Image Acquisition

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Version 5.2

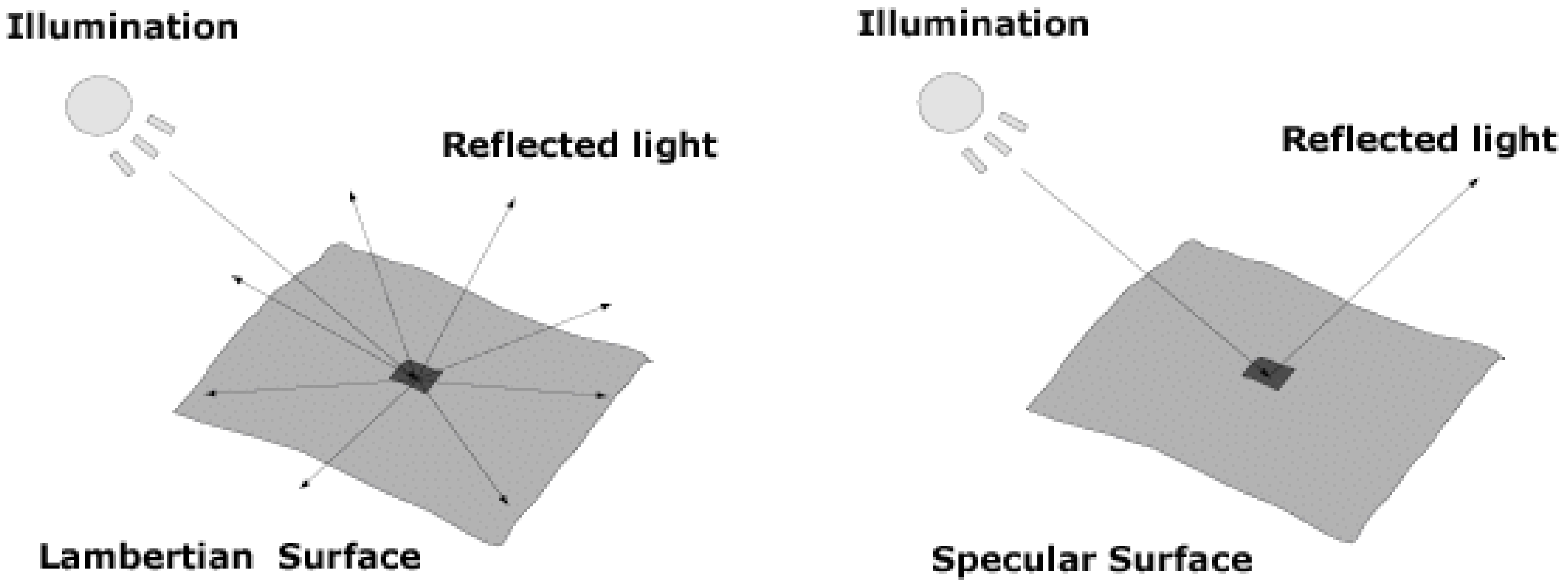
Image Acquisition

- **Light Reflection**
- Camera Structure
- Camera Lens
- Sensor Technologies
- Image Digitization
- Image Corrections
- Image File Formats
- Scanners
- Image noise

Light Reflection

- Cameras capture objects that reflect or emit light.
- In general, reflection can me decomposed in two components:
  - ***Diffuse reflection***: Distributes light energy equally along any spatial direction.
  - ***Specular reflection:*** Light energy is strongest along the direction of the incident light.
- Surfaces performing diffuse reflection, aka ***Lambertian surfaces***, are described as dull or matte; while specular reflection can be observed on glass surfaces and mirrors.

Light Reflection

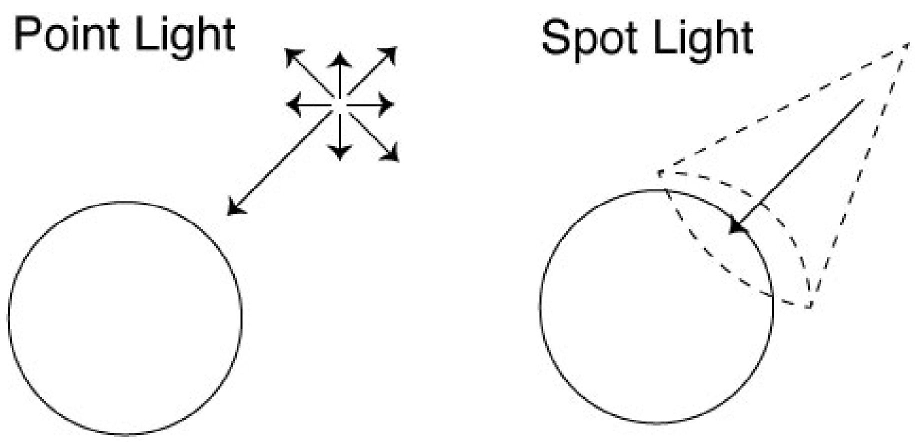


Lamβertian and specular surfaces [WOO2007].

Light Reflection

- ***Ambient illumination*** sources emit the same light energy in all directions and thus, the position of the source is not that important for the reflecting surface (e.g., cloudy sky).

- ***Point illumination*** sources emit light energy isotropically (e.g., sun) or anisotropically (e.g., light bulb) along various directions making the position of the light source important.



Light Reflection

- The reflected irradiance when object surface produces diffuse reflectance is given

- for ***ambient illumination*** by:

$$f_r(X,Y,Z,t,\lambda) = r(X,Y,Z,t,\lambda)E_a(t,\lambda)$$

  - for ***point light source*** by:

$$f_r(X,Y,Z,t,\lambda) = r(X,Y,Z,t,\lambda)E_p(t,\lambda)cos\theta.$$

- Distant point source and ambient illumination:

$$E(t,\lambda) = E_a(t,\lambda) + E_p(t,\lambda)cos\theta.$$

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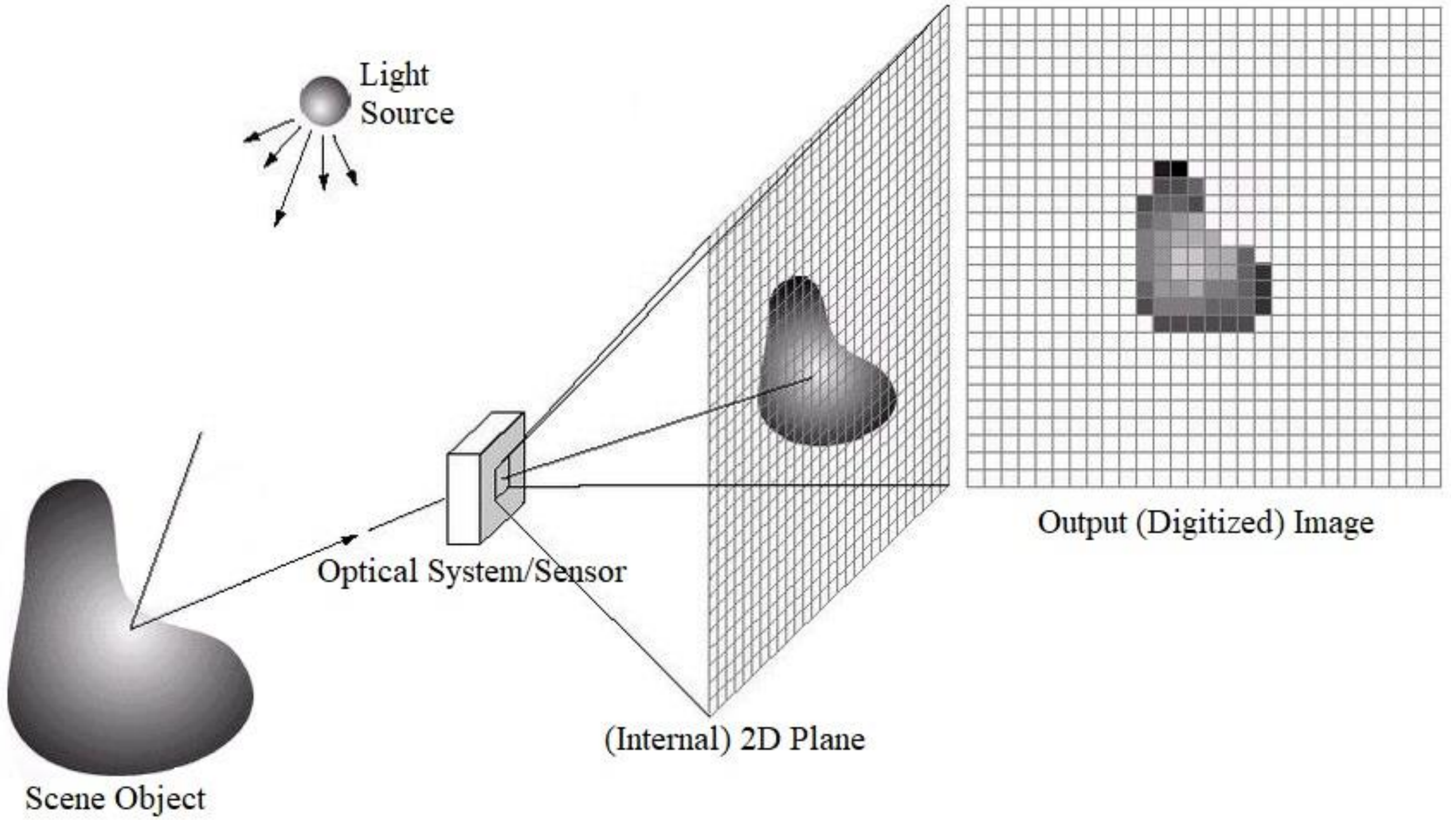
Image Acquisition

- We define an image as a ***2D function*** $f(x, y)$, where (x, y) corresponds to a co-ordinate in two-dimensional space and $f(x, y)$ represents the light intensity at this co-ordinate.
- In a discrete image, the (i, j) point is called a ***pixel*** (or picture element).
- Our main goal is to ***project*** a 3D scene into a 2D plane in which every point can be represented as a pixel.
- To achieve that we need an optical system that attracts the energy reflected from the object, as well as a ***sensor*** which computes the energy absorbed.

Image Acquisition

- The basic idea is that incoming illumination energy is converted into voltage and which can be subsequently sampled to obtain a digital image.
- CCD/CMOS sensor output varies according to the input electric energy.



Basic Image Acquisition Model [MIS2017].

