Empirical Bayes Approach**, In Proceeding of International Conference on Image Processing, 2009.

J. S. Lee, **Digital image smoothing and the sigma filter**, In Proceedings of International Computer Vision, Graphics and Image Processing, vol. 24, 1983.

C. Tomasi, R. Manduchi, **Bilateral Filtering for Gray and Color Images**, In International Conference on Computer Vision (ICCV-98), pp. 839–846, 1998.