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# **Imagery numérique**

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## **Theme 3**

# **Image acquisition and sensing**

# Content of course

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## Semester 1

Theme 1: Introduction to image processing

Theme 2: The HVS perception and color

Theme 3: Image acquisition and sensing

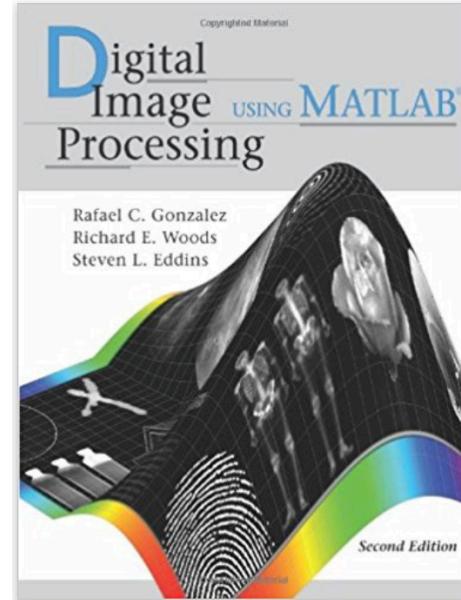
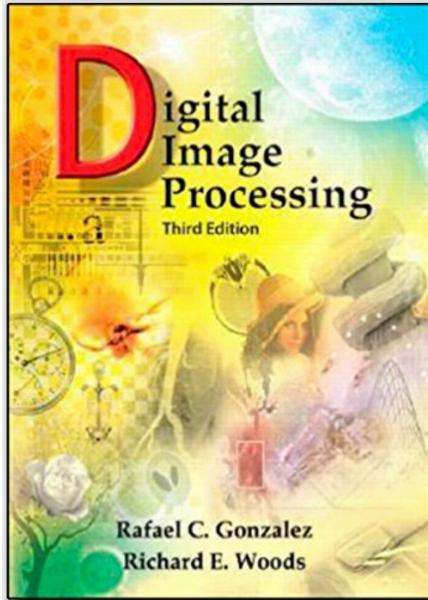
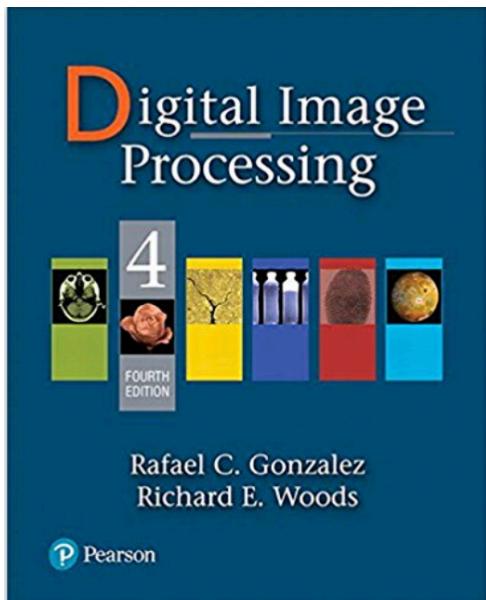
Theme 4: Histograms and point operations

Theme 5: Geometric operations

Theme 6: Spatial filters

# Recommended books

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YouTube lectures

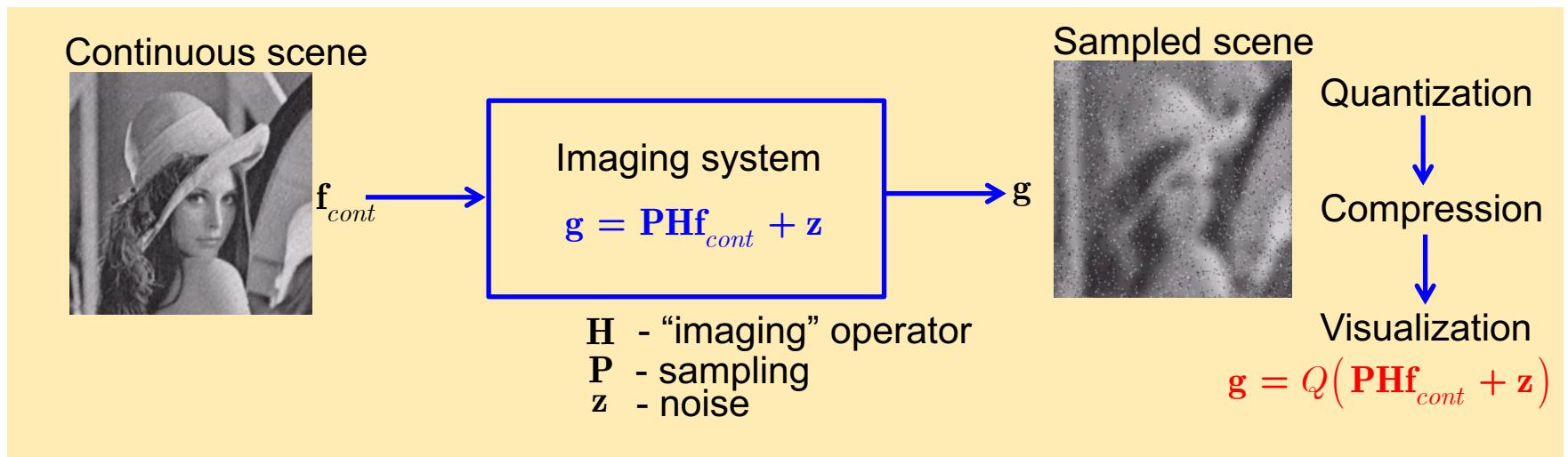
Intro to Digital Image Processing (ECSE-4540) Lectures, Spring 2015

by Prof. Rich Radke from Rensselaer Polytechnic Institute



# Goal

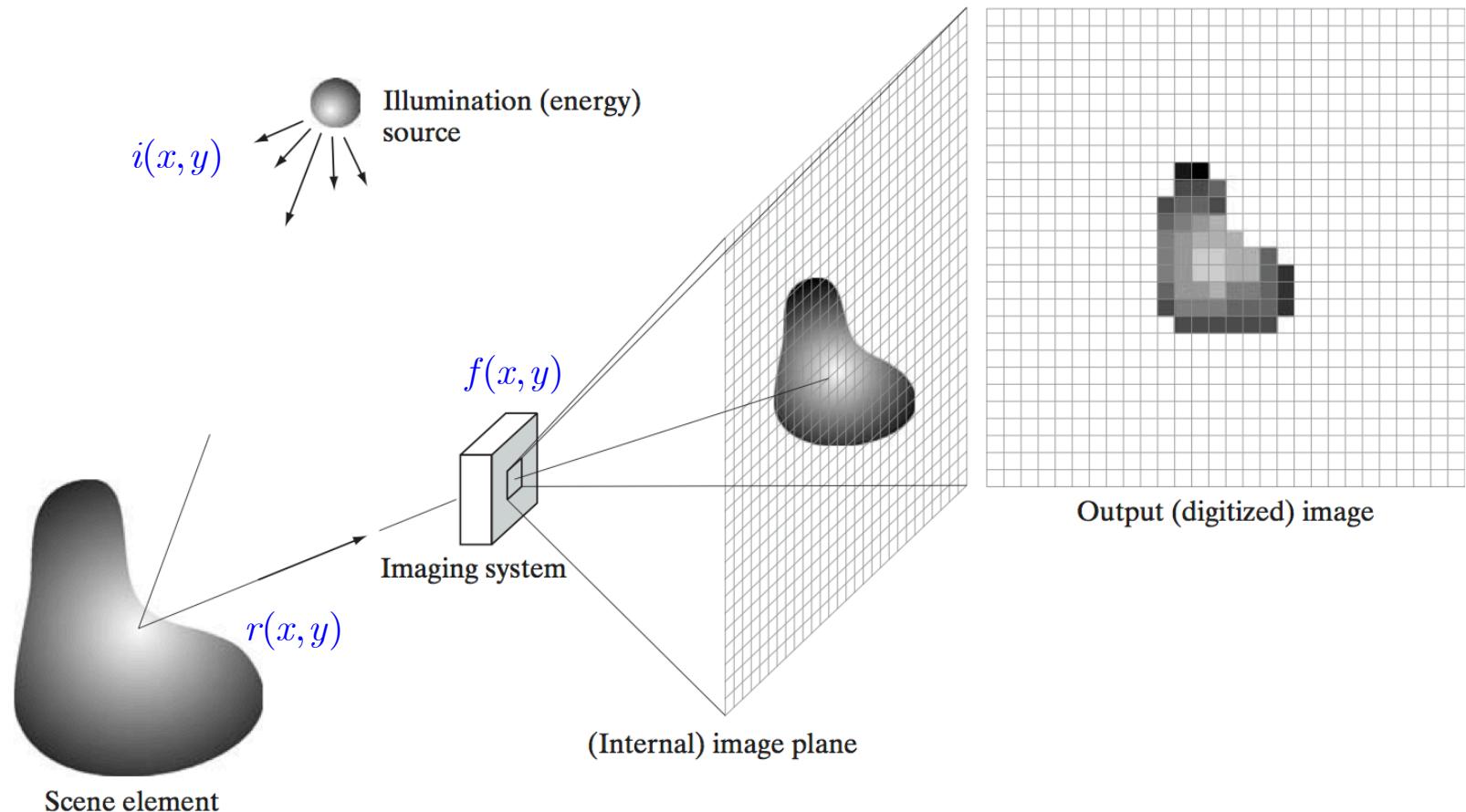
- In lecture 1, we have seen many applications of modern image processing:
  - Different imaging principles
  - Different wavelength
- However, despite of all this diversity of imaging tools and applications, all of them share a lot of common principles that can be generalized to a model



**Our goal:** To consider common principles in the design of imaging systems, to generalize them and to introduce a uniform approach to most of image processing applications

# Digital image acquisition – general setup

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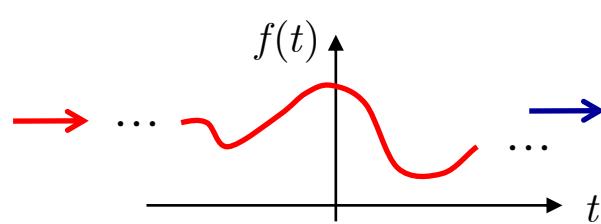


Gonzalez, p. 51

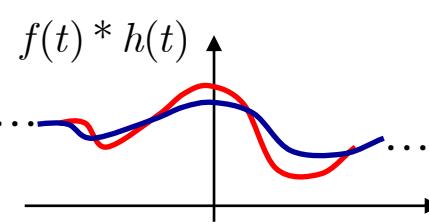
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# Imaging, Sampling and Quantization

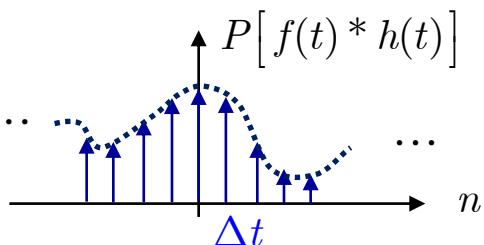
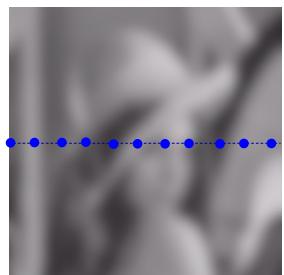
Continuous scene/image    Continuous signals



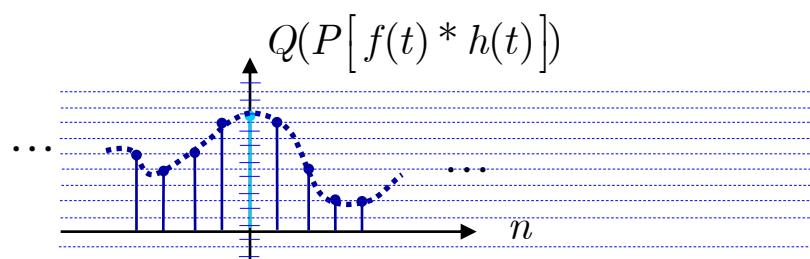
Signals after H



Discrete signals - sampling P

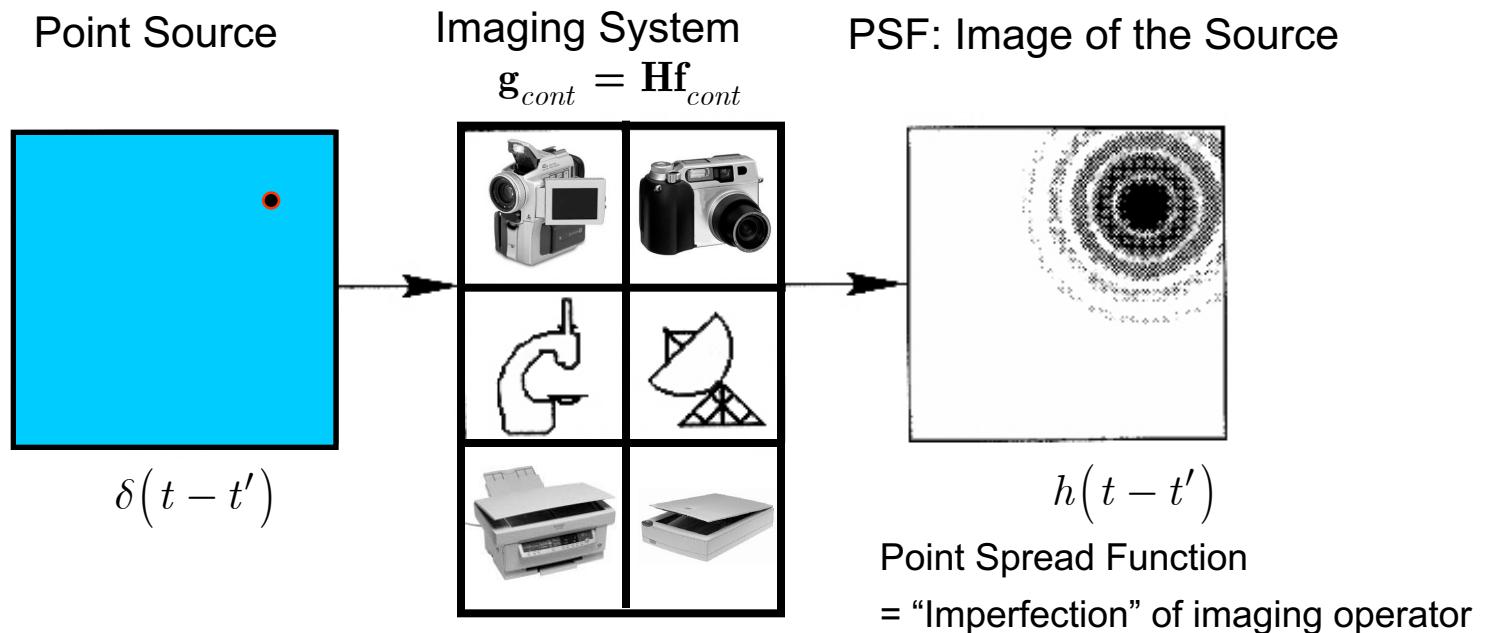


Discrete quantized signals – Q(.)



# Typical imaging pipeline – “imaging” operator

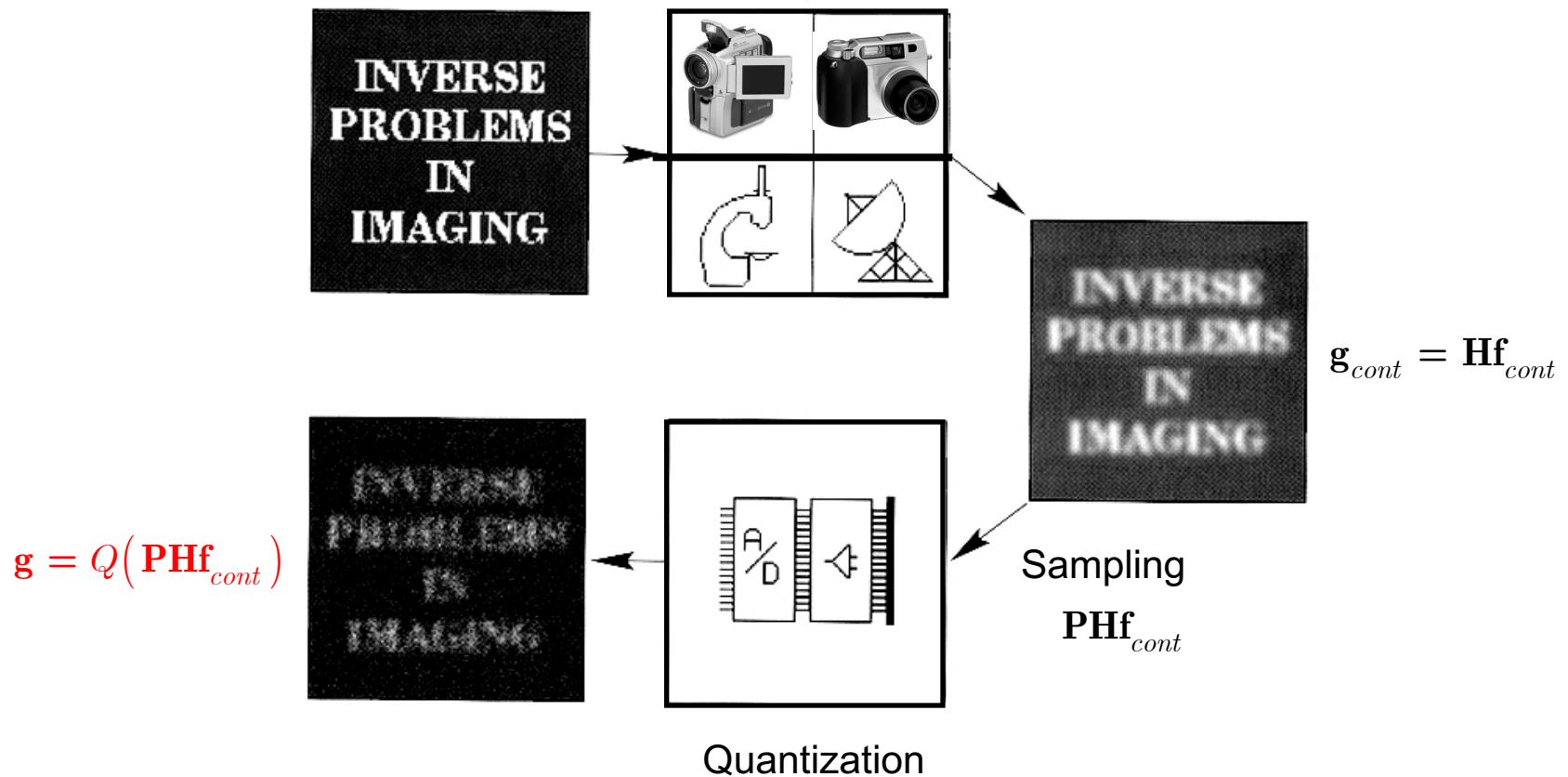
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Different systems designed for imaging in different parts of electromagnetic spectrum have different PSFs (note that they might be called differently but the physics is the almost same)

# Typical issues: blur, sampling, quantization

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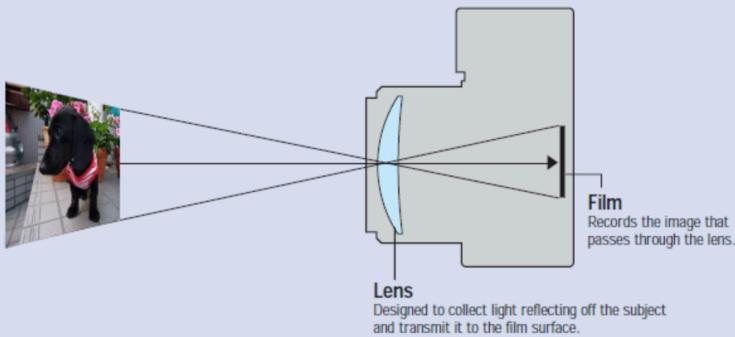


# Typical issues: blur, sampling, quantization

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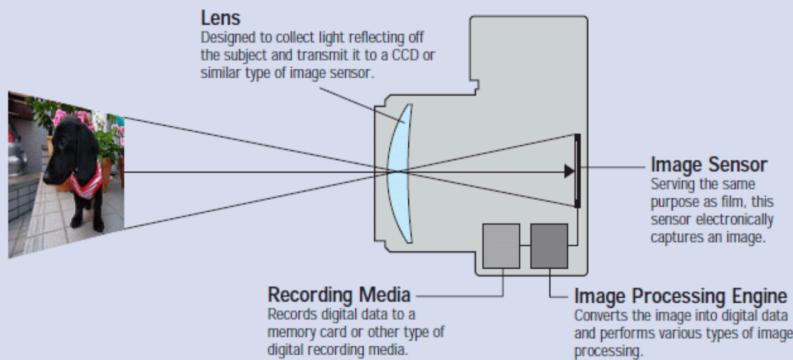
## [ Film Camera ]

- A camera that records images passing through the camera's lens on film is called a film camera.



## [ Digital Camera ]

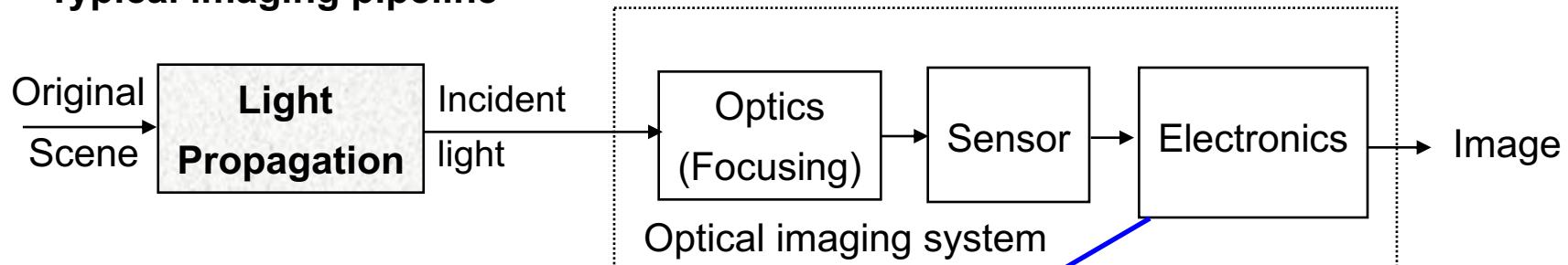
- The digital camera is designed to convert an image into digital data and record it.



<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow01.html>

# Typical issues: blur, sampling, quantization

## Typical imaging pipeline



- **ADC** – analog-to-digital convertor
- **Processing** – demosaicing, gamma correction, white balancing, denoising, compression

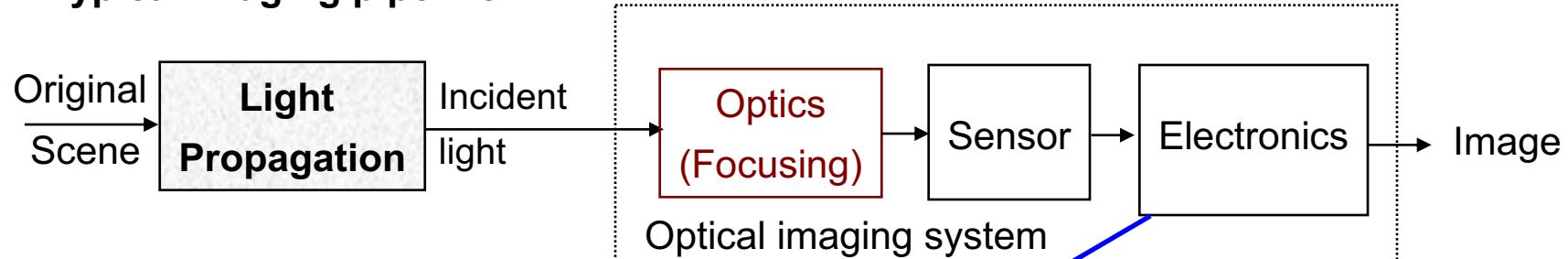
## Main issues:

- Every camera has its own optics, sensors and processing algorithms
- Many algorithms are not standardized
- The order of processing may vary
- The parameters of algorithms remain often unknown and proprietary

# Typical issues: blur, sampling, quantization

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## Typical imaging pipeline

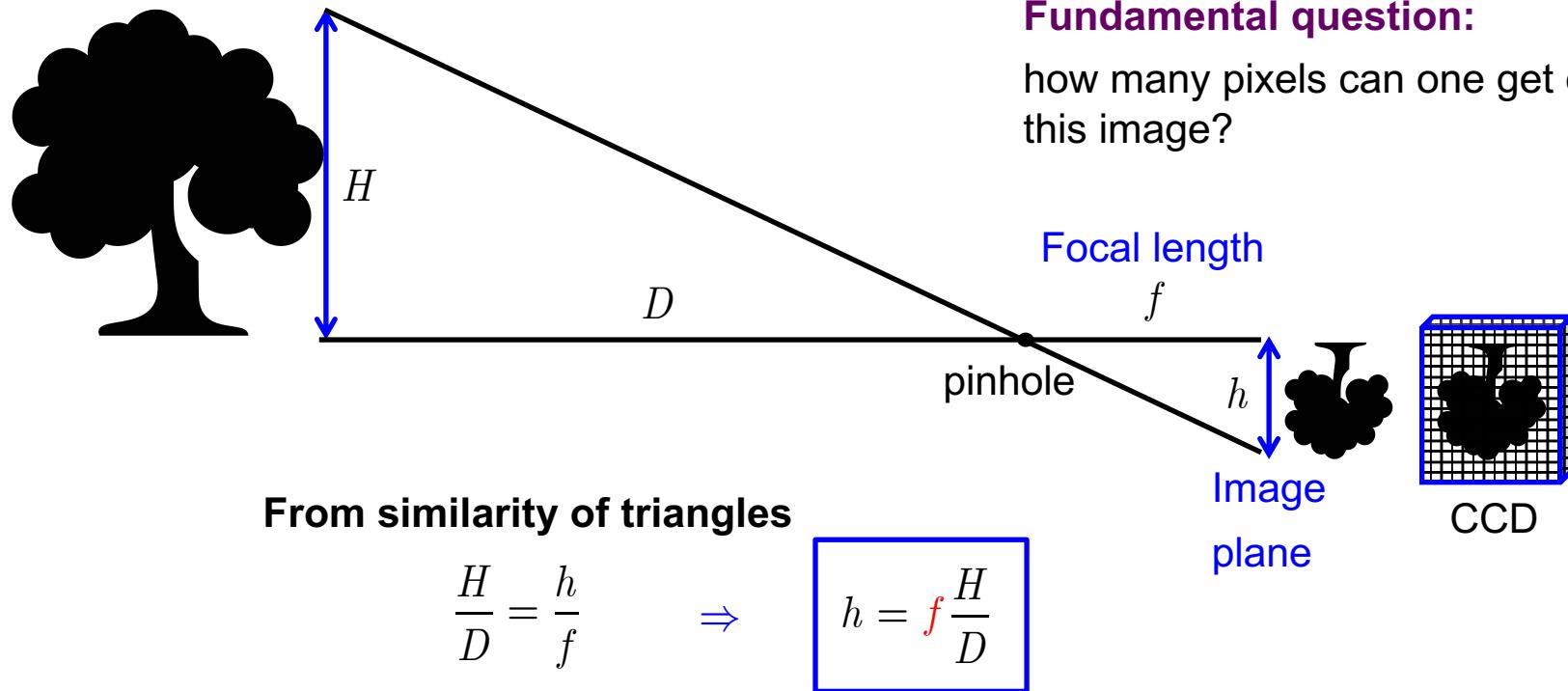


- **ADC** – analog-to-digital convertor
- **Processing** – demosaicing, gamma correction, white balancing, denoising, compression

## Main elements:

- **Optics**
- Sensors
- Electronics - Processing

# Imaging operator $H$ : focal length and focusing

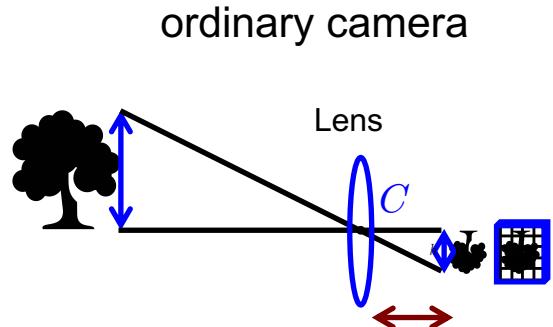


The focal length is a distance between the pinhole and the image plane.  
It is a very small number.

