

MICRO-428: Metrology

Week Eleven: Electrical Metrology

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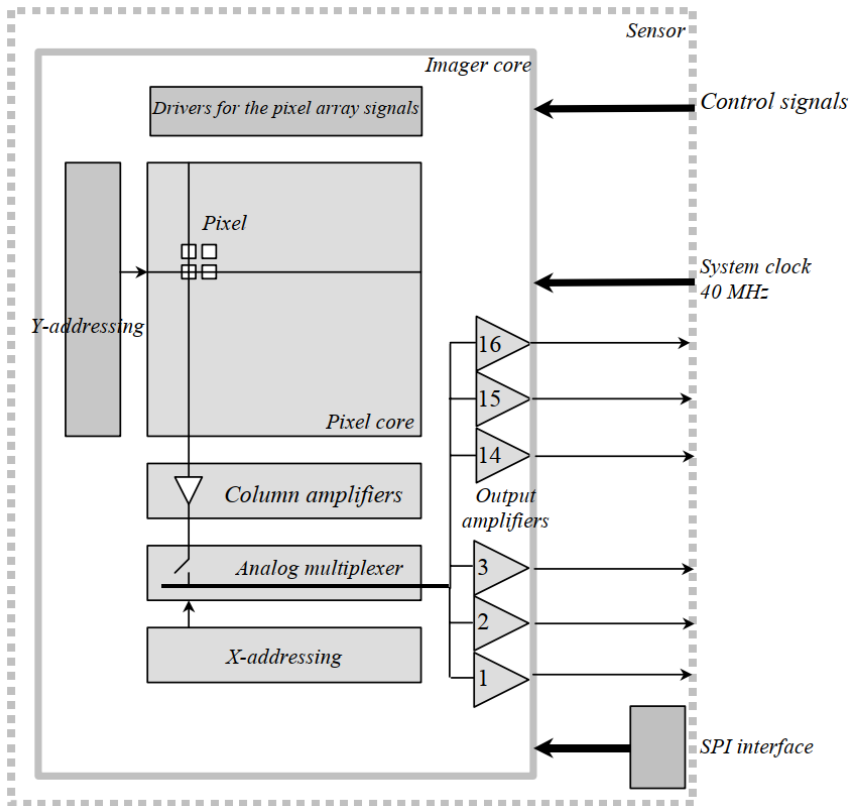
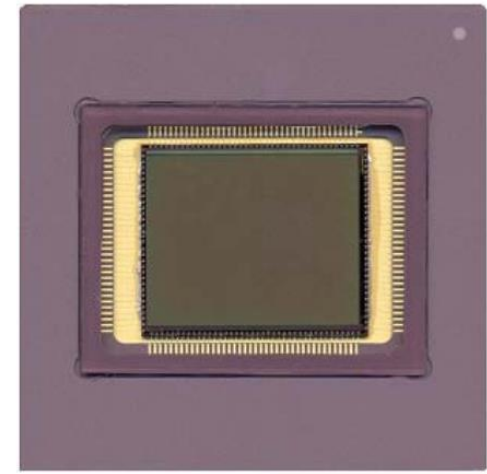
Advanced Quantum Architectures Laboratory (AQUA)

EPFL at Microcity, Neuchâtel, Switzerland



Exercise 1: Video digitization

- The objective is to determine the appropriate ADC to utilize in a cell phone camera alongside a CMOS array. An instance of a high-speed CMOS sensing chip is the LUPA-1300 from Cypress Electronics



Relevant information derived from the specifications are:

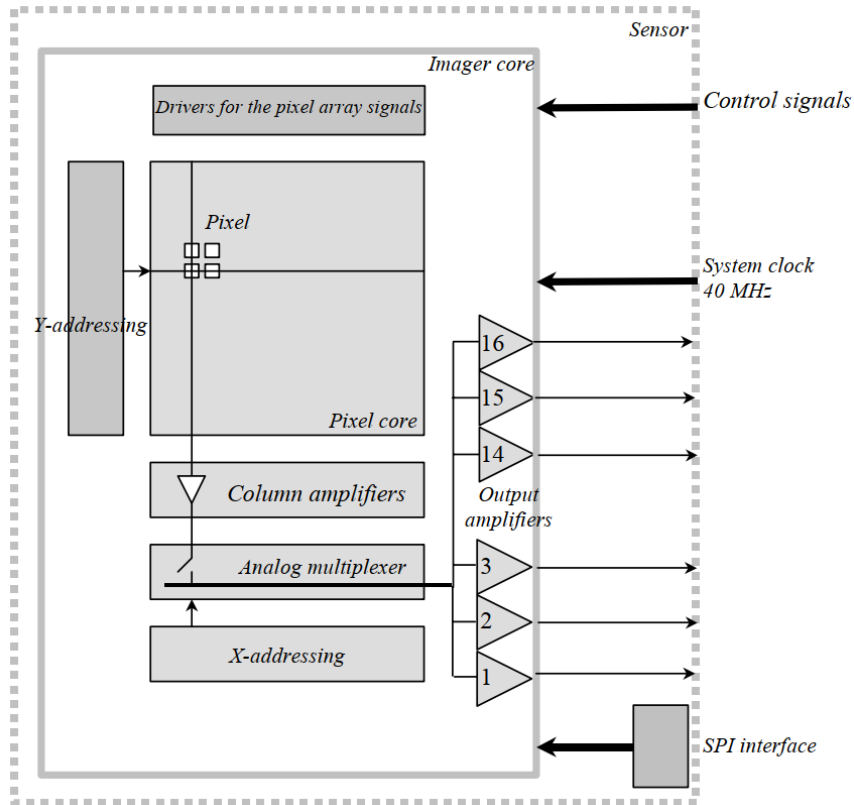
- 1280×1024** pixels, each **14 μm square**.
- Full well capacity: **62500** electrons.
- Output at **60,000** electrons: **1 V**.
- Typical quantum efficiency across the visible spectrum: **15%**.
- Dark current and read noise: **45 e^-/pixel**
- Recommended clock speed (pixel read rate): **40 MHz**