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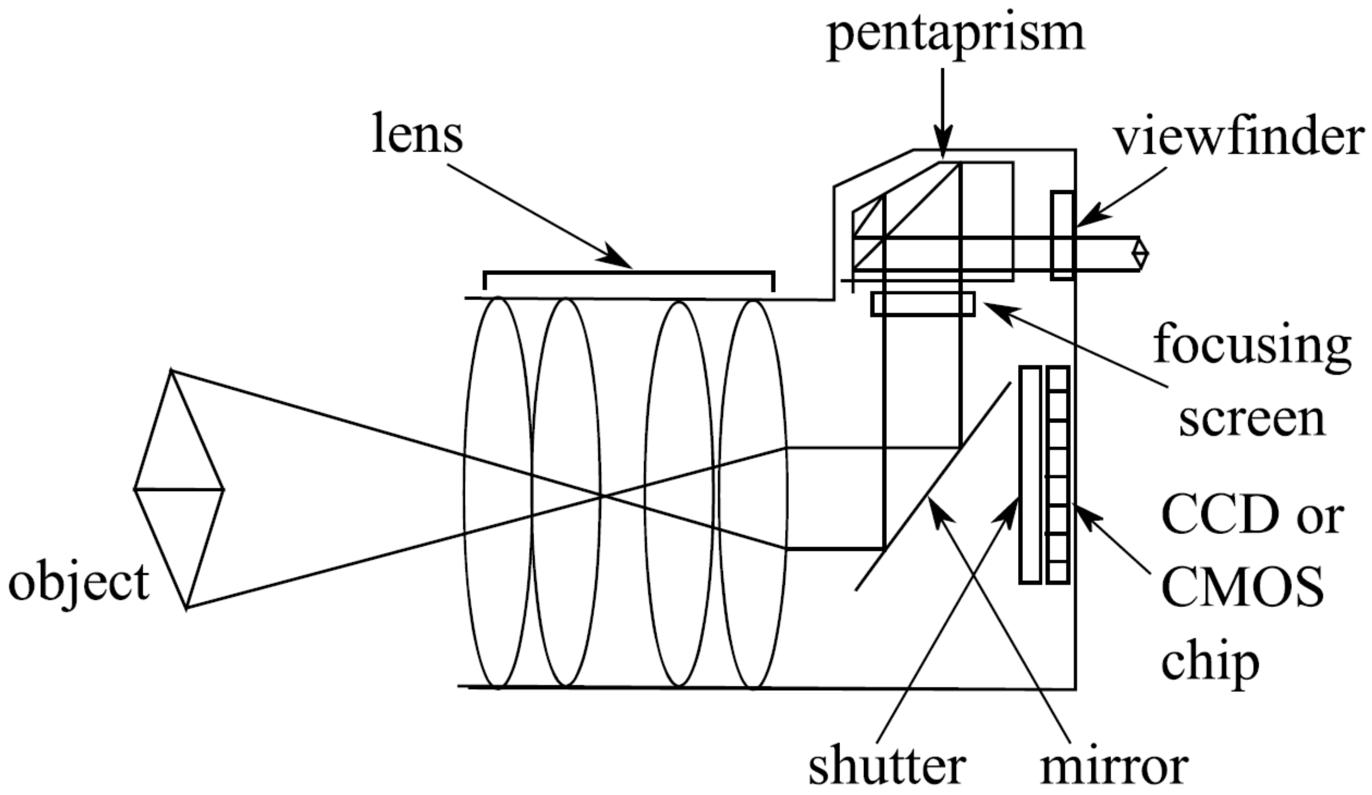
Camera Structure

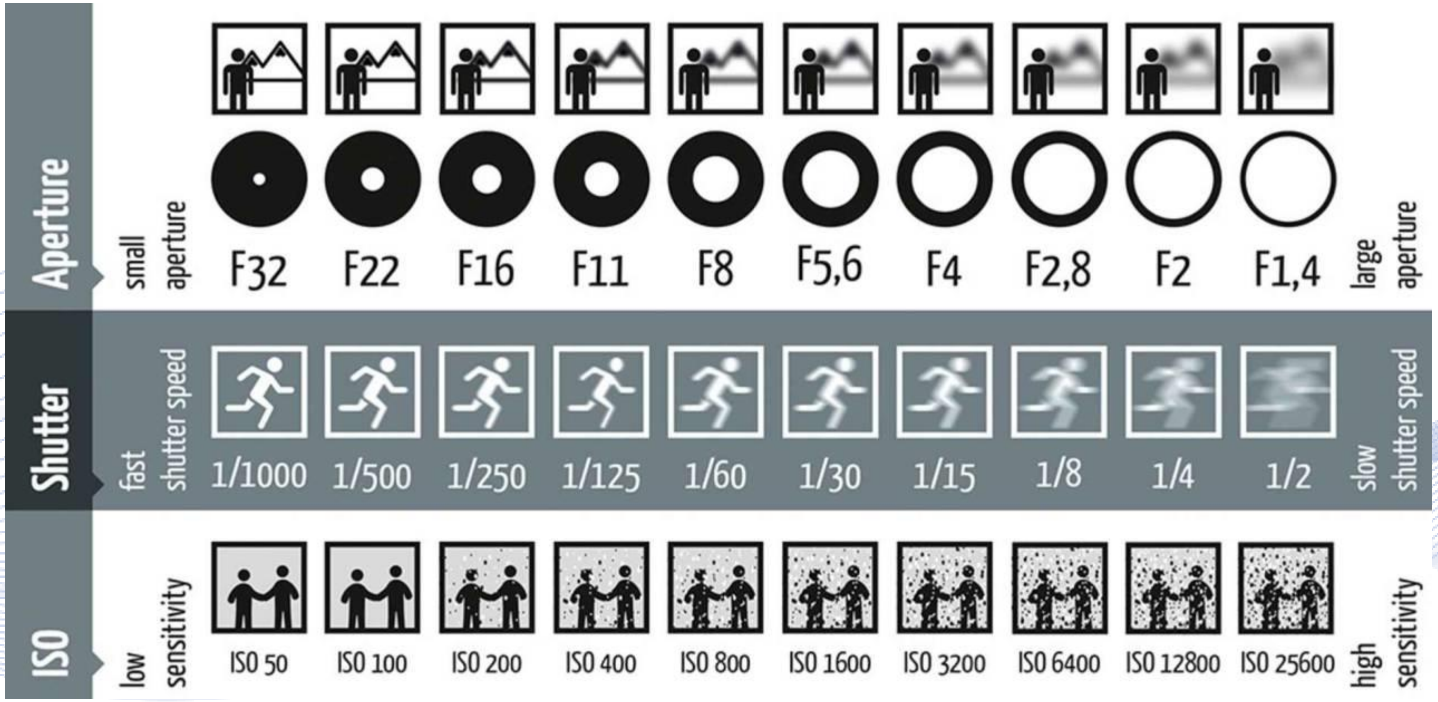


Camera Exposure

- When it comes to exposure, the 3 basic camera terms are: aperture, shutter and ISO.
- ***Aperture*** refers to how “open” or “closed” the iris of a lens is, which affects the amount of light we let in.
- We measure aperture in ***f-stops*** and for larger f-stop numbers we get more closed iris which means that less light passes through.
- Also, by changing the f-stop we can control the depth of field.
- ***Shutter*** defines the time period that we are going to allow light rays to pass through and hit the camera’s sensor.

Camera Exposure

- High ***shutter speed*** is used when we want to capture fast moving scenes or get pictures without motion blur.
- **ISO** refers to sensor sensitivity to light.



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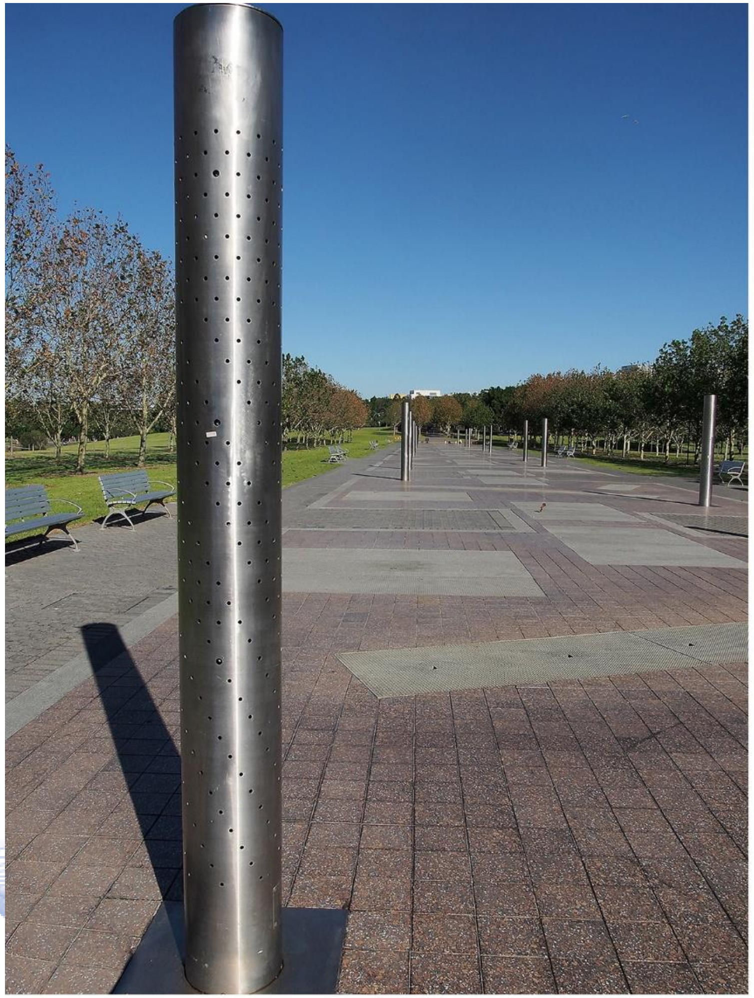
Camera Lens

- ***Camera lens*** are responsible for directing the light rays in order to recreate the scene as accurately as possible on the digital sensor.
- ***Focal length*** of a lens characterizes its angle of view and thus how much magnified will an object look for a given position.
- ***Wide angle lenses*** have short focal lengths, while ***telephoto lenses*** have longer focal lengths.
- ***Zoom*** lens gives you the ability to vary the focal length within a pre-defined range.
- A ***prime or fixed*** focal length lens cannot zoom.

Camera Lens



28mm wide-angle lens

300mm telephoto lens

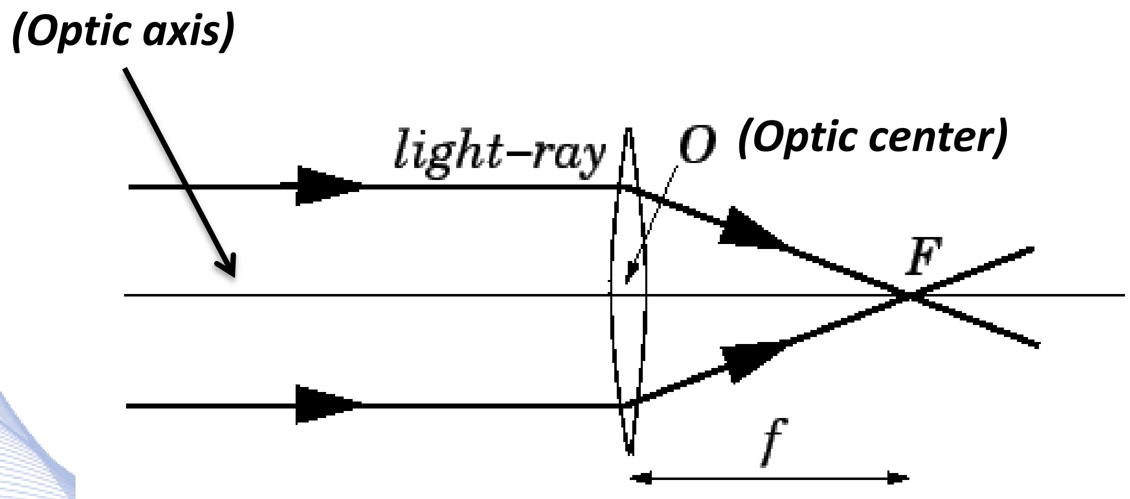
Wide-angle and telephoto lenses [PHO2013].

Optical Lens

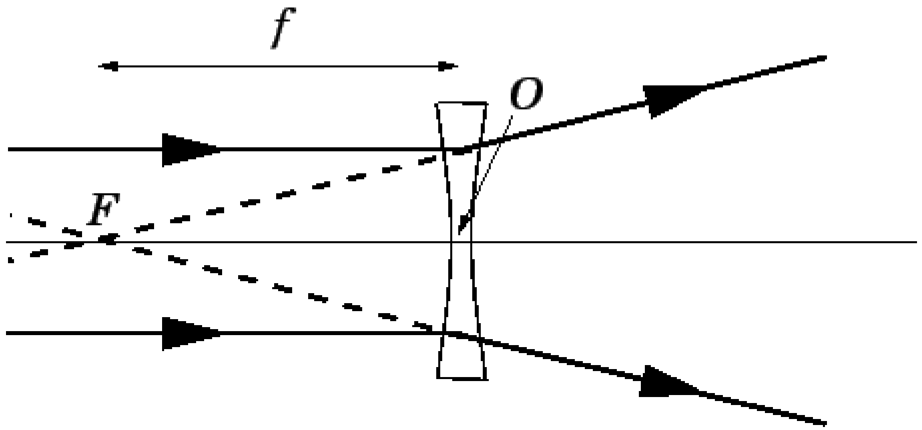
- A lens is a transparent medium (usually glass) bounded by two curved surfaces.
- The two major kinds of lenses are converging and diverging.

