UiO : Department of Informatics
University of Oslo

INF5442 – Image Sensor Circuits and Systems

Lecture 3 – Noise, Dynamic Range, and S/N

8-September-2014

Agenda

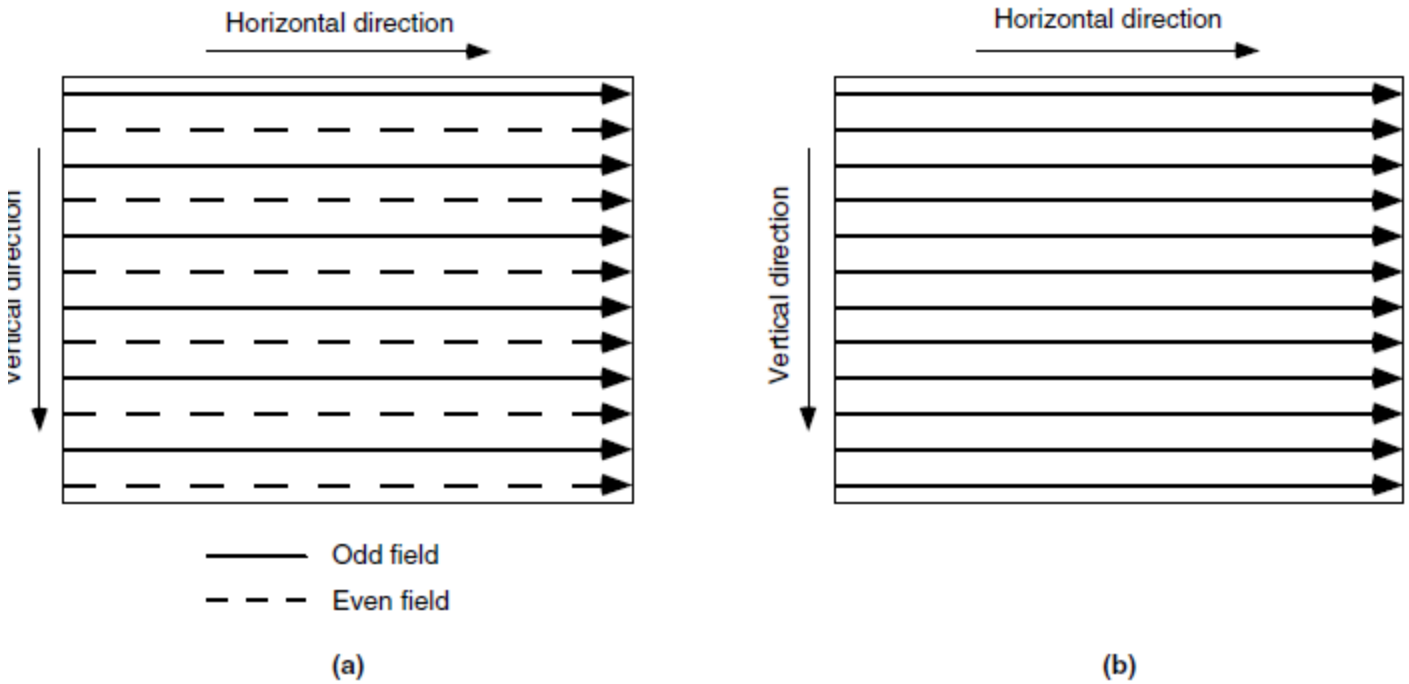
- Key takaways from previous week
- Catch up on last few slides

- Lecture3 – Noise, DR, and SNR
  - References: Nakamura, Ch. 3.3 and 3.4

Key takeaways from previous lecture

- CCD vs CMOS image sensor architecture
- Global shutter vs rolling shutter
  - Check out: <insert youtube link from JP>
- Cut-off wavelength: $\lambda_{cut\text{-}off} = hc/Eg$
- Source-follower gain: ~0.8
- Conversion gain: $CG = q / C_{FD}$ (uV/e-)
- Full-well capacity
- 1T, 3T, and 4T pixel structures
- Interlaced vs progressive scan

