Digital Image Formation summary

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Information Analysis Lab

Digital Image Formation

- **Image formation**
- Optical sensors and cameras
- Image digitization
- Image noise

Digital Image Formation

An image is the optical representation of an object illuminated by a radiating source.

Image formation involves:

- Object;
- Radiating/illumination source;
- Image formation system (camera).

Primary image formation model:

- visible light reflected on an object.
- Other modes: X-ray, ultrasound, seismic sources.

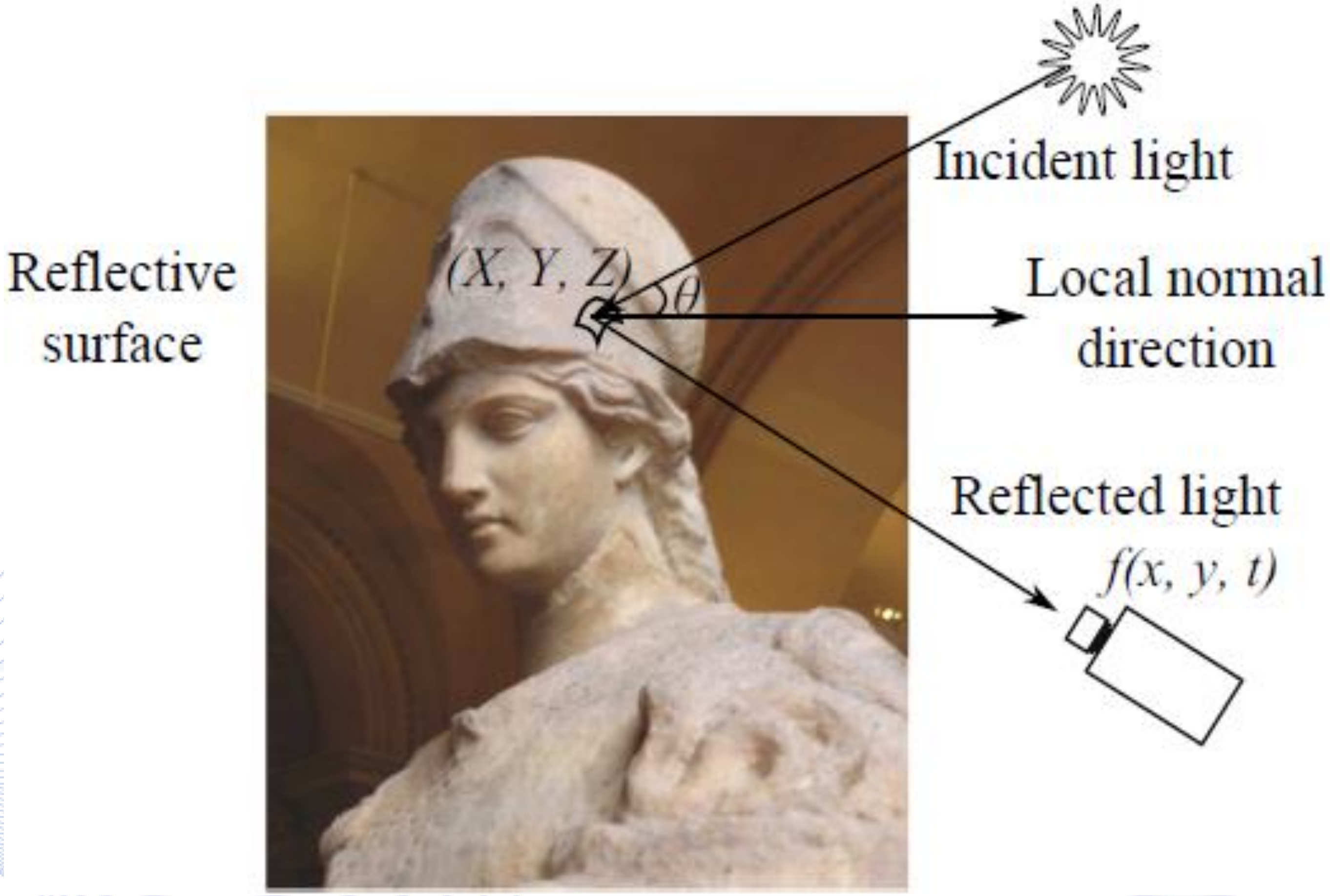
Light reflection

- Objects reflect or emit light.
- ***Reflection*** can be decomposed in two components:
  - ***Diffuse reflection*** (distributes light energy equally along any spatial direction, allows perceiving object color).
  - ***Specular reflection*** (strongest along the direction of the incident light, incident light color is perceived).
- ***Lambertian surfaces*** perform only diffuse reflection, thus being dull and matte (e.g., cement surface).

Light reflection

- ***Ambient illumination*** sources emit the same light energy in all directions (e.g., a cloudy sky).
- ***Point illumination*** sources emit light energy isotropically or anisotropically (e.g., ordinary light bulbs) along various directions.
  - If point illumination sources are far away (e.g., sun), their rays are considered to be parallel.

Light reflection



Reflection geometry.

Light reflection

Reflected irradiance when object surface produces diffuse reflectance and incident light source comes from:

- Ambient illumination:

$$f_r(X,Y,Z,t,\lambda) = r(X,Y,Z,t,\lambda)E_\alpha(t,\lambda).$$

- Point light source:

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

- Distant point source and ambient illumination:

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

  - This is a special case of ***Phong reflection model***.