Output read by **16 parallel amplifier** channels (so each channel only looks at an **80×1024 subarray**).

 https://www.asdlib.org/onlineArticles/elabware/Scheeline_ADC/

Exercise 1: Video digitization

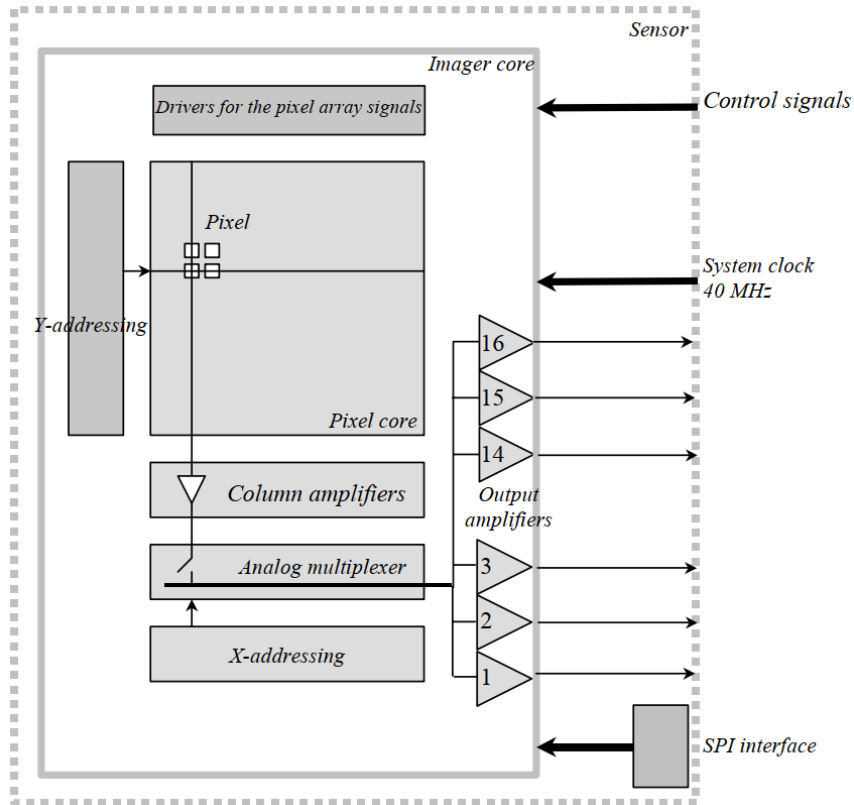
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1/ What is the appropriate number of bits for resolution?