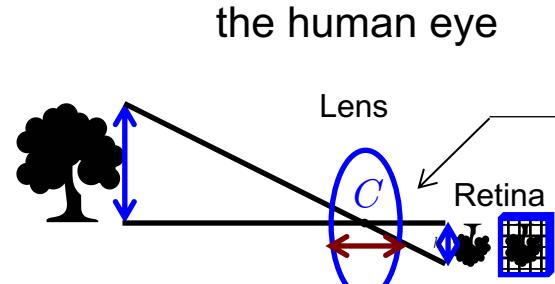
# Imaging operator H: focal length and focusing

## Reminder

**Important difference in focusing:**



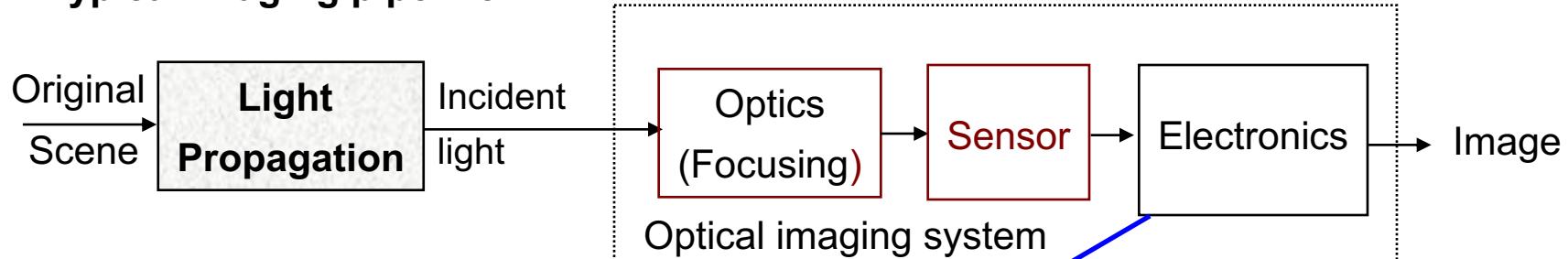
To focus - change the distance between the lens and the image plane



To focus - change the focal distance by varying the lens

# Typical issues: blur, sampling, quantization

## Typical imaging pipeline



- **ADC** – analog-to-digital convertor
- **Processing** – demosaicing, gamma correction, white balancing, denoising, compression

## Main elements:

- Optics
- **Sensors**
- Electronics – Processing (we will not consider it here; see later)

We will see it later

# Image sensors - optical

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**Imaging sensors are responsible for:**

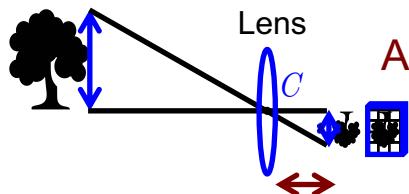
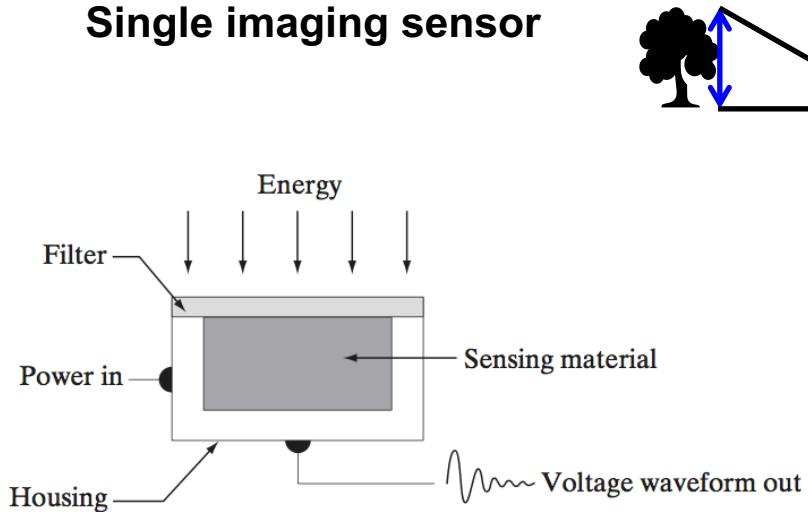
- ① Sampling of scene projected on the focal plane
- ② Conversion of light (photons) into the electric current (electrons)
- ③ Conversion of current into the bits (analog-to-digital conversion) and corresponding low-level processing accompanying such a conversion (like gamma correction)

The role of image sensor in the overall process of image formation is very important and complex.

We will start with simple optical sensors, extend them to more complex optical systems, show several applications requiring dedicated processing and show the links with the radio and microwave imaging systems.

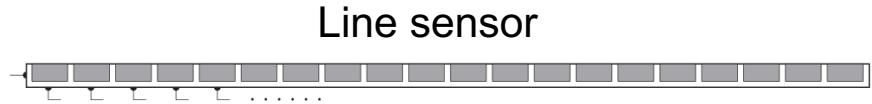
# Image sensors - optical

## Single imaging sensor

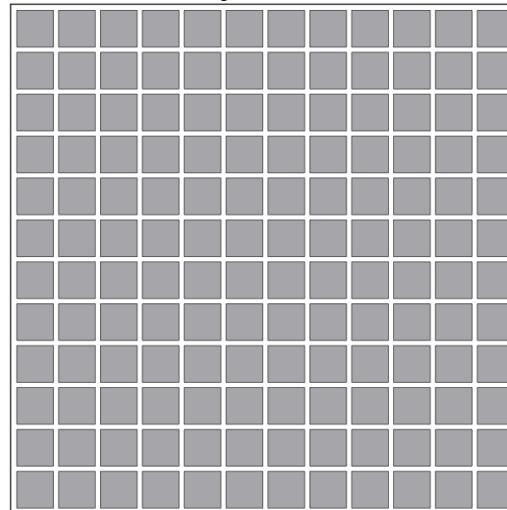


Assume after optics  $Hf_{cont}$

Line sensor



Array sensor



## Photon counting

The larger size of sensor, the higher sensitivity (more photons can be collected)

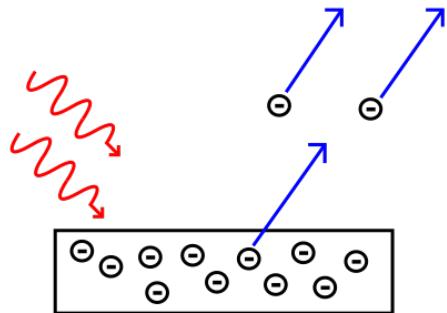
P - sampling  
z - noise

Gonzalez, p. 47

Note: the output of array represents  $PHf_{cont}$

# Image sensors – optical: foundations

## Photon-to-electron conversion



- A photon of light might lead to the emission of an electron, when a photon hits metal. The emission depends on the photon energy, which is a function of its wavelength

$$E_{\text{photon}} = h \frac{c}{\lambda} = h f \quad h - \text{Planck constant}$$

- Remark: there is no definition of brighter or darker photons. One only distinguishes more or fewer of photons achieving the sensor

[https://en.wikipedia.org/wiki/Photoelectric\\_effect](https://en.wikipedia.org/wiki/Photoelectric_effect)

# Image sensors - optical

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## Quantum efficiency

- Not all photons produce an electron:
  - depends on quantum efficiency of device (sensor)

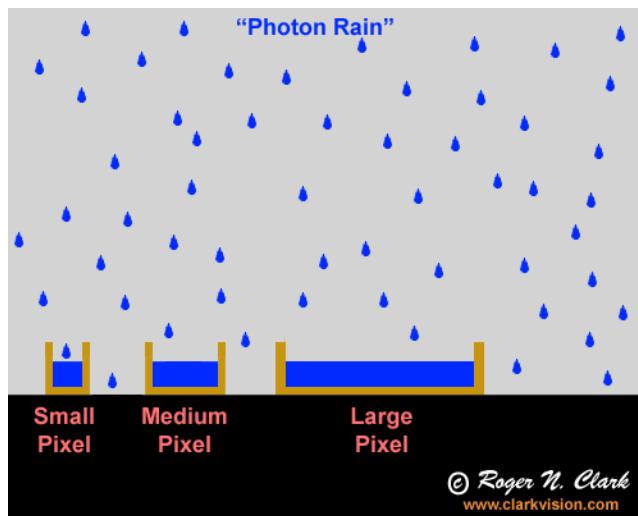
$$QE = \frac{\text{No electrons}}{\text{No photons}}$$

- Human vision: about 15%
- Typical digital camera: <50%
- Best CCD: >90%

# Image sensors – optical: photon counting

## Pixel size (**but be careful with what will follow!**)

- Assume a system without a lens and any aperture
- Consider a “rain” of photons that hits pixels of different sizes



## Intuition:

**The larger pixel, the more photons can be “collected”**

Typical sizes of pixels:

1.4um x 1.4um

2.5um x 2.5um

6.5um x 6.4um

- The current from a single electron is very small
- Therefore, one can “accumulate” multiple photons to produce more electrons by:
  - accumulating over space (larger pixel size or adding pixels) – **loss of resolution**
  - accumulating over time (larger exposure time) – **not applicable for moving objects**

# Image sensors – optical: photon shot noise

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## Pixel size (**but be careful with what will follow!**)

- Why is it so important to collect more electrons per pixel?
  - the number of photons arriving during an exposure varies from exposure to exposure and from pixel to pixel, even if the scene is completely uniform
  - this number is governed by **the Poisson distribution**

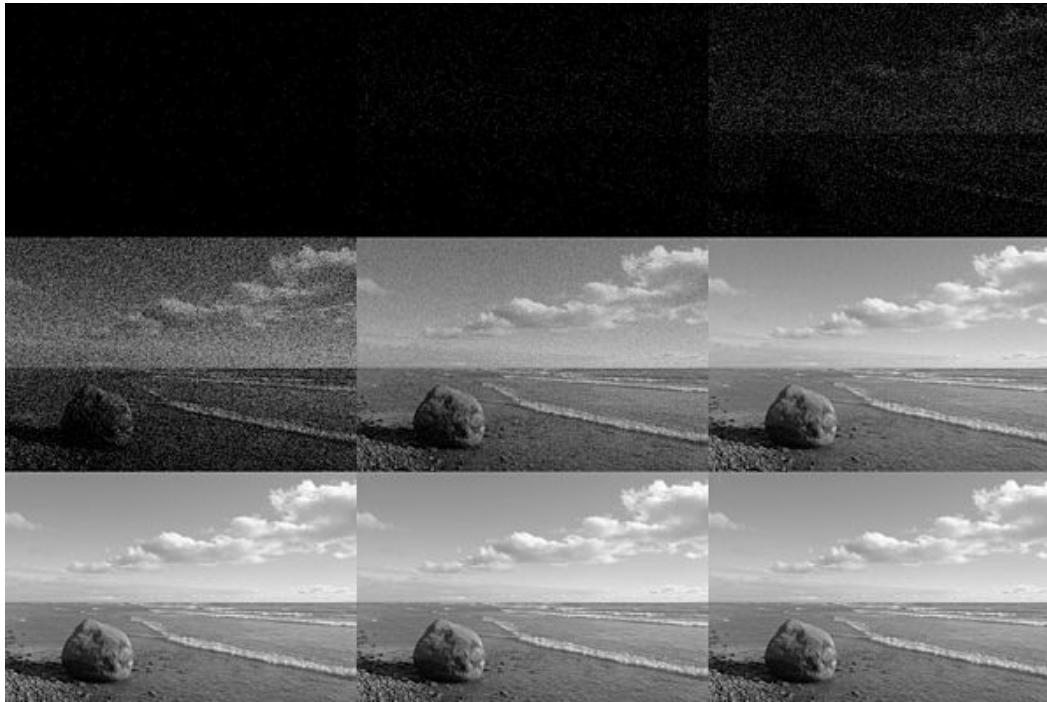
# Image sensors – optical: photon shot noise

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## Pixel size (**but be careful with what will follow!**)

- Why is it so important to collect more electrons per pixel?

Less photons



More photons

Number of photons per pixel increases from left to right and from upper row to bottom row.

[https://en.wikipedia.org/wiki/Shot\\_noise](https://en.wikipedia.org/wiki/Shot_noise)

# Noise in digital images: photon noise

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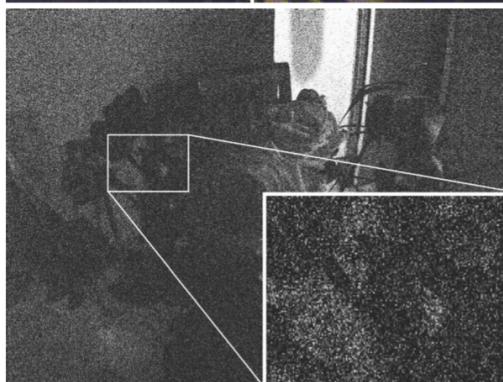
High light environment



Low light environment



Canon PowerShot S90



Blue channel

RENOIR - A Dataset for Real Low-Light Image Noise Reduction

Josue Anaya<sup>a</sup>, Adrian Barbu<sup>a,\*</sup>

<https://arxiv.org/pdf/1409.8230.pdf>

# Image sensors – optical: photon shot noise

**Pixel size (but be careful with what will follow!)**

## Poisson distribution

- Governs the probability that a certain number of events will occur during an interval of time
- To apply the Poisson pmf we should:
  - Define the average rate  $\alpha$
  - Assume the independence of events
- If on average  $\alpha$  events occur on some defined interval of time, the probability  $p$  that  $k$  events occur instead is defined as:

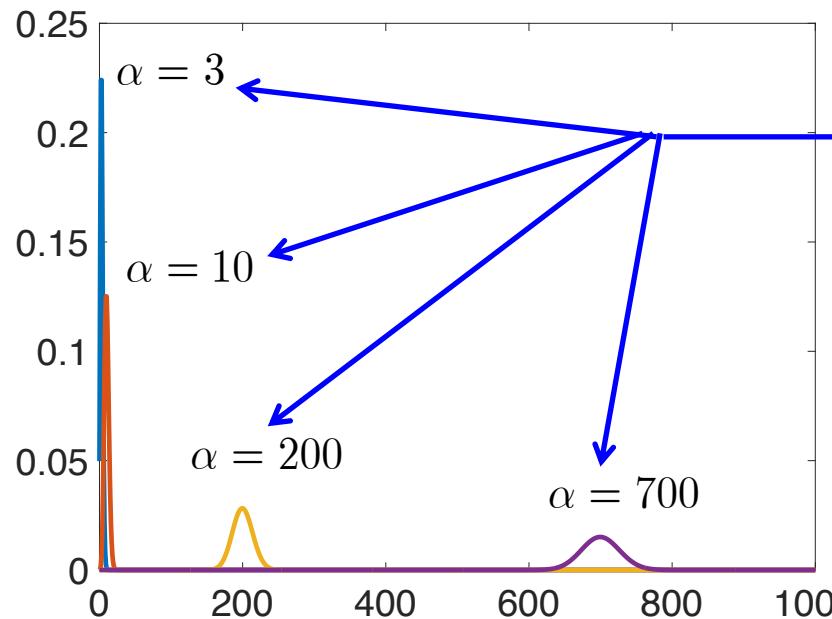
$$p(k; \alpha) = \frac{\alpha^k e^{-\alpha}}{k!} \quad k = 0, 1, 2, \dots, \infty$$

# Image sensors – optical: photon shot noise

Pixel size (**but be careful with what will follow!**)

Poisson distribution

$$p(k; \alpha) = \frac{\alpha^k e^{-\alpha}}{k!}$$



$$\mu = E[K] = \sum_{k=0}^{\infty} kp(k) = \alpha$$

$$\sigma^2 = Var[K] = \sum_{k=0}^{\infty} (k - E[K])^2 p(k) = \alpha$$

$$\sigma = \sqrt{\alpha}$$

**Std grows slower than the mean**

$$k = 1000$$

Matlab: k = poissrnd(alpha)

Note: if  $\alpha \rightarrow \infty$ ,  $p(k; \alpha) \rightarrow N(\alpha, \alpha)$

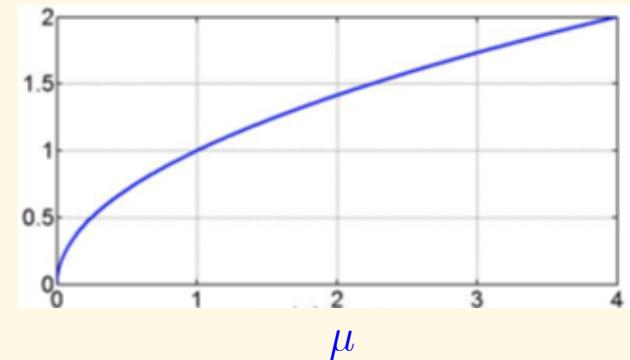
# Image sensors – optical: photon shot noise

**Pixel size (but be careful with what will follow!)**

**Signal-to-noise ratio**

$$SNR = \frac{\text{mean pixel value}}{\text{standard deviation of pixel value}} = \frac{\mu}{\sigma}$$

$$SNR[dB] = 20 \log_{10} \left( \frac{\mu}{\sigma} \right)$$



In our case of Poisson pmf:

$$SNR[dB] = 20 \log_{10} \left( \frac{\alpha}{\sqrt{\alpha}} \right) = 20 \log_{10} (\sqrt{\alpha}) = 10 \log_{10} (\alpha)$$

**The SNR of Poisson noise (photon counting) increases with the average number of photons.**

It means that we have less deviation from the mean value for more photons.  
As a result, we observe less noise.

**Conclusion:** the larger pixel size, the more photons we collect....but ....

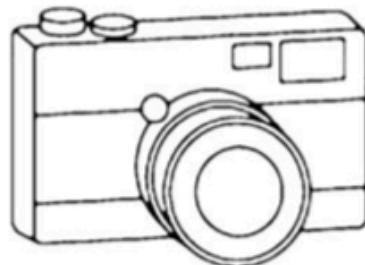
# Image sensors – optical: photon shot noise

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Experimental confirmation with RAW data

A simple experiment

Take photos of a gray scale test ramp

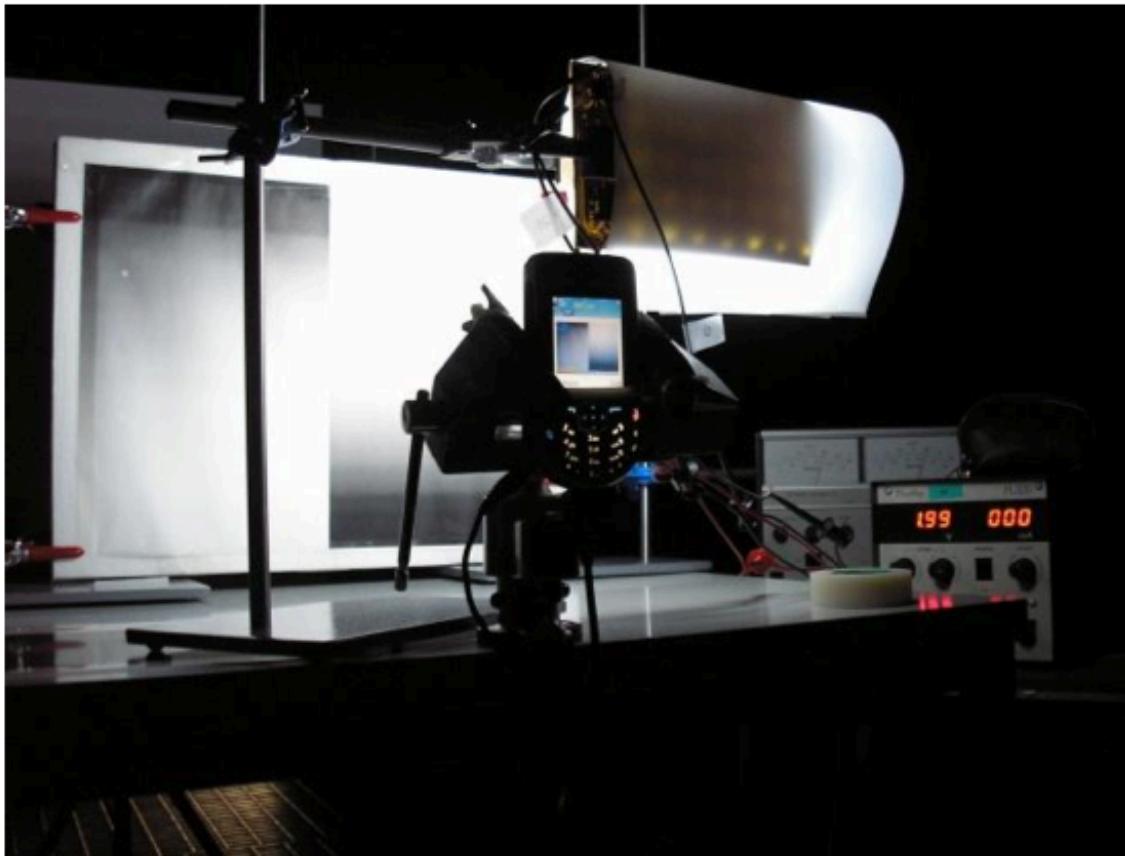


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# Image sensors – optical: photon shot noise

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Experimental confirmation with RAW data



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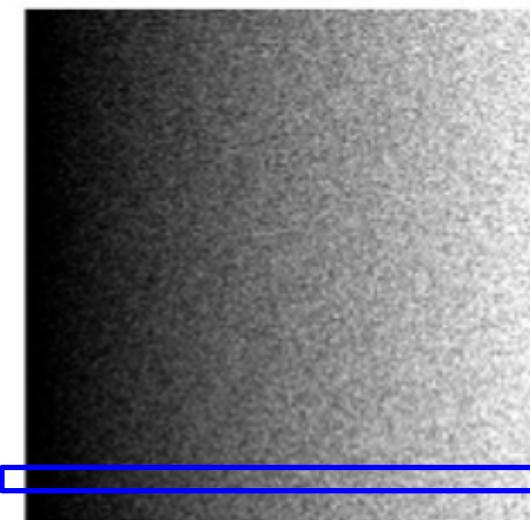
# Image sensors – optical: photon shot noise

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Experimental confirmation with RAW data

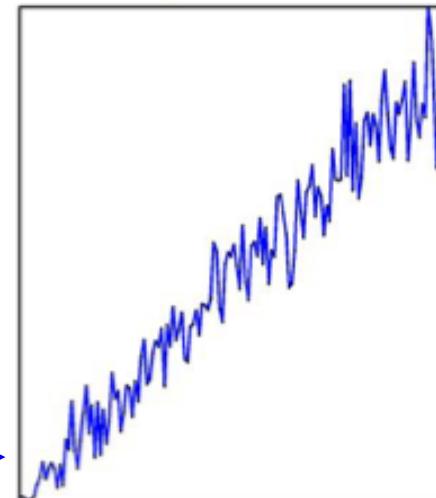
A simple experiment

Shot #1



A simple experiment

Cross-section



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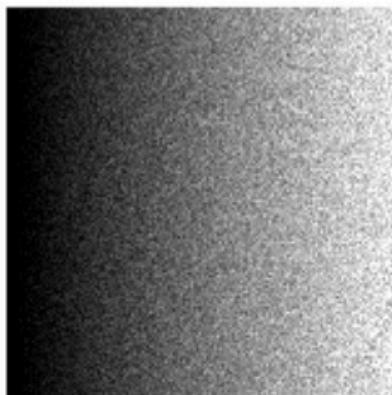
# Image sensors – optical: photon shot noise

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## Experimental confirmation with RAW data