Interlaced scan versus progressive scan



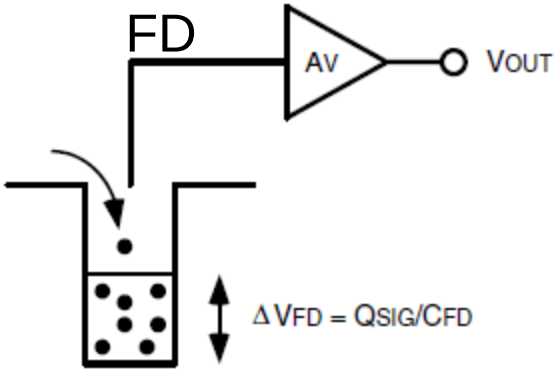
Interlaced scan
(output even and odd fields sequentially, ie trade off vertical resolution against bandwidth and power)

Progressive scan
(output every pixel row in every frame for maximum resolution)

Ref: J Nakamura, ch-3

Conversion gain

From electrons to volts



Conversion gain: $$C.G. = \frac{q}{C_{FD}} \quad [\mu V/\text{electron}]$$

$q = 1.6 \times 10^{-19}$ C

C_{FD} = floating diffusion capacitance

Voltage swing at FD node: $\Delta V_{FD} = CG\ S_{electrons}$

Ref: J Nakamura, ch-3

Photodiode full well capacity (FWC)

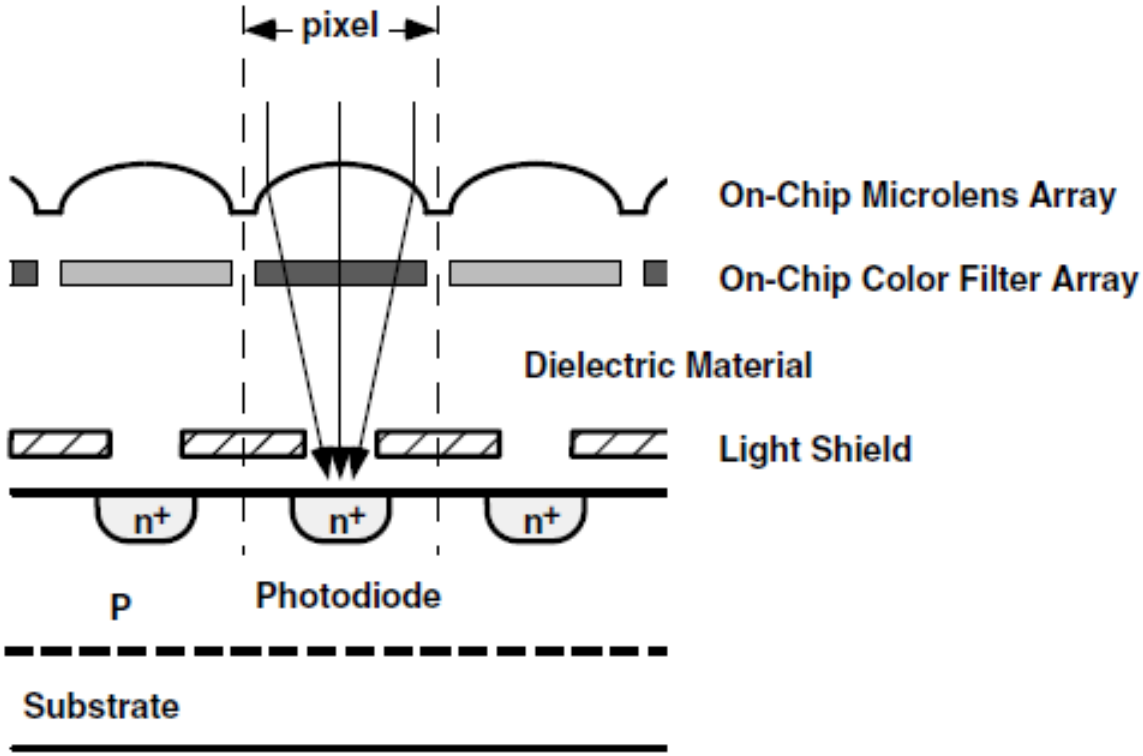
- Maximum number of electrons that can be stored in the pixel
- Sometimes called pixel saturation level

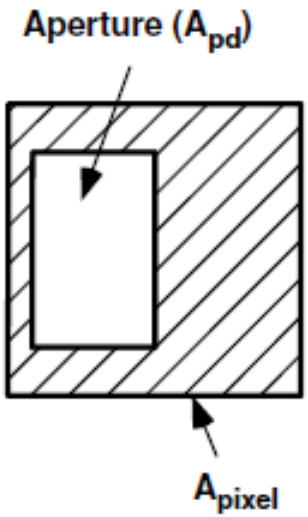
$$N_{sat} = \frac{1}{q} \int_{V_{reset}}^{V_{max}} C_{PD}(V) \cdot dV \quad \text{[electrons]}$$