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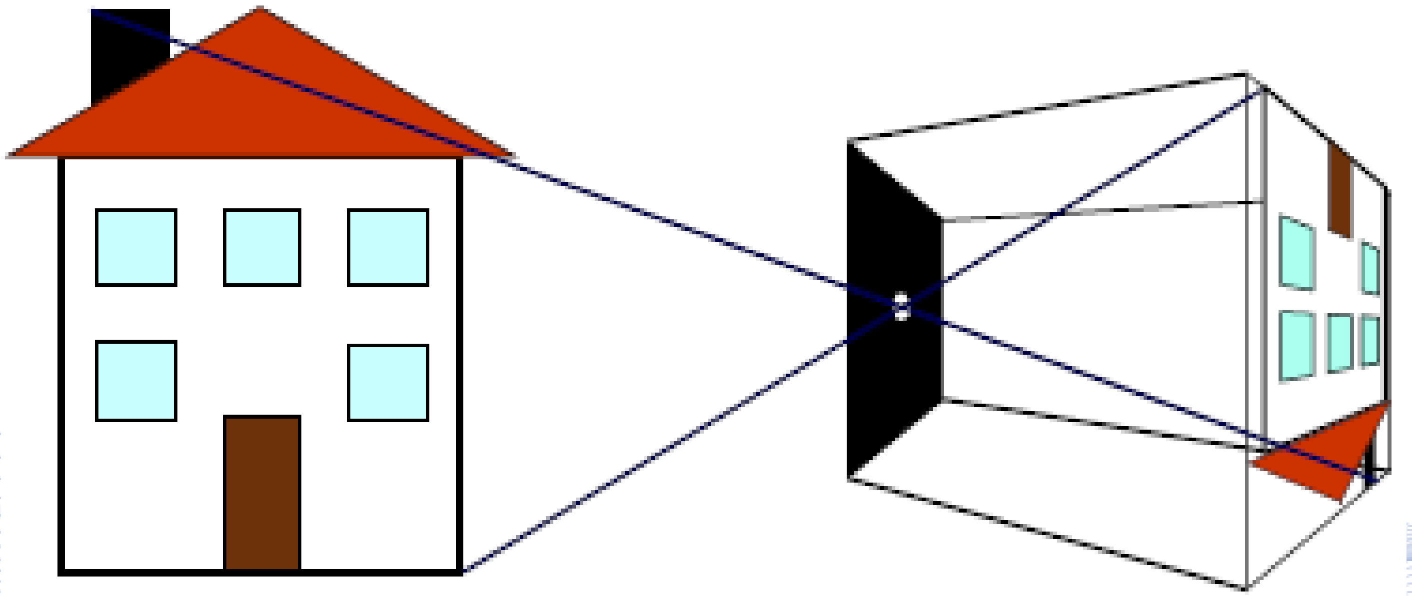
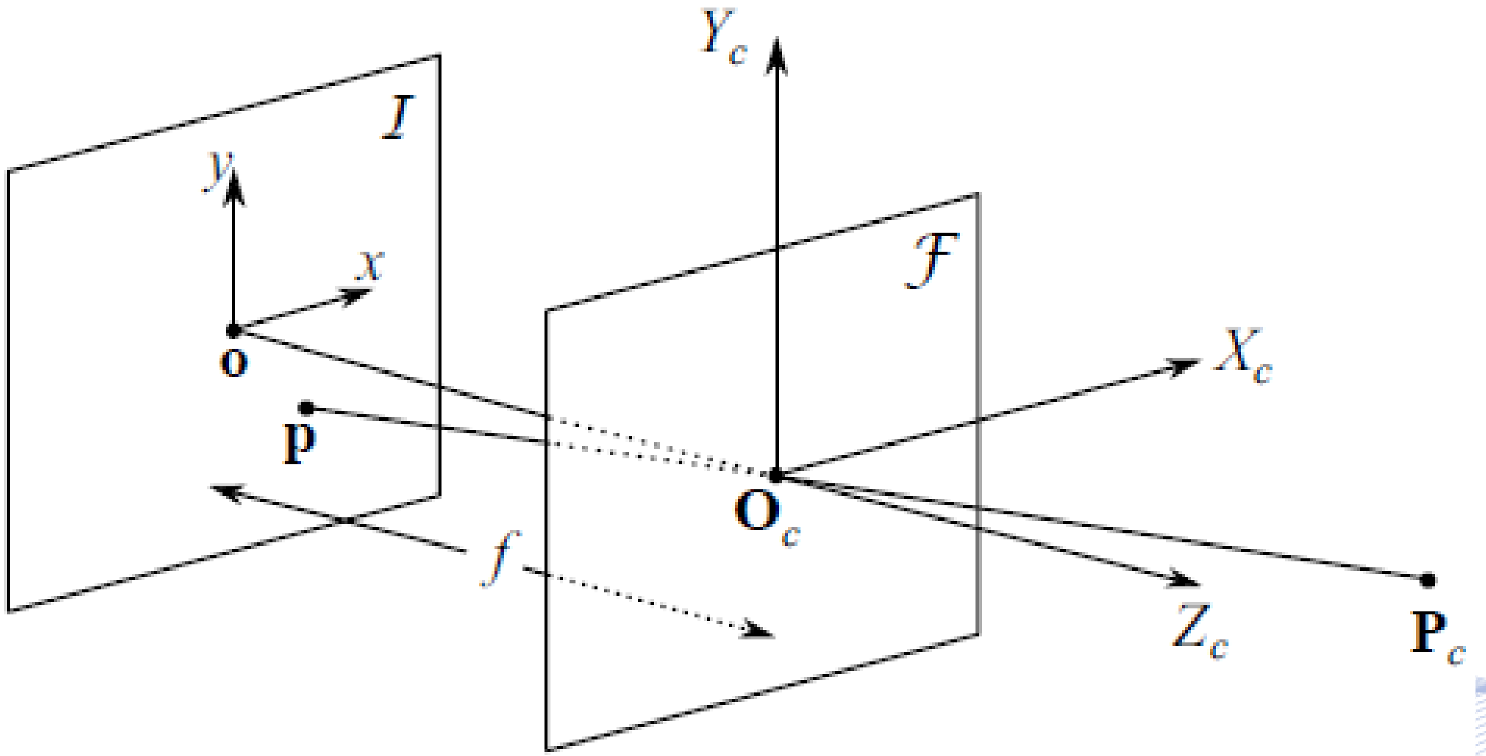
Pinhole Camera



Pinhole camera geometry.

Pinhole Camera



Depiction of focal length f.

Camera Structure

- There are two kinds of lenses:

  - Fixed focal length (e.g., ***prime lens***) and
  - Variable focal length (e.g., ***zoom lens***).