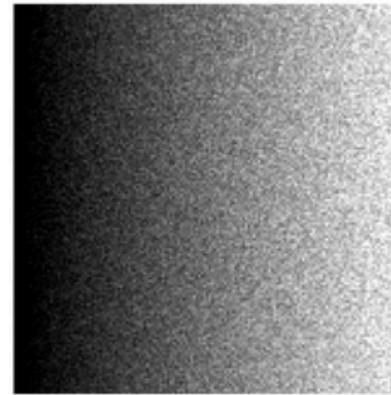
A simple experiment

Shot #2



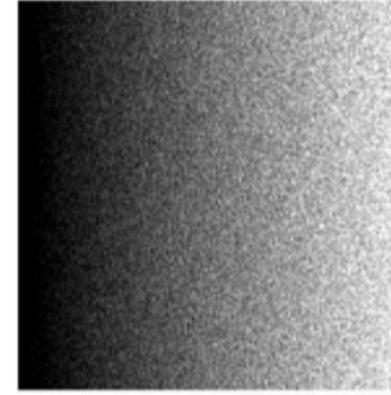
A simple experiment

Shot #3



A simple experiment

Shot #4



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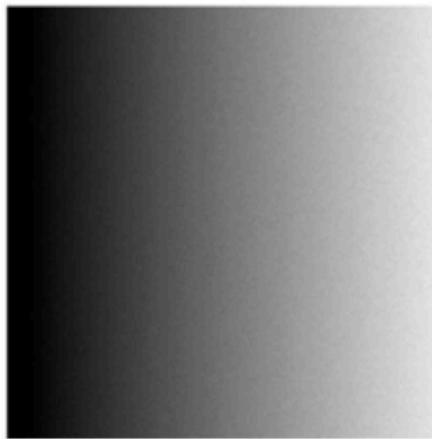
# Image sensors – optical: photon shot noise

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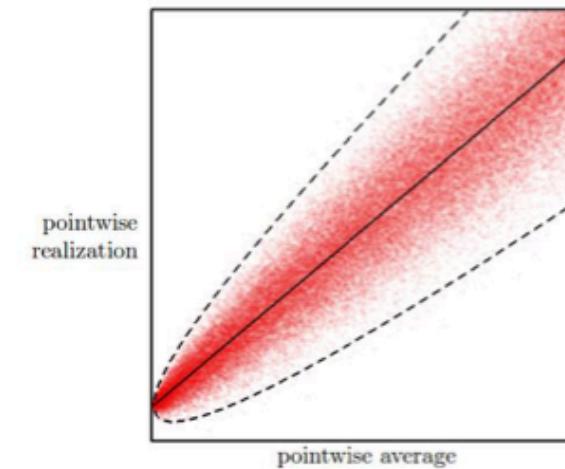
TAKE MANY MORE SHOTS, AND THEN AVERAGE THEM ALL

$$\frac{1}{N} \sum \quad + \quad + \quad + \quad \dots \quad + \quad = \quad$$

TAKE MANY MORE SHOTS, AND THEN AVERAGE THEM ALL



Scatterplot: average vs realization

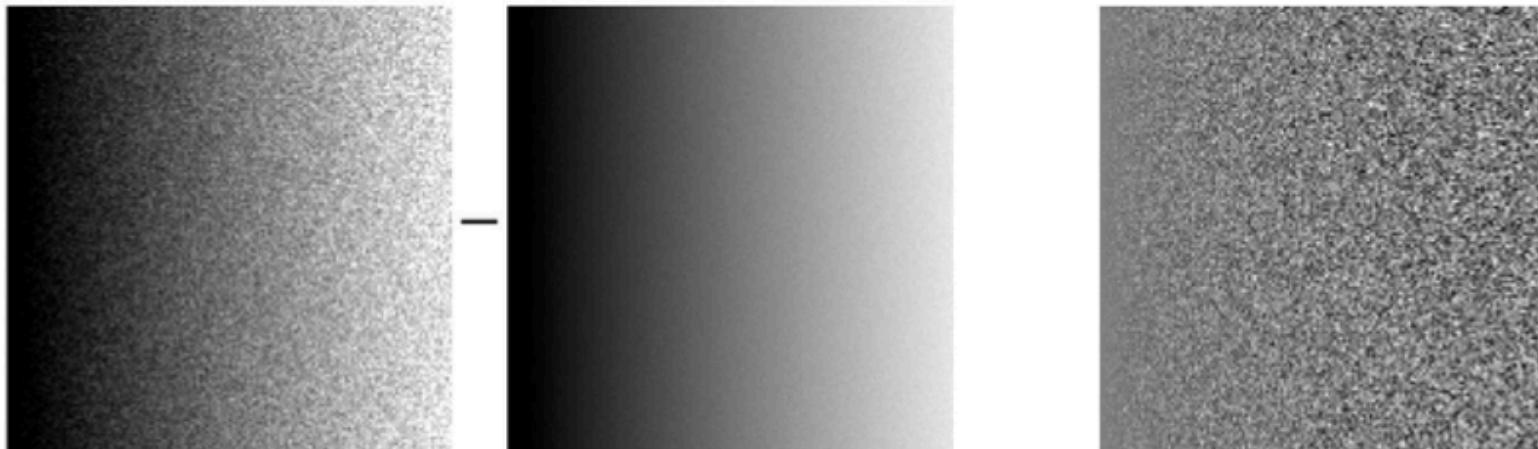


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# Image sensors – optical: photon shot noise

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SUBTRACT THE AVERAGE OF ALL SHOTS FROM ANY OF THE SHOTS

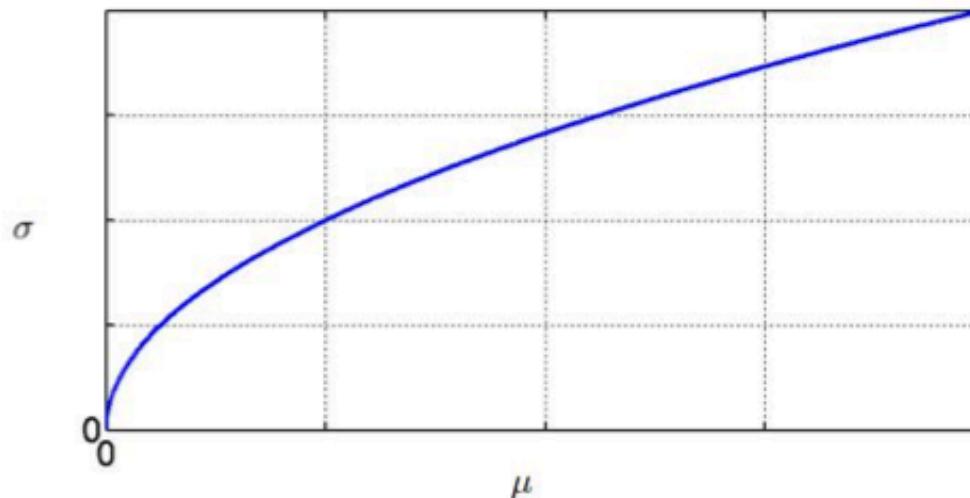


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# Image sensors – optical: photon shot noise

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FOR EACH PIXEL, COMPUTE  
*SAMPLE MEAN* AND *SAMPLE STANDARD DEVIATION*  
W.R.T. THE VARIOUS SHOTS



NOISE IS STRONGER WHERE THE AVERAGE IMAGE IS BRIGHTER:  
STANDARD-DEVIATION IS A FUNCTION OF MEAN

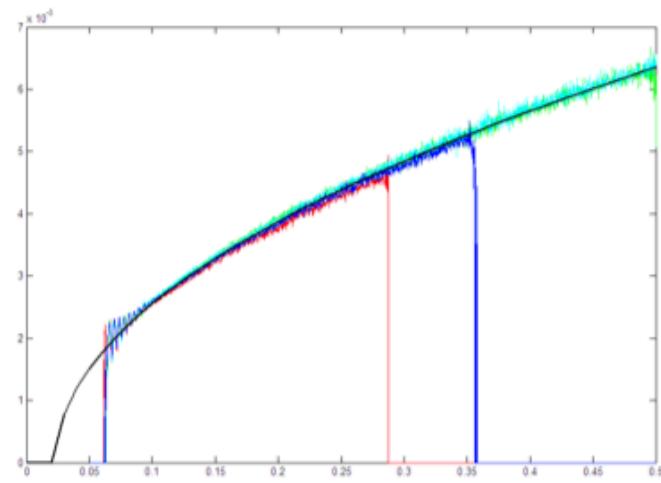
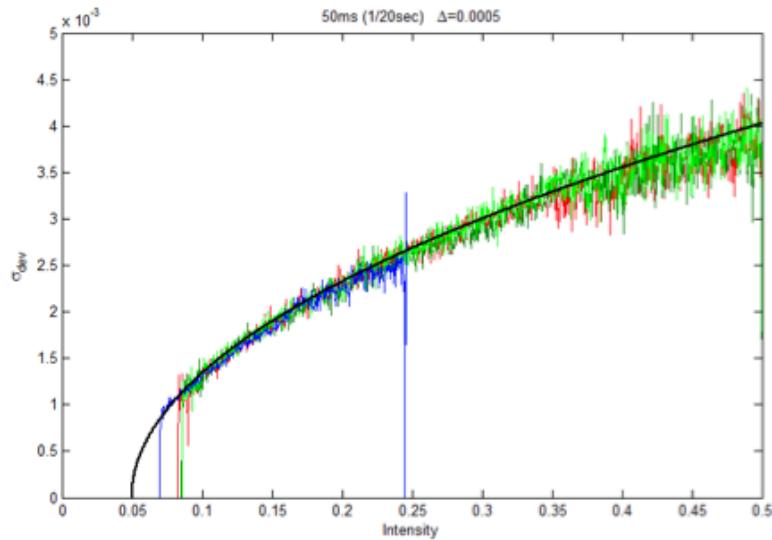
***SIGNAL-DEPENDENT NOISE***

Karen Egiazarian, Tamptere University of Technology

# Image sensors – optical: photon shot noise

The analysis of experimental data demonstrates that:

1. The model of noise is close to the Poissonian one
2. Model parameters depend neither on the color channel nor on the exposure time



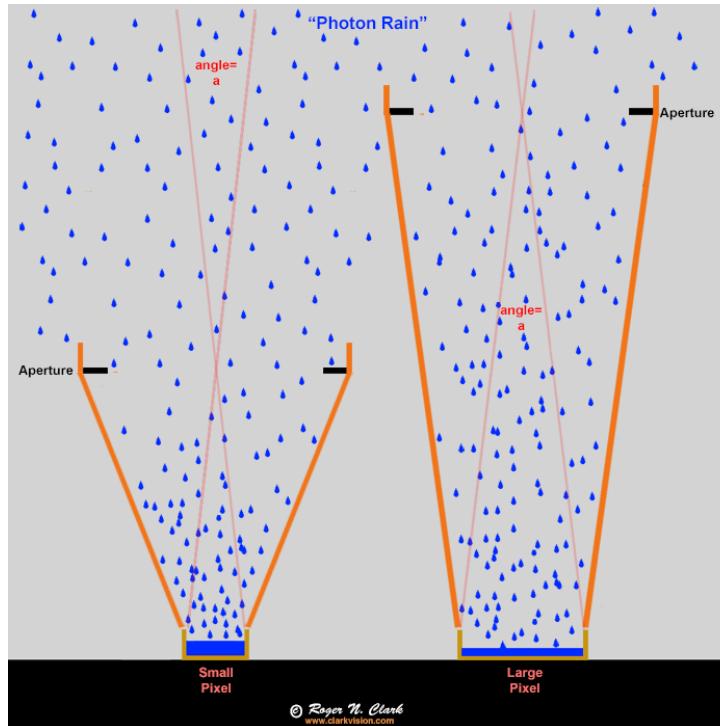
Karen Egiazarian, Tamptere University of Technology

# Image sensors – optical: photon counting

## Pixel size and aperture

The number of photons that is collected is not only controlled by the pixel size.

Remember: we have assumed no lens and no aperture. We can control the process.



### Note:

The aperture size is the same in both cases

But the focusing is different!

**Conclusion:** theoretically (neglecting diffraction for small pixels) we can collect the same amount of electrons for small and large pixels -> **aperture matters**

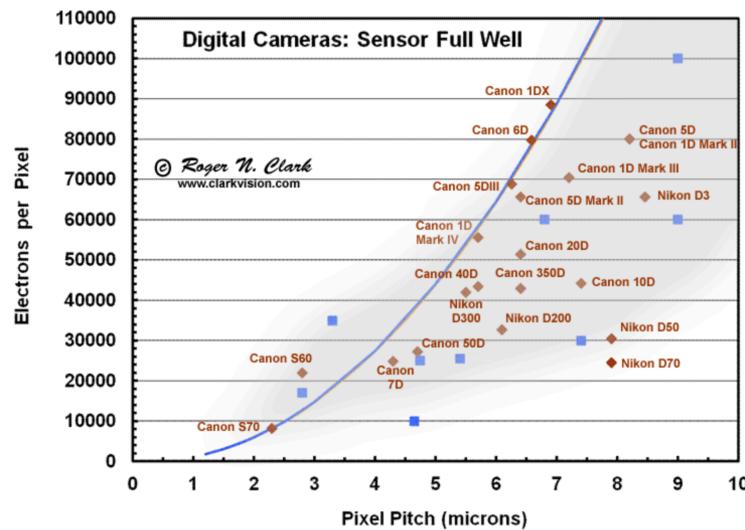
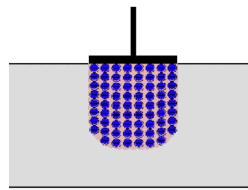
# Image sensors – optical: photon counting

## Pixel size and full well capacity

However, there is one more important issue related with the size of pixel.

The capacity to hold the electrons in each pixel that are generated from photons is called the **Full Well Capacity**.

Too many electrons (like an overflow for a small pixel size) might cause a **saturation** (white spot in images)



Because of the finite and fixed absorption lengths of photons in silicon, the full well capacities are basically a function of pixel area (and not volume).

**Conclusion:** larger pixel size has higher Full Well Capacity that prevents the saturation

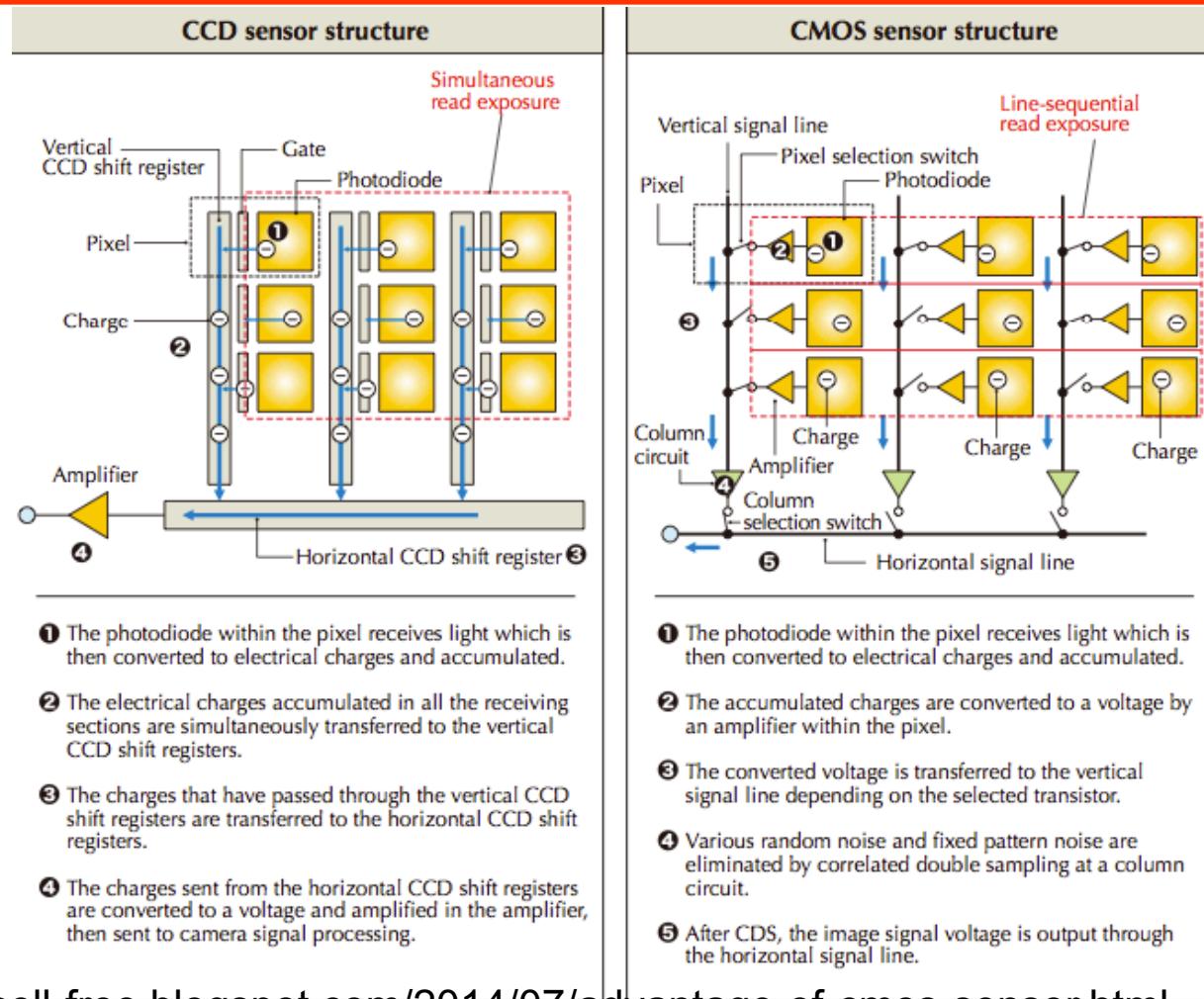
# Image sensors – main types of optical sensors

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- **CMOS** = complementary metal-oxide semiconductor
  - Each pixel has its own amplifier; each row has its own ADC
  - Output is digital
  - Low power, fast but generally noisy (recent models are better)
- **CCD** = charge-coupled device
  - Charge shifted along columns to an output amplifier and ADC (off chip)
  - Historically among the first solid-state image sensors
  - Highest image quality but more expensive than CMOS
  - Slow but low noise

The main difference between **CCD** and **CMOS** is how they amplify and transfer the charge out of the pixel.

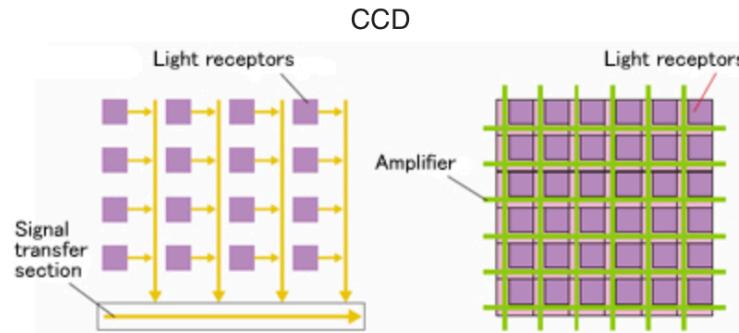
# Image sensors – main types of optical sensors



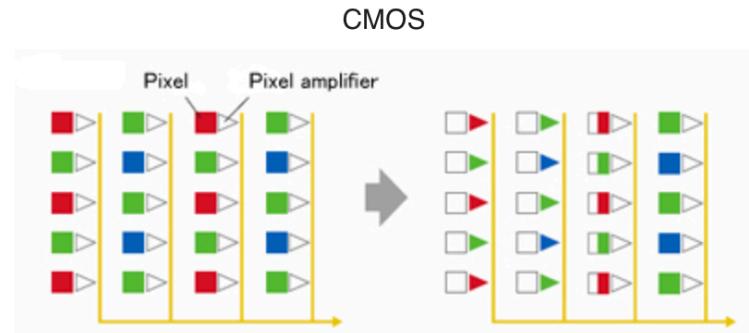
<http://market-sell-free.blogspot.com/2014/07/advantage-of-cmos-sensor.html>

# Image sensors - optical

## CCD and CMOS Image Sensor Differences



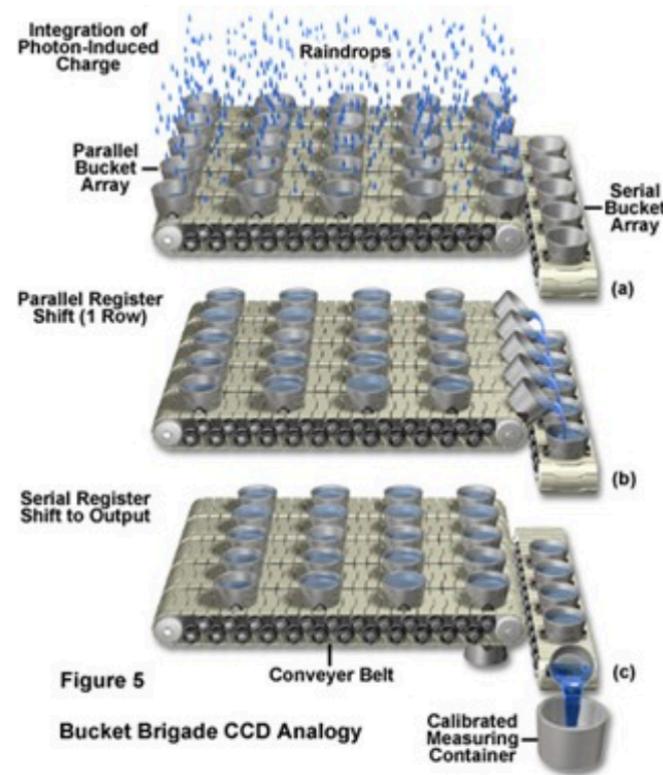
CCD image sensors apply a voltage to each electrode, then use a relay system to transfer the charge and amplify the signal.



In a CMOS image sensor, each pixel consists of a photodiode and a switch that employs a CMOS transistor. The signal from each pixel is amplified. Another switch is mounted to each of the photodiodes, which are arranged in a lattice pattern, and the successive operation of these switches allows each pixel to be directly read and its data to be transferred at high speed.

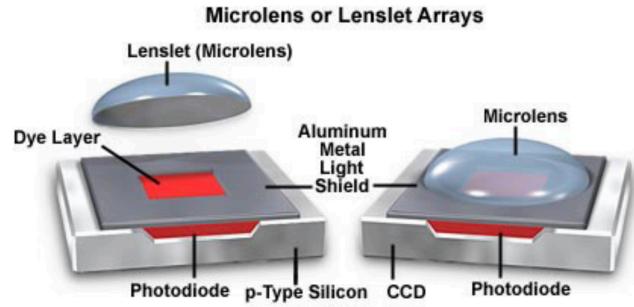
# Image sensors – CCD read out

CCD “bucket-brigade” analogy

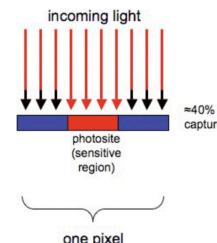


<https://slideplayer.com/slide/10531209/>

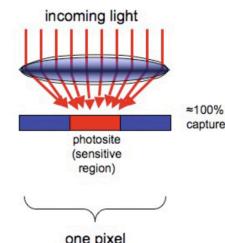
# Image sensors – CCD microlens



Without microlens



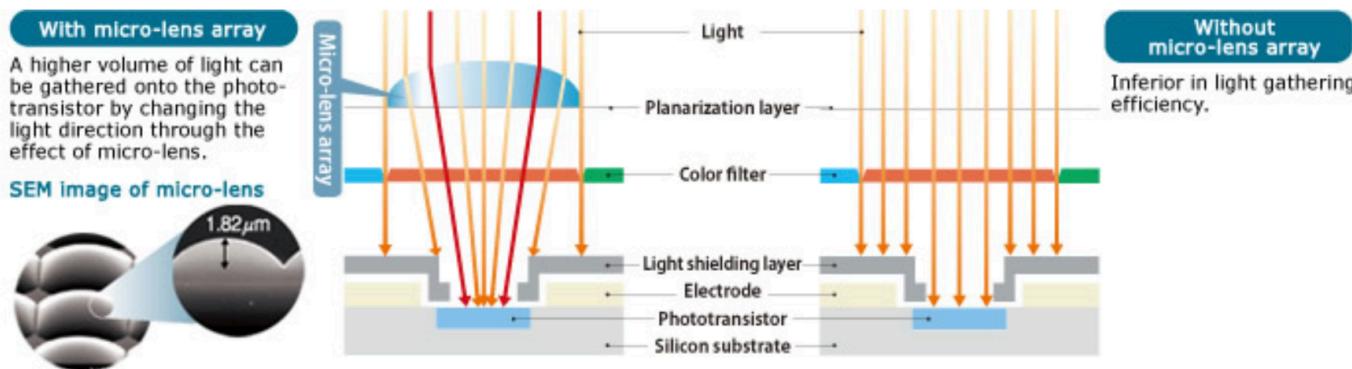
With microlens



<http://hamamatsu.magnet.fsu.edu/articles/microlensarray.html>

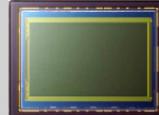
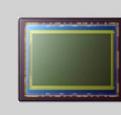
<http://www.digitalbirdphotography.com/2.3.html>

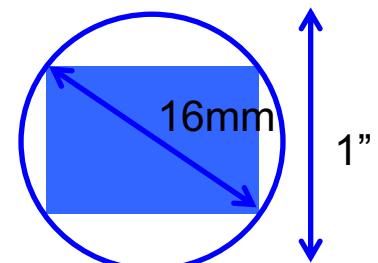
Microlenses increase the number of photons. This also increases the quantum efficiency of pixel and focus the photons into the photosensitive area



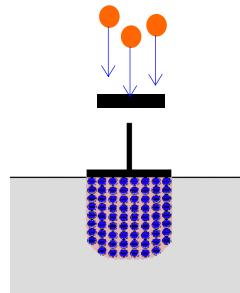
<https://www.toppan.co.jp/electronics/english/semicon/onchip/>

# Image sensors

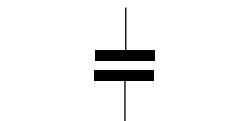
Sensor Name	Medium Format	Full Frame	APS-H	APS-C	4/3	1"	1/1.63"	1/2.3"	1/3.2"
Sensor Size	53.7 x 40.2mm	36 x 23.9mm	27.9x18.6mm	23.6x15.8mm	17.3x13mm	13.2x8.8mm	8.38x5.59mm	6.16x4.62mm	4.54x3.42mm
Sensor Area	21.59 cm <sup>2</sup>	8.6 cm <sup>2</sup>	5.19 cm <sup>2</sup>	3.73 cm <sup>2</sup>	2.25 cm <sup>2</sup>	1.16 cm <sup>2</sup>	0.47 cm <sup>2</sup>	0.28 cm <sup>2</sup>	0.15 cm <sup>2</sup>
Crop Factor	0.64	1.0	1.29	1.52	2.0	2.7	4.3	5.62	7.61
Image									
Example									



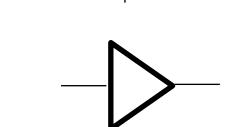
# Image sensors - summary



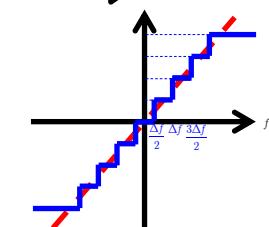
A number of **photons** hit a **pixel** during the **exposure time** for a given **aperture**



... create a number of **electrons** ...  
... forming a **charge** that is converted by a **capacitor** to a **voltage** ...