C_{PD} = photodiode capacitance (F)
V_{reset} = photodiode reset level (V)
V_{max} = photodiode voltage when potential well is filled (V)

Ref: J Nakamura, ch-3

Photodiode in a pixel



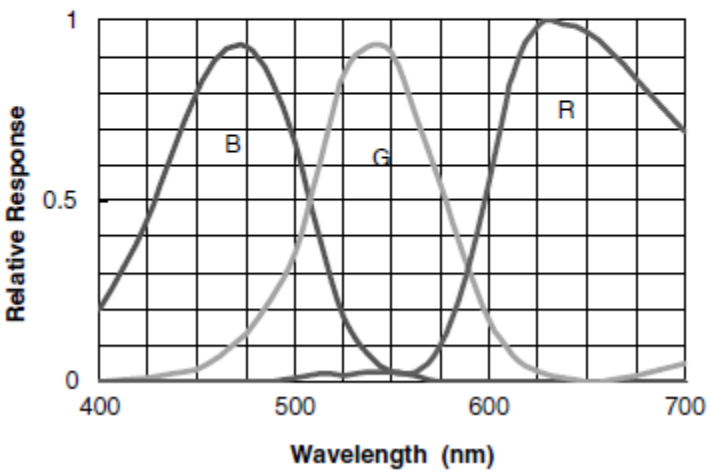


$$\text{Fill factor} = (A_{pd} / A_{pix}) \times 100 \quad [\%]$$

Ref: J Nakamura, ch-3

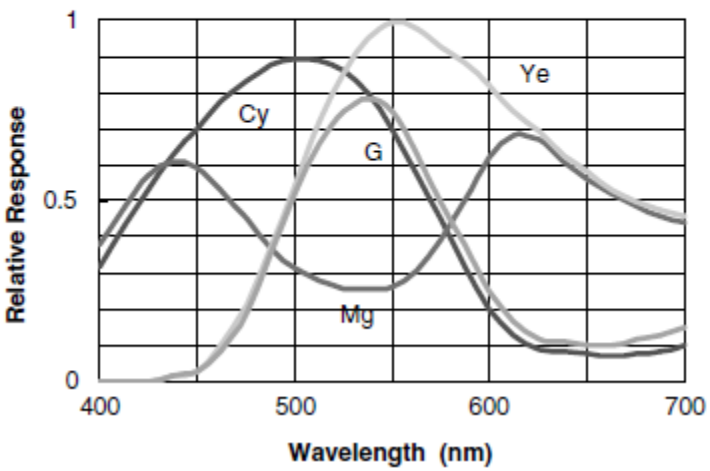
Bayer CFA versus CMY CFA

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



Bayer CFA

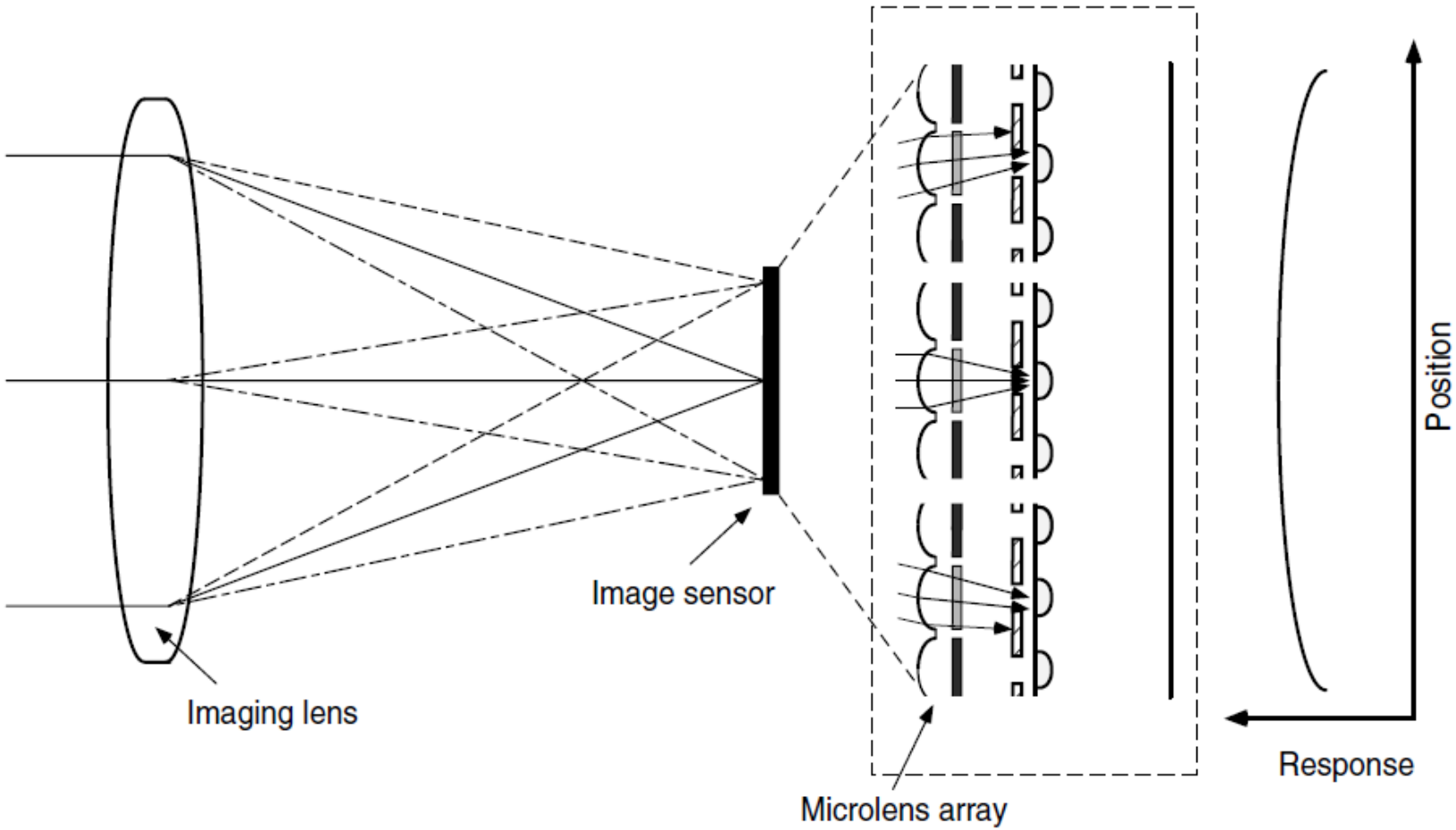
Mg	G	Mg	G
Cy	Ye	Cy	Ye
Mg	G	Mg	G
Cy	Ye	Cy	Ye



Complimentary CFA

Ref: J Nakamura, ch-3

Shading caused by incident light angle



Sensors with pixels <2.8um can have different shading curve for R, G, and B. In which case a 3-channel compensation scheme is utilized before color interpolation.

Ref: J Nakamura, ch-3

NOISE SOURCES IN IMAGE SENSORS

What is noise in images?

- Noise is any signal variation that deteriorates an image or «signal»
- Noise deteriorates image quality
- Noise determines the minimum light level for acceptable image quality

- Two noise categories:
  1. Fixed pattern noise (FPN)
  2. Temporal noise

Fixed pattern noise (FPN)

- Time invariant (fixed) offset value added to pixels at fixed positions in the image
- E.g. vertical stripes, horisontal stripes, white pixels, black pixels, pixel clusters, shading, …
- Easy to recognize when panning a video camera (scene moves while FPN pattern remains static)

FPN compensation in software

- FPN can be measured in darkness and then removed (by subtraction) in subsequent captures

A B A - B

Original picture Dark image After compensation

Dark current

- Thermally generated electrons (or holes) in the pixel. Adds on top of the photo-generated signal charge (mean value is unwanted FPN):