- A ***converging lens*** brings all light-rays parallel to optical axis together at the so-called focal point **F**.
- A ***diverging lens*** spreads out all light-rays parallel to optical axis in such a way that they appear to diverge from a virtual focal point **F** in front of the lens.

Optical Lens



a) Converging Lens



b) Diverging Lens

Optical Lens

- ***Lensmaker's equation*** gives us the focal length (f):

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right).$$

  - n: index of refraction
  - R_1, R_2: radii of curvature of the two surfaces

- Thin lens equation:

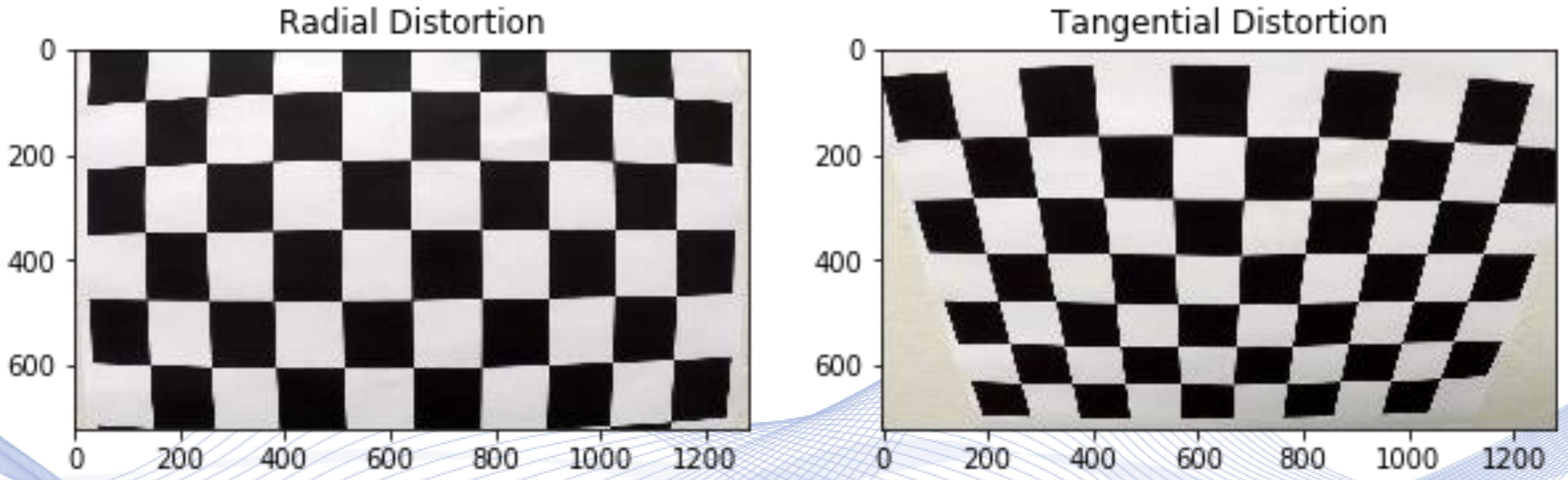
$$\frac{1}{d} + \frac{1}{d'} = \frac{1}{f}$$

  - d: object distance
  - d': image distance

Lens Distortion

- A common problem that occurs when trying to produce a digital image via a camera is lens distortion.
- This causes physical straight lines to appear as curves in the output image.
- The two main categories of lens distortions are:
  - ***Radial distortion.***
  - ***Tangential distortion.***

Lens Distortion

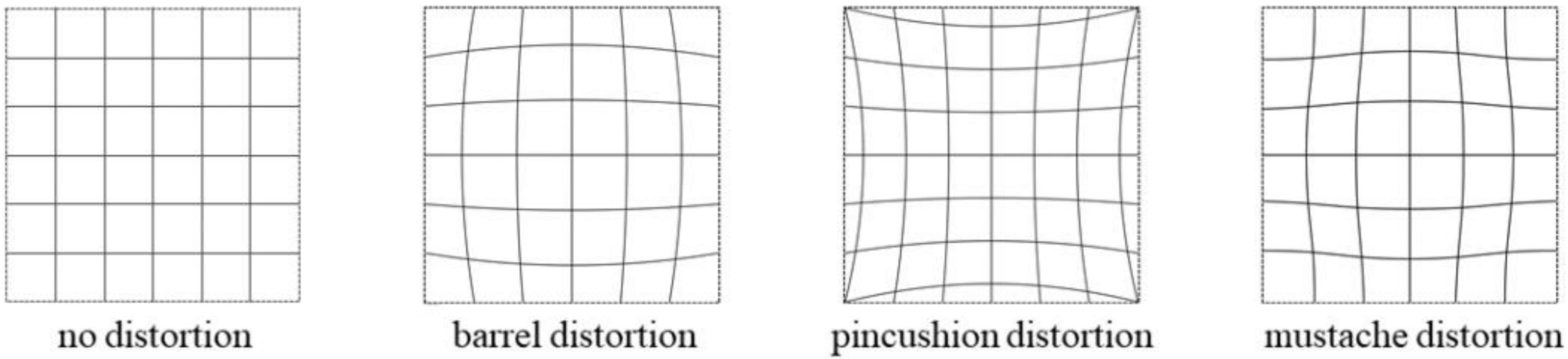


Lens Distortion

Radial distortion

- It is caused by the geometric shape of the lens and affects the imaging of straight lines.
- Most often, radial distortion affects to a much greater degree, the geometry of the image than tangential distortion.
- The types of radial distortions are:
  - ***Barrel Distortion.***
  - ***Pincushion distortion.***
  - ***Mustache Distortion.***

Lens Distortion



- We can observe that radial distortions are symmetric about the image center.
- Barrel distortion is found in wide-angle/panoramic images, while pincushion distortion is associated with telephoto lenses to eliminate globe effects.

Lens Distortion

- To correct radial distortion, we use:

$$x_{ud} = x_d(1 + k_1 r^2 + k_2 r^4 + k_3 r^6),$$

$$y_{ud} = y_d(1 + k_1 r^2 + k_2 r^4 + k_3 r^6),$$

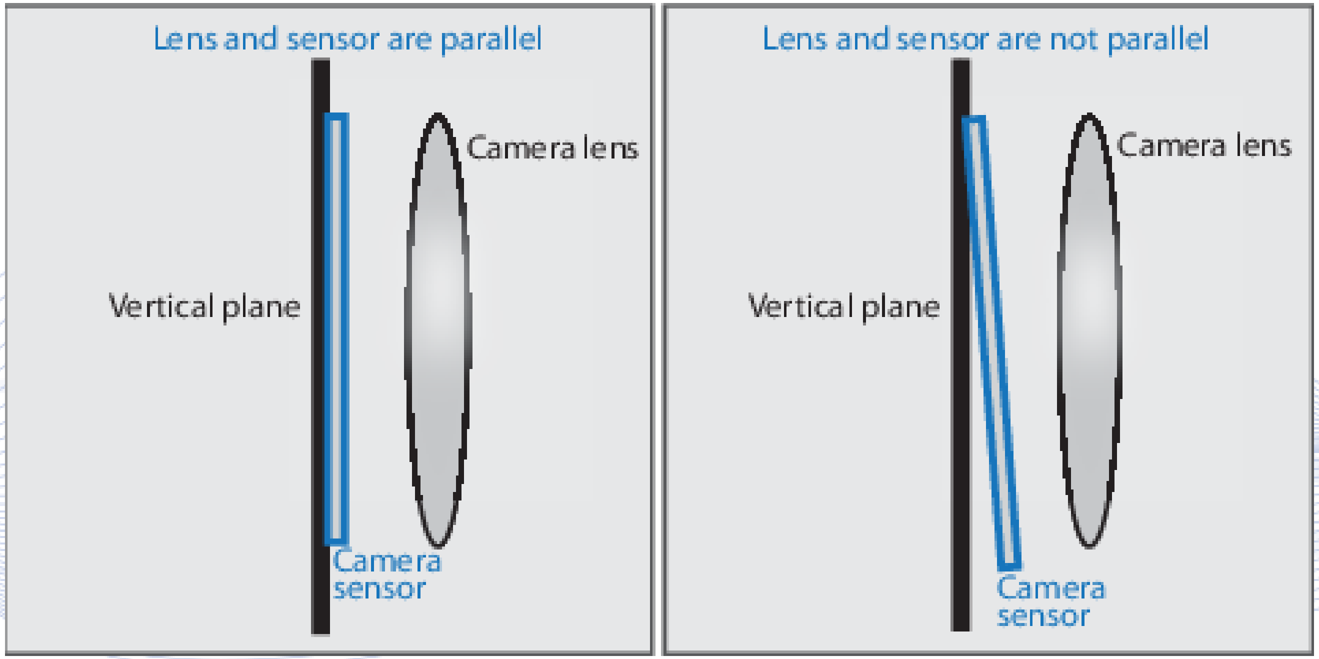
$$r^2 = {x_d}^2 + {y_d}^2.$$

- where $x_d = \frac{x^C}{z^C} = \frac{u-u_0}{f_x}$ and $y_d = \frac{y^C}{z^C} = \frac{v-v_0}{f_y}$ are obtained from the distorted image.
- k_1, k_2 and k_3 are three parameters used for radial distortion correction.

Lens Distortion

***Tangential distortion*:**

- It occurs when the lens installed is not perfectly parallel to the image plane.



(3.1) Source: Mathworks

Lens Distortion

- The correction formula for tangential distortion is:

$$x_{ud} = x_d + [2p_1 x_d y_d + p_2(r^2 + 2{x_d}^2)],$$
$$y_{ud} = y_d + [p_1(r^2 + 2{y_d}^2) + 2p_2 x_d y_d].$$

- where p_1 and p_2 are two intrinsic parameters that can be estimated using the appropriate collection of images.

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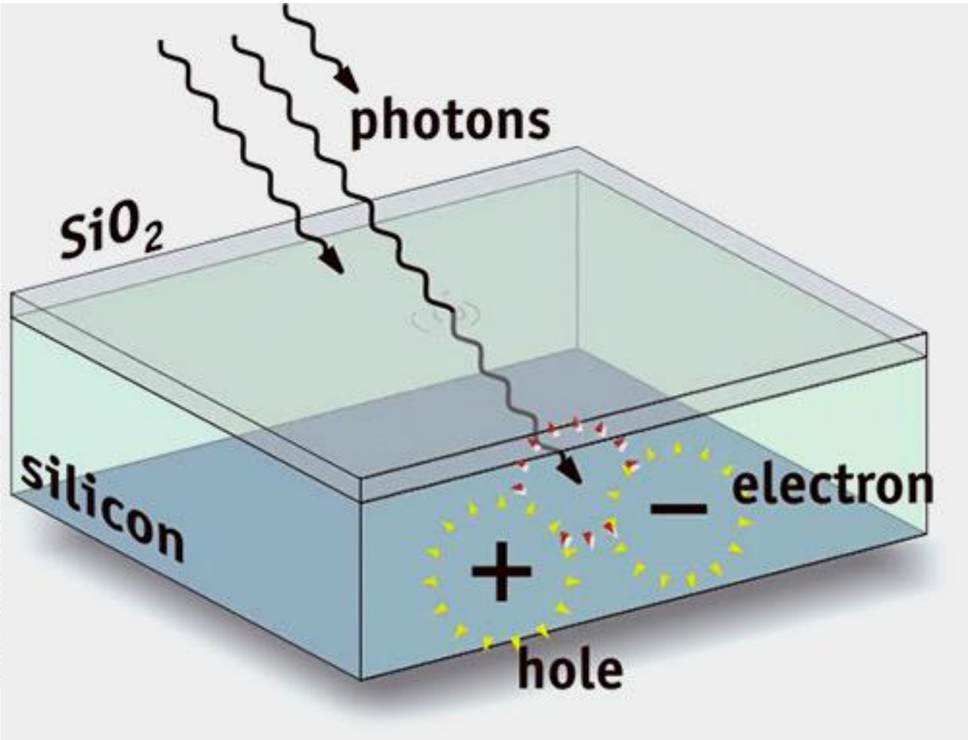
Sensor Technologies

- ***CCD*** and ***CMOS*** are the two most common sensor technologies that digital cameras use are.
- Both convert light energy into electrons.