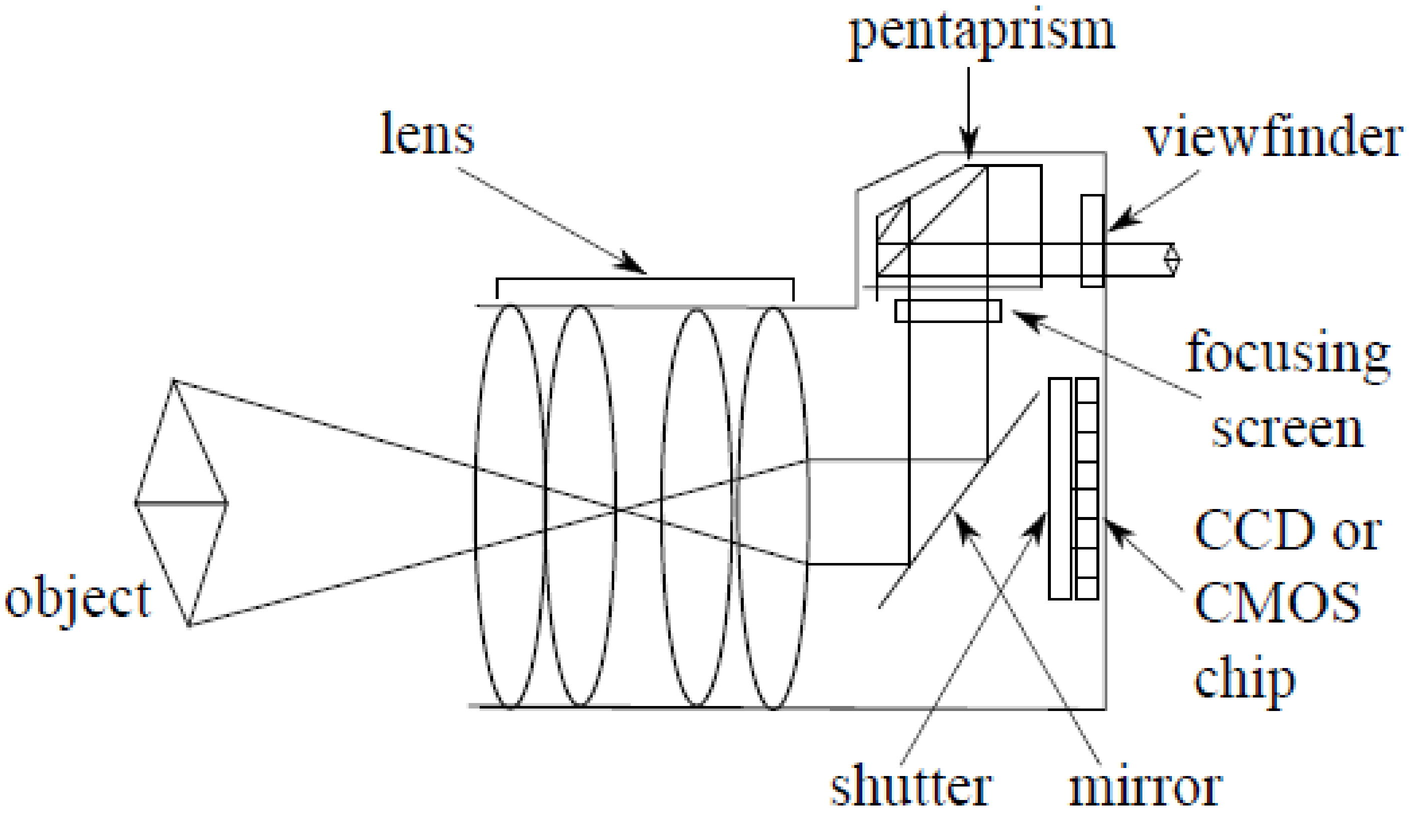
Camera Structure

- Based on their focal length, lenses are categorized in wide-angle, normal and telephoto lenses:
  - ***Wide-angle lens*** has smaller focal length than normal, thus capturing wider parts of the scene and exaggerating differences in the relative distance and size between foreground and background objects.
  - ***Telephoto lens*** has larger focal length and can take photos from a distance.

Camera Structure

- Aperture size is usually expressed in ***f-numbers***. The bigger the f-number the smaller the aperture size.
- It controls the ***Depth of Field*** (***DOF***), the distance between the nearest and farthest focused objects in the image.
- The smaller the aperture size is, the longer the depth of field, since less light rays are captured on the image for each visible 3D scene point.

Camera Structure



Camera structure.

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Camera Structure

Color temperature of a light source is the temperature of a black body (expressed in Kelvin) that emits a light of the same hue to that of the light source.

- Light sources range from warm ones (~1000 K) to cool ones (up to 10000 K).

Temperature In Kelvins	Light Source
1000 – 2000 K	Candle Light
2500 – 3500 K	Tungsten Bulb
3000 – 4000 K	Sunrise/Sunset (clear sky)
4000 – 5000 K	Fluorescent lamps
5000 – 5500 K	Electronic Flash
5000 – 6500 K	Daylight with clear sky
6500 – 8000 K	Moderately overcast sky
9000 – 10000 K	Shade or heavily overcast sky

Camera Structure

Image before white balance.

Image after white balance.

Camera Model

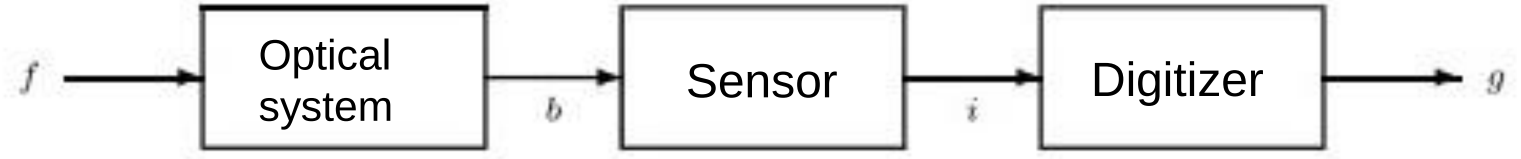
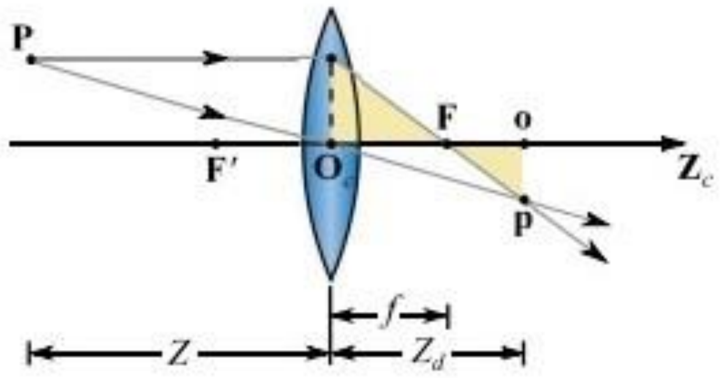


Image acquisition model.