$$N_{dark} = \frac{Q_{dark}}{q} = \frac{I_{dark} \cdot t_{INT}}{q}$$

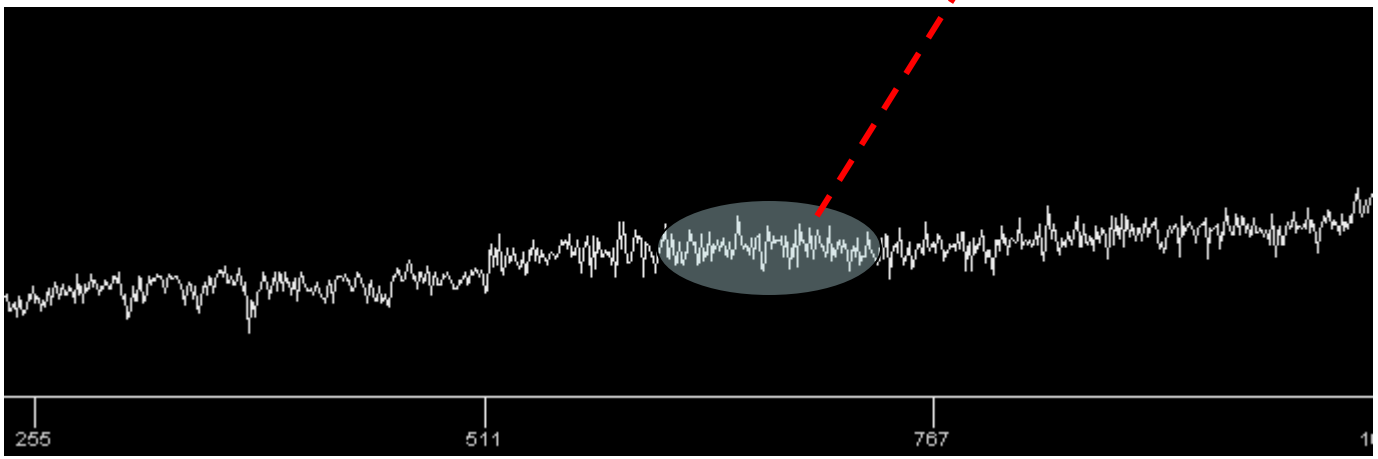
- Mean value (N_{dark}) can be estimated and removed from the picture in digital domain
- PS. Dark current also has a temporal noise component because it follows Poisson statistics as does photons (more Poisson statistics later).

Temporal noise

- General noise term for random variation over time
- Pixel values are «frozen» in capture below, but the values change randomly in subsequent pictures
- Human eye tends to average (filter) out temporal noise

Example pixel row profile:

Temporal noise changes randomly every capture



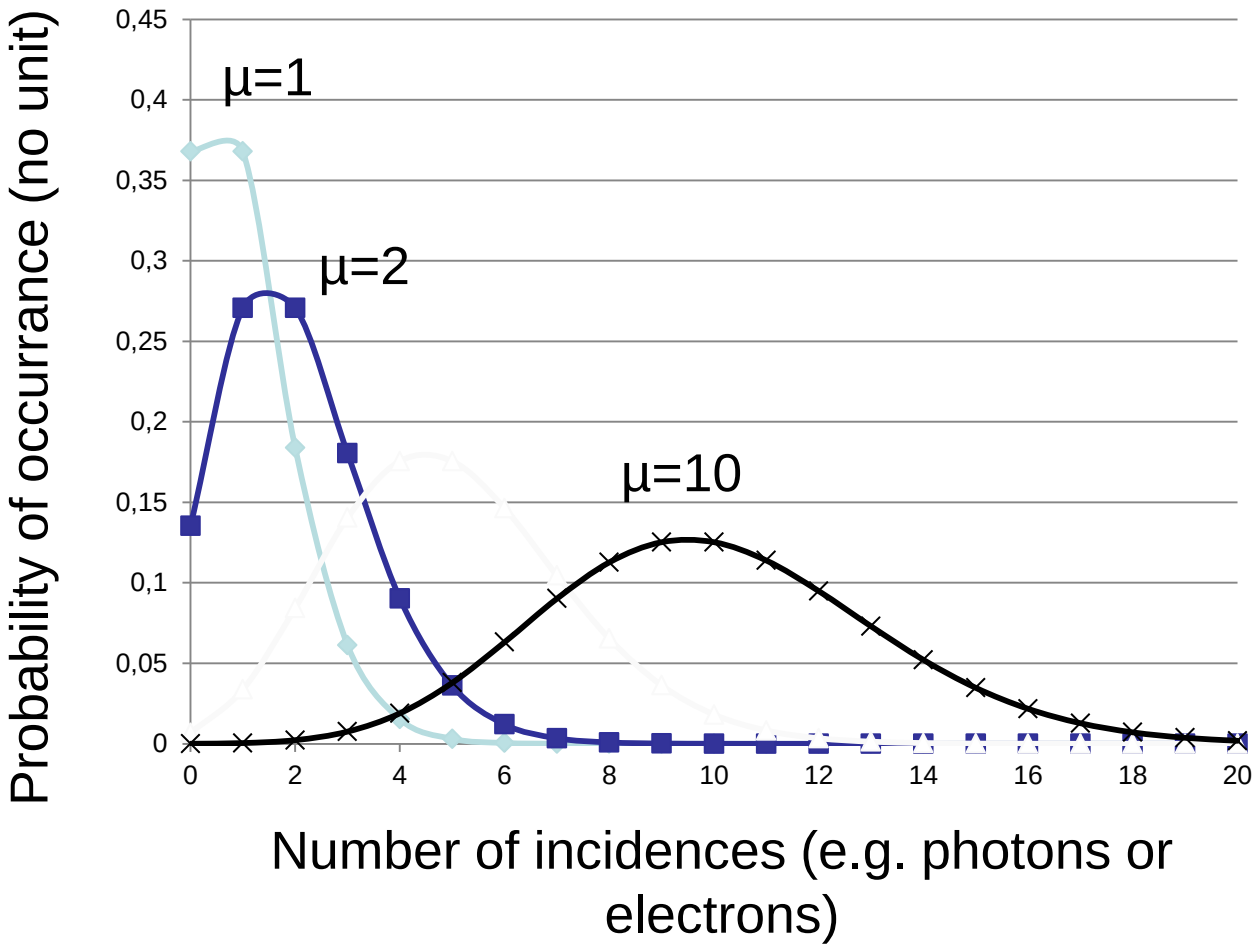
Photon shot noise

- Fundamental in all photon detectors
- Photoelectricity is random by nature (hence noisy) and follows Poisson's probability distribution:

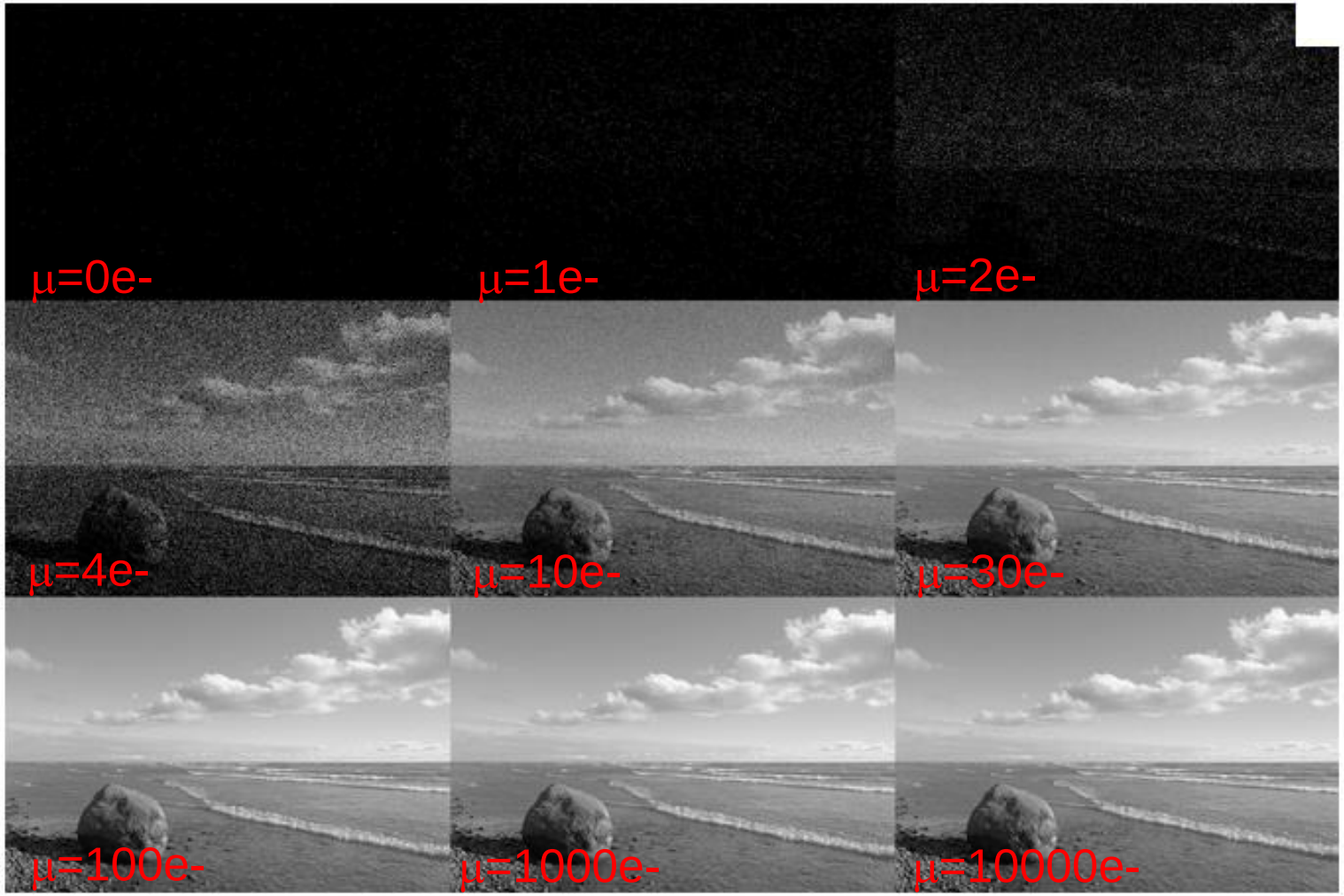
$$p(x) = \frac{\mu^x e^{-\mu}}{x!}$$

- p(x) = probability of x incidents (e.g. x electrons in a pixel),
- e = natural logarithm base (~2.72),
- μ = mean value, i.e. statistical average of x
- Shot noise is a temporal noise source

Poisson distribution plots at various mean values (μ)



Photon shot noise examples



Ref: Wikipedia

In a Poissonian process, the variance value equals the mean value (=μ)

$$\boldsymbol{Var(x)} = \sum_{x=0}^{\infty} (x-\mu)^2 p(x) = \boldsymbol{\mu}$$

Signal/Noise of ideal photon detector:

$$\boldsymbol{SNR} = \frac{Mean(x)}{\sqrt{Var(x)}} = \frac{\mu}{\sqrt{\mu}} = \sqrt{\boldsymbol{\mu}}$$

Ex: if a pixel detects an average of 100photons, then S/N=10 (20dB)

Thermal noise

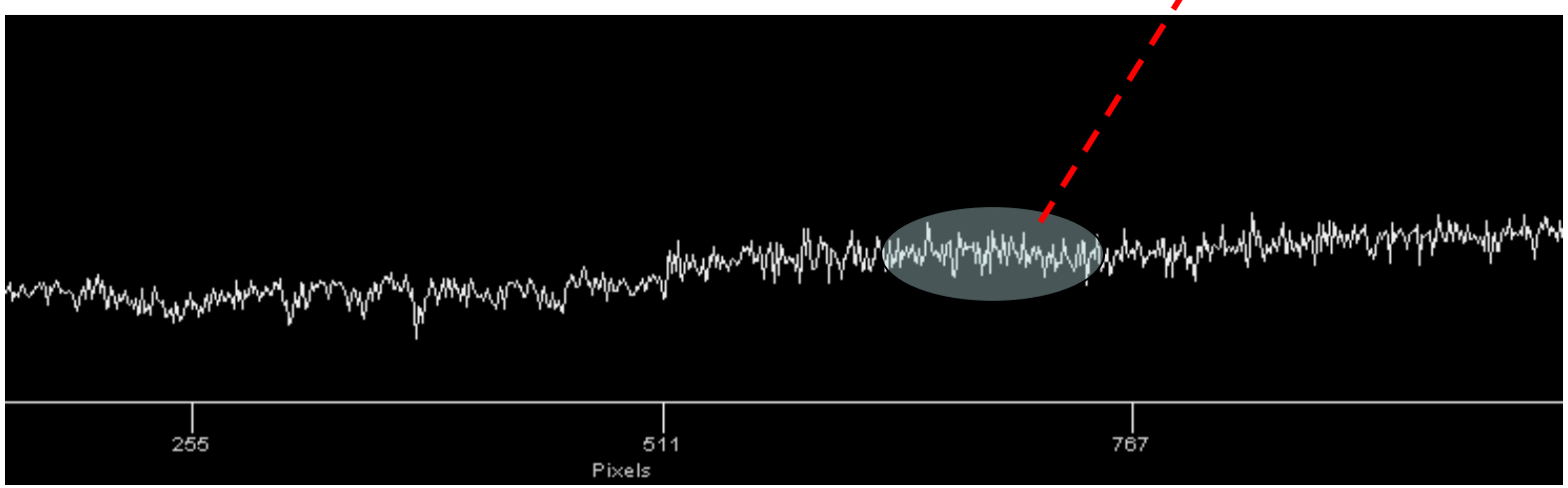
- Thermal agitations of electrons within a resistance (fundamental in all circuits)