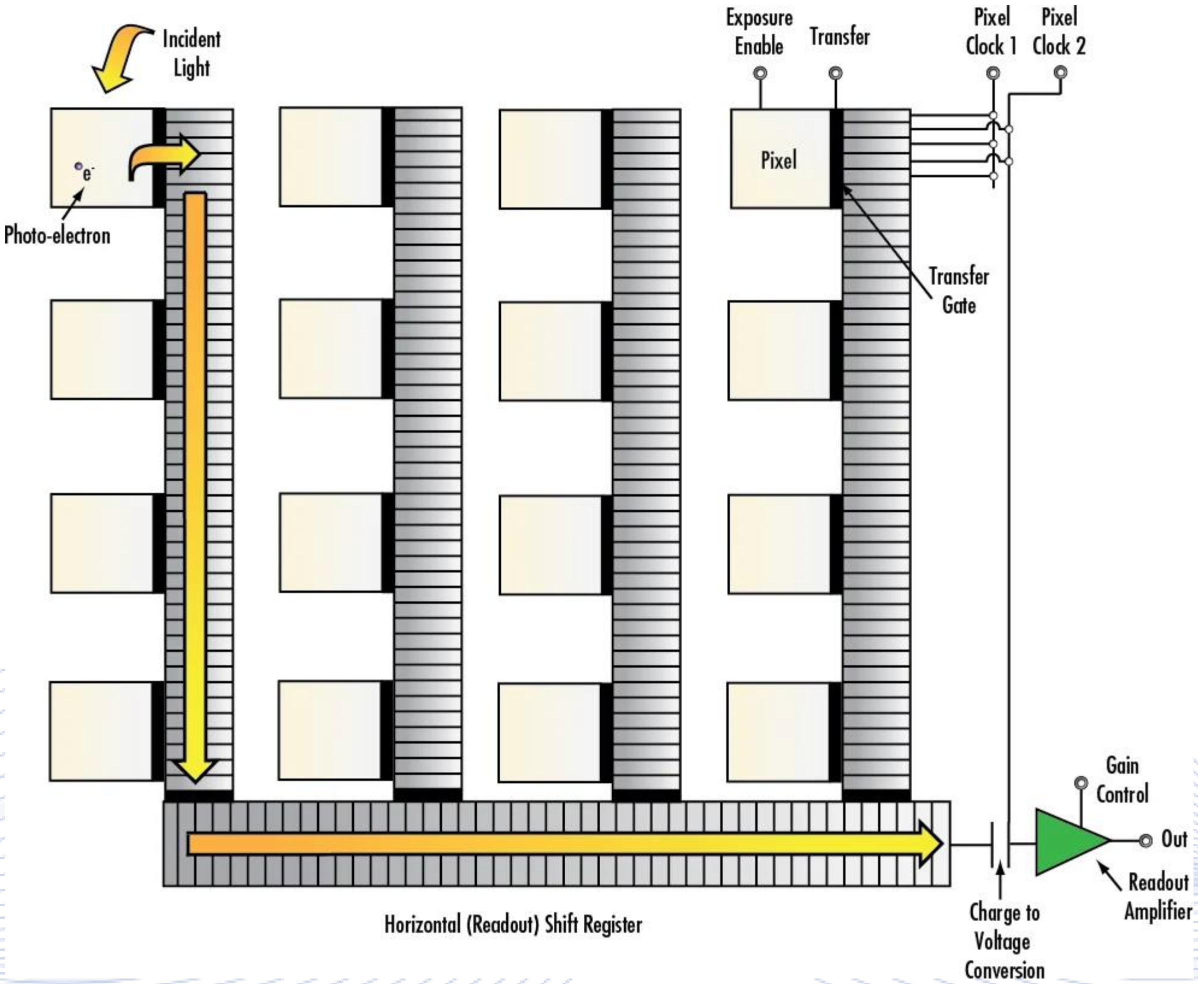
Light sensing [LIT2001] .

Sensor Technologies

Charge-Coupled Device (***CCD***)

- A silicon chip that holds an array of photosensitive areas.
- Charged packets are transferred from these areas into a shift register.
- Ultimately, electron energy passes into an analog-to-digital (A/D) converter which outputs the pixel value.
- Efficiency in speed relies on the advance of charged packets across the chip. Thus, it is limited.
- Yet, this phenomenon contributes to the high sensitivity and pixel-to-pixel consistency of the CCD (uniformity).

Sensor Technologies



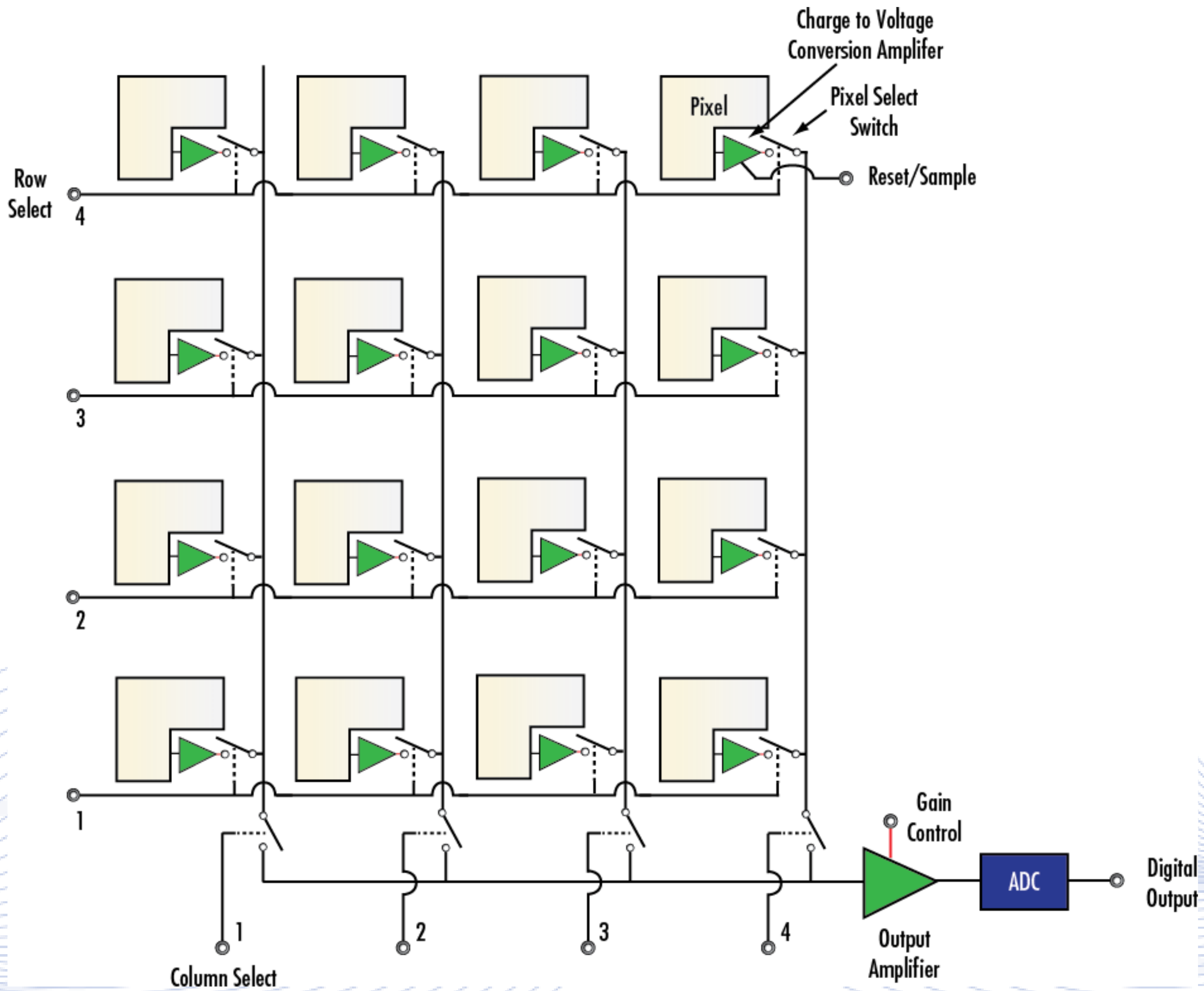
CCD architecture [EDM2021].

Sensor Technologies

Complementary Metal Oxide Semiconductor (***CMOS***)

- The charge from the photosensitive pixel is converted to a voltage at the pixel site and gets amplified
- The signal is multiplexed by row and column with the rest of the chip.
- Each pixel has its own charge-to-voltage conversion, and often also contains amplifiers, noise-correction, and digitization circuits
- This parallel process allows for high bandwith/speed but decreases its uniformity.

Sensor Technologies



CMOS architecture [EDM2021].

CCD VS CMOS

- ***Responsivity*** is the amount of signal the sensor delivers per unit of input energy. CMOS are slightly superior to CCD.
- ***Dynamic range*** is the ratio of a pixel saturation level to its signal threshold. CCDs gives better results.
- ***Uniformity*** is the consistency for different pixels under the same illumination circumstances.
    - CMOS sensors are traditionally worse in that area, but latest CMOS technologies come close to the CCD.
- ***Speed.*** CMOS has bigger speed than CCD.

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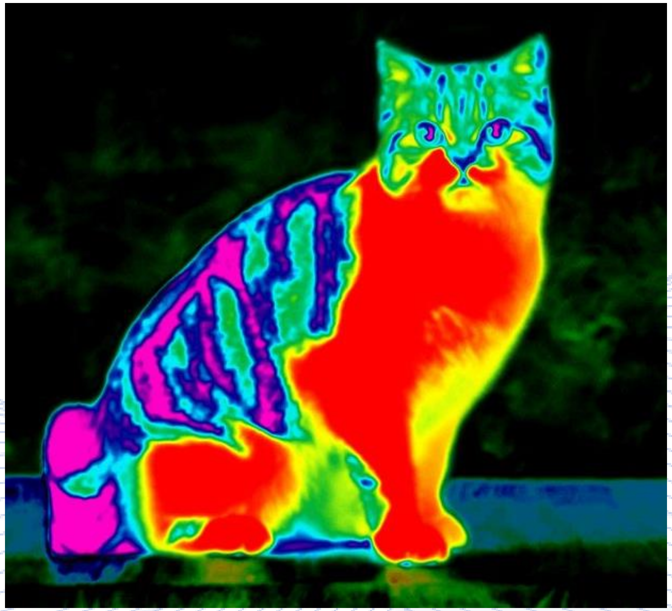
Image Types

- The image acquired depends on the type of camera (and film) that we use.

a) X-ray image



b) Infrared image

c) Visible light image

Image Types

The three basic types of images are:

- ***Binary images***: Each pixel can take a value of 0 or 1: $g(x, y) \in \{0,1\}$.

- ***Gray-scale images***: Each pixel can take a value from 0 to 255:

$$f(x, y) \in \{0, \dots, 255\}$$

- ***Color images***: Each pixel consists of three channels (RGB). Each of them is assigned with a value from 0 to 255: $[f_R(x, y), f_G(x, y), f_B(x, y)]^T \in \{0, \dots, 255\}^3$.