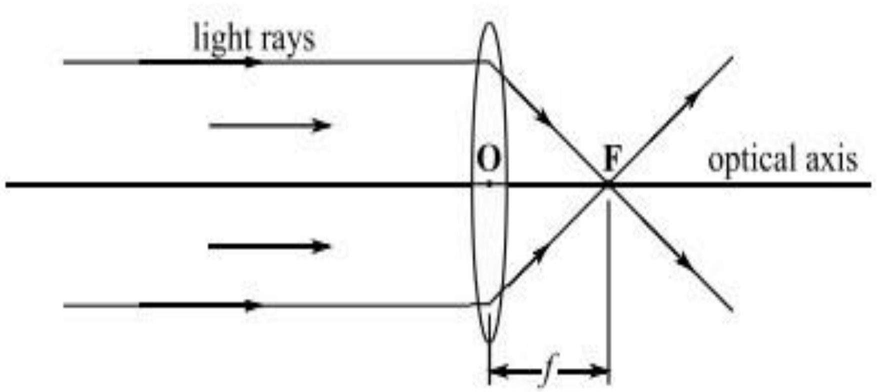
Optical Lens Models

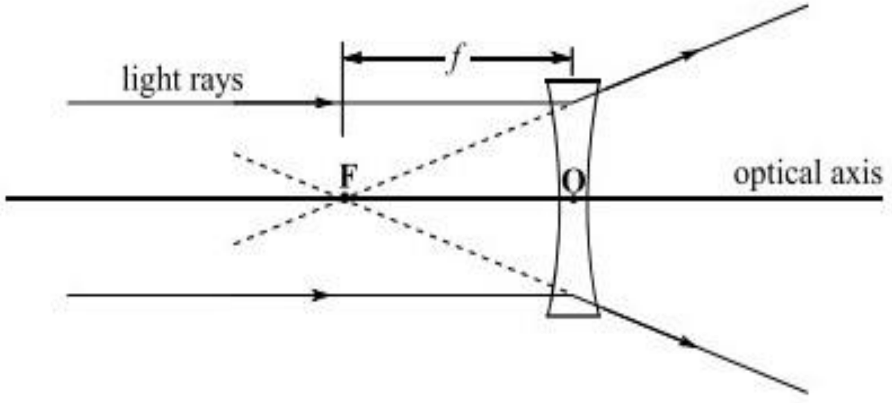
- The simplest optical systems use ***thin lenses***. There are two dominant types of thin lenses, the *converging* and the *diverging* ones.



Graphical model of a thin lens.

Optical Lens Models





Converging thin lens.

Diverging thin lens.

Optical Lens Models

Fundamental Equation of Thin Lenses:

$$\frac{1}{Z} + \frac{1}{Z_d} = \frac{1}{f},$$

- Z is the distance of a scene point $\mathbf{P}$ from the lens along the optical axis.
- Z_d is the distance of its corresponding focused image point $\mathbf{p}$ from the lens along the optical axis.
- f is the lens focal length.

Optical Lens Models

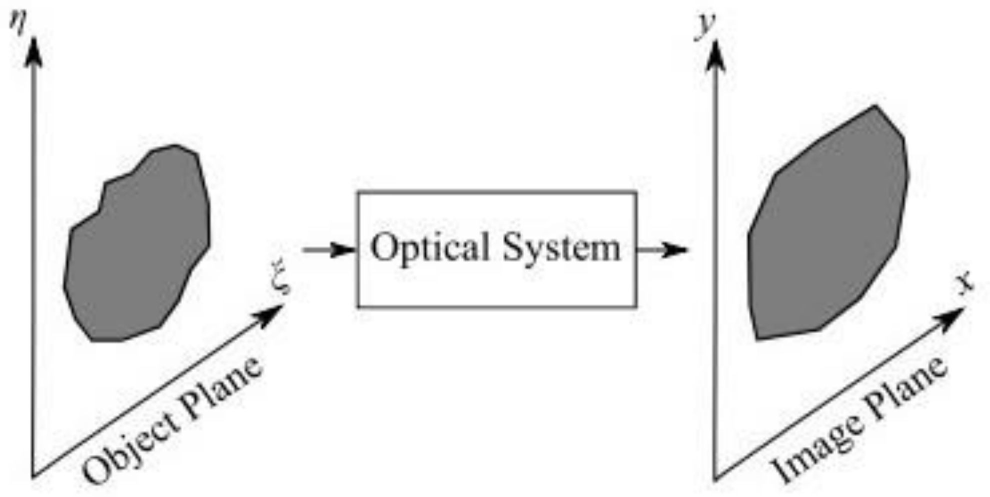
- For a thin double-convex lens, having a small diameter in comparison to its focal length, f is given by the famous ***Lensmaker's equation***.

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

- n is the lens material refractive index.

- R_1, R_2 are the radii of the front and rear spherical lens surfaces.

Image Formation Models



Optical system input and output images.

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Image Formation Models

Both signals $f(\xi,n),\ b(x,y)$ represent optical intensities:

- They must take non-negative values, therefore:

$$f(\xi,n) \geq 0, \qquad b(x,y) \geq 0.$$

The input-output relation of the optical subsystem is given by a ***2D convolution***:

$$b(x,y) = \iint_{-\infty}^{\infty} f(\xi,n)h(x-\xi,y-n)d\xi dn\,.$$

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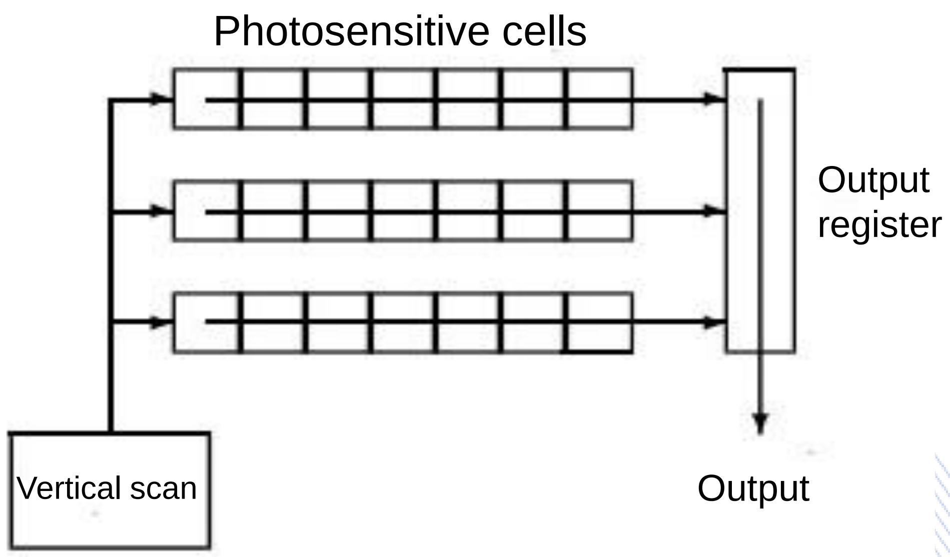
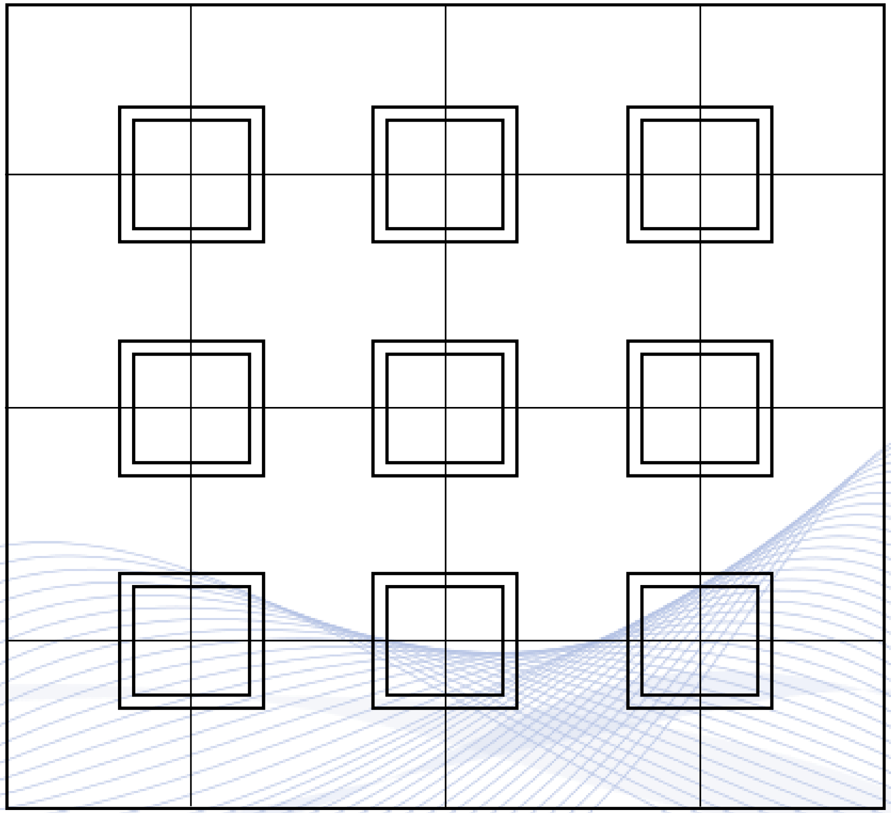
Optical sensors



CCD Camera Structure.

Optical sensors

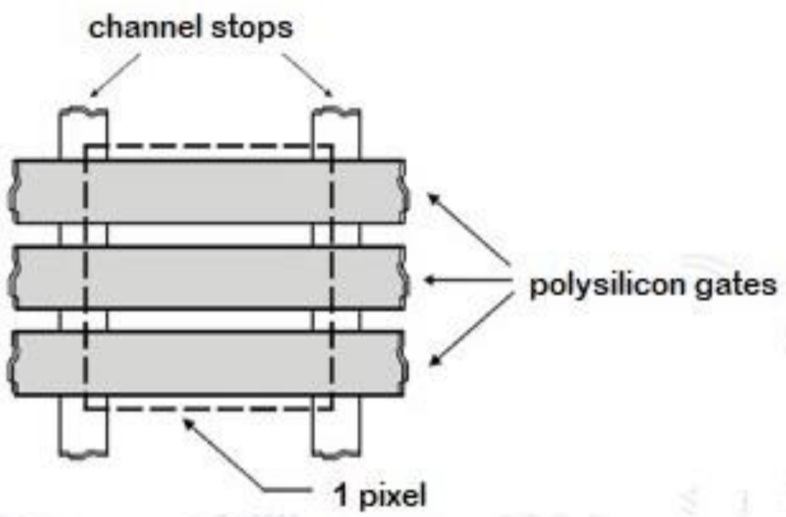


Square CCD cell grid.

Optical sensors

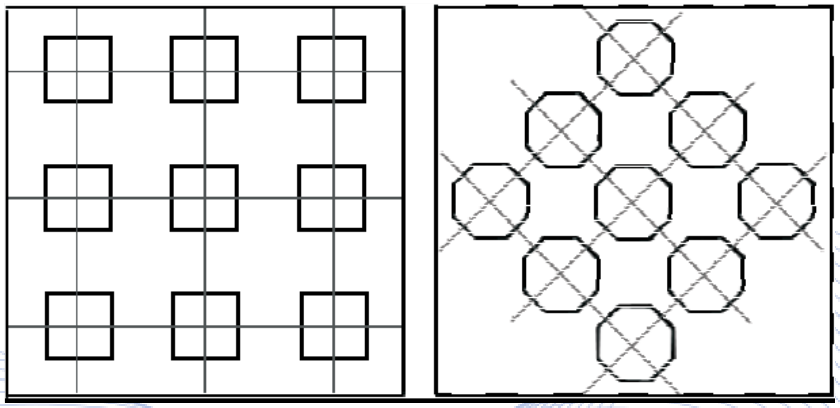
- ***Charge-Coupled Device*** (***CCD***) is the most popular optical sensor technology.
- A three-phase CCD pixel consists of three polysilicon gates vertically oriented towards two channel stops.
- There are some CCD structures which use one, two or four polysilicon gates to define a pixel.
- CCD grid topology can be square or orthorhombic.

Optical sensors



Three-phase CCD cell.

Optical sensors



CCD cell grid topologies: (a) square; (b) orthorhombic.