... and then **amplified** ...



... and then **digitized (ADC)** ...

127

... resulting in a **digital gray level value**.

**CCD:** high image quality, lower speed

**CMOS:** high speed, lower quality, lower energy consumption

# Image sensors – quality and origin of noise

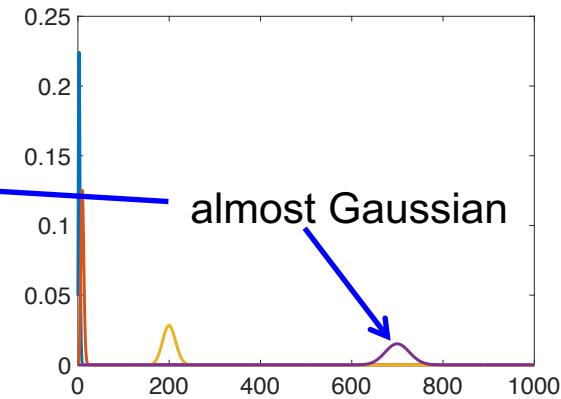
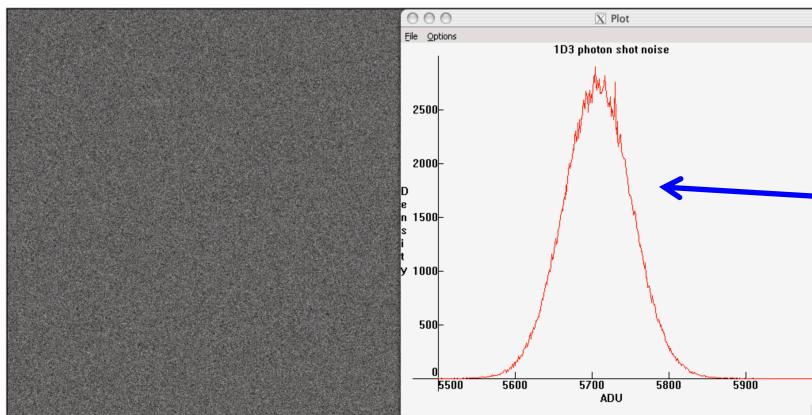
---

- **Pixel size and number**
- **Aperture and exposure time**
- **Quantum efficiency:** the fraction of photons hitting the CCD that converted to electrons
- **Full well depth:** total number of electrons that can be recorded per pixel
  
- **Noise origin:**
  - **Shot noise / Photon noise:**
    - Photon counting
  - **Dark current or thermal noise:**
    - The rate at which electrons are produced due to thermal effects (potential cooling of sensors)
  - **Pattern noise**
  - **Quantization noise:**
    - Errors caused by ADC process

# Noise in digital images: photon noise

## Origin of noise

- Discrete nature of photon counting (see slide 24)
- The more intense the light, the higher the number of photons per second that illuminate the scene (the better SNR)



Photon shot noise in an image of the sky from a Canon 1D3 (in the green channel).

The photon noise was estimated by taking the difference of two successive images; the raw values for any one pixel then differ only by the fluctuations in the photon count due to Poisson statistics (in fact it leads to “double” noise – compare with slide 32)

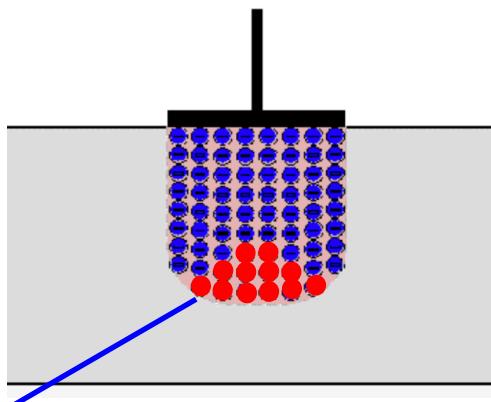
<http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/#patternnoise>

# Noise in digital images: dark current or thermal noise

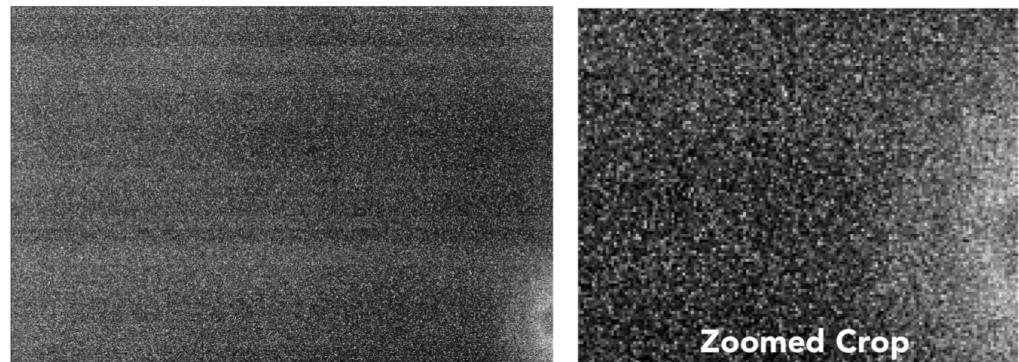
---

## Origin of noise

- Thermal agitation of electrons in a sensor can liberate a few electrons
- These electrons are independent of sensor incident light
- Increases linearly with exposure time and exponentially with temperature



Electrons of thermal origin  
(independent to input)



Zoomed Crop

<http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/#patternnoise>

# Noise in digital images: pattern noise

---

## Origin of noise

- Not all pixels in a sensor have exactly the same efficiency in capturing and counting photons
- This might cause a so-called **pattern noise**:
  - **Fixed pattern noise (FPN)**: pixel to pixel differences **when not exposed to light** (**additive** in nature)
  - **Photo response non-uniformity (PRNU)**: depends on illumination (**multiplicative** in nature)
- **Both types of noise are systematic for a given sensor**

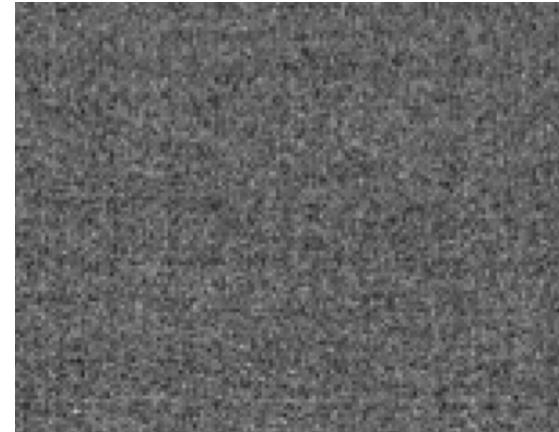
<http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/#patternnoise>

# Noise in digital images: pattern noise

---

## FPN:

- Crystal defects in the silicon lattice introduced during growth
- Impurities
- The size of detector/potential well
- Contamination during fabrication
- Non-uniform oxide/gate thickness
- In CMOS: additional variability for each transistor
- Does not change over time; FPN can be estimated and removed from each image



<http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/#patternnoise>

# Noise in digital images: pattern noise

---

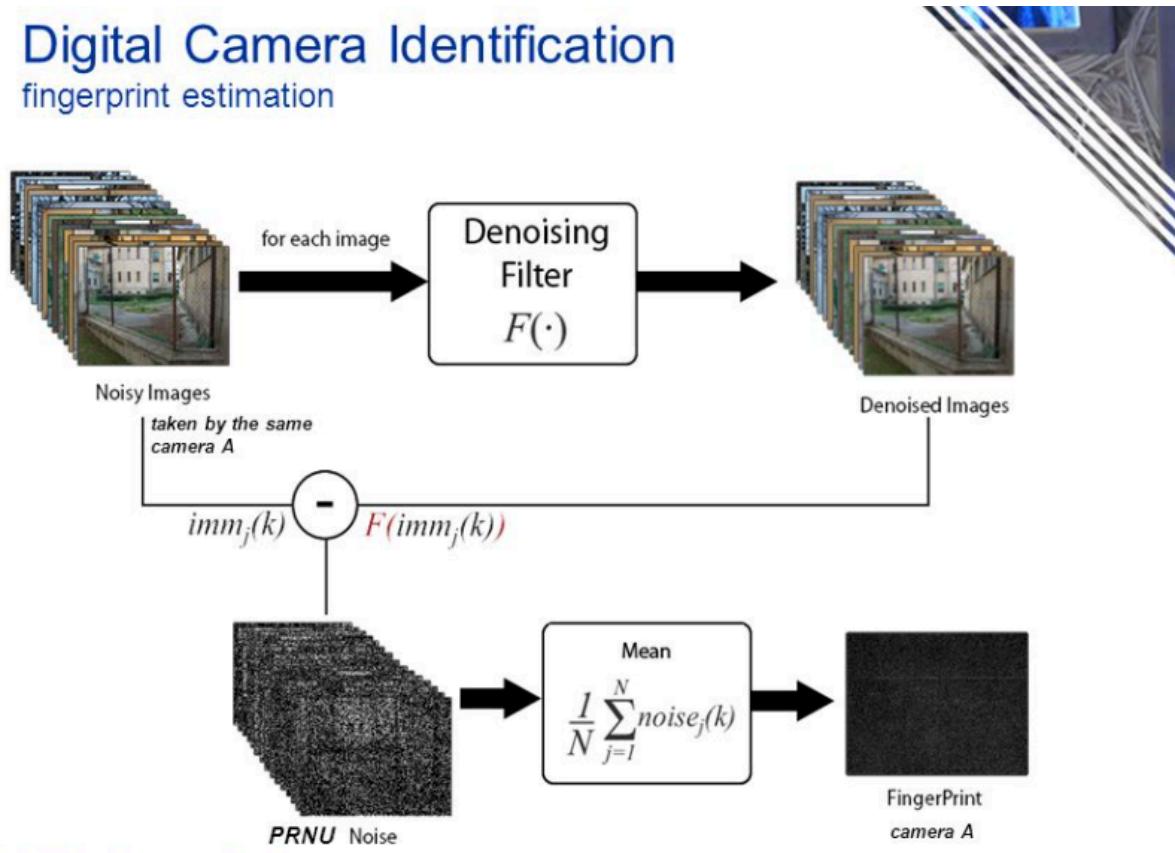
## PRNU:

- The depth of the detector/potential well
- Larger active areas – more incident photons
- Non-uniform oxide layer: results in non-uniform potential wells
- Deeper potential well: more photons absorbed (wavelength dependent)
- PRNU can be estimated and removed from each image

**PRNU is a “fingerprint” of sensor**

<http://theory.uchicago.edu/~ejm/pix/20d/tests/noise/#patternnoise>

# Noise in digital images – pixel response non-uniformity (PRNU)

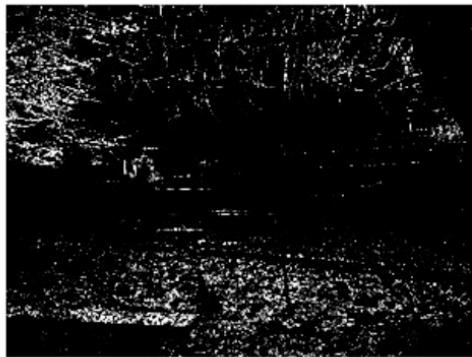


<https://slideplayer.com/slide/10390280/>

# Noise in digital images – pixel response non-uniformity (PRNU)

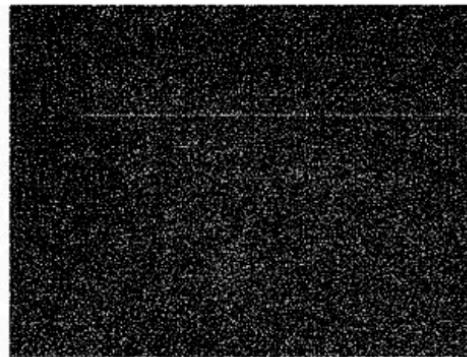
---

The test image  $imm(k)$  is taken by camera A?



Residual Noise Image

$$noise(k) = imm(k) - F(imm(k))$$



Fingerprint  
camera A

$$> \theta$$

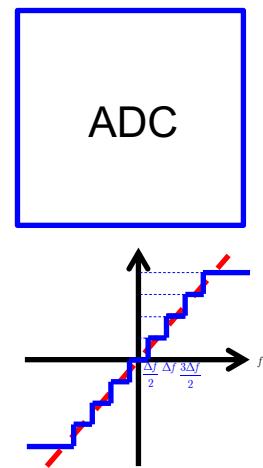
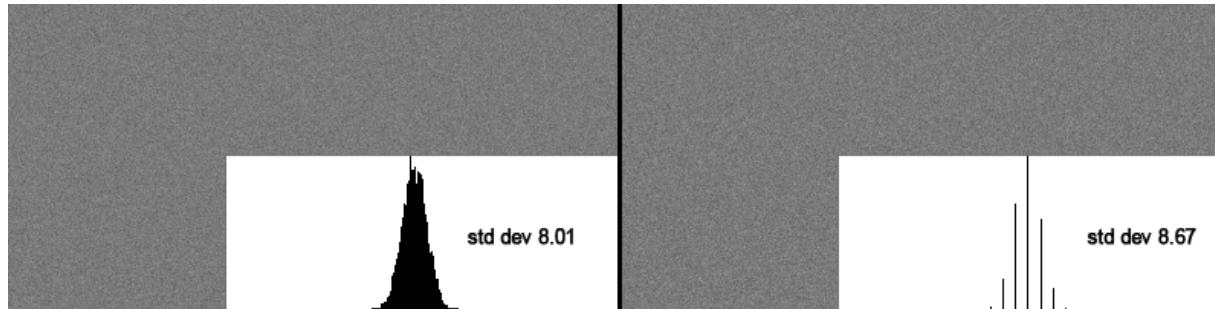


$imm(k)$  is taken by camera A



# Noise in digital images – quantization noise

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# Noise in digital images – summary

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## Photon shot noise:

- Unavoidable randomness in number of photons arriving
- Grows as the square root of the number of photons, so brighter lighting and longer exposures will be less noisy

## Dark current noise:

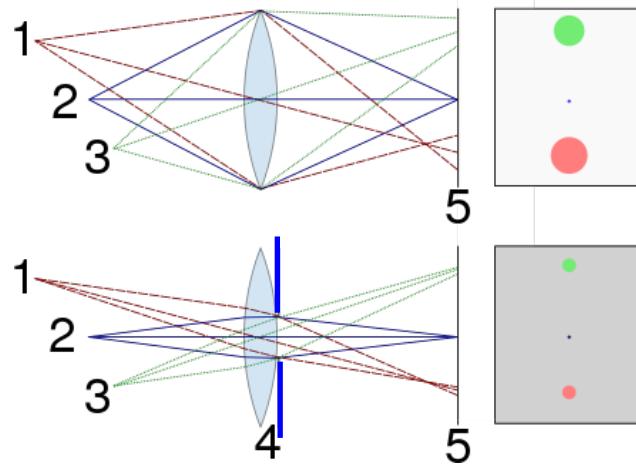
- Grows with exposure time and sensor temperature
- Minimal for most exposure times used in photography
- Corrected for average dark current

## Quantization noise:

- Determined by the ADC: quantization step, properties of quantizer

# Factors impacting image quality

---



Positive impact of aperture on  
**depth of field (DoF)**

**Effect of aperture** on blur and DOF. The points in focus (2) project points onto the image plane (5), but points at different distances (1 and 3) project blurred images, or circles of confusion. Decreasing the aperture size (4) reduces the size of the blur spots for points not in the focused plane, so that the blurring is imperceptible, and all points are within the DoF.

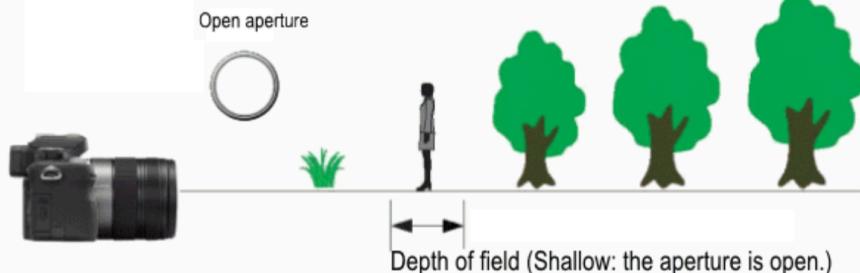
[https://en.wikipedia.org/wiki/Depth\\_of\\_field](https://en.wikipedia.org/wiki/Depth_of_field)

# Factors impacting image quality

## Result of Using Different Depths of Field

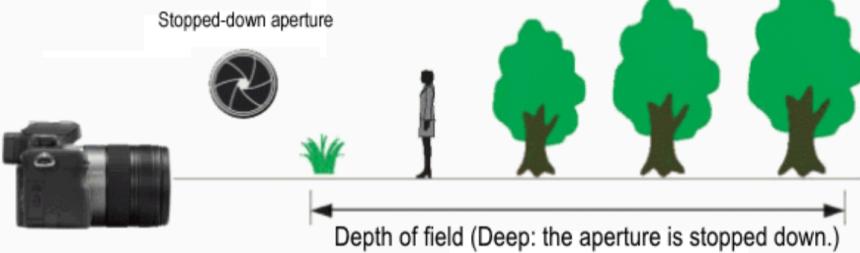
As the aperture of the lens is opened (becomes larger), the depth of field becomes shallower, and as the aperture is closed (becomes smaller), the depth of field becomes deeper.

### ■ Shallow depth of field



Due to the shallow depth of field, only the figure is in focus and the background is "soft focus."

### ■ Deep depth of field



Due to the deep depth of field, both the figure and background are in focus.

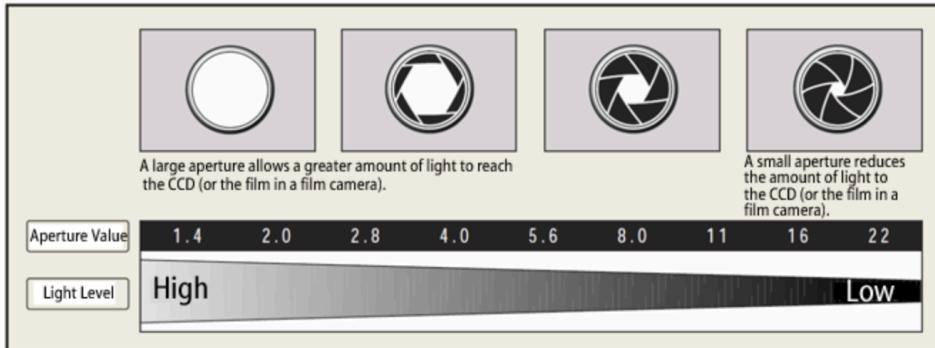
<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow05.html>

# Factors impacting image quality

However, the **aperture restricts the amount of light** (number of photons) and thus impacts the level of noise

The f-number is the focal length divided by the "effective" aperture diameter.

## ■ Aperture and light level



## ■ Here, the shutter speed was kept the same, and the aperture was varied...



- Aperture value: F2.8
- Shutter speed: 1/125 sec

At maximum aperture, too much light turned the image whitish.

smaller aperture value  
←



- Aperture value: F5.6
- Shutter speed: 1/125 sec

larger aperture value  
→



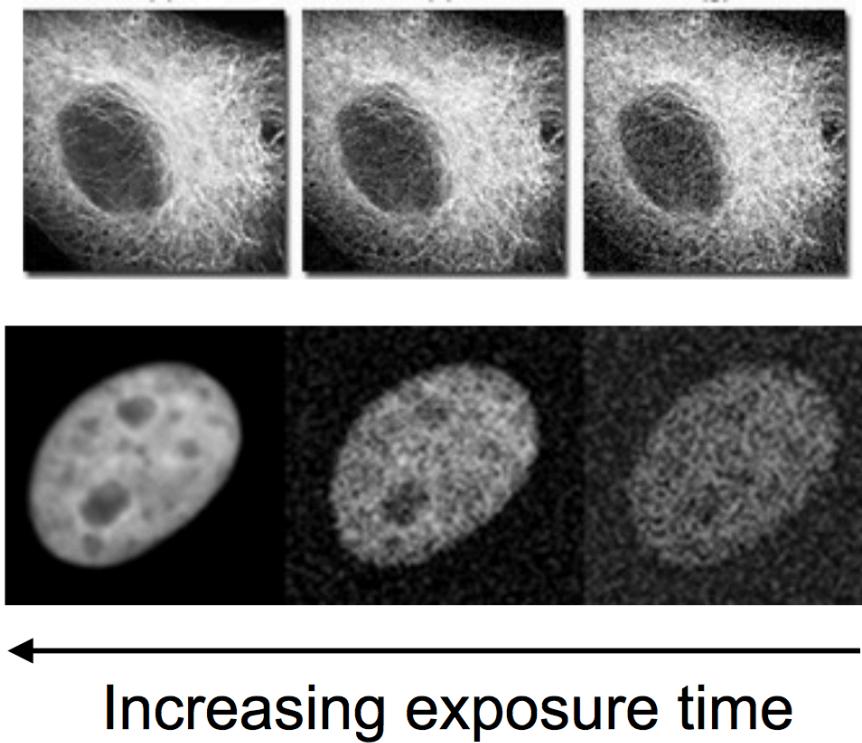
- Aperture value: F11
  - Shutter speed: 1/125 sec
- A smaller aperture size caused insufficient light, making the image dark.

<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow06.html>

# Factors impacting image quality

---

It can be compensated by **longer exposure time** – more photons are collected



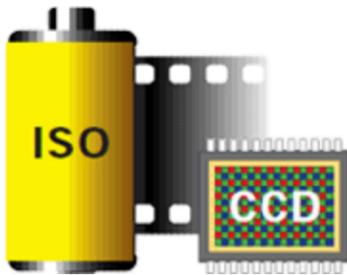
<https://slideplayer.com/slide/10531209/>

# Factors impacting image quality - ISO

---

## ISO in Traditional/Film Photography

In traditional (film) photography ISO (or ASA) was the indication of how sensitive a film was to light. It was measured in numbers (100, 200, 400, 800 etc). The lower the number the lower the sensitivity of the film and the finer the grain in the shots.



## ISO in Digital Photography

In Digital Photography ISO measures the sensitivity of the image sensor.

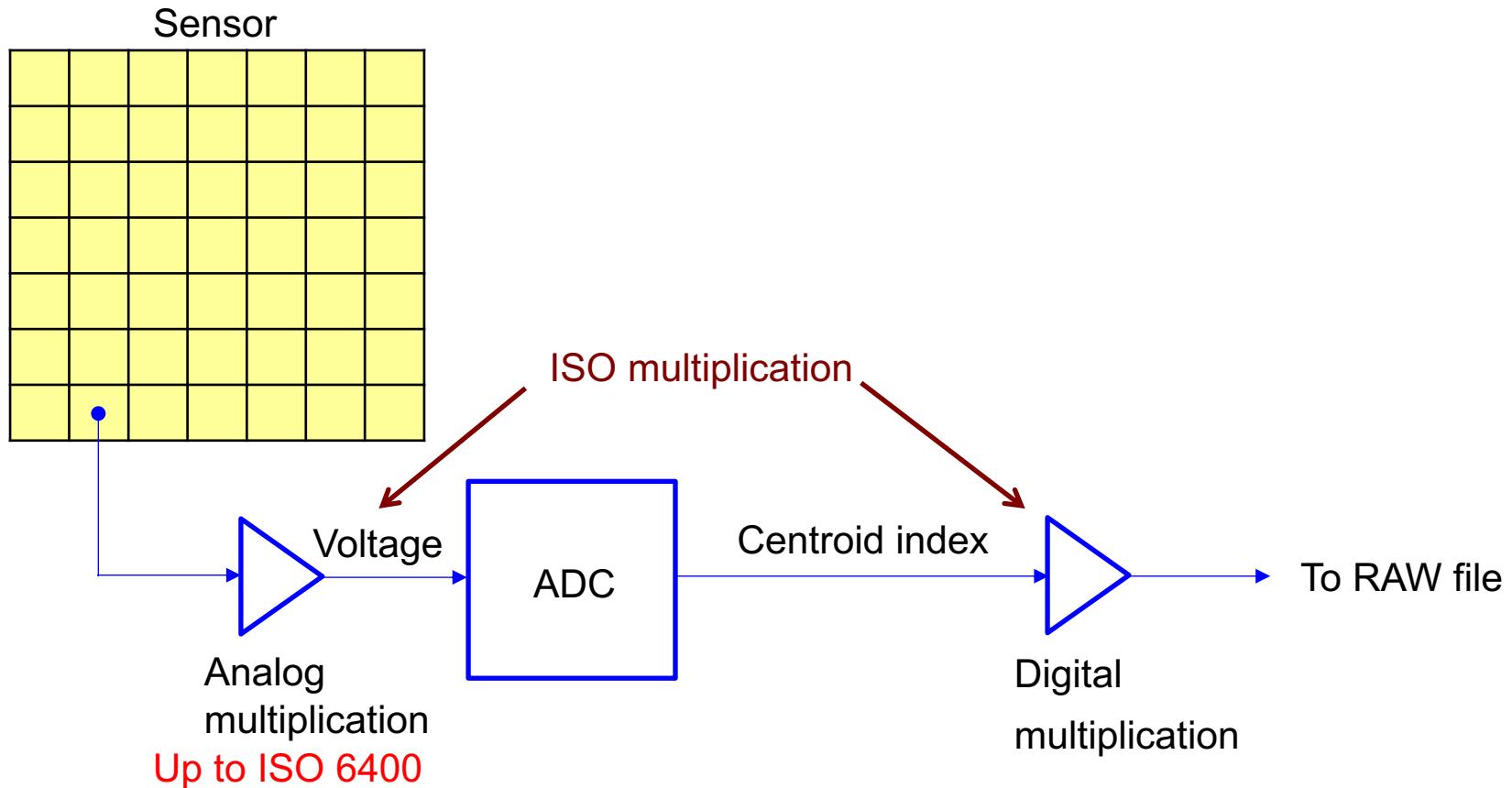
The same principles apply as in film photography – the lower the number the less sensitive your camera is to light and the finer the grain.