Image Digitization

- As we previously seen the sensor produces an internal 2D plane which is basically a projection of the 3D scene that has been captured.
- In order to represent that 2D plane digitally in a computer we need to go through the process of digitization.
- Specifically, this consists of two basic subprocess:

1. ***Spatial sampling*** of the 2D plane.
2. ***Quantization*** of the light intensity values that has been taken via the sensor.

Quantization

- Each point in the 2D plane has a light intensity value that ranges from 0 to ∞, so it must be quantized.
- Usually we produce 8-bit images, so for example in a gray-scale image we can use up to $256 = 2^8$ gray levels.

a) 256 gray levels *b) 64 gray levels* *c) 16 gray levels* *d) 2 gray levels*

- Correspondingly, in RGB values should be quantized for each channel.

Quantization

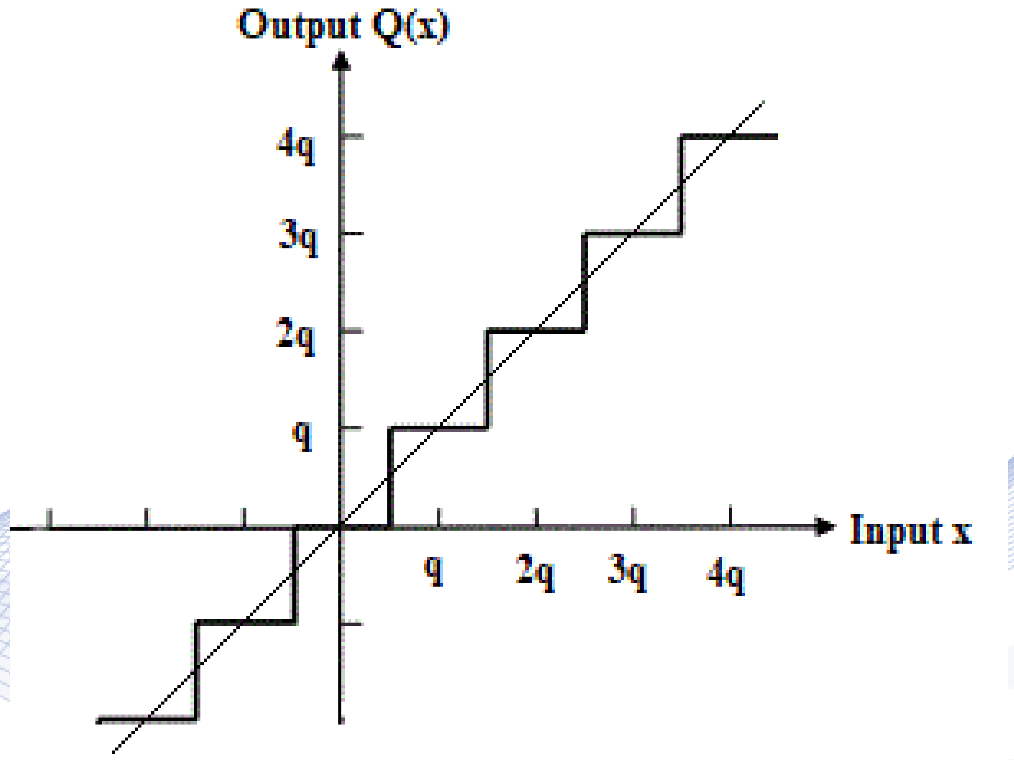
- For uniform distribution, we define q as the quantization step:

$$q = \frac{1}{2^b}.$$

- for 8-bit images we have $b = 8$.

- And to quantize the light intensity levels:

$$kq, \qquad k = 0,1,2, \ldots, 2^b - 1.$$



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Quantization

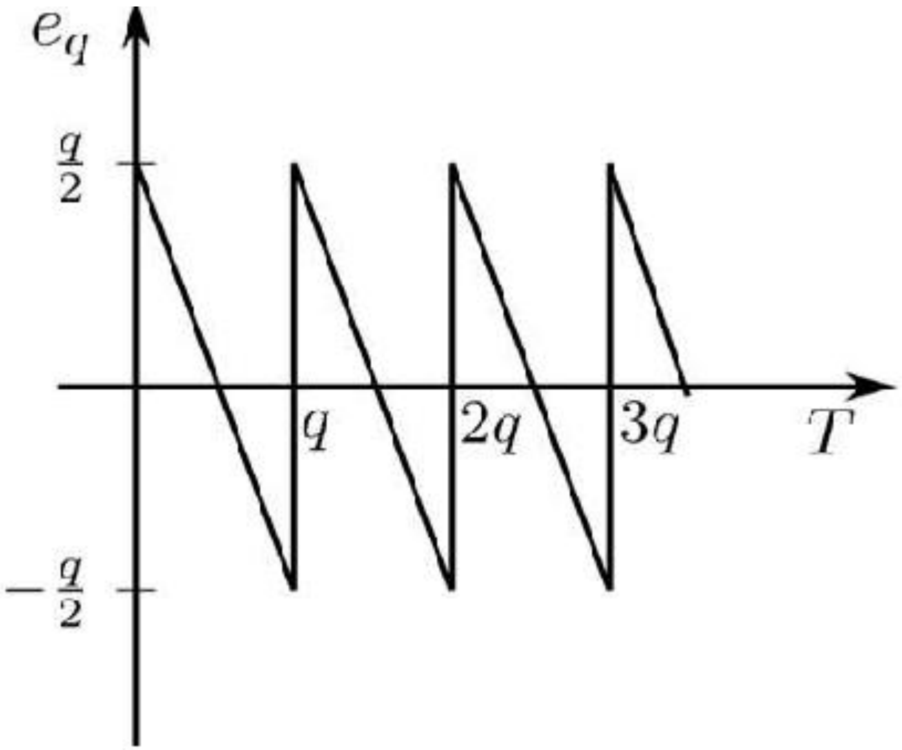
- ***Mean square Error*** (***MSE***) of quantization:

$$e_q = E\left[\left(x - Q(x)\right)^2\right] = \int_{-\infty}^{\infty} \left(x - Q(x)\right)^2 p(x)dx.$$

- $p(x)$ is distribution of input x.

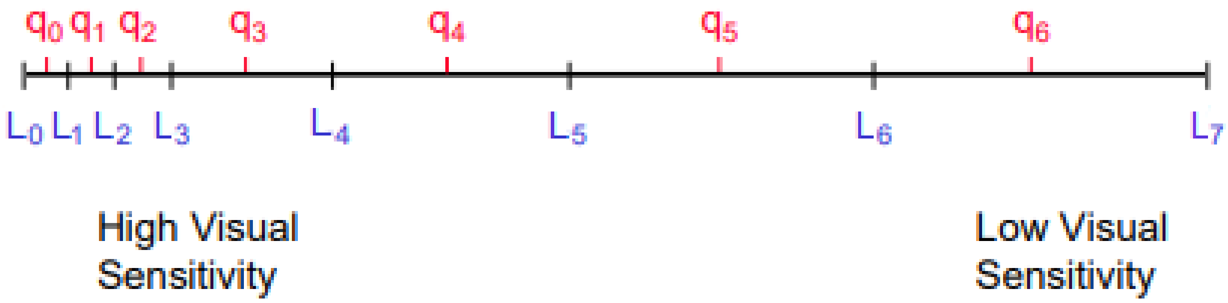
- ***Signal-to-Noise Ratio*** (**SNR**) is given by:

$$SNR = 20log_{10}\left(2^b\right) \approx 6.02b\ dB.$$

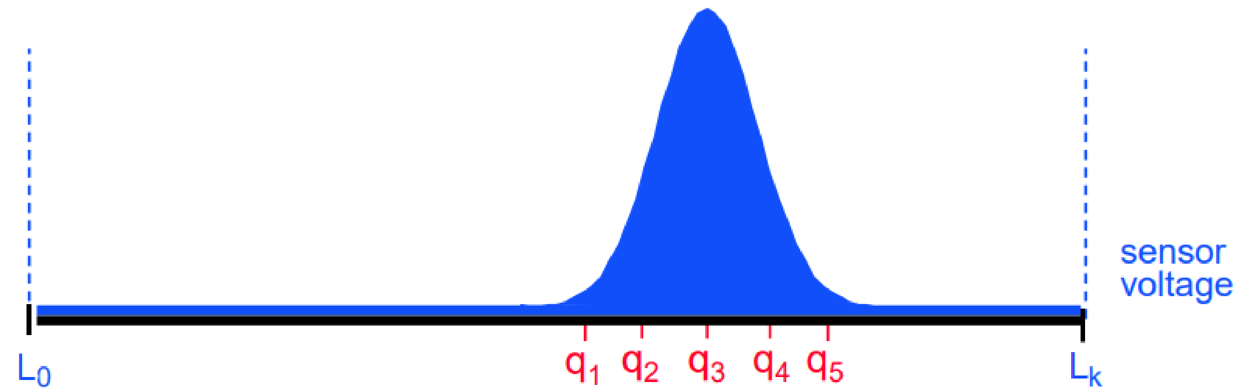


Non-uniform Quantization

- Using Weber's law, we can quantize regarding visual sensitivity:



- We can also quantize according to sensor output:



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Gamma (γ) Correction

- Gamma defines the relation between the given pixel value and its actual luminance.
- Cameras do not capture luminance in a linear fashion so in order to correct that we use the gamma correction:

$$v_{out} = {v_{in}}^{\gamma}.$$

- Image displays also suffer from non-linear light intensity depiction.
- Most common Gamma used are 2.2, 2.4, 2.6.

Gamma (γ) Correction

Gamma Correction [ROS2021].

Contrast equalization

- ***Just Noticeable Difference*** (***JND***) is the minimum amount something must be changed for the difference to be apparent.
- Perceived contrast is a function of the intensity, specifically via **Weber's law** we get:

$$\frac{\Delta f}{f} = k.$$

where f is the intensity and Δf is the intensity difference (contrast).

- This implies that sometimes human eye can not perceive the contrast between different intensities on an object and its background.

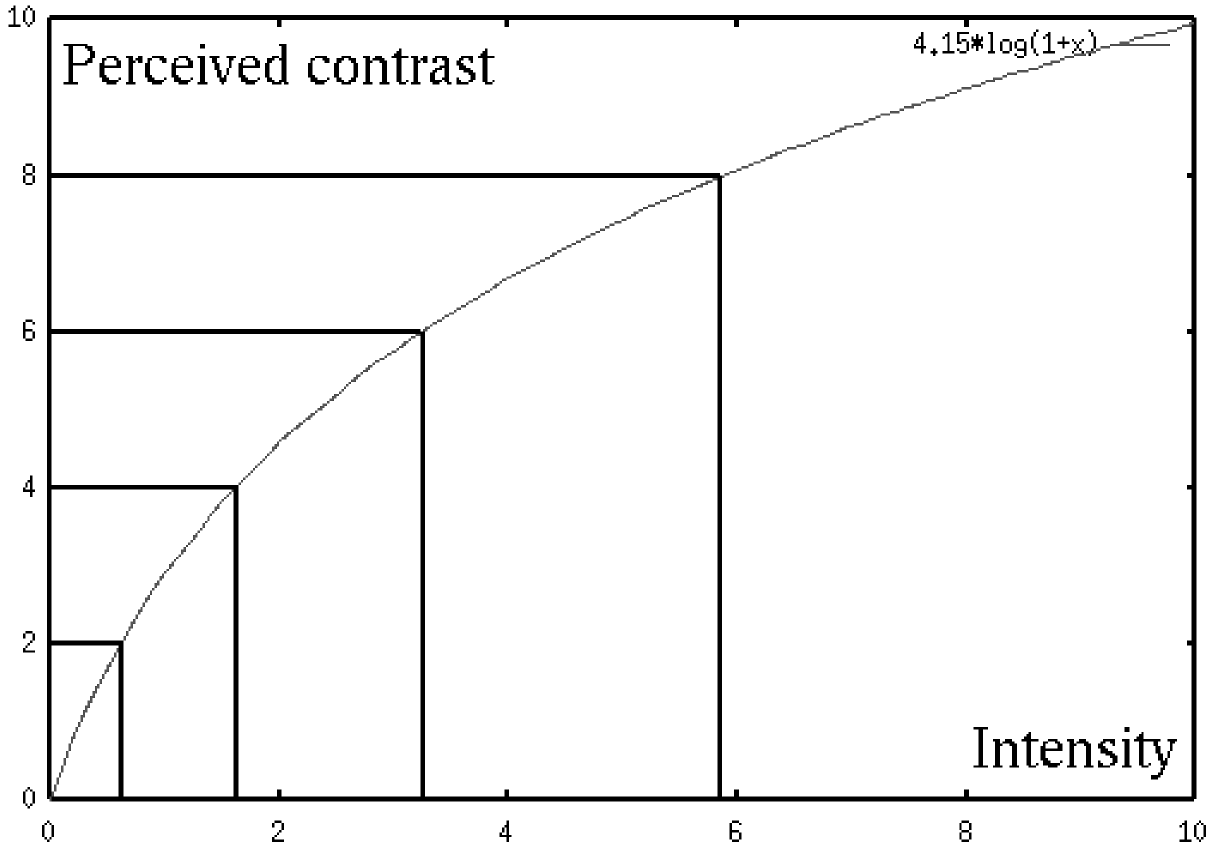
Contrast equalization

- For example, a high contrast $\Delta f = 200 - 100$ at a background intensity $f = 100$ is observed the same way as lower contrast $\Delta f = 20 - 10$ with $f = 10$ (because they both equal 1).