Optical sensors

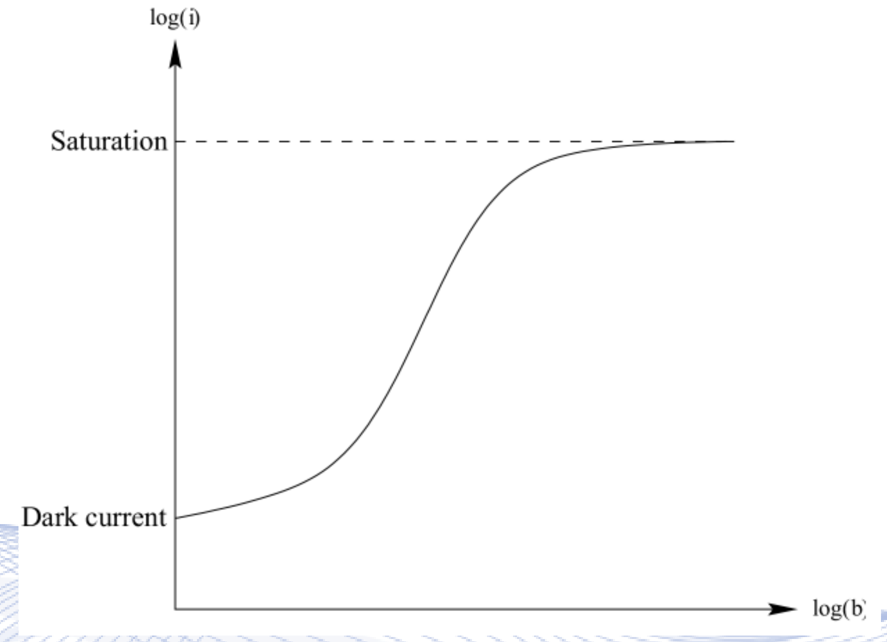
- A simplified image recording model with a CCD sensor follows the form:

$$i = g^{\gamma}(b+n)^{\gamma},$$

- b, i: input and output (recorded) image brightness.
- g: ***sensor gain*** (can be set automatically).
- γ: sensor $\boldsymbol{\gamma}$ ***coefficient*** determining sensor nonlinearity. It can be evaluated for each sensor. In many cameras, it is in the range $[0.55, 1.00]$.
- n: CCD noise.

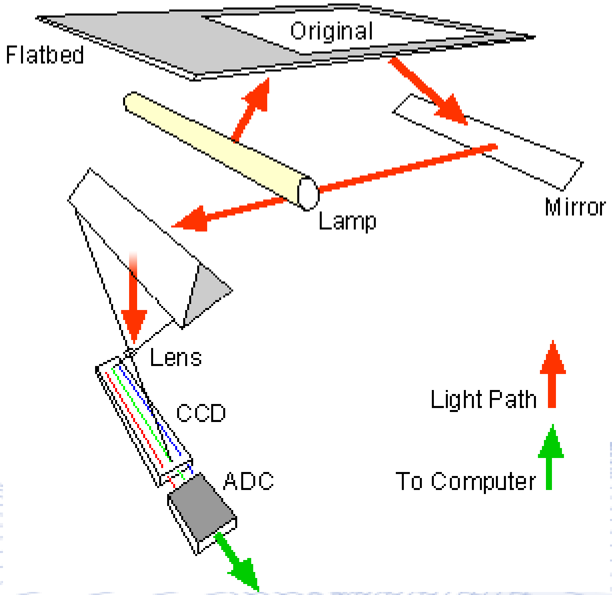
Optical sensors

- b: input luminance.
- i: output current.



Characteristic curve of the light sensor.

Image scanners



Scanner structure [CIR].

γ Correction

Before gamma correction.

After gamma correction.

Digital Image Formation

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- Image noise

Digital Image Formation

Sampling and digitization:

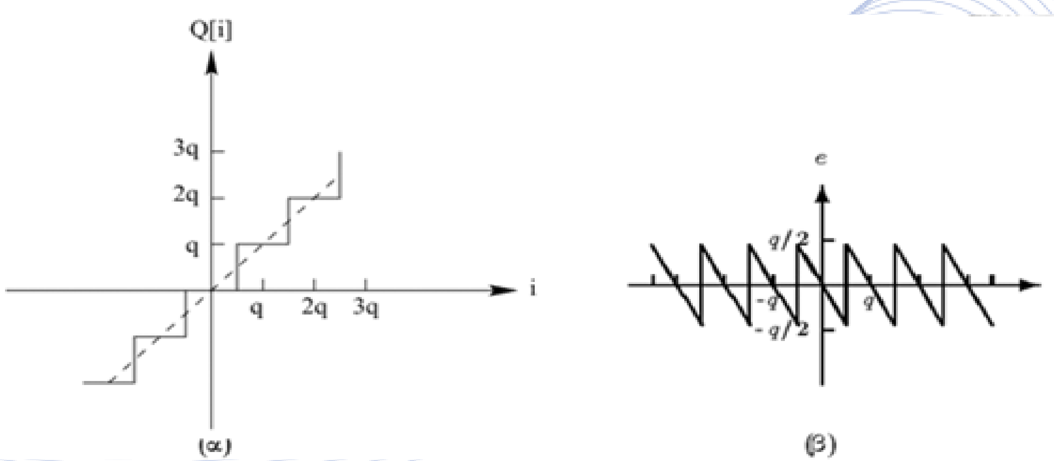
- They are performed by an A/D converter (in a frame grabber).
- It transforms the analog image $i(x, y)$ to a digital image:

$$i(n_1, n_2) = i(n_1 T_1, n_2 T_2), \quad n_1 = 1, \ldots, N, \; n_2 = 1, \ldots, M.$$

Image digitization

Quantization:

- It is performed by the A/D converter;
- q: quantization step $q = \frac{1}{2^b}$;
- quantized image illumination levels $kq, k = 0,1,2,\ldots,2^b - 1$.



a) Input-output curve of quantizer; b) Quantization error.

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Image digitization

- ***Grayscale*** images are quantized at 256 levels:
  - 1 byte (8 bits) for pixel representation.
- ***Binary*** images have only two quantization levels: $\{0,1\}$.
  - They are represented with 1 bit per pixel.

Image digitization


(a)


(b)


(c)


(d)

(a) Original image at 256 grayscale levels; (b) 64 levels; (c) 8 levels; (d) 2 levels.