Exercise 1: Video digitization

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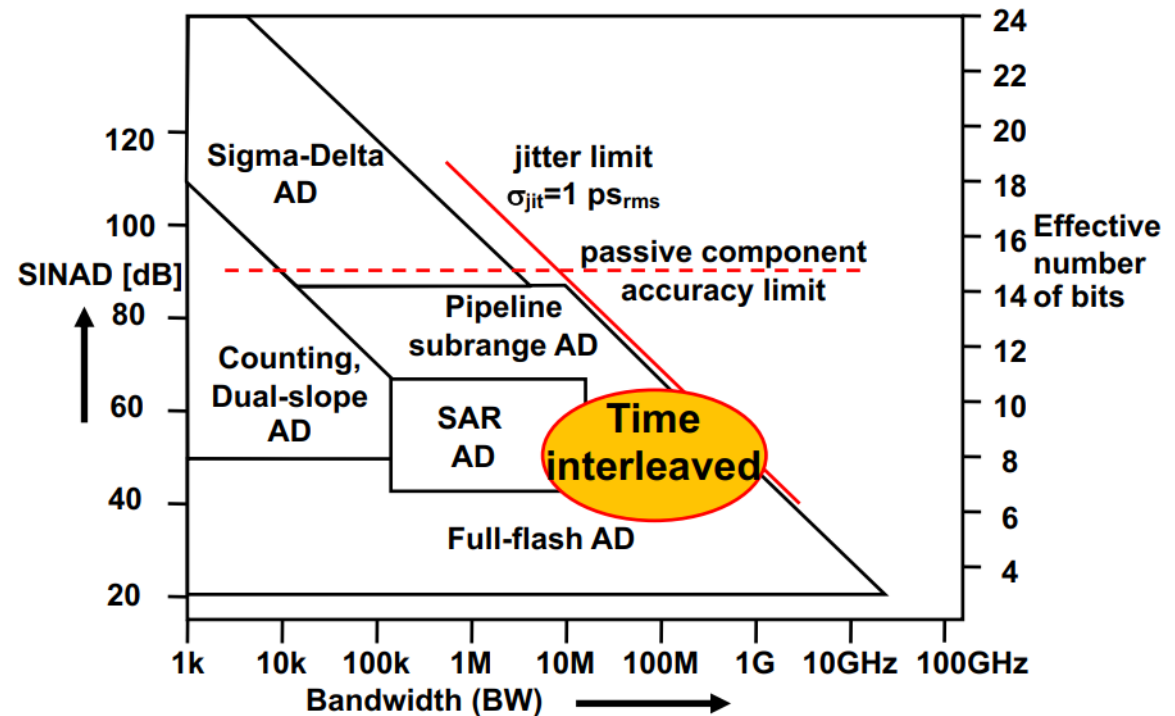
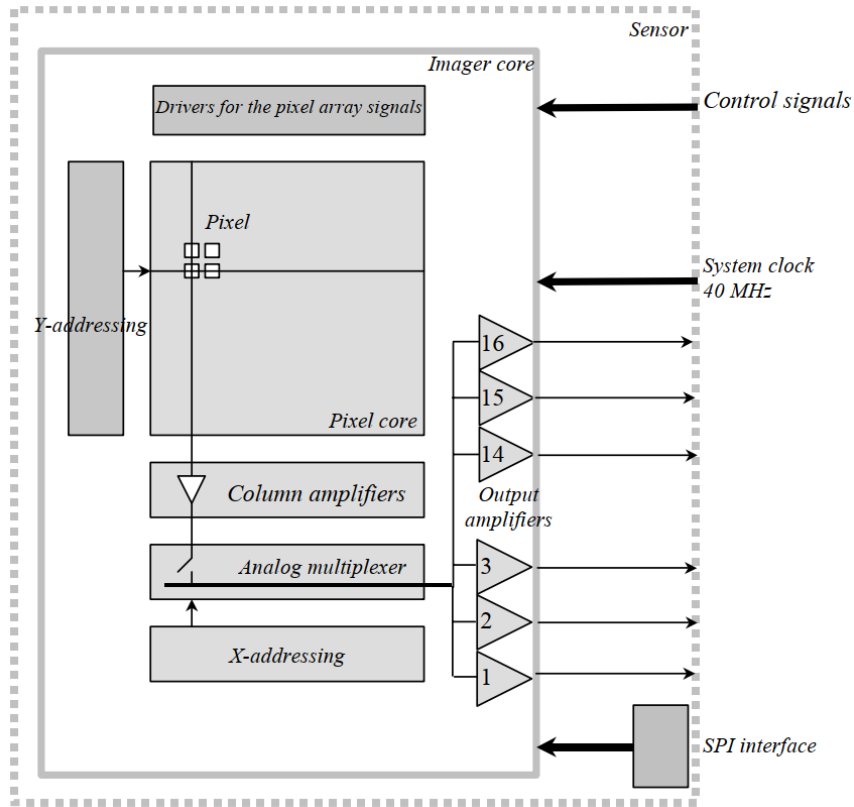
2/ What is the required number of ADC conversions per second?

Hint: Each ADC is dedicated to a single channel. The problem specifies the conversion rate per channel, which makes it possible to calculate the number of pixels associated with that particular channel.