- This basically means that we are less sensitive when the intensity level is high.

- **Perceived contrast equation:**

$$y = a\,log(1 + x).$$



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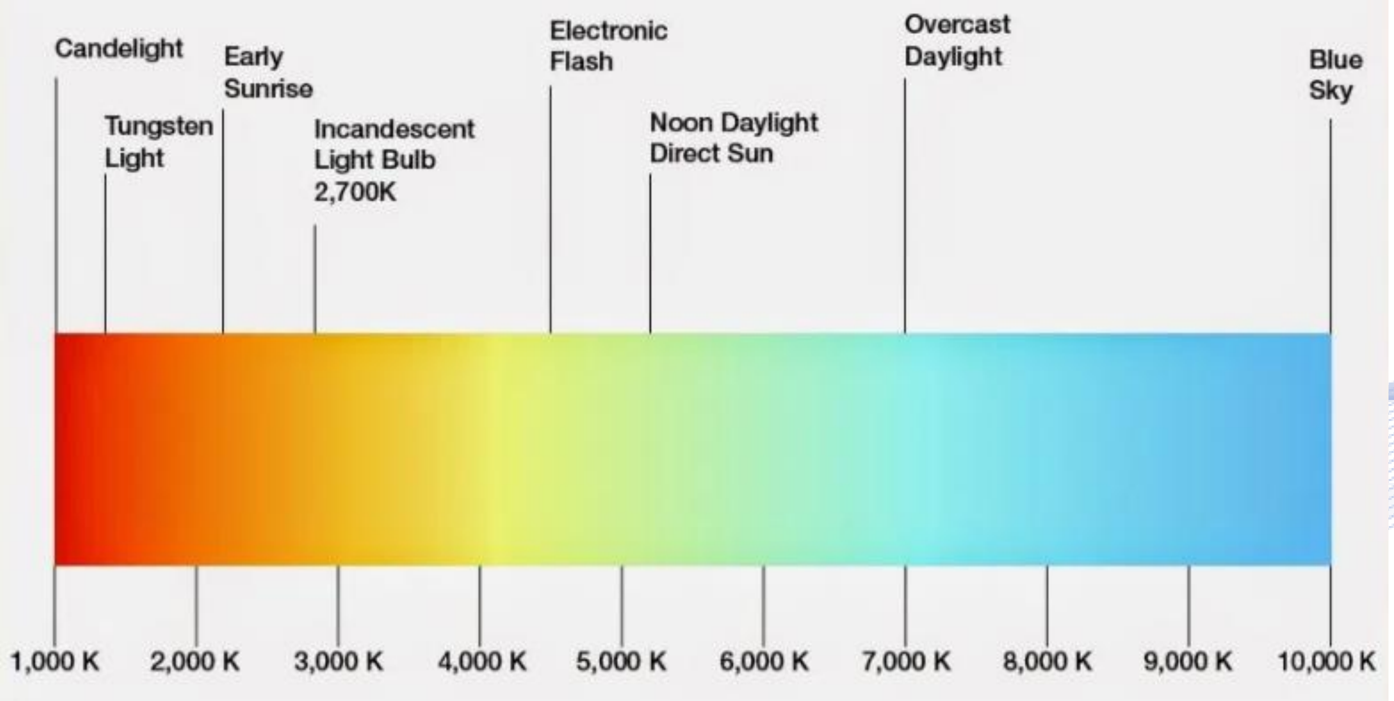
White balance

White balance is the process of removing unrealistic colors that are cast into the image, in order to achieve natural ones.

- To achieve that we must consider the color temperature of the light source.

White balance

- We measure ***color temperature*** in Kelvin (K) and is a physical feature of light.
- As the color temperature rises, we move from warm colors to cooler ones.



White balance

White balance in photography [WIL2021].

White balance

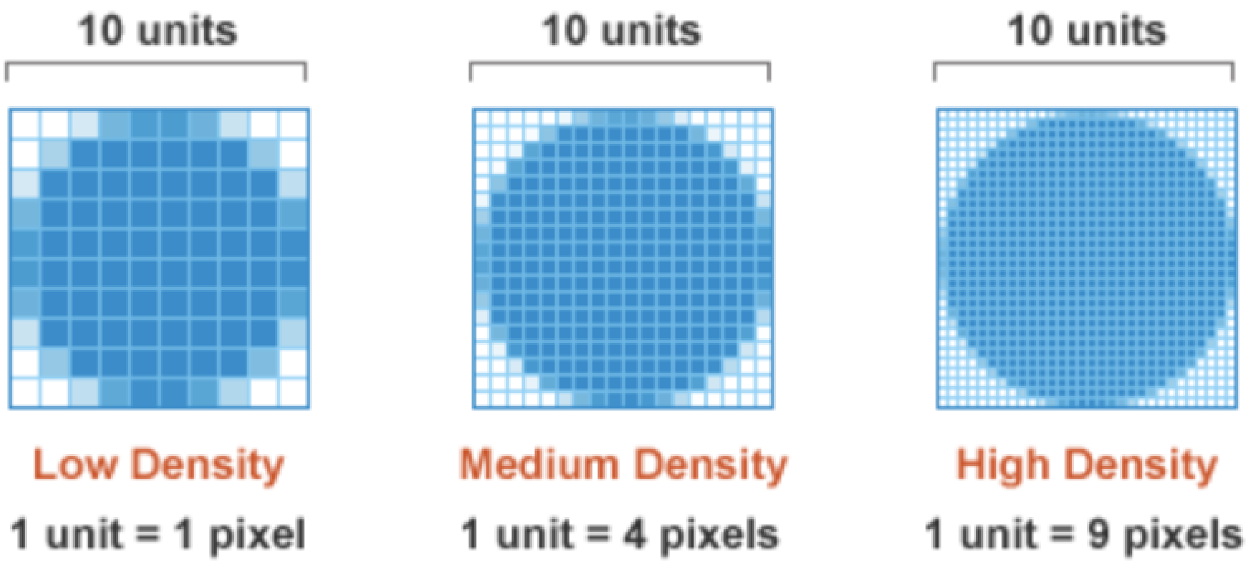
- To balance the colors in a picture we need to scale the relative luminances, by using as reference a white/neutral object in the image.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 255/R'_w & 0 & 0 \\ 0 & 255/G'_w & 0 \\ 0 & 0 & 255/B'_w \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}.$$

- where R, G and B are the color balanced RGB values of a pixel in the image; R', G' and B' are the RGB components before color balancing and R'_w, G'_w, B'_w corresponds to the RGB values of a pixel that is believed to be a white surface.

Spatial Sampling

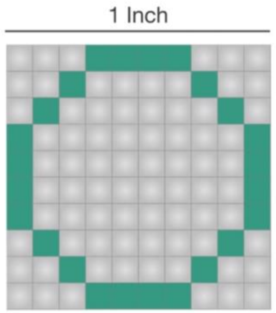
- The continuous 2D plane needs to be spatially sampled in order to be rasterized.
- The more pixels a rasterization unit has the best of a resolution we can achieve.



Different pixel densities [RAH2021].

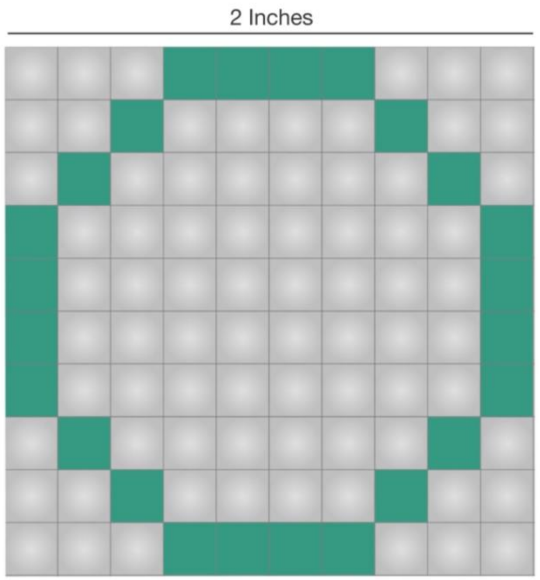
Image Resolution

- Two frequently misunderstood terms are ***image size*** and ***image resolution*.**
- Image size refers to **pixel dimensions** of the image while image resolution refers to **pixel density** (PPI). (Note: DPI≠PPI)

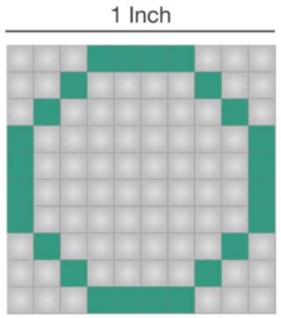


Pixel Dimensions = 10x10 px
Resolution (Pixel Density) = 10 Pixels/Inch

> ➢ *If we increase the physical size (inches) and keep the same dimensions (pixels) we have lower resolution.*

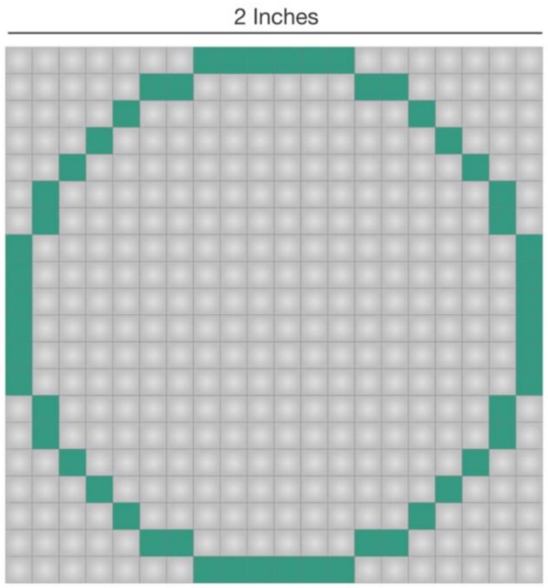


Pixel Dimensions = 10x10 px
Resolution (Pixel Density) = 5 Pixels/Inch



Pixel Dimensions = 10x10 px
Resolution (Pixel Density) = 10 Pixels/Inch

> ➢ *We need to increase the pixel dimensions when physical size gets bigger in order to preserve the resolution.*



Pixel Dimensions = 20x20 px
Resolution (Pixel Density) = 10 Pixels/Inch

Sampling Rate

- **Aliasing** occurs when sampling a continuous signal/image the sampling rate isn't high enough and results to faulty capture of the image.