Higher numbers mean your sensor becomes more sensitive to light which allows you to use your camera in darker situations. The cost of doing so is more grain.

# Factors impacting image quality - ISO

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## ISO implementation



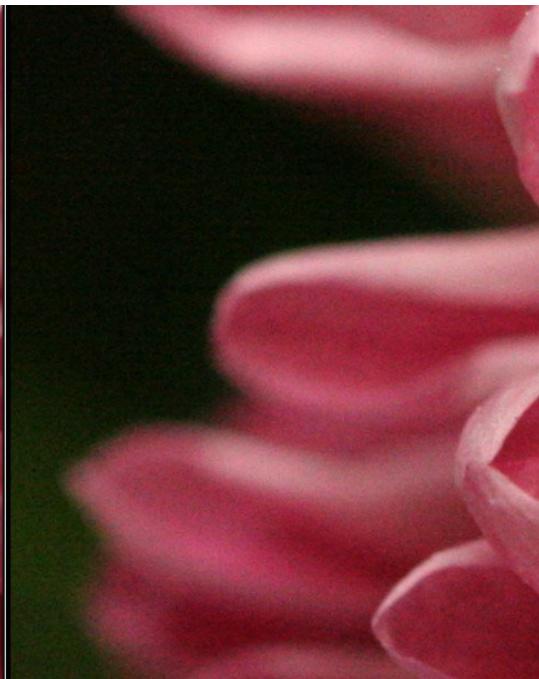
# Factors impacting image quality - ISO

---

100 ISO

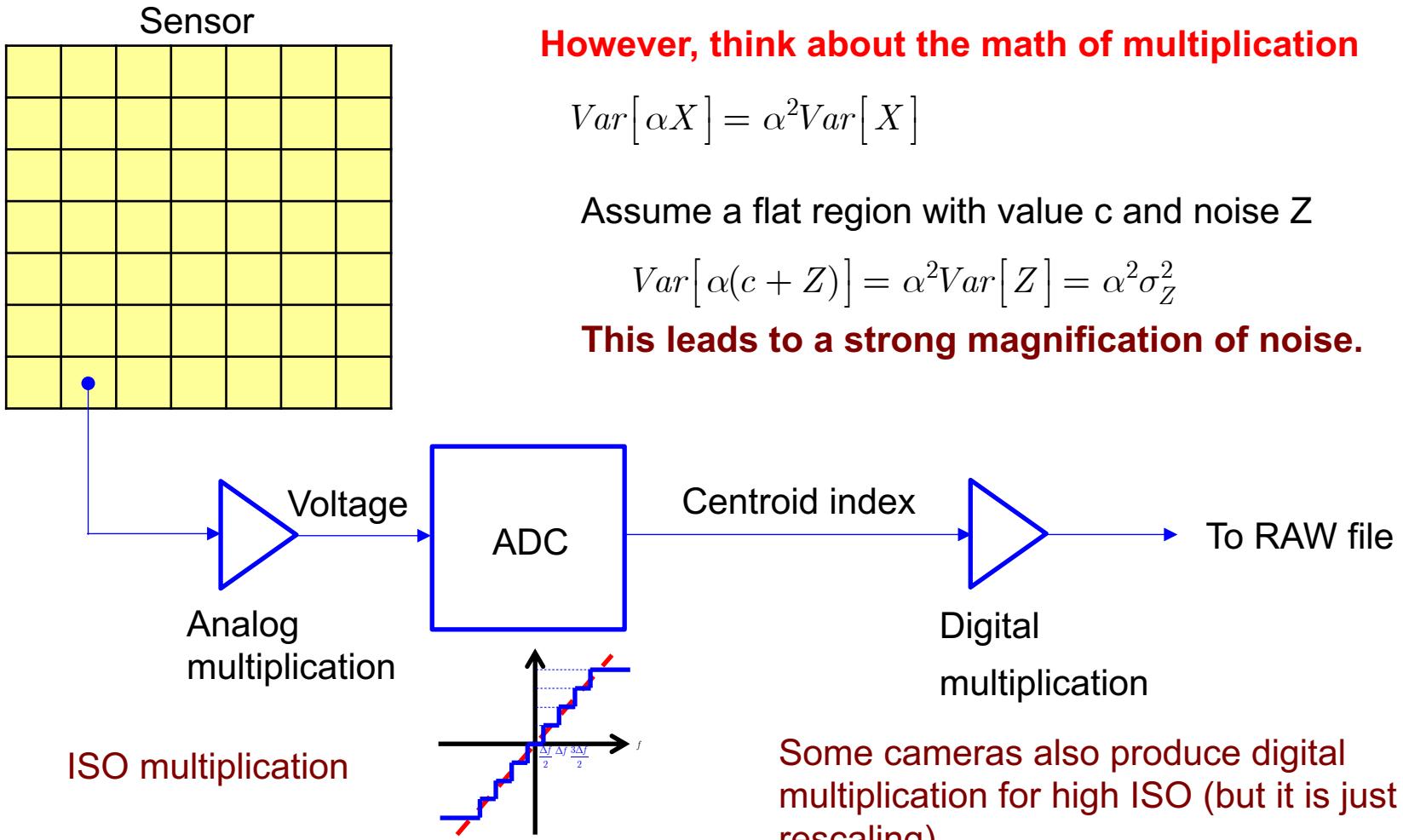


3200 ISO

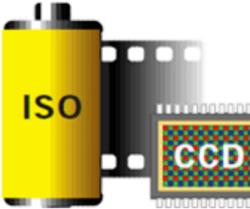
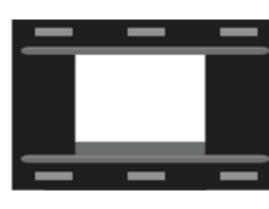


<https://digital-photography-school.com/iso-settings/>

# Signal amplification pipeline



# Three factors determining the exposure

Film Sensitivity	Lens Aperture	Shutter Speed	Final Exposure
Film sensitivity indicates how sensitive a film (or CCD) is to light. This sensitivity is represented using ISO values, such as ISO100 or ISO200. The larger the ISO value becomes, the greater the film/sensor's sensitivity to light. Similarly, the smaller the ISO value becomes, the less the film/sensor's sensitivity to light.	Much like the pupil of the human eye, the amount of light passing through the lens can be controlled by changing the lens aperture value. As this value increases and the aperture becomes smaller, the amount of light passing through the lens decreases, and as it decreases and the aperture becomes larger, the amount of light increases.	After the shutter is opened, the period of time that light strikes the film can be controlled via the shutter speed. When the shutter speed is high, the amount of light allowed to enter the camera from the lens is small. Similarly, when the shutter speed is low, the amount of light entering the camera from the lens is large.	Final exposure is: $(\text{Film sensitivity}) \times (\text{Lens aperture value}) \times (\text{Shutter speed})$
<b>Low Sensitive</b>	<b>Minimum aperture</b>	<b>High speed</b>	<b>Underexposure</b> The overall image is dark. Detail and shadow sections have turned to black. 
 ↑ ISO	 ↑ Minimum aperture	 ↑ High speed	 ↑ Optimal exposure
<b>High Sensitive</b>	<b>Maximum aperture</b>	<b>Low speed</b>	<b>Overexposure</b> The overall image is whitish. Detail and highlight sections have blown out. 

<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow03.html>

# Image processing methods to reduce the noise

---

General approaches to fight with noise in imaging systems (assuming we proceed with the reduction of pixel size):

1. Use simple downsampling by NN averaging (single frame): when displayed on lower resolution displays, the loss of number of pixels is almost unperceived but image quality is superior; – loose resolution but gain in SNR (less noise)
2. Use frame averaging (assuming scene is static and noise is different in each frame)
3. Use denoising methods (single frame) – image processing (like BM3D, more recently CNN based)
4. Use trained mappers (DNN) to map low photon acquired images to high quality images (problem: like a black box)

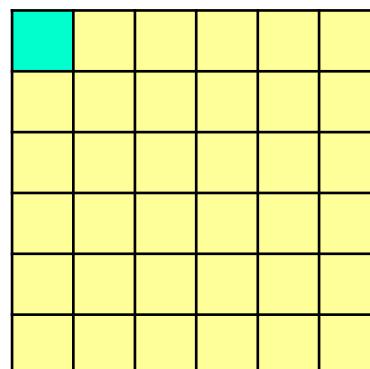
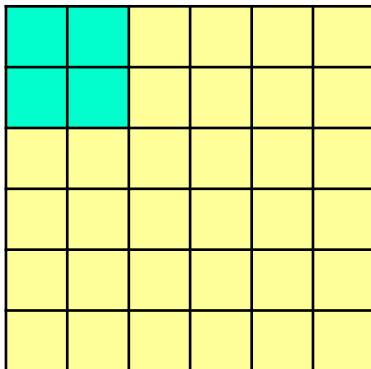
# Image processing methods to reduce the noise

---

## Motivation for downsampling based noise removal:

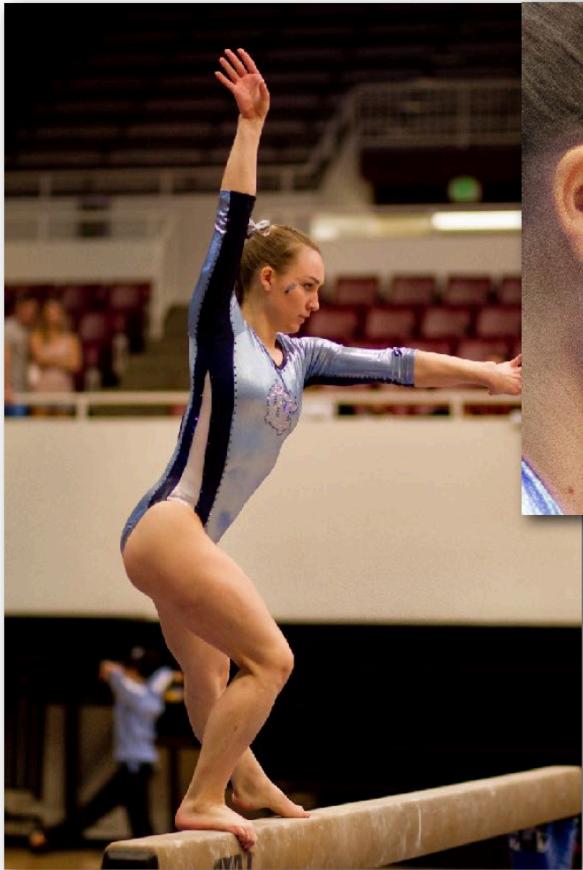
Remarks:

- A lot of improvements to increase the quality of sensors leading to the overall increase of SNR
- At the same time the number of pixels (still megapixels, soon gigapixels) increases. This leads to the decrease of pixel size and so to the increase of level of noise
- The evolution of displays is not so fast
- Practically, we reduce the resolution of image to fit it to those of a display
- The simplest operation of reducing the resolution is an averaging



# Image processing methods to reduce the noise

Effect of downsizing on image noise



averaged  
down



point  
sampled



Levoy

# Image processing methods to reduce the noise

---

Noise reduction by multi-frame image averaging (assume static images)



Single frame in dark room using iPhone 4

Levoy

# Image processing methods to reduce the noise

---

Noise reduction by multi-frame image averaging (assume static images)



Average of  
~30 frames using  
SynthCam app by Marc  
Levoy

Levoy

# Image processing methods to reduce the noise

## Learning to See in the Dark

Chen Chen  
UIUC

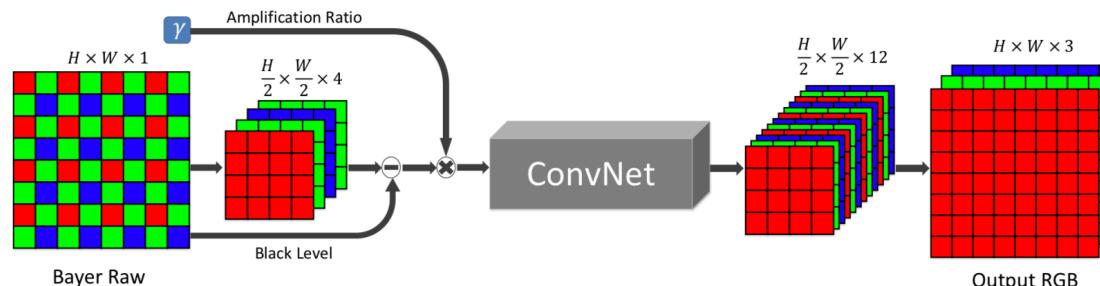
Qifeng Chen  
Intel Labs

Jia Xu  
Intel Labs

Vladlen Koltun  
Intel Labs



Figure 1. Extreme low-light imaging with a convolutional network. Dark indoor environment. The illuminance at the camera is  $< 0.1$  lux. The Sony  $\alpha$ 7S II sensor is exposed for 1/30 second. (a) Image produced by the camera with ISO 8,000. (b) Image produced by the camera with ISO 409,600. The image suffers from noise and color bias. (c) Image produced by our convolutional network applied to the raw sensor data from (a).



<http://cchen156.web.engr.illinois.edu/SID.html>

# Image processing methods to reduce the noise

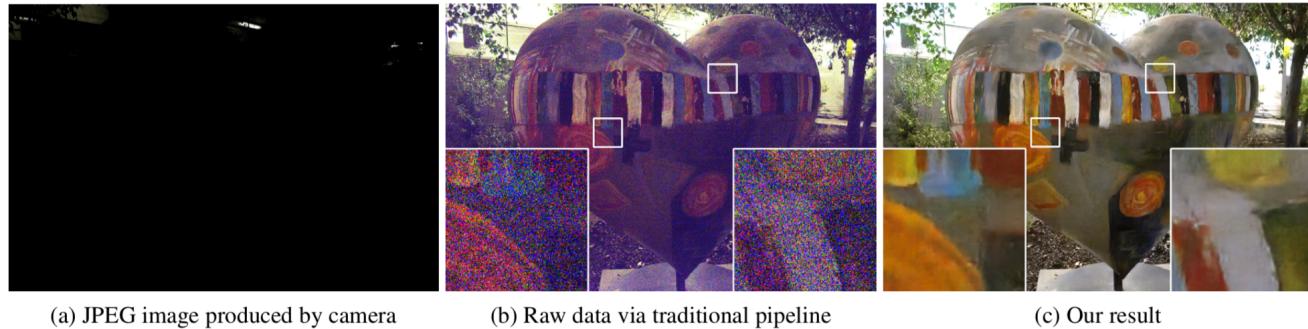


Figure 5. (a) An image captured at night by the Fujifilm X-T2 camera with ISO 800, aperture f/7.1, and exposure of 1/30 second. The illuminance at the camera is approximately 1 lux. (b) Processing the raw data by a traditional pipeline does not effectively handle the noise and color bias in the data. (c) Our result obtained from the same raw data.

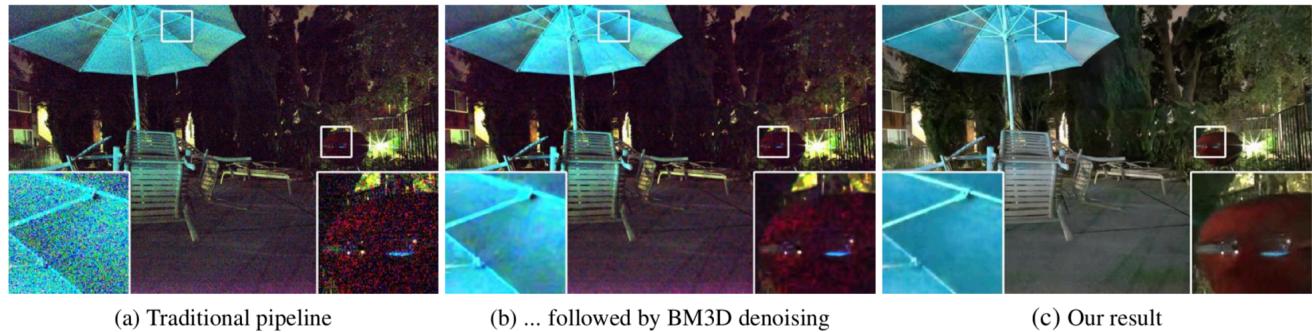


Figure 7. An image from the Sony x300 set. (a) Low-light input processed by the traditional image processing pipeline and linear scaling. (b) Same, followed by BM3D denoising. (c) Our result.

<http://cchen156.web.engr.illinois.edu/SID.html>

# Lens distortions

## Aberrations

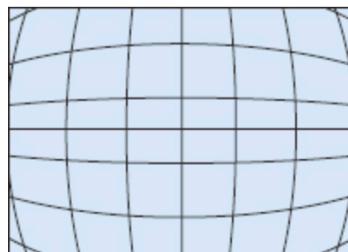
When light refracts inside the lens, image quality is degraded. This is called a lens aberration, or flaw. A wide variety can occur, such as curvilinear, spherical, coma, astigmatic, and chromatic aberration.

Example of barrel distortion



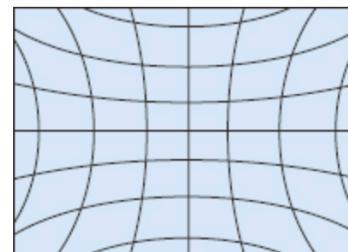
When objects consisting of straight lines are photographed, the effect of curvilinear aberration is strongly felt. This photo is an example of curvilinear aberration.

Barrel distortion  
(Curvilinear aberration)



When the periphery of the image bulges outwards, it is called barrel distortion. This often occurs at the widest angle of a zoom lens.

Pincushion distortion  
(Curvilinear aberration)

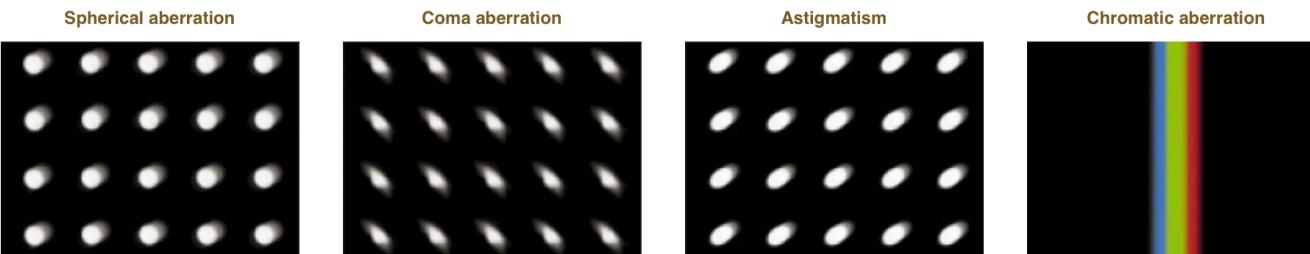
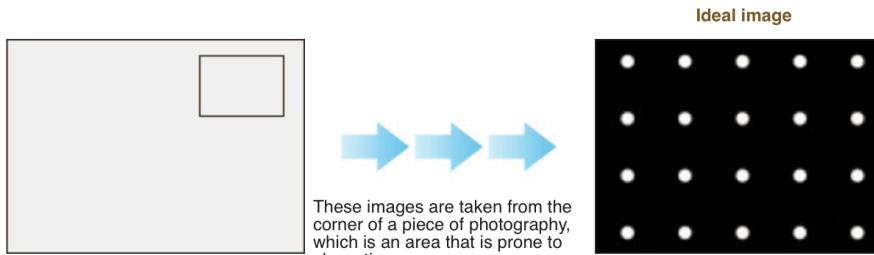


This is the opposite of barrel distortion. It also appears at the edges of an image, where lines appear pulled in towards the center. Generally, this is most often seen at the telephoto end of a zoom lens.

# Lens distortions

## Other Types of Aberration

There are also a number of other types of aberration. Let's have a look at the sample images. Each image's white circles show the kind of deformation caused by that type of distortion.



This is an inevitable type of aberration when using spherical lenses. Differences occur between the light in the center of the lens and the light at the edge of the lens, creating a halo-like blur.

This type of distortion occurs at the edge of lenses designed to correct for spherical aberration. The name "coma" is used because the blur caused by this aberration looks like a comet's tail.

This type of aberration is caused by the lens used to correct spherical and coma aberrations. It occurs when the lens shifts from the optical axis, causing points on the edge of the lens to become either elliptical or linear.

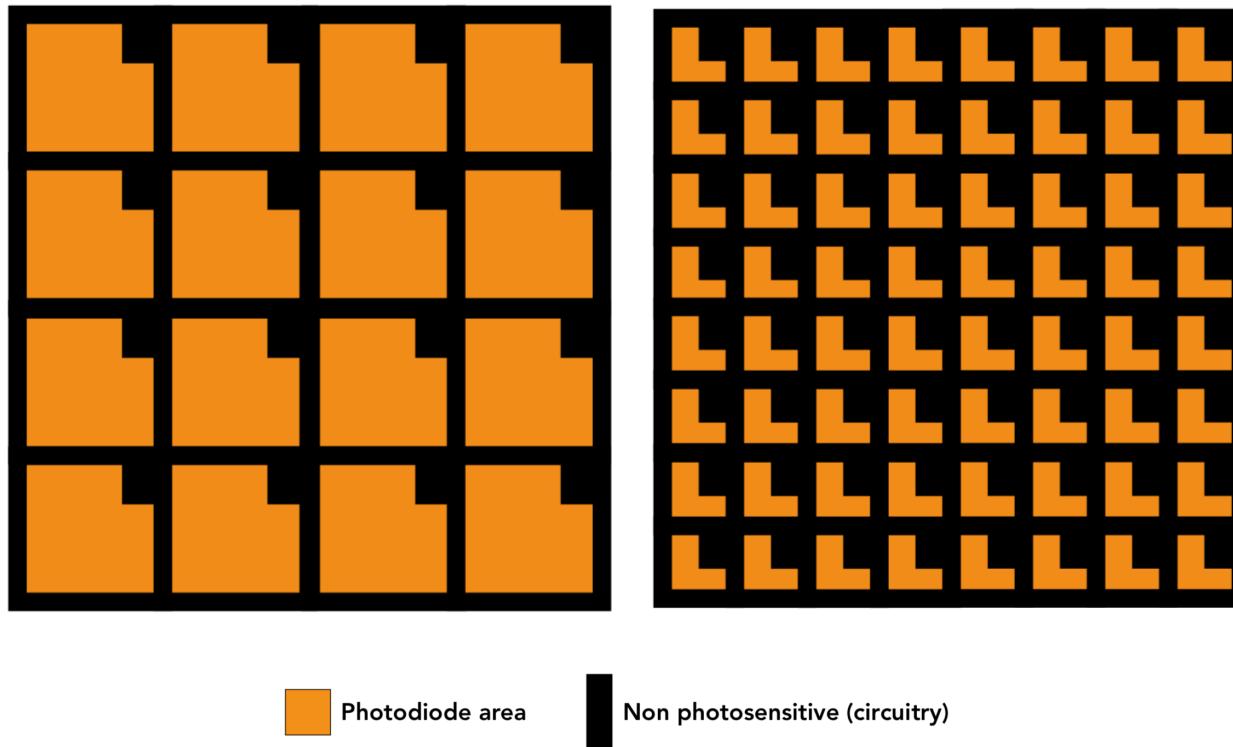
Based on the same principle as a prism breaking light into a rainbow spectrum, these aberrations cause color shifts. They are seen especially in telephoto lenses and increase as the power of the lens increases.

<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow15.html>

# Pixel fill factor

---

Fraction of pixel area that integrates incoming light



# Pixel sampling and aliasing

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[https://cs184.eecs.berkeley.edu/uploads/lectures/30\\_sensors-2/30\\_sensors-2\\_slides.pdf](https://cs184.eecs.berkeley.edu/uploads/lectures/30_sensors-2/30_sensors-2_slides.pdf)

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# Image sensors – color imaging (history)



The Emir of Bukhara, Alim Khan, in a 1911 color photograph by Sergey Prokudin-Gorsky. At right is the triple color-filtered black-and-white glass plate negative, shown here as a positive.