$$S_V(f) = 4kTR \quad [\mathrm{V^2/Hz}] \tag{3.27}$$

where k is Boltzmann's constant; T is the absolute temperature; and R is the resistance.

Example row profile in darkness:

Random variation for every capture



Smear and blooming (noise at strong light)

Smear (CCD only)

Electron charge leakage from photodiode to vertical CCD registers during frame readout

Blooming (CIS and CCD)

Electron charge leakage from photodiode to neighboring pixels

Signal-to-Noise and Dynamic Range

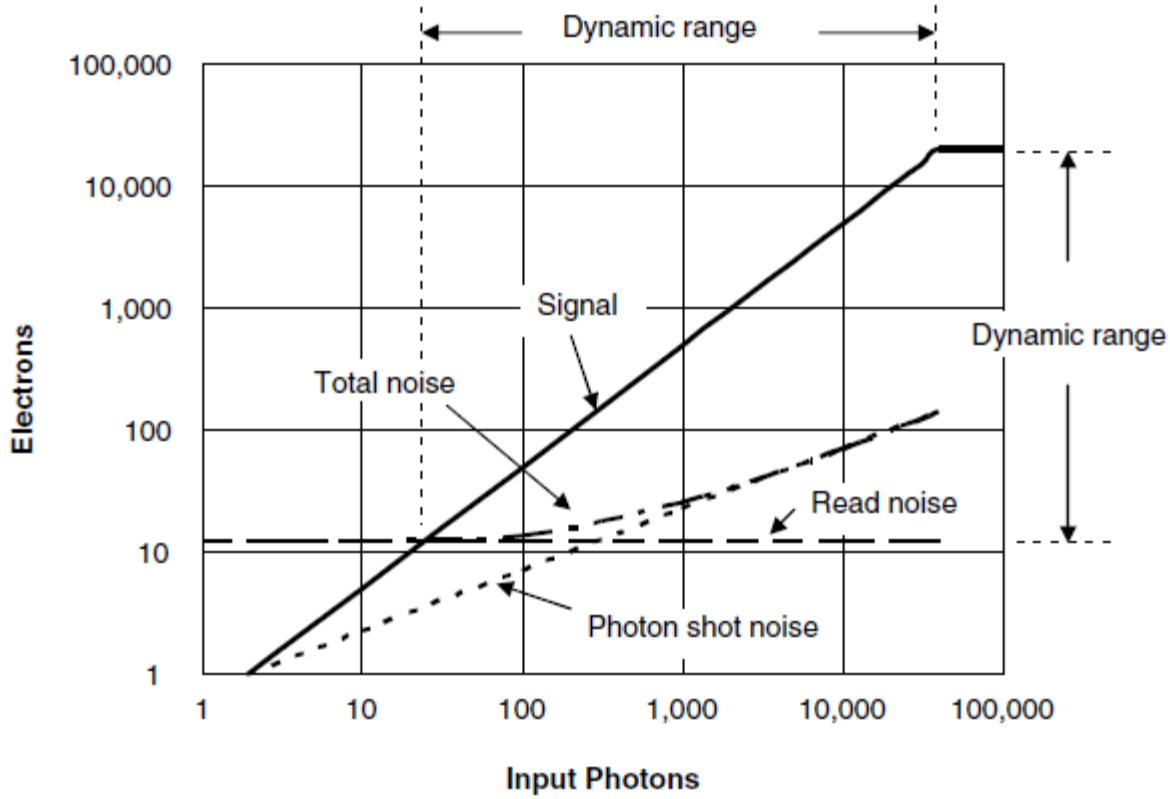


FIGURE 3.19 Example of photoconversion characteristics. A_{pix} = 25 μm²; C.G. = 40 μV/e⁻, N_{sat} = 20,000 e⁻, n_{read} = 12 e⁻.

Low vs High Dynamic Range capture

Low DR High DR

CAMERA DEMO