Probabilistic Image Description

- In many cases, it is useful to estimate a probabilistic characterization of an image. In this case we assume that each pixel is a random variable.
- The image vector has a probability distribution of the form:

$$p(\mathbf{i}) = p\{i(1,1), \dots, i(N,M)\}.$$

- If the probability distribution is Gaussian, it is of the form:

$$p(\mathbf{i}) = (2\pi)^{-\frac{NM}{2}} |C_i|^{-\frac{1}{2}} e^{\{-\frac{1}{2}(\mathbf{i}-\mathbf{m}_i)^T \mathbf{C}_i^{-1}(\mathbf{i}-\mathbf{m}_i)\}}.$$

Digital Image Formation

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Image generation noise

- Digital image corruption by noise:
  - during a) image acquisition or b) image transmission.
- Image acquisition noise:
  - photoelectronic noise;
  - film-grain noise (signal-dependent).
- Image formation model:

$$g(x,y) = c\big(f(x,y)\big)^{\gamma} n(x,y).$$

Image generation noise

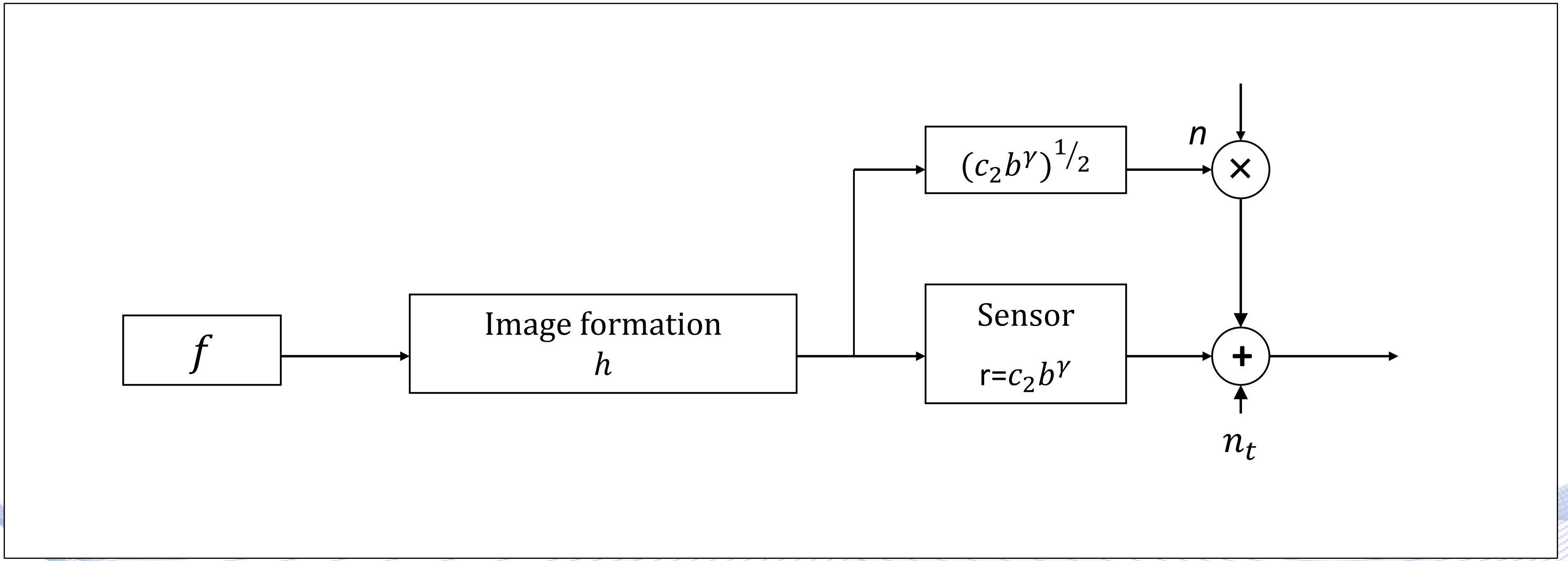


Image formation model.

Image noise generators

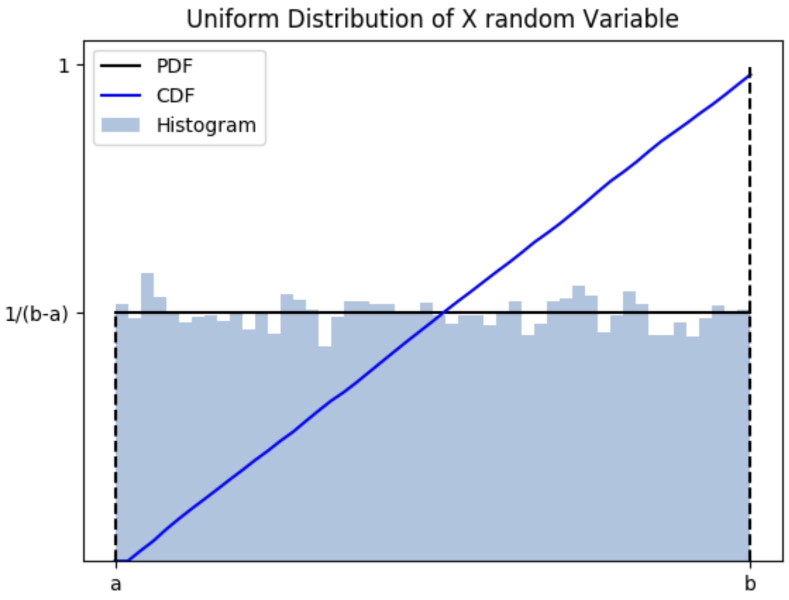
Artificial noise generation is needed for:

- Simulations
- Certain artistic applications (e.g. for the simulation of film-grain noise).
- Noise $n(i, j)$ generation:
  - Random number generators: uniform noise in $[0,1]$.
  - Noise transformation to a different pdf, e.g., Gaussian or Laplacian.