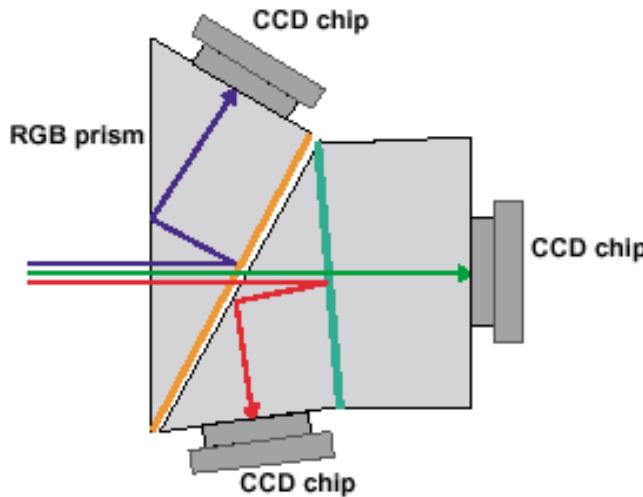
- Images have been shot sequentially through R, G and B filters

[https://en.wikipedia.org/wiki/Color\\_photography](https://en.wikipedia.org/wiki/Color_photography)

# Image sensors – color imaging

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## 3-CCD architecture

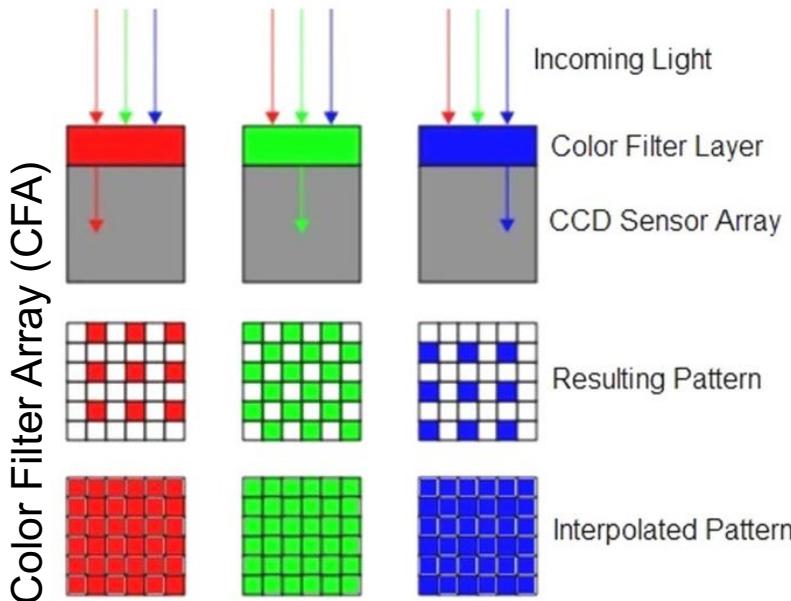


- High quality cameras
- Prism and mirrors split the image into 3 colors directed to separate sensors (CCD)
- No light loss (in comparison to filters which absorb light, see below)
- Expensive and quite complicated lens design

<http://spectracore.com/cameras/digital/c7780.html>

# Image sensors - color imaging

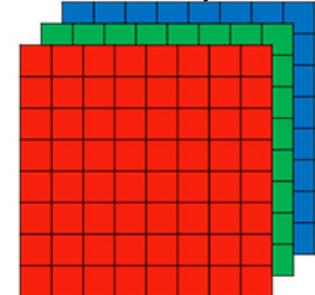
## Single CCD Color Camera



Raw sensors' outputs

G	R	G	R	G	R	G	R
B	G	B	G	B	G	B	G
G	R	G	R	G	R	G	R
B	G	B	G	B	G	B	G
G	R	G	R	G	R	G	R
B	G	B	G	B	G	B	G
G	R	G	R	G	R	G	R
B	G	B	G	B	G	B	G

RGB components



Special type of interpolation

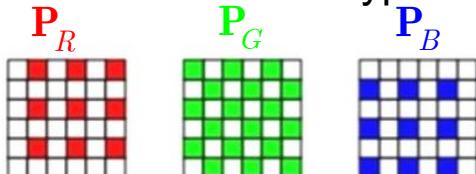
(aka demosaicing)

$$\mathbf{g}_R = Q_R \left( \mathbf{P}_R \mathbf{Hf}_{cont} \right)$$

$$\mathbf{g}_G = Q_G \left( \mathbf{P}_G \mathbf{Hf}_{cont} \right)$$

$$\mathbf{g}_B = Q_B \left( \mathbf{P}_B \mathbf{Hf}_{cont} \right)$$

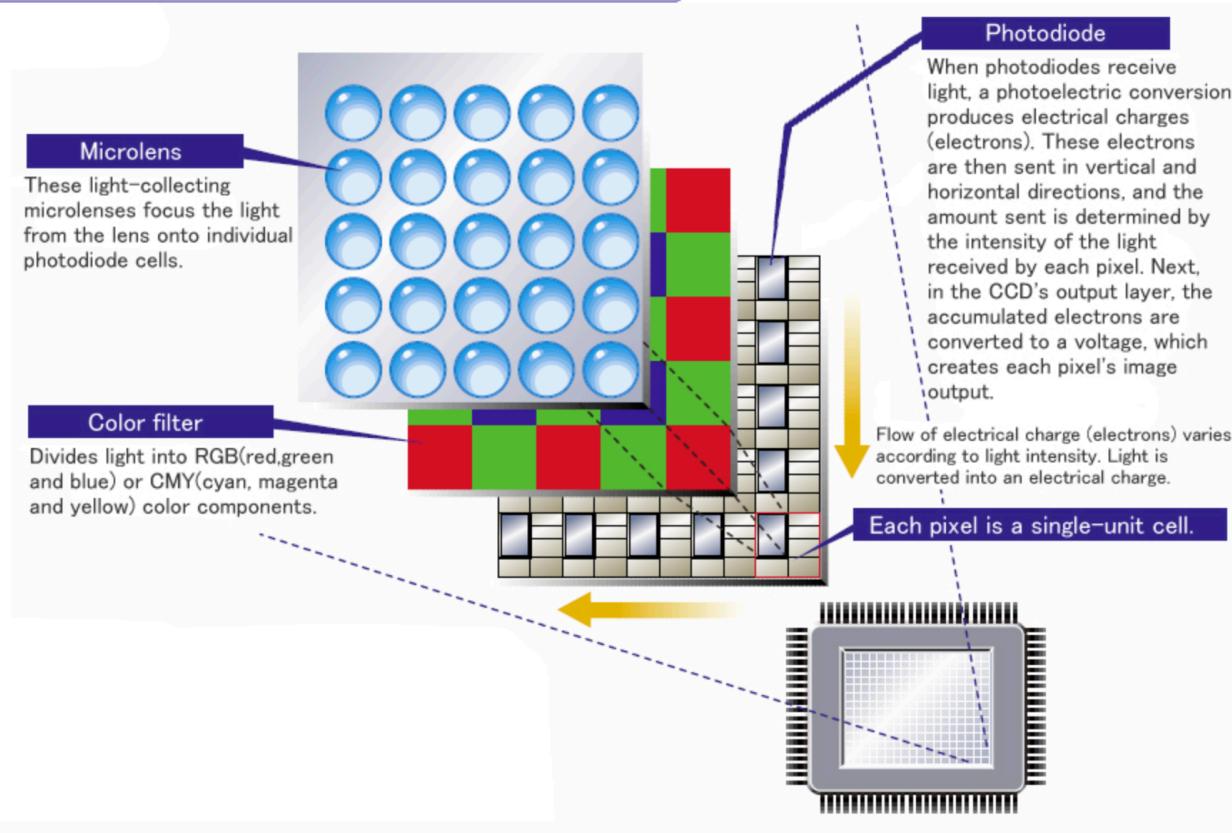
One can consider as 3 types of sampling



# Image sensors - color imaging

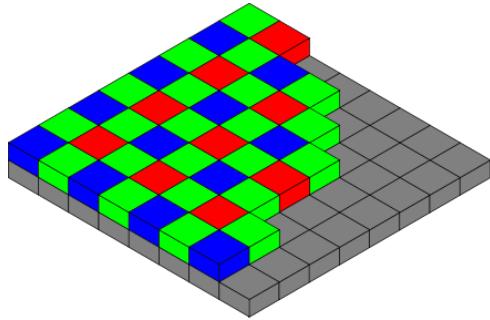
## Single CCD Color Camera

### How a CCD Converts Light to Voltage



<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow27.html>

# Image sensors – color filters



The Bayer color filter mosaic. Each two-by-two submosaic contains 2 green, 1 blue, and 1 red filter, each filter covering one pixel sensor

## Various proprietary designs

Image	Name	Description	Pattern size (pixels)
	Bayer filter	Very common RGB filter. With one blue, one red, and two green.	2x2
	RGBE filter	Bayer-like with one of the green filters modified to "emerald"; used in a few Sony cameras.	2x2
	CYYM filter	One cyan, two yellow, and one magenta; used in a few cameras of Kodak.	2x2
	CYGM filter	One cyan, one yellow, one green, and one magenta; used in a few cameras.	2x2
	RGBW Bayer	Traditional RGBW similar to Bayer and RGBE patterns.	2x2
	RGBW #1	Three example RGBW filters from Kodak, with 50% white. (See <a href="#">Bayer filter#Modifications</a> )	4x4
	RGBW #2		
	RGBW #3		
	X-Trans	Fujifilm-specific RGB matrix filter, with a large pattern, studied for diminishing Moiré effect.	6x6

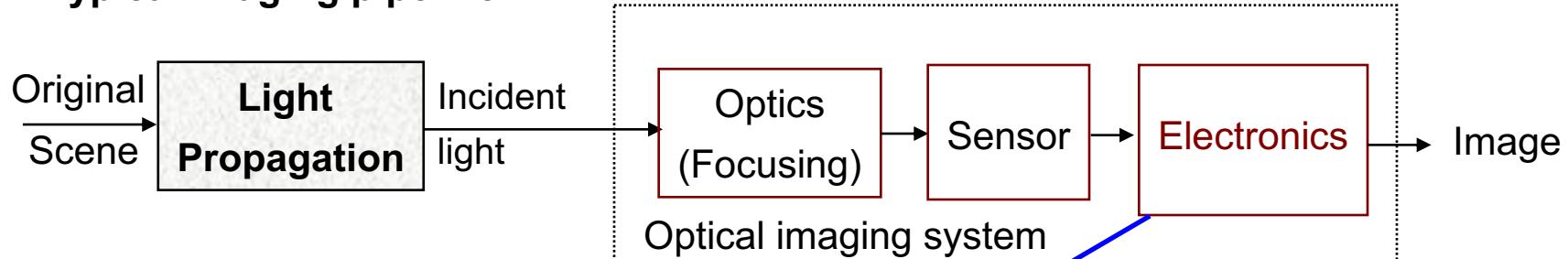
## Why more green pixels than red and blue?

Humans are more sensitive to the “green” range of spectrum (see lecture 2)

[https://en.wikipedia.org/wiki/Color\\_filter\\_array](https://en.wikipedia.org/wiki/Color_filter_array)

# Typical issues: blur, sampling, quantization

## Typical imaging pipeline



- **ADC** – analog-to-digital convertor
- **Processing** – demosaicing, gamma correction, white balancing, denoising, compression

## Main elements:

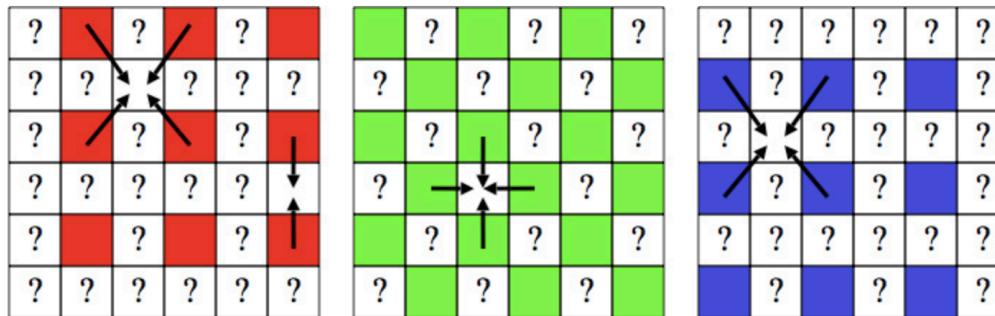
- Optics
- Sensors
- **Electronics - Processing**
  - **Demosaicing**
  - **Quantization**

# CCD arrays – demosaicing

---

## Linear interpolation (naïve way)

- for each pixel, fill in the two missing channels by averaging either the four or the two neighboring known channel values:



## Modern cameras use special demosaicing:

- Special filtering along edges (mostly proprietary)
- Combination with denoising and sharpening

## New directions:

- Usage of machine learning for demosaicing based on training

# CCD arrays – demosaicing

## Matlab implementation

### Syntax

```
RGB = demosaic(I,sensorAlignment)
```

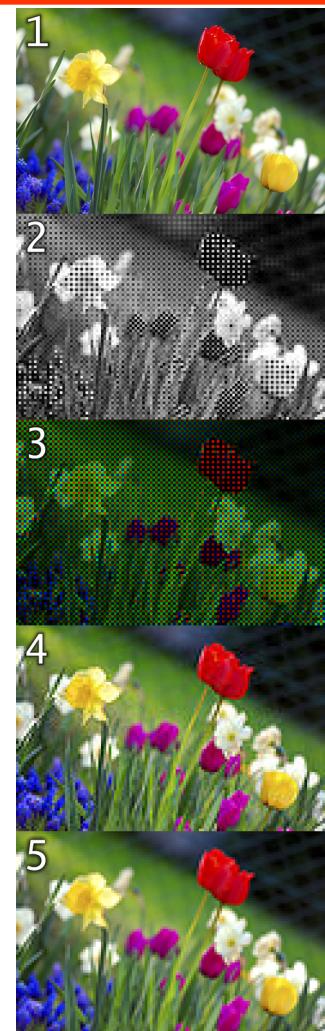
▼ **sensorAlignment** — Bayer pattern  
'gbrg' | 'grbg' | 'bggr' | 'rggb'

Pattern	2-by-2 Sensor Alignment	
'gbrg'	Green	Blue
	Red	Green
'grbg'	Green	Red
	Blue	Green
'bggr'	Blue	Green
	Green	Red
'rggb'	Red	Green
	Green	Blue

## Python implementation

<https://colour-demoslicing.readthedocs.io/en/develop/index.html>

[https://colour-demoslicing.readthedocs.io/en/develop/\\_modules/colour\\_demoslicing/bayer/demoslicing/bilinear.html](https://colour-demoslicing.readthedocs.io/en/develop/_modules/colour_demoslicing/bayer/demoslicing/bilinear.html)



1 Original scene

2 Output of a  $120 \times 80$ -pixel sensor with a Bayer filter

3 Output color-coded with Bayer filter colors

4 Reconstructed image after interpolating missing color information

5 Full RGB version at  $120 \times 80$ -pixels for comparison (e.g. as a film scan might appear)

# 3-CDD vs Bayer CCD

---



5 Megapixel Bayer image after  
demosaicing



2 Megapixel AT-200 image (no  
demosaicing)

<https://www.1stvision.com/machine-vision-solutions/2016/11/jai-3ccd-camera-color-machine-vision.html>

# Demosaicing – practical advise

---

**For many useful practical hints see:**

Processing RAW Images in MATLAB

Rob Sumner

Department of Electrical Engineering, UC Santa Cruz

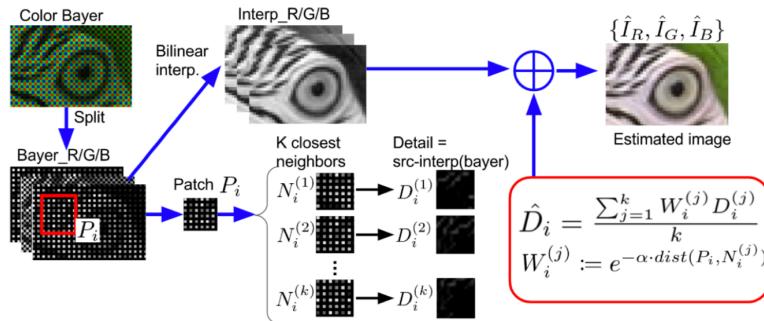
May 19, 2014

[https://rcsumner.net/raw\\_guide/Rawguide.pdf](https://rcsumner.net/raw_guide/Rawguide.pdf)

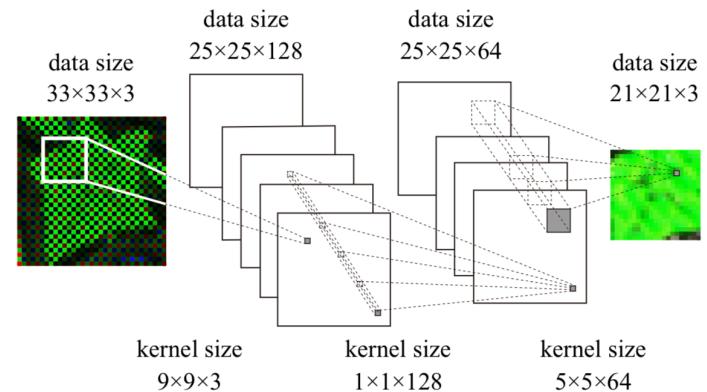
# Demosaicing – machine learning landscape

## Machine learning algorithms

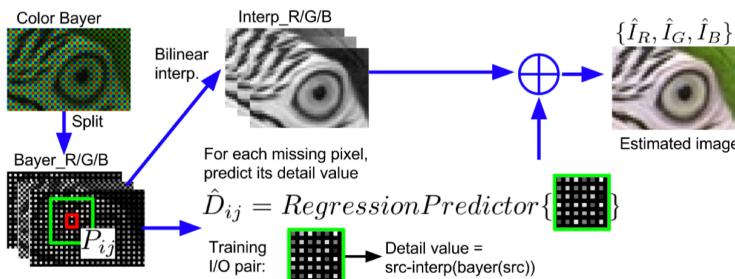
### K-NN based regressor



### CNN trained regressors



### Specially trained regressor



<https://arxiv.org/pdf/1802.03769.pdf>

$$L(\Theta) = \frac{1}{n} \sum_{i=1}^n \|F(\mathbf{Y}_i; \Theta) - \mathbf{X}_i\|^2,$$

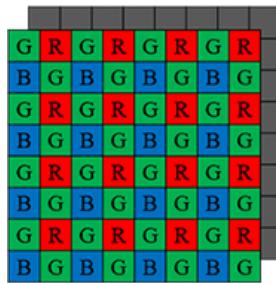
[http://stanford.edu/class/ee367/Winter2017/Chen\\_Sanchez\\_ee367\\_win17\\_report.pdf](http://stanford.edu/class/ee367/Winter2017/Chen_Sanchez_ee367_win17_report.pdf)

# Image sensors – summary

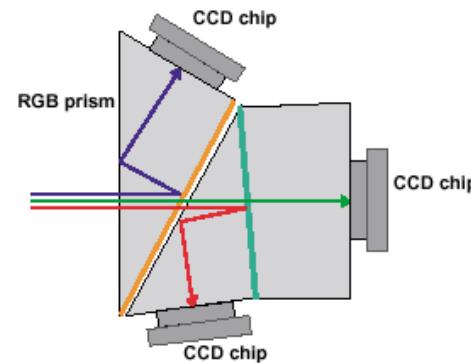
---

## Single chip vs 3-CCD architecture

### Single CCD Color Camera



### 3-CCD Color Camera

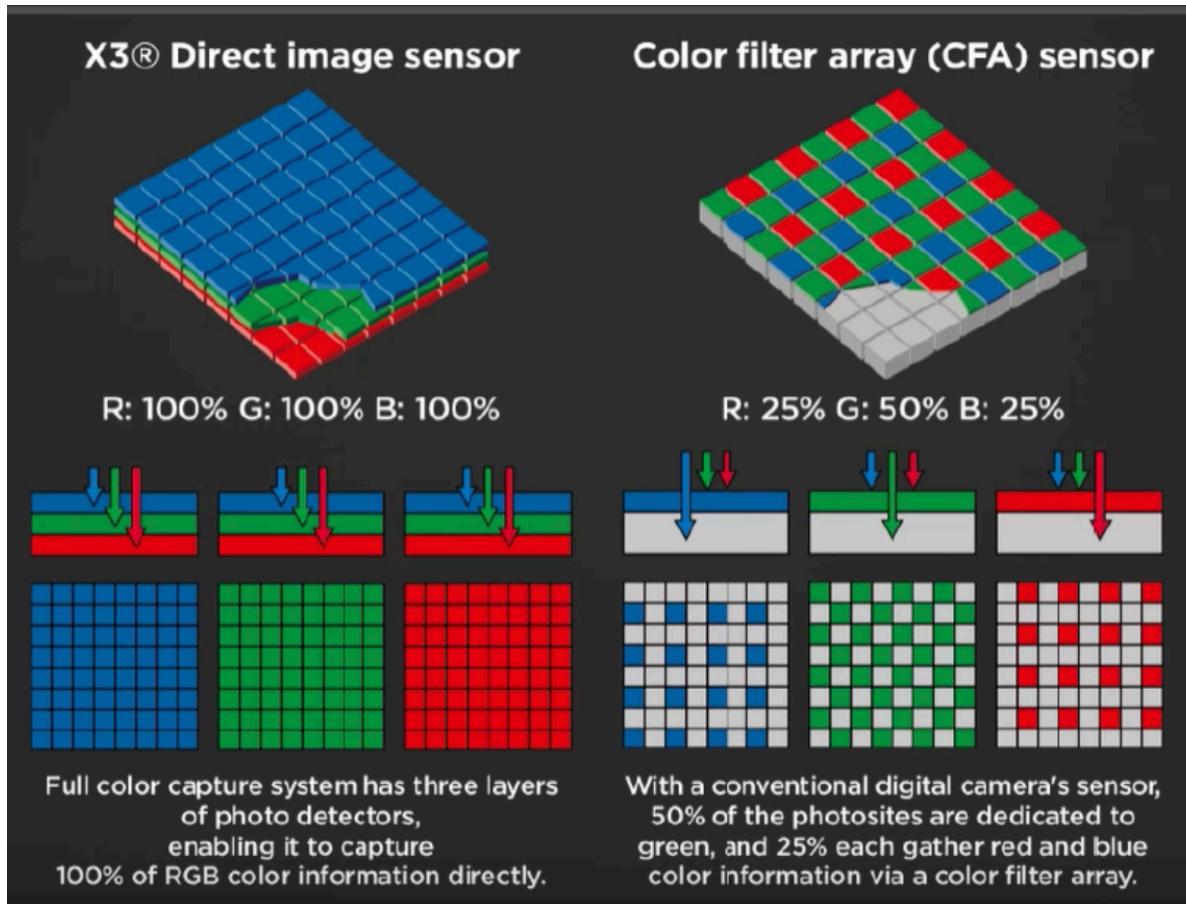


- Each pixel has one color filter
- Color interpolation needed (demosaicing)
- Not true color
- Spectral response depends on the design of the color filter

- Each pixel has its own CCD
- No need in interpolation
- True RGB data for each pixel
- Spectral response can be flexible
- Superior quality of image for the same CCD resolution (see previous slide)

# CCD arrays – beyond CFA – Foveon X3 sensor

More advanced systems (**Foveon sensor**) – every pixel might have its own color



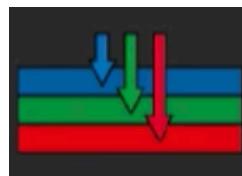
<http://www.foveon.com/article.php?a=67>

# CCD arrays – beyond CFA

---

**Foveon sensors** – every pixel might have its own color

- Longer wavelengths penetrate deeper into silicon
- A set of vertical detectors is arranged as:



- However, there is no control on spectral responses. Processing is needed
- No need in demosaicing

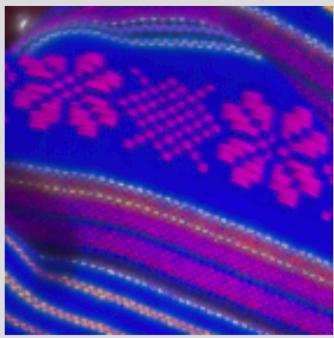
# CCD arrays – beyond CFA

## Color Detail

Mosaic Capture

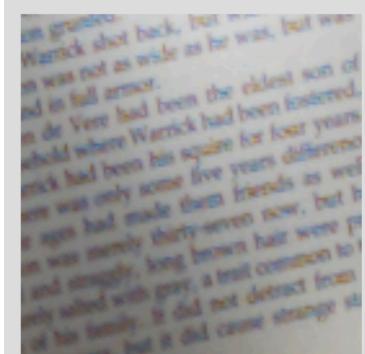


Foveon X3

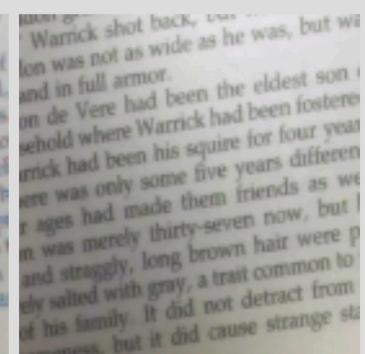


## Sharpness

Mosaic Capture

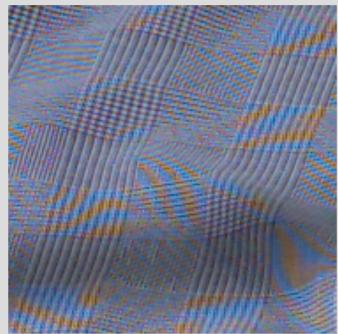


Foveon X3

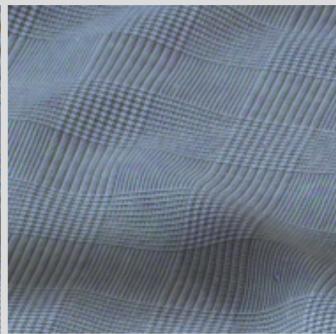


## Artifacts

Mosaic Capture



Foveon X3



# CCD arrays – beyond Foveon X3

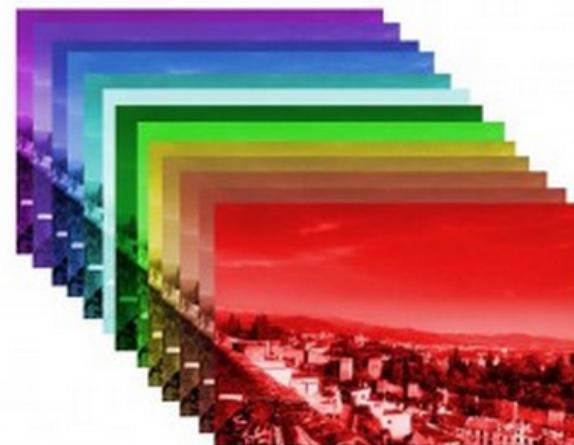
---



3 canales de color  
(RGB convencional)



Imagen original



36 canales de color  
(nuevo sistema)

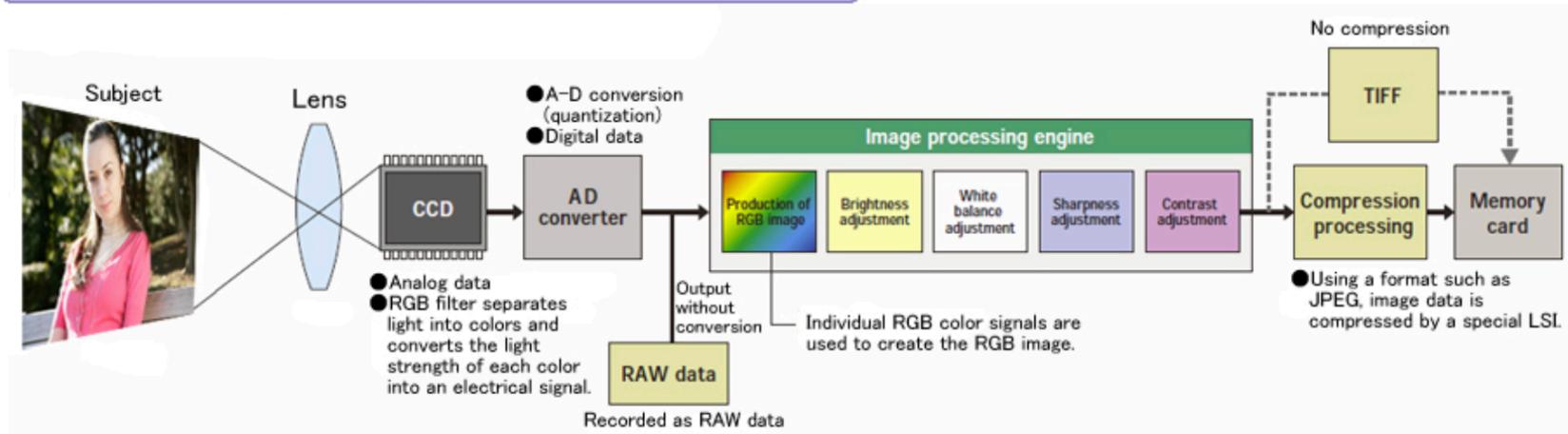
The authors claim to take advantage of a physical phenomenon by virtue of which each photon penetrates at a different depth depending on its wavelength, i.e., its color.