- From **Nyquist rule**, the image sampling rate should be greater than double the maximal spatial image frequency in the image to avoid aliasing:

$$f_{sx} > 2f_{xmax}, \qquad f_{sy} > 2f_{ymax}.$$

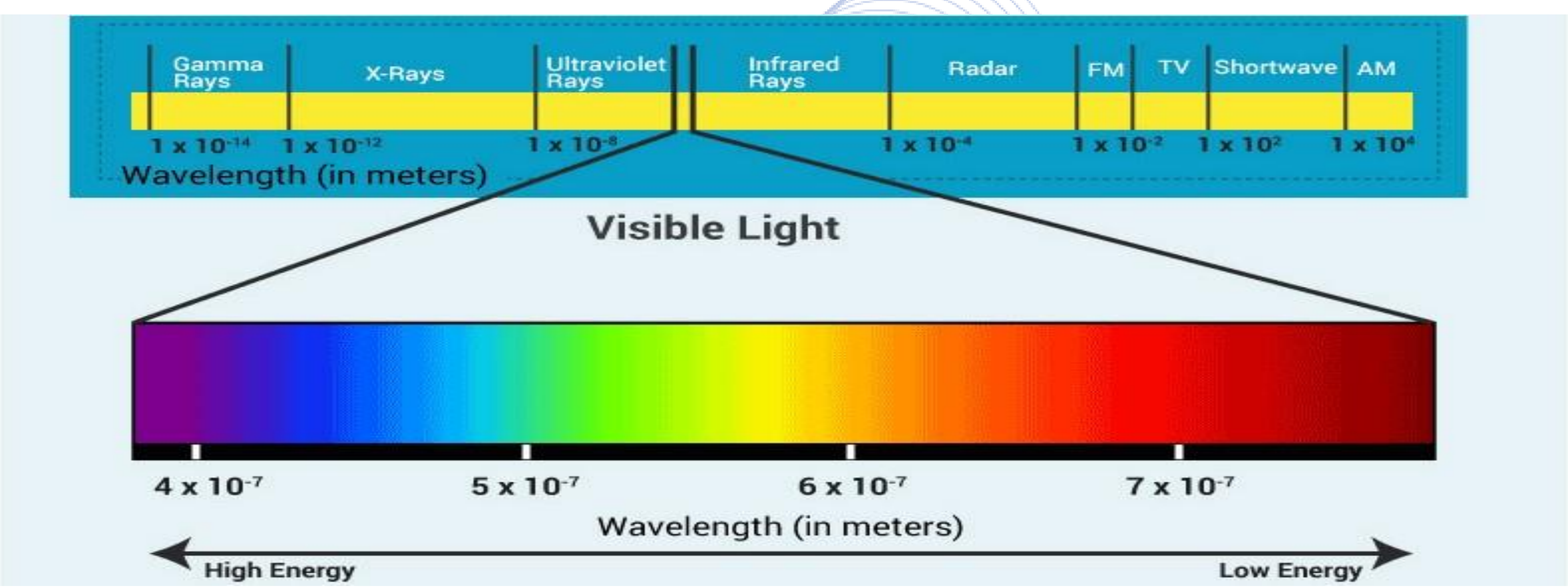
- Problematic sampling process can lead to picture artefacts, like Moire patterns.

Sampling Rate

- Examples of Moire patterns:

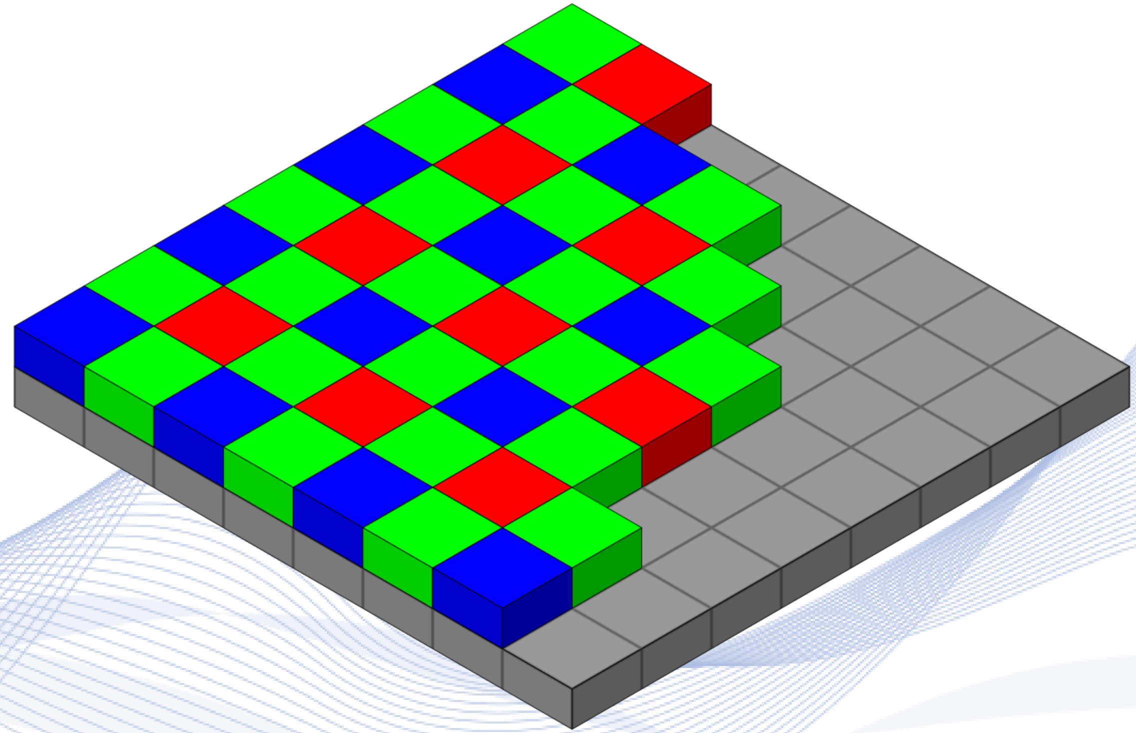
Demosaicing

- **Color filter array** or **color filter mosaic** is an array consisting of tiny color filters that are placed in front of the camera sensor.
- They are essential for capturing RGB images because sensor by themselves can only produce gray-scale images.
- Each color filter allows different wavelength range of light to pass in order to obtain information about the color of light.



Demosaicing

- The most common type of Color filter array is the **Bayer filter.**
- The filter patterns consists of 50% green, 25% red and 25% blue.
- This happens because human eyes are more sensitive to green and distinguish luminance intensity better in green channel than in red or blue.



Bayer Filter [BAY2021].

Demosaicing

- To construct the full RGB image an algorithm is implemented which interpolates the missing color values for all the pixels.

- Simple algorithms that implement demosaicing interpolation are:

  - **Nearest neighbor interpolation**: simply copies the closest pixel of the same color channel (low quality method)

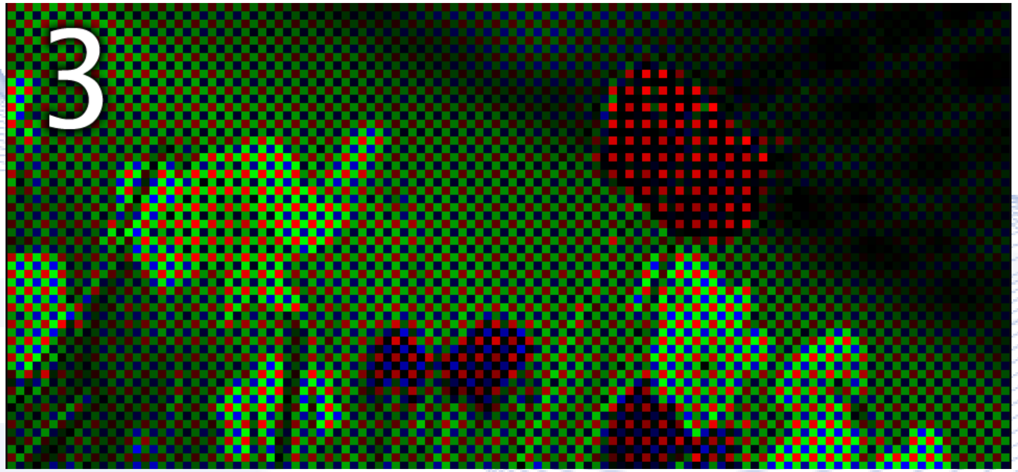
  - **Bilinear interpolation**: where for example a blue value is computed for a non-blue pixel as an average of the four nearest blue color pixels (or two nearest if it's linear interpolation)

- Better quality methods include bicubic interpolation, spline interpolation.

Demosaicing

1) Original scene

2) Gray-scale output of sensor array



3) Output array via Bayer filter

4) Reconstructed image after interpolation

Demosaicing interpolation [BAY2021].

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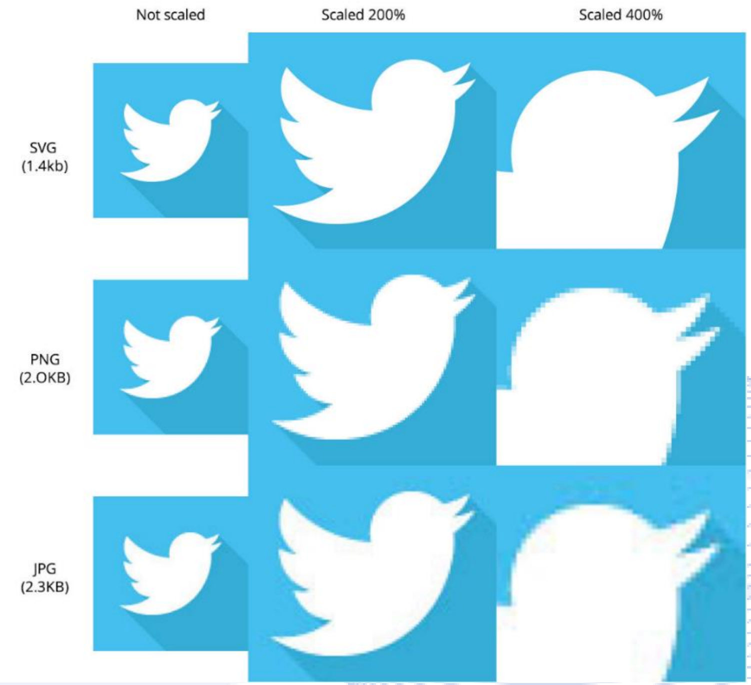
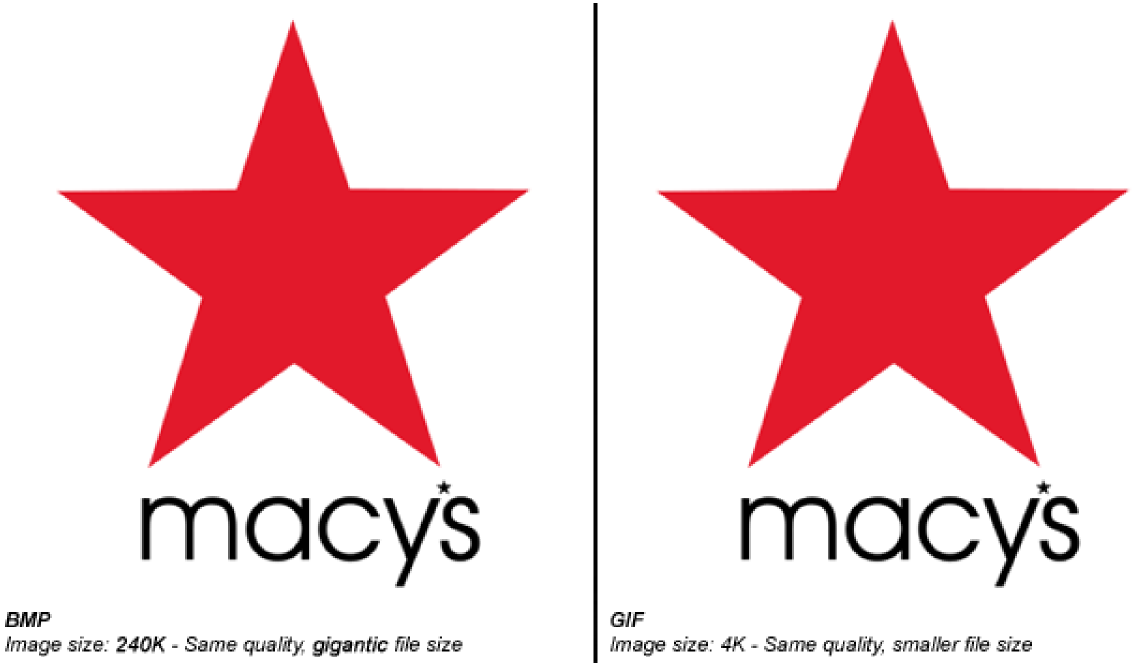
Image File Formats