Image noise generators

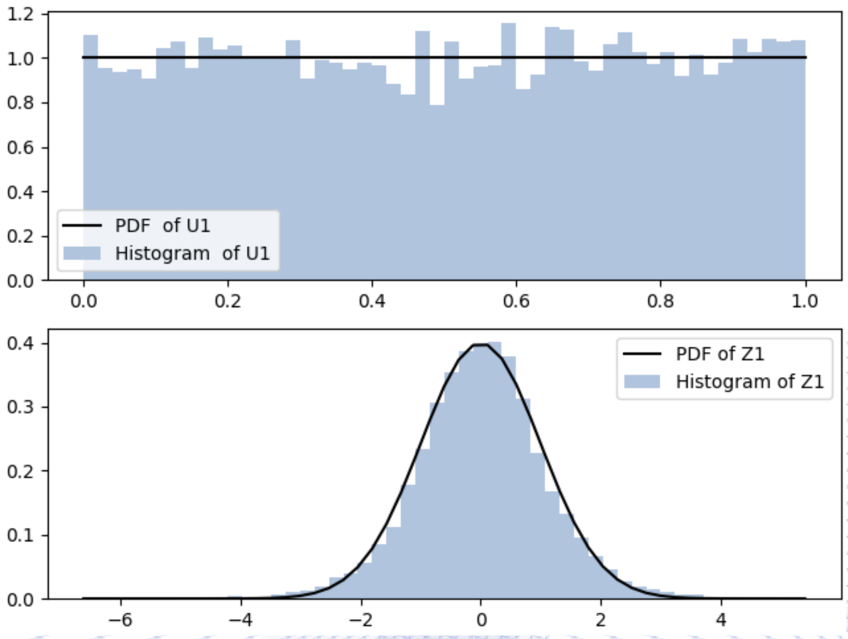
(a) Original image; (b) Image corrupted by additive Gaussian noise; (c) Image corrupted by multiplicative Gaussian noise; (d) image corrupted by salt-pepper noise.

Image noise generators



Uniform random number generation in $[0,1]$.

Image noise generators



Gaussian random number generation using uniform distribution.

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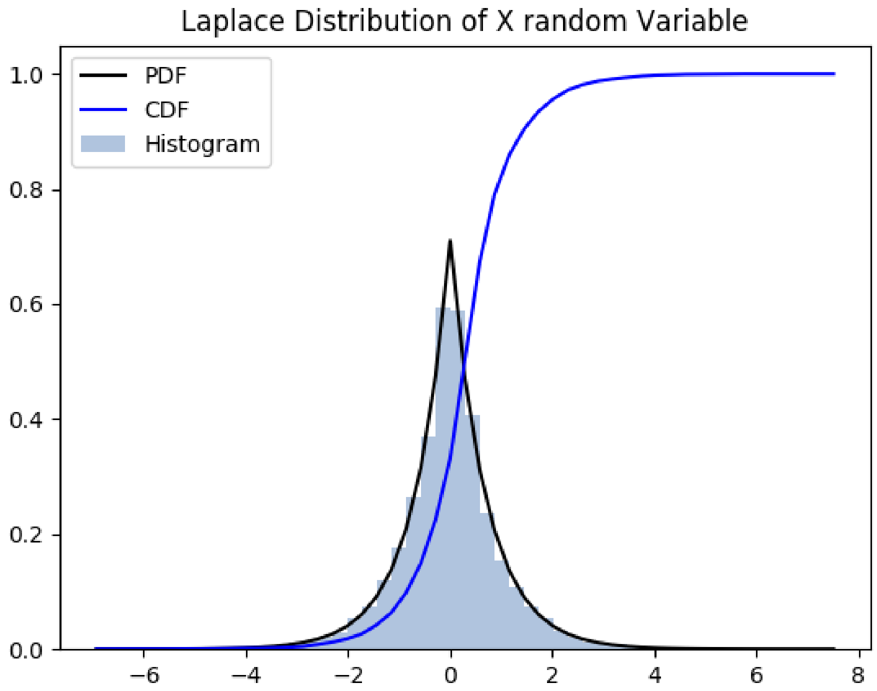
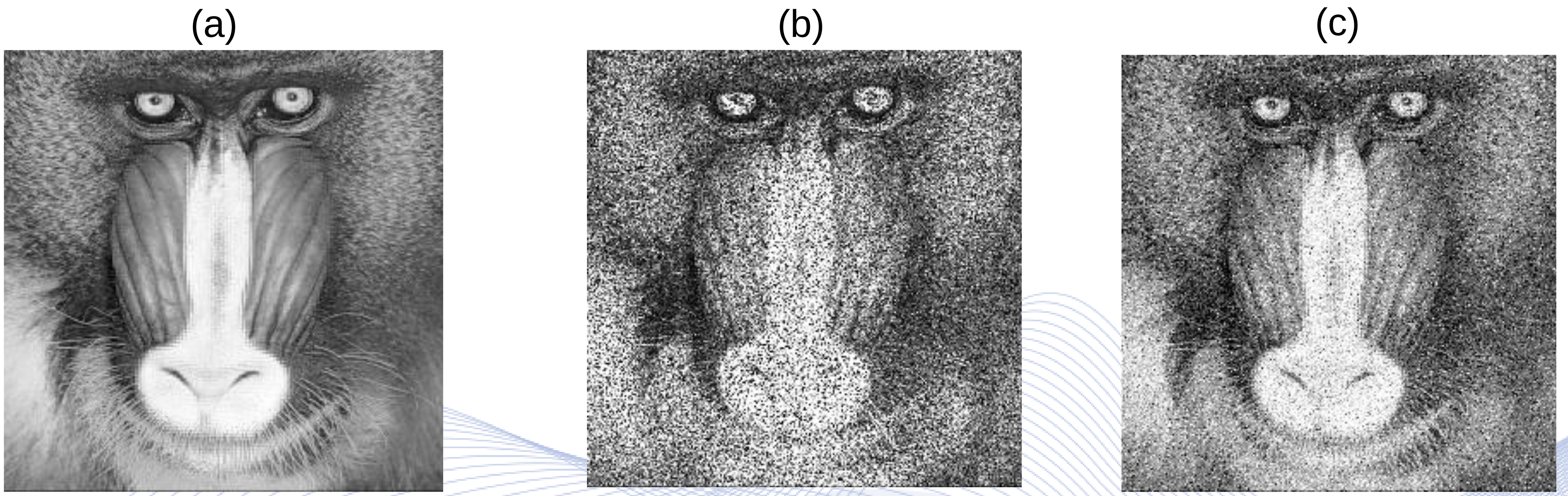
Random Number Generation



Laplacian random number generator histogram.

Image noise generators



(a) Original image; (b) Image corrupted by multiplicative Gaussian noise; (c) image corrupted by additive Laplacian noise.

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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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