In this way, by collecting these photons at different depths on the silice surface of the sensor, the different channels of color can be separated without the necessity of filters.

<https://www.mirrorlessrumors.com/new-tfd-foveon-alike-sensor-has-36-layers/>

# Image sensors: summary on optical cameras

## Digital Camera Signal Processing Flow



<http://av.jpn.support.panasonic.com/support/global/cs/dsc/knowhow/knowhow30.html>

# Image sensors – beyond “classical” sensors

---

## Traditional sensors

- Increase of amount of pixels (better resolution)
- However it has also side effects:
  - Larger storage memory and communication burden
  - New compression algorithms are needed
  - More pixels = smaller size of pixel = less photons = a lot of noise especially for the dark environment:
    - Image quality
    - More noise = higher entropy = more bits are used for nothing

# Image sensors – beyond multipixel sensors

---

## Compressive sensing

- An alternative to classical imaging
- **Based on computational methods**
- In a limit, a single pixel (!) is needed to create Mega pixel size image
- Price:
  - More time of observation is needed
  - It might not be suitable for highly dynamic scene imaging
  - Computing to reconstruct the image

# Image sensors – beyond multipixel sensors

## Main idea behind Compressive sensing

Sensing – as a projection (matrix-by-vector multiplication)

$$\begin{array}{c} \mathbf{g} \quad \Phi\text{-sampling operator} \\ M \times 1 \\ \text{measurements} \end{array} = \begin{array}{c} \mathbf{f} \\ M \times N \\ \text{sparse signal} \\ K \text{ nonzero entries} \end{array}$$

$M = O(K \log(N/K))$

$\mathbf{g} = \Phi\mathbf{f}$   
can be random or structured  $\Phi = \mathbf{P}\mathbf{H}$

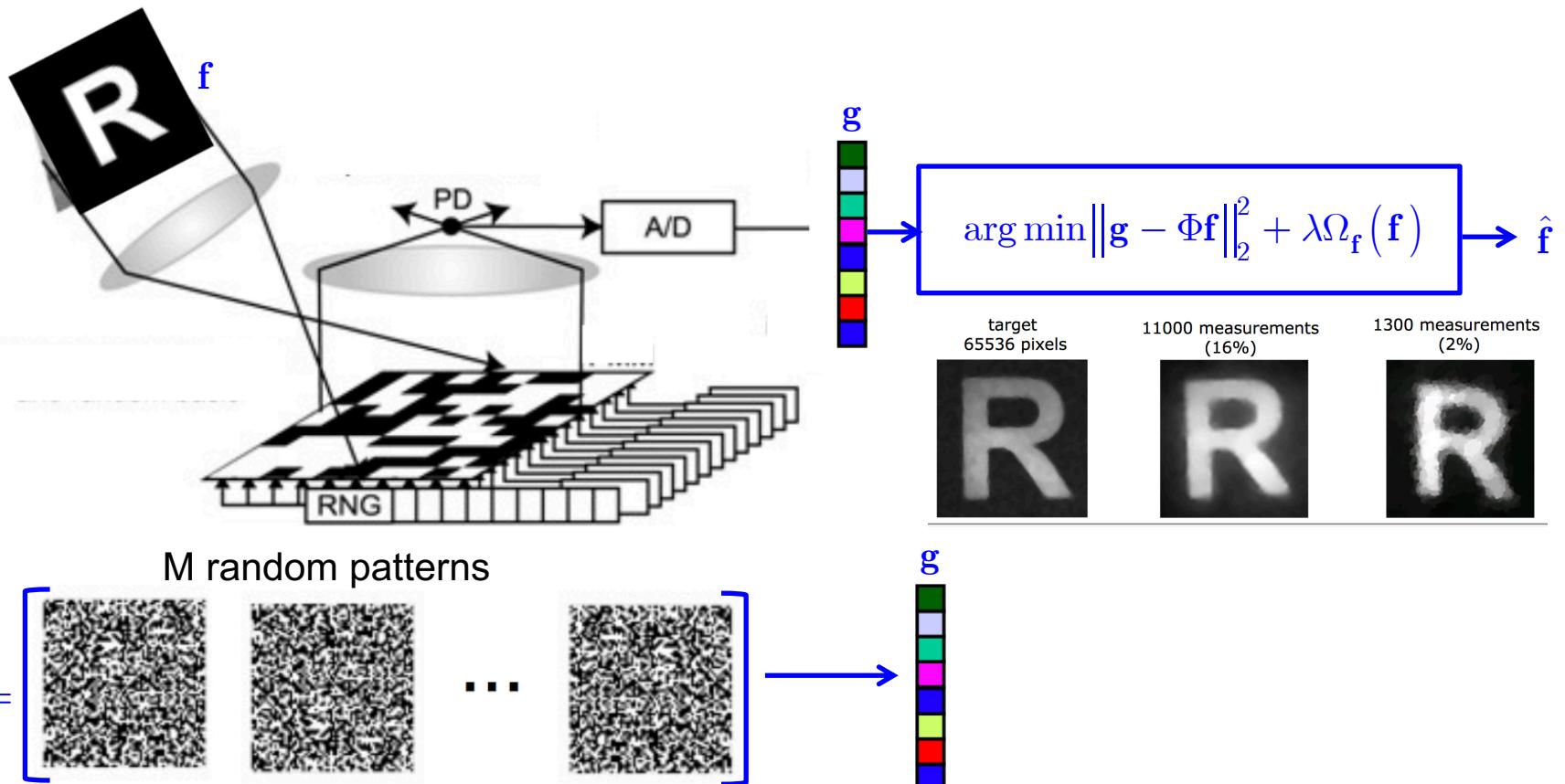
Recovery – as inverse (ill-posed) problem solution

$$\hat{\mathbf{f}} = \arg \min \|\mathbf{g} - \Phi\mathbf{f}\|_2^2 + \lambda \Omega_{\mathbf{f}}(\mathbf{f})$$

Prior to compensate the loss of information

# Image sensors – beyond multipixel sensors

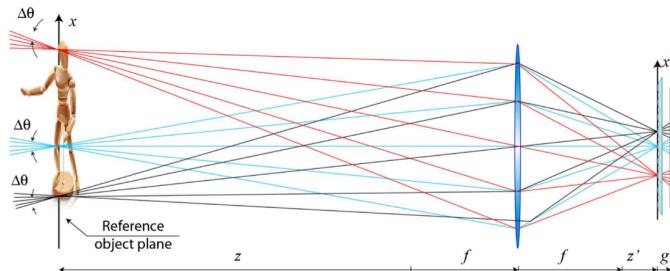
## “Single pixel” CS camera



# Image sensors – beyond optical band

## Plenoptic cameras

Figure 21



Single scheme of a plenoptic camera.

$$\begin{aligned} \mathbf{\hat{y}} &= \begin{bmatrix} \mathbf{y}^{R,1} \\ \mathbf{y}^{G,1} \\ \mathbf{y}^{B,1} \\ \mathbf{y}^{R,2} \\ \mathbf{y}^{G,2} \\ \mathbf{y}^{B,2} \\ \vdots \\ \mathbf{y}^{R,s} \\ \mathbf{y}^{G,s} \\ \mathbf{y}^{B,s} \end{bmatrix} = \underbrace{\begin{bmatrix} \Phi^{1,R,1} & \dots & \Phi^{\nu,R,1} & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & \dots & 0 & \Phi^{1,G,1} & \dots & \Phi^{\nu,G,1} & 0 & \dots & 0 \\ 0 & \dots & 0 & 0 & \dots & 0 & \Phi^{1,B,1} & \dots & \Phi^{\nu,B,1} \\ \Phi^{1,R,2} & \dots & \Phi^{\nu,R,2} & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & \dots & 0 & \Phi^{1,G,2} & \dots & \Phi^{\nu,G,2} & 0 & \dots & 0 \\ 0 & \dots & 0 & 0 & \dots & 0 & \Phi^{1,B,2} & \dots & \Phi^{\nu,B,2} \\ \vdots & \vdots & \ddots & \vdots & & \vdots & & & \vdots \\ \Phi^{1,R,s} & \dots & \Phi^{\nu,R,s} & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & \dots & 0 & \Phi^{1,G,s} & \dots & \Phi^{\nu,G,s} & 0 & \dots & 0 \\ 0 & \dots & 0 & 0 & \dots & 0 & \Phi^{1,B,s} & \dots & \Phi^{\nu,B,s} \end{bmatrix}}_{\triangleq \Phi \in \mathbb{R}^{\omega \lambda s \times \omega \nu \lambda}} \begin{bmatrix} \mathbf{x}^{1,R} \\ \mathbf{x}^{\nu,R} \\ \mathbf{x}^{1,G} \\ \vdots \\ \mathbf{x}^{\nu,G} \\ \mathbf{x}^{1,B} \\ \vdots \\ \mathbf{x}^{\nu,B} \end{bmatrix}, \\ \mathbf{y} &= \mathbf{P} \Phi \mathbf{x}, \end{aligned}$$

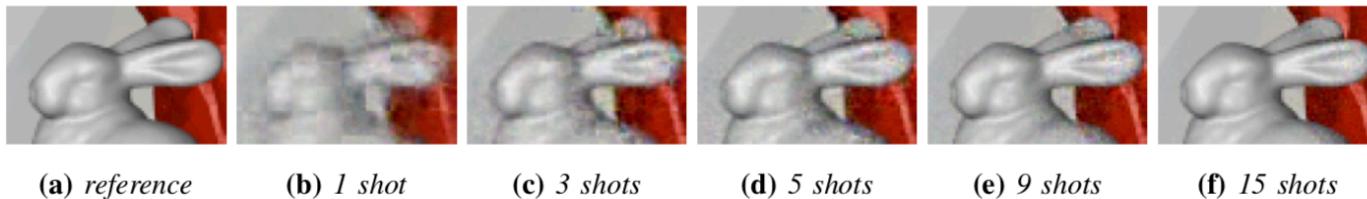


Fig. 3: Visual quality comparison for the number of shots ( $s$ ). See Fig. 4 for the corresponding PSNR values.

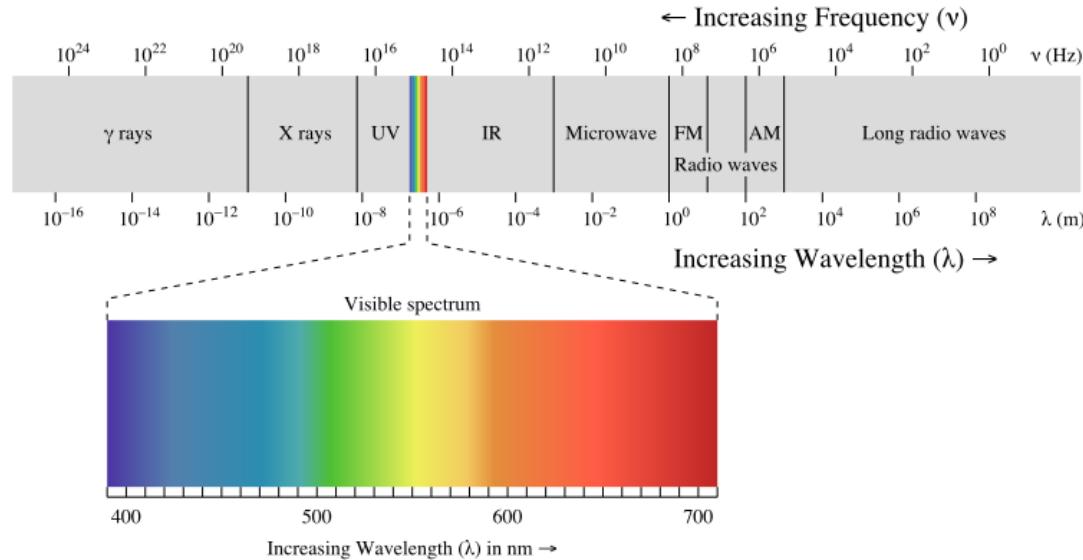
Multi-Shot Single Sensor Light Field Camera  
Using a Color Coded Mask

Ehsan Miandji  
dept. of Science and Technology  
Linköping University, Sweden

Jonas Unger  
dept. of Science and Technology  
Linköping University, Sweden

Christine Guillemot  
INRIA, Campus de Beaulieu  
Rennes, France

# Image sensors – beyond optical band



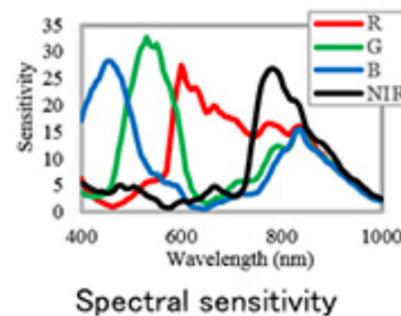
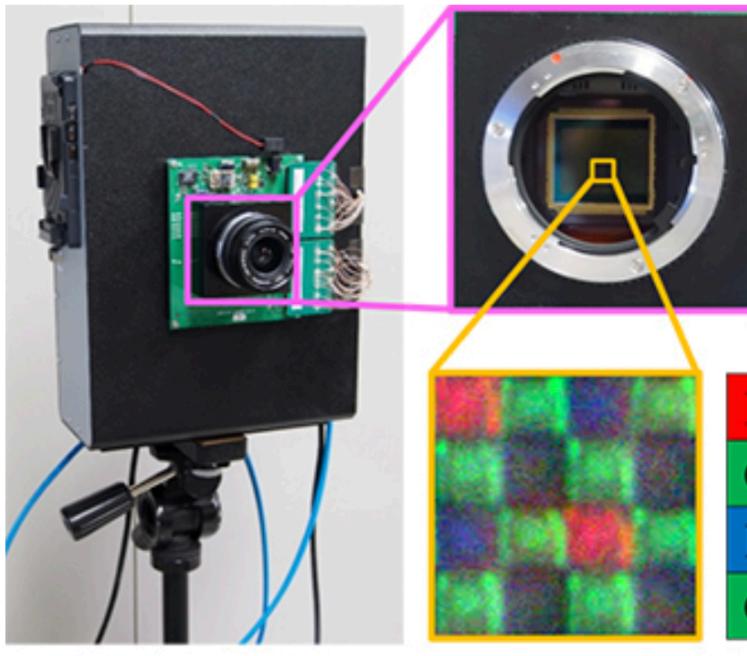
Imaging in infrared band

Imaging in microwave-radio frequency bands

# Image sensors – beyond optical band

Olympus shows a new “hybrid” RGB-IR sensor

Near IR (NIR)



R	G	B	G
G	N	G	N
B	G	R	G
G	N	G	N

Image processing

Demosaicking,  
Color correction,  
etc.

$$\mathbf{g}_R = Q_R (\mathbf{P}_R \mathbf{Hf}_{cont})$$
$$\mathbf{g}_G = Q_G (\mathbf{P}_G \mathbf{Hf}_{cont})$$
$$\mathbf{g}_B = Q_B (\mathbf{P}_B \mathbf{Hf}_{cont})$$
$$\mathbf{g}_N = Q_N (\mathbf{P}_N \mathbf{Hf}_{cont})$$



<https://www.43rumors.com/olympus-presents-new-olympus-rgb-ir-sensor/>

# Image sensors – beyond optical band (NIR)

**FLIR**

**Separate sensors RGB and FLIR**



$$\begin{aligned} \mathbf{g}_R &= Q_R \left( \mathbf{P}_R \mathbf{Hf}_{cont} \right) \\ \mathbf{g}_G &= Q_G \left( \mathbf{P}_G \mathbf{Hf}_{cont} \right) \\ \mathbf{g}_B &= Q_B \left( \mathbf{P}_B \mathbf{Hf}_{cont} \right) \\ \mathbf{g}_N &= Q_N \left( \mathbf{P}_N \mathbf{Hf}_{cont} \right) \end{aligned}$$

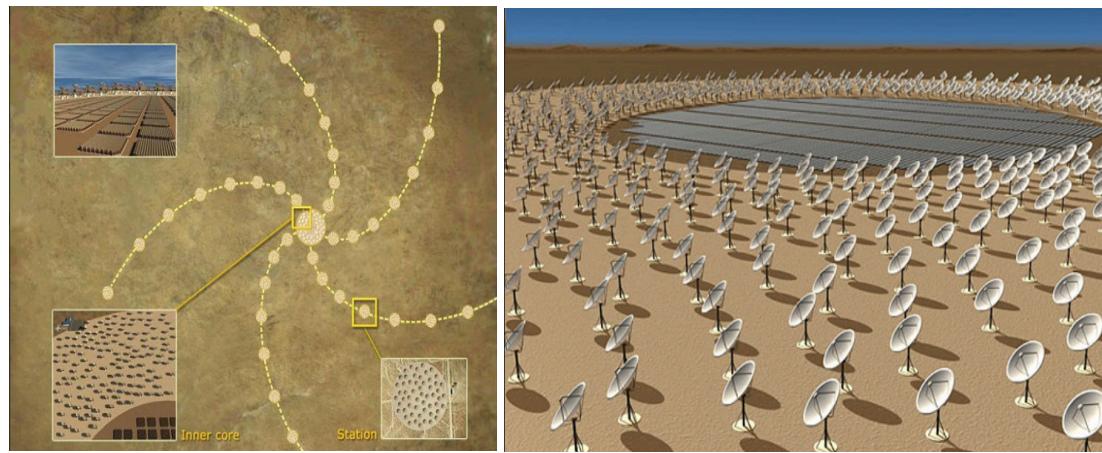
<https://www.flir.com>



# Imaging in the microwave band

Radio imaging – not CCD but antenna that register electromagnetic radiation in microwave and radio bands

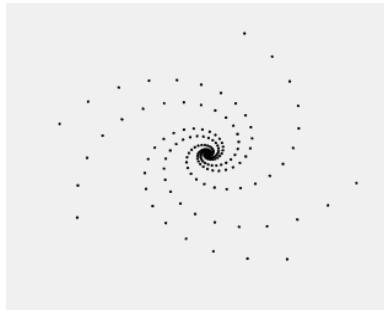
SKA geometry for radioastronomy



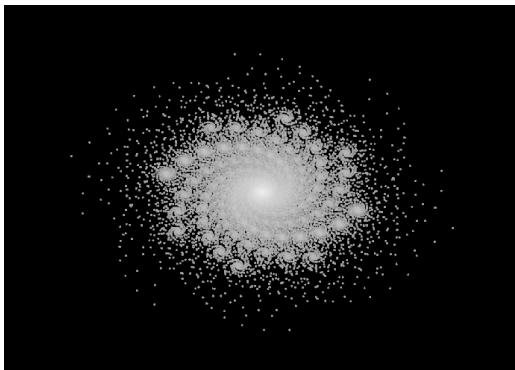
Credits: SKA

# Imaging in the microwave band

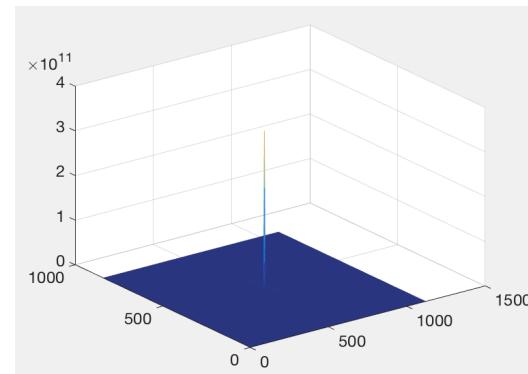
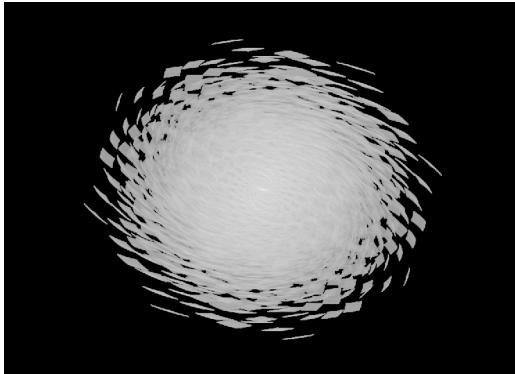
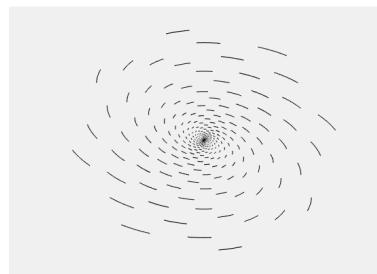
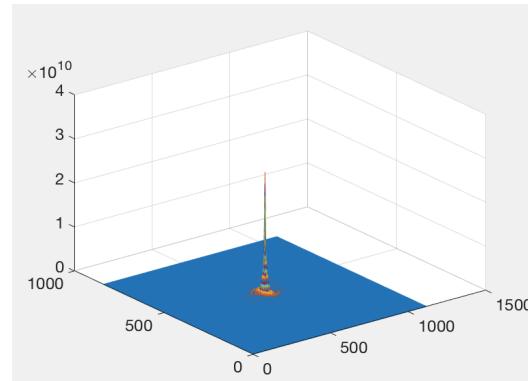
Geometry of antenna



Spatial spectrum (uv-plane)



PSF (directional antenna pattern)



$P\Psi$

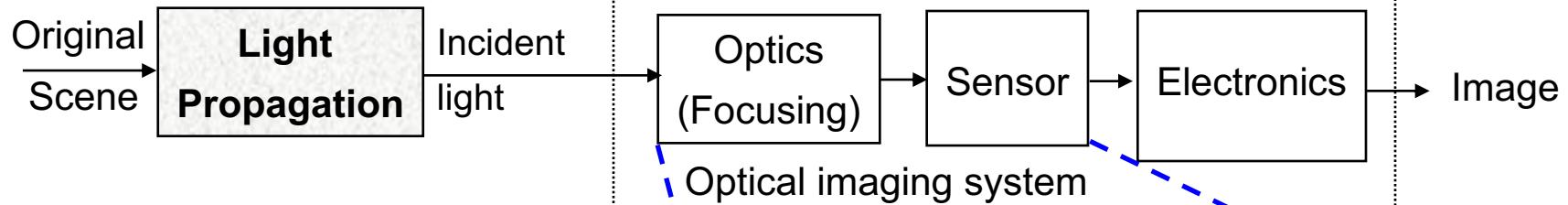
$\Psi$  - unitary transform (like Fourier)

Equivalent  $H$

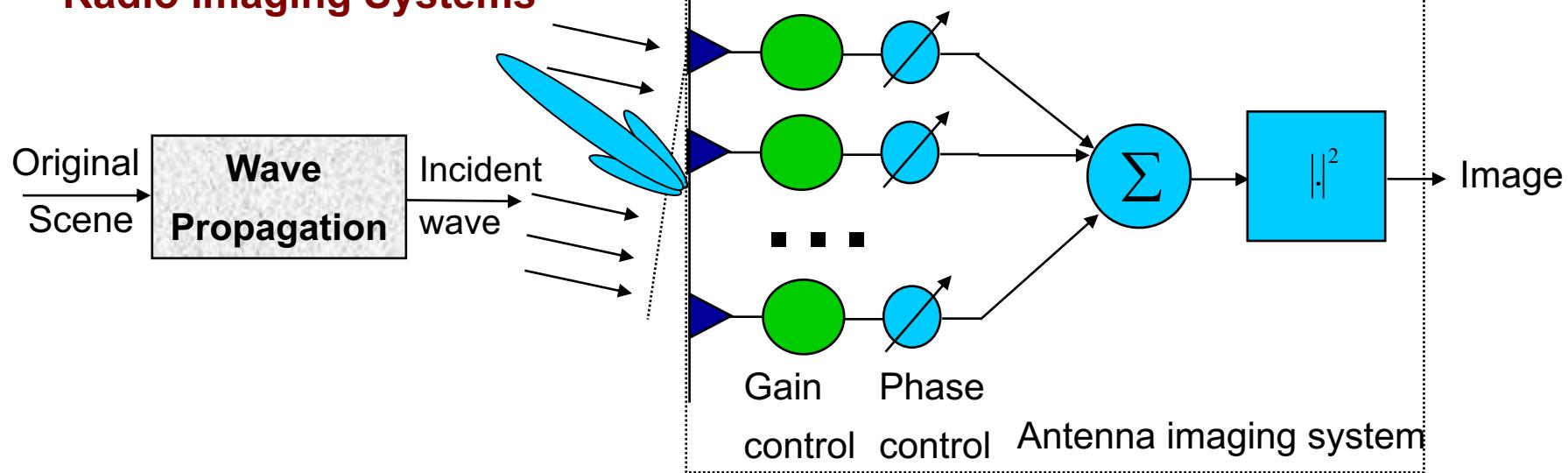
Credits: SKA

# Image sensors – generalized diagram

## Optical and NIR Imaging Systems



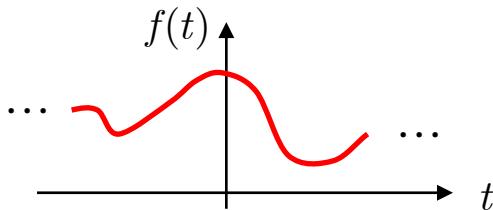
## Radio Imaging Systems



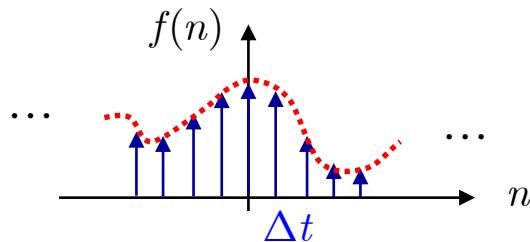
# Sampling and quantization

---

## Continuous signals



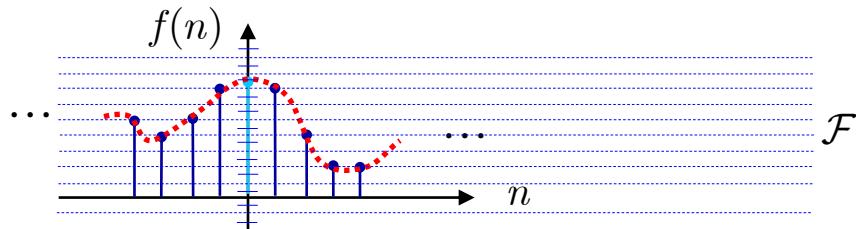
## Discrete signals



The discrete signals are defined only on a discrete grid  $n = 0, \pm 1, \pm 2, \dots$

Information between the samples is lost!