- The types of formats that an image data can be stored are:
  - **Uncompressed format**: Contains all the data without any compression applied. This results in very big image sizes. (TIFF, RAW, BMP)
  - **Compressed format**: Compression algorithms are applied, 2 subcategories:
    - **Lossless**: File size is reduced without losing any of the uncompressed image data. (PNG, GIF, FLIF)
    - **Lossy**: File size is reduced but data from the uncompressed image are thrown away which can lead to noise/artifacts appearing in the image. (JPEG)

Image File Formats

- **Vector format**: Unlike the previous ones, vector format (SVG, CGM) does not apply rasterization, instead it contains a geometric description of the image. Therefore, it can be displayed smoothly at any desired size.





Scalable Vector Graphic Examples [REA2021] .

Image Acquisition

- Light Reflection
- Camera Structure
- Camera Lens
- Sensor Technologies
- Image Digitization
- Image Corrections
- Image File Formats
- **Scanners**
- Image noise

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Scanners

- Most common types of scanners are:
  - **Flatbed scanners**: Most versatile and commonly used scanners.
  - **Sheet-fed scanners**: Similar to flatbed scanners except that the document is moving and the scan head is fixed.
  - **Handheld scanners**: Same basic technology as flatbed scanner but rely on the user to move them. Typically, mediocre quality but is a quick-scan method.
  - **Drum scanners**: Mostly used by publishing industry to obtain incredibly detailed images.

Scanners

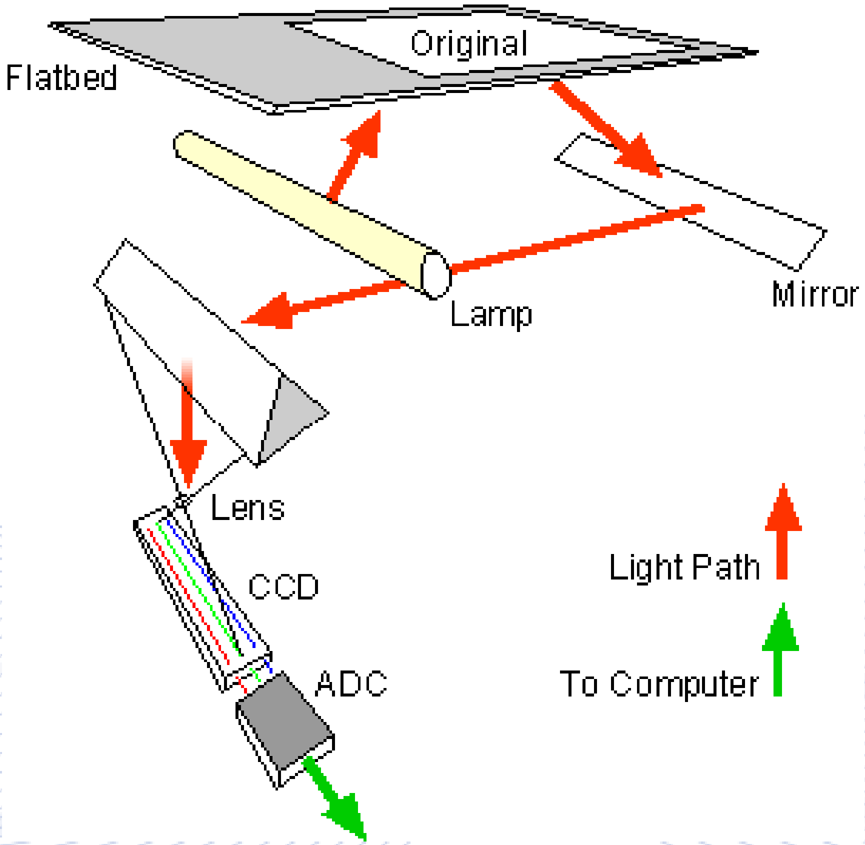
a) Flatbed scanner

b) Sheet-fed scanner

c) Handheld scanner

d) Drum Scanner

Scanners



Anatomy of the flatbed scanner [COP2021].

Scanners

<u>Scanning process</u>:

- Document is placed on the glass plate and the **scan head** (mirrors, lens, CCD) is placed in the starting position.
- Lamp illuminate the sheet of paper and reflects back to the **mirror** while the scan head is moving slowly across the document.
- The image of the document is reflected from the first **angled mirror** to another mirror and then finally onto a **lens**.
- The lens focuses the image through a filter on the **CCD**.
- Finally, A/D converter is used to get the digital output of CCD.

Image Acquisition

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Image noise

- Image noise can be mainly of two kinds:
  - **Photoelectronic noise:** Generated by the image sensor and the circuits inside the digital camera.
  - **Film-Grain noise:** Optical texture that appears mainly in processed photographic film. It can be added on deliberately for stylistic purposes or to make a digital image look less "flat".
- Most common noise types observed in digital images are Gaussian noise, Poisson noise, Speckle noise and Salt-and-Pepper noise.

Image noise

(Digital Noise)

(Film Grain)

Image noise

Gaussian noise:

- Arises in amplifiers or detectors and is caused by natural sources (e.g. thermal vibration of atoms).
- Gaussian noise mainly distorts gray values in the image.
- PDF of gaussian noise is given by:

$$p(f) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(f-\mu)^2}{2\sigma^2}}$$

- f represents the gray level, μ the mean and σ the standard deviation

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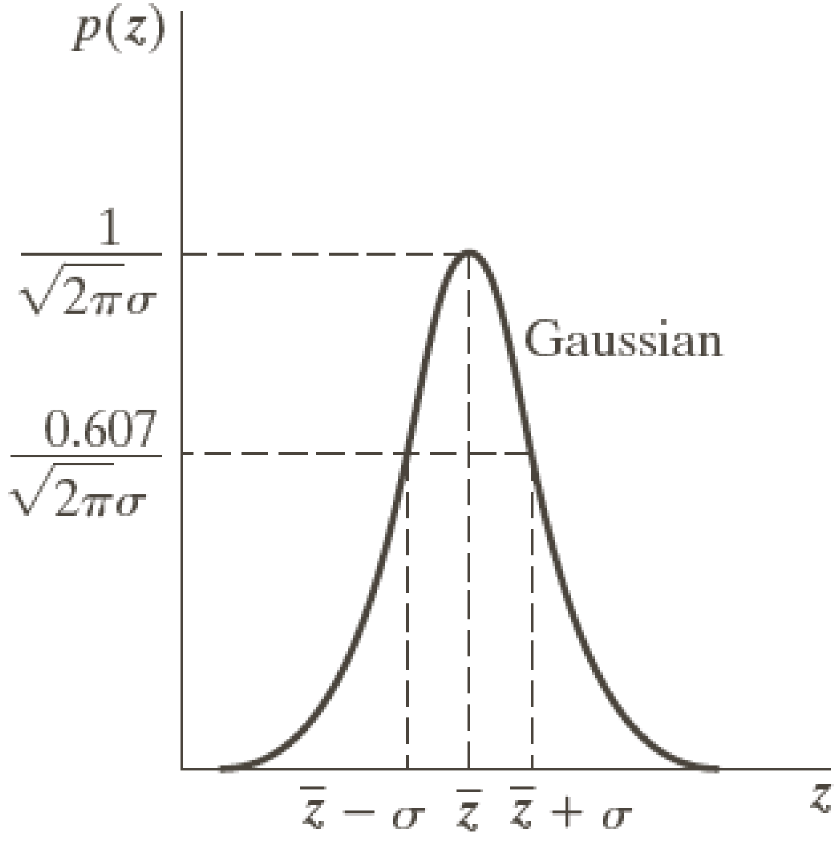
Image noise



Gaussian noise PDF.

Image noise

Salt-and-Pepper noise:

- Usually caused by sharp and irregular disturbances in the image signal.
- Also called impulse noise because it consists of black and/or white impulses which alter random pixels in the image.
- Model:

$$g(i,j) = \begin{cases} z(i,j), & \text{with probability } p \\ f(i,j), & \text{with probability } 1-p. \end{cases}$$

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Image noise

Speckle noise:

- Multiplicative type of noise that inherently exists in systems such as active radar and ultrasound.
- It's caused by the interference of the returning wave collected by the transducer.
- It can be expressed by:

$$g(n,m) = f(n,m) * u(n,m) + \xi(n,m)$$

- where $g(n,m)$ is the observed image, $u(n,m)$ multiplicative component and $\xi(n,m)$ additive component of the speckle noise.

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Image noise

Poisson noise (or Shot noise):

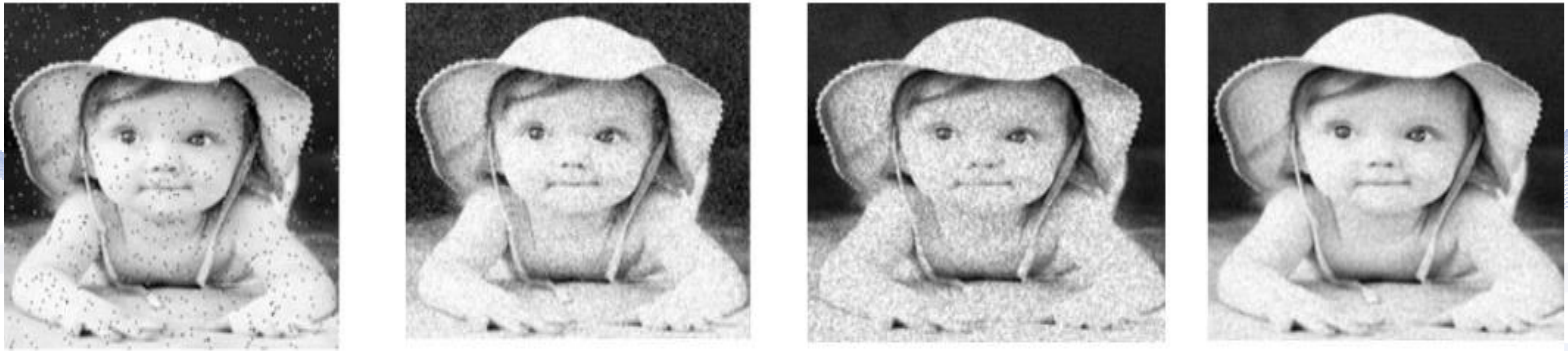
- Mainly appears in the brighter parts of the image and is caused by fluctuations of the number of photons detected.
- Probability distribution function for each pixel is given by:

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

- $\lambda > 0$ is a Poisson distribution parameter.

Image noise

(Original)



a. Salt & pepper noise b. Gaussian noise c. Speckle noise d. Poisson noise

Various image noise types [SAR2016].

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Q & A

Thank you very much for your attention!

More material in
http://icarus.csd.auth.gr/cvml-web-lecture-series/

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