## Discrete quantized signals=digital signals



Additionally, the signal can be quantized, i.e., each sample might take a value from some alphabet  $f(n) \in \mathcal{F}$

Information between the quantization levels is lost!

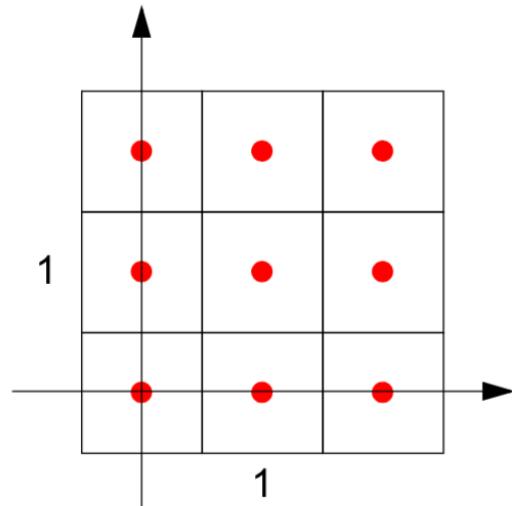
# Sampling in 2D

---

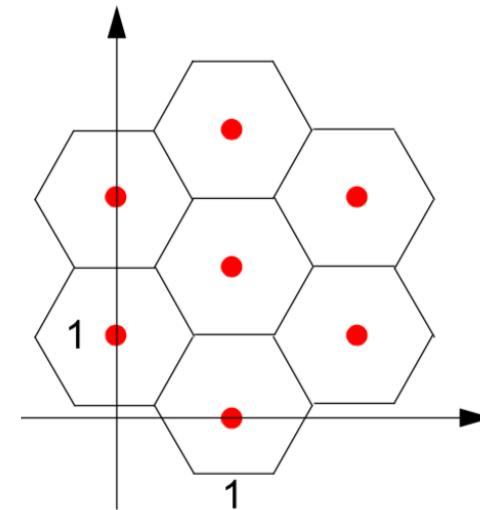
In time domain (1D signals), the sampling grid is equally spaced train of delta functions.

The sampling grid in 2D is more flexible

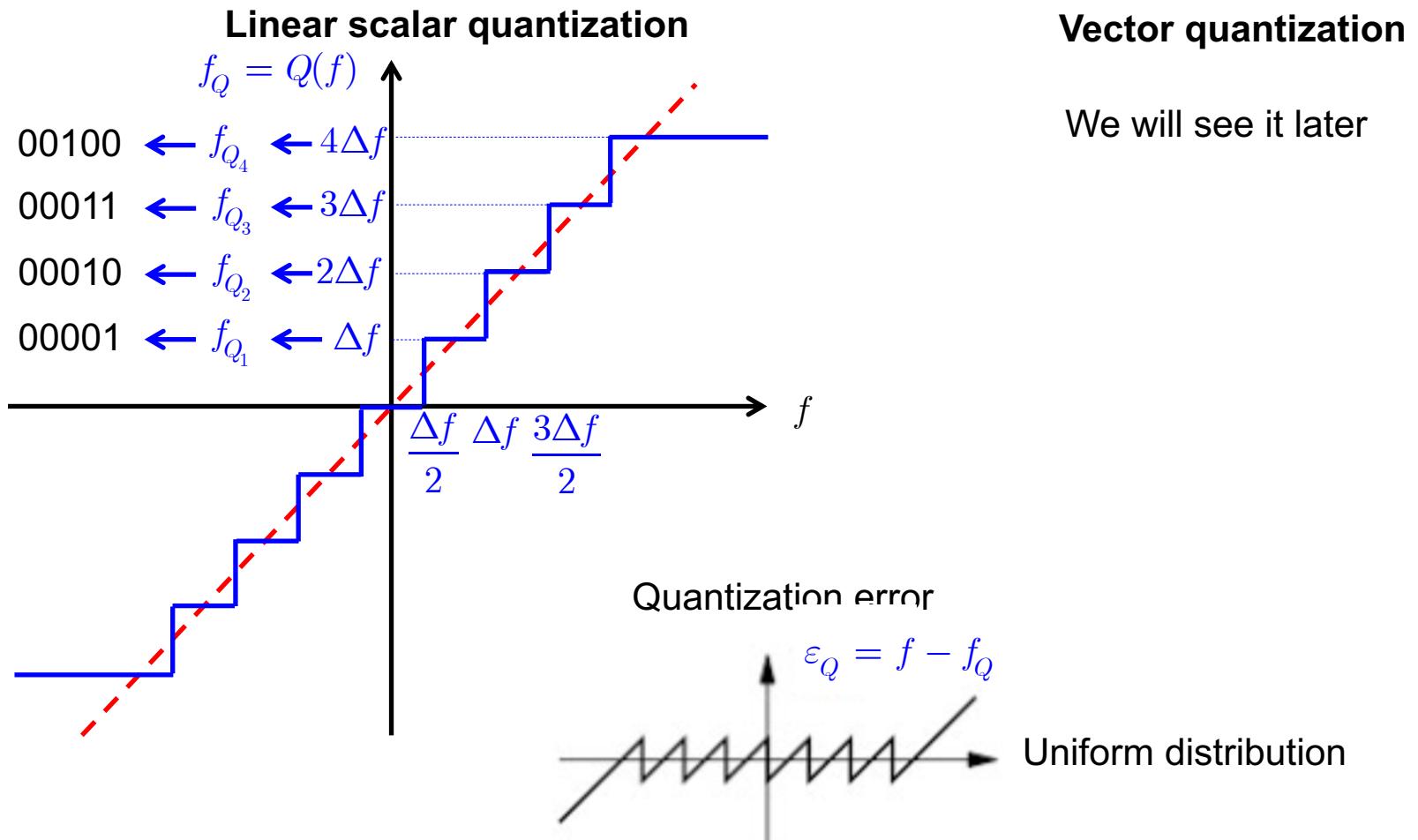
Rectangular grid



Hexagonal grid

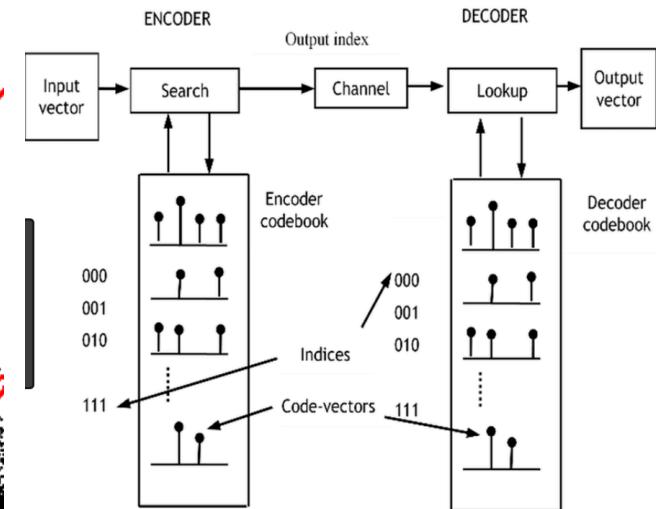
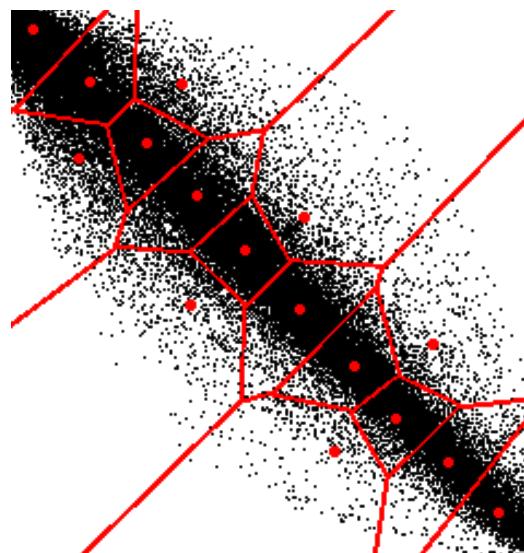
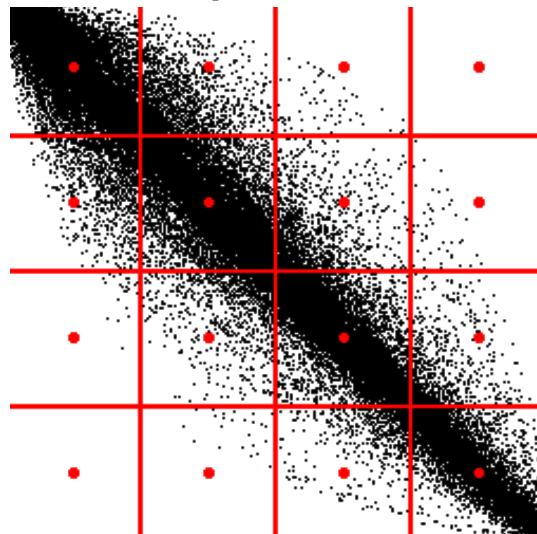


# Scalar and vector quantization



# Scalar and vector quantization

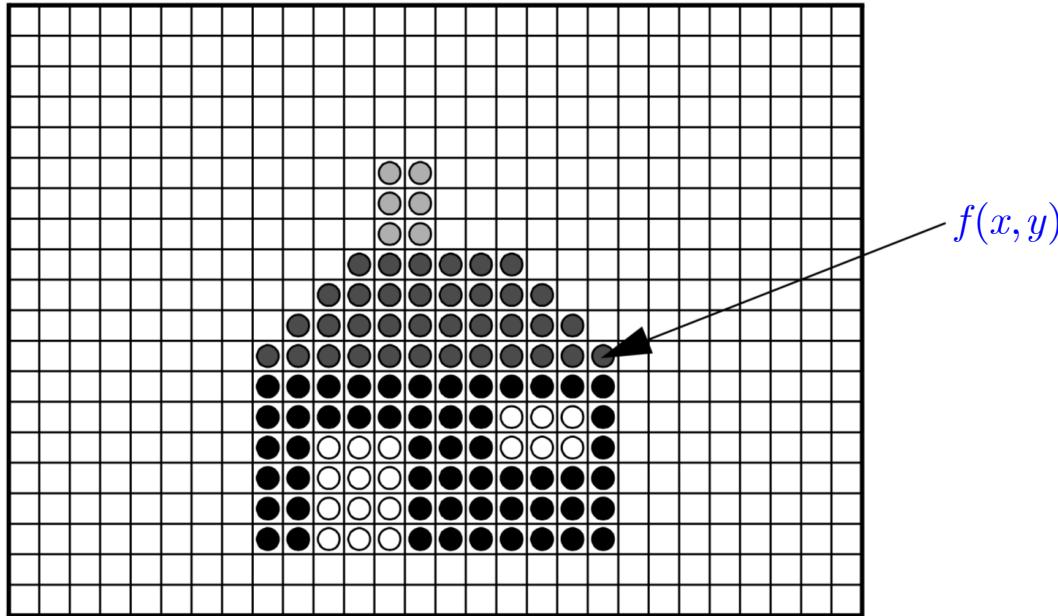
## Vector quantization



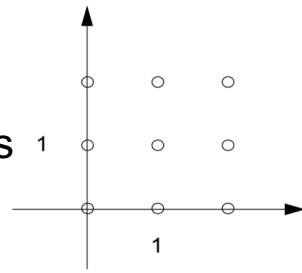
# Discrete grids and notation for pixel

## Pixel notations

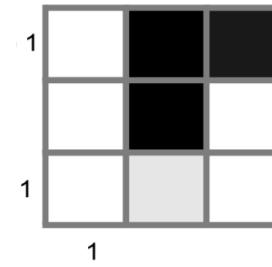
Digital image



Logical pixels



Physical pixels



Acquisition: CCD

Reproduction: LCD or  
printed dot

# Pixel representation

---

## Values of pixels:

- Binary images:  $f(x, y) \in \{0, 1\}$
- Grayscale images:  $f(x, y) \in \{0, 1, \dots, 255\}$   
assuming 8 bits/pixel

Black pixel: 0

White pixel: 255

Gray pixel: 127



- Color images: in RGB space with each component 8 bits/pixel. In total 24 bits/pixel

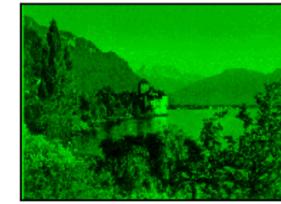


$\Rightarrow$



$$f_R(x, y) \in \{0, 1, \dots, 255\} \quad f_G(x, y) \in \{0, 1, \dots, 255\} \quad f_B(x, y) \in \{0, 1, \dots, 255\}$$

G



B



# Impact of the number of gray levels

---

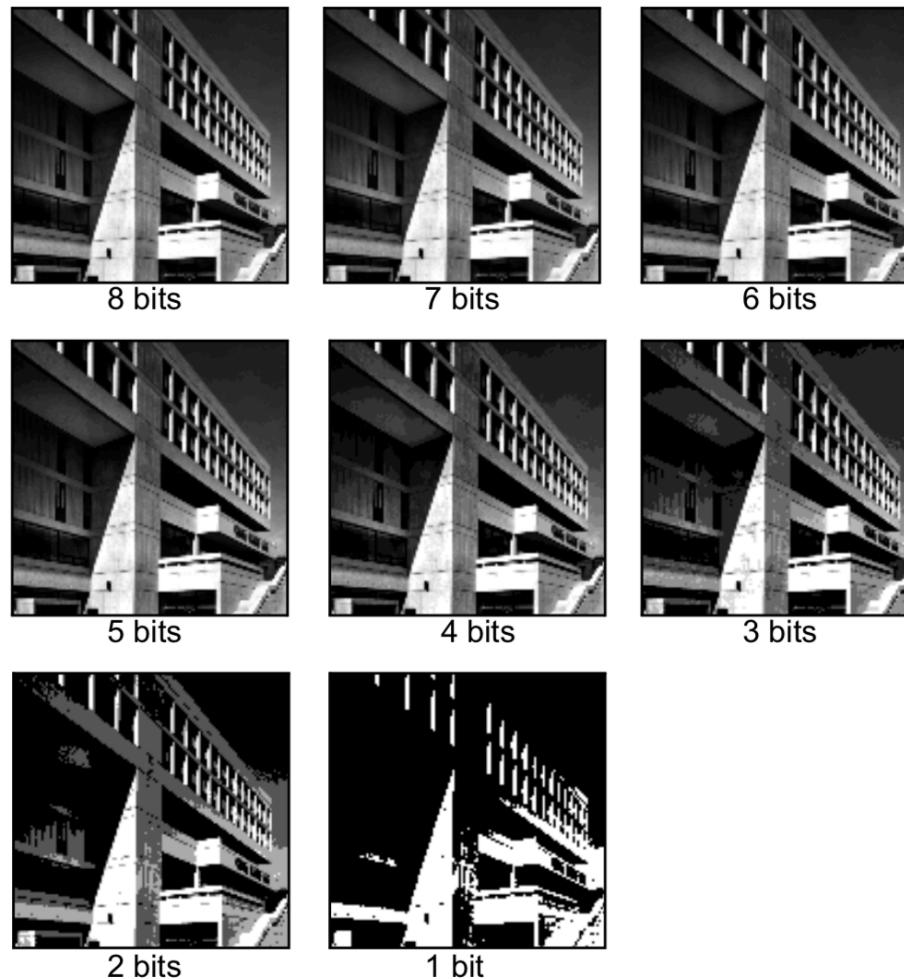


Image T. Pun

# Image representation by bit planes

---



bit 1



bit 2



bit 3



bit 4



bit 5



bit 6



bit 7



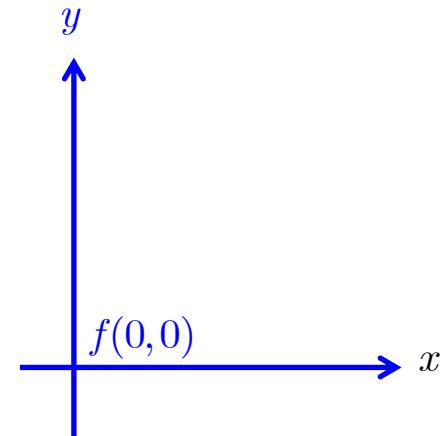
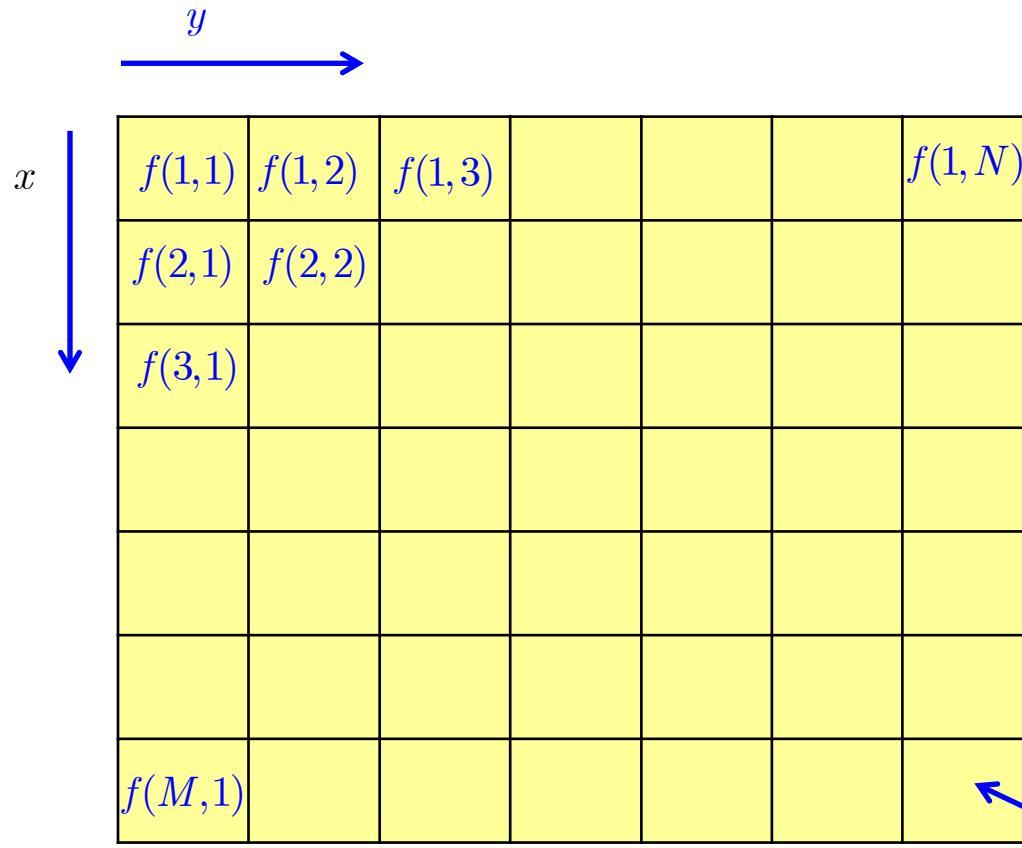
bit 8

plans de bits  
d'une image  
(bit 1 = LSB)

Image T. Pun

# Image representation

Images are considered as 2D  $M \times N$  arrays of real numbers



Confusion with the Cartesian coordinates

# Image representation

---

## General notations as a matrix

$$f(x, y) = \begin{bmatrix} f(0,0) & f(0,1) & f(0,N-1) \\ f(1,0) & f(1,1) & f(1,N-1) \\ f(M-1,0) & f(M-1,1) & f(M-1,N-1) \end{bmatrix}$$

## Matlab: (0,0)->(1,1)

```
>> f=magic(4)
```

f =

16	2	3	13
5	11	10	8
9	7	6	12
4	14	15	1

```
>> f(1,1)
```

ans =

16

```
>> f(4,1)
```

ans =

4

```
>> f(1,4)
```

ans =

13

```
>> f(4,2)
```

ans =

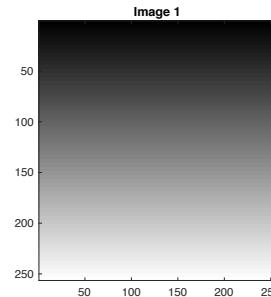
14

# Test image: unit8 vs double

---

Consider a **ramp image**

$$\begin{bmatrix} 0 \\ \vdots \\ \vdots \\ 255 \end{bmatrix} \times \begin{bmatrix} 1 & \dots & \dots & 1 \end{bmatrix} =$$



```
% Test image and difference between unit8 and double
clear all;

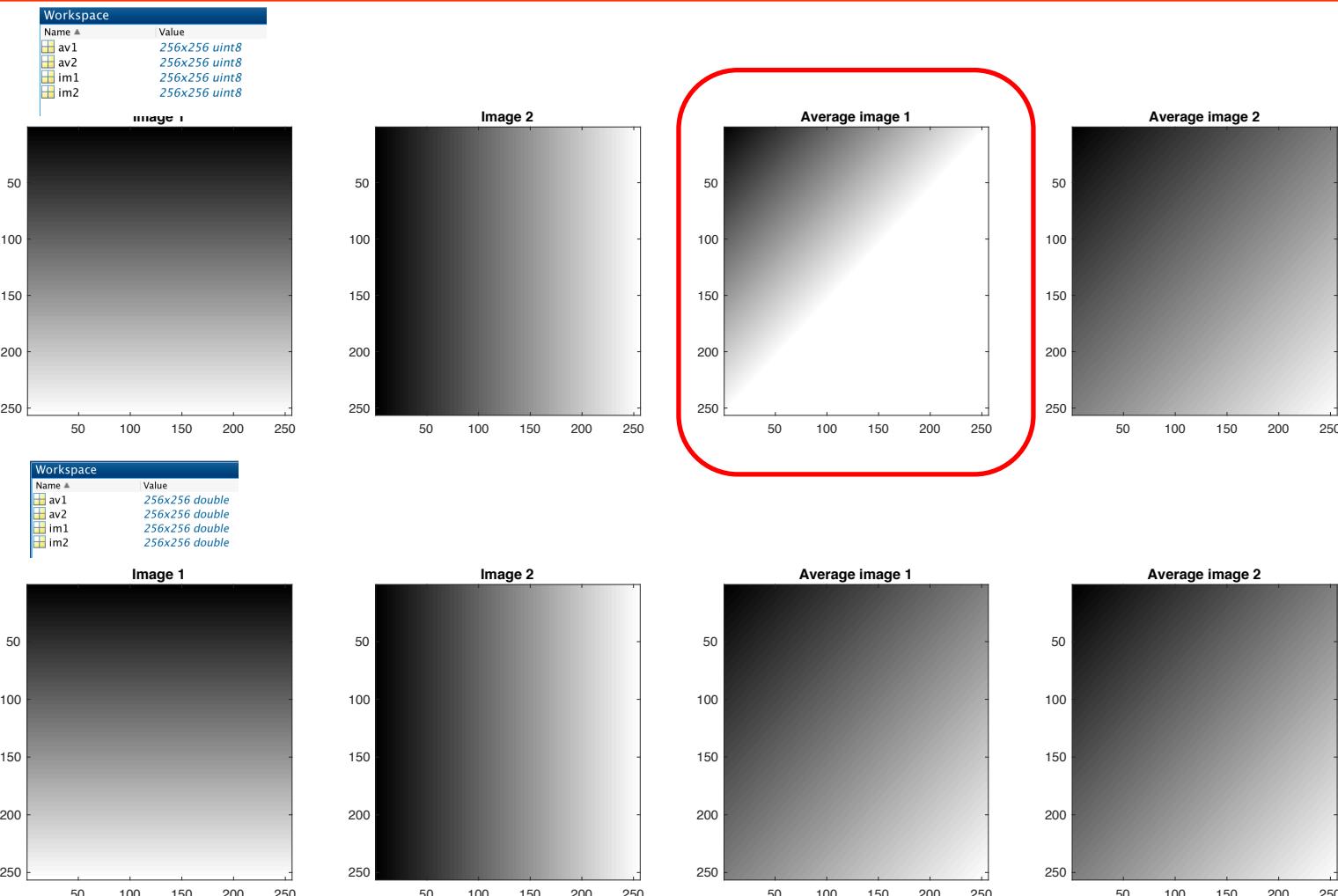
im1=[0:255]*ones(1,256);
im1=uint8(im1);
im2=im1';

av1=(im1 +im2)/2;
av2=im1/2 +im2/2;

% Visualize the output
figure;
subplot(1,4,1); imagesc(im1); title('Image 1'); colormap(gray)
subplot(1,4,2); imagesc(im2); title('Image 2')
subplot(1,4,3); imagesc(av1); title('Average image 1')
subplot(1,4,4); imagesc(av2); title('Average image 2')
```

**Attention to image types!**

# Test image: unit8 vs double



# Image type conversion

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## Functions

<code>gray2ind</code>	Convert grayscale or binary image to indexed image
<code>ind2gray</code>	Convert indexed image to grayscale image
<code>mat2gray</code>	Convert matrix to grayscale image
<code>rgb2gray</code>	Convert RGB image or colormap to grayscale
<code>rgb2ind</code>	Convert RGB image to indexed image
<code>ind2rgb</code>	Convert indexed image to RGB image
<code>label2rgb</code>	Convert label matrix into RGB image
<code>demosaic</code>	Convert Bayer pattern encoded image to truecolor image