Exercise 1: Video digitization

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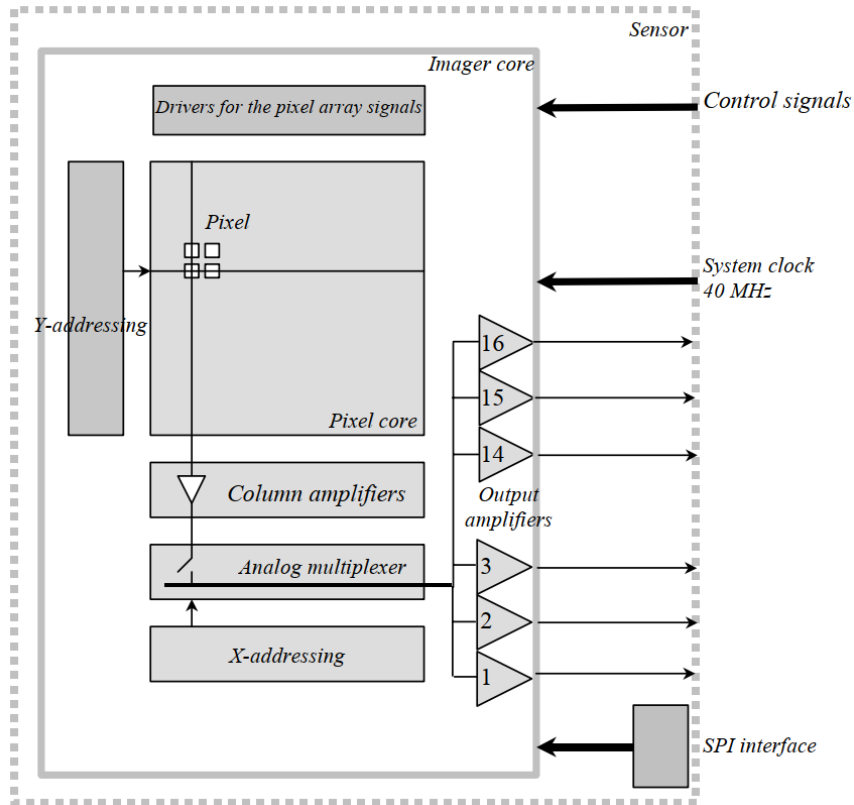
3/ Which ADC type would you suggest using?



Mead courses, "Data converters", 2021

Exercise 1: Video digitization

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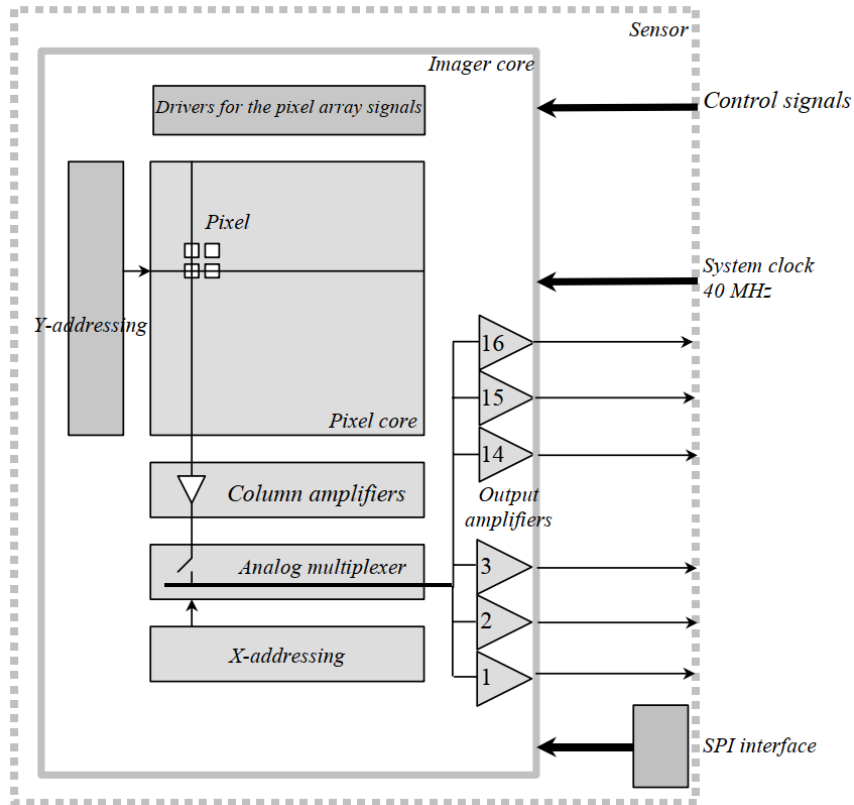


4/ What would be the signal-to-noise ratio (SNR) of an intensity measurement for a single read cycle?

Hint: Let's examine different sources of noise. Even if the ADC had infinite resolution, we would still encounter shot noise and readout noise. Which of these noise sources is the most significant?

Exercise 1: Video digitization

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5/ What would be the new SNR value if we average all the data for 1 second?

Reminder: The new standard deviation of the mean can be calculated by dividing the original standard deviation by the square root of the number of measurements averaged (N)

Exercise 2: Group explanation

1. Divide yourself in small groups (2-3 ppl).
2. Discuss the following example taken from the lecture, focusing on understanding what is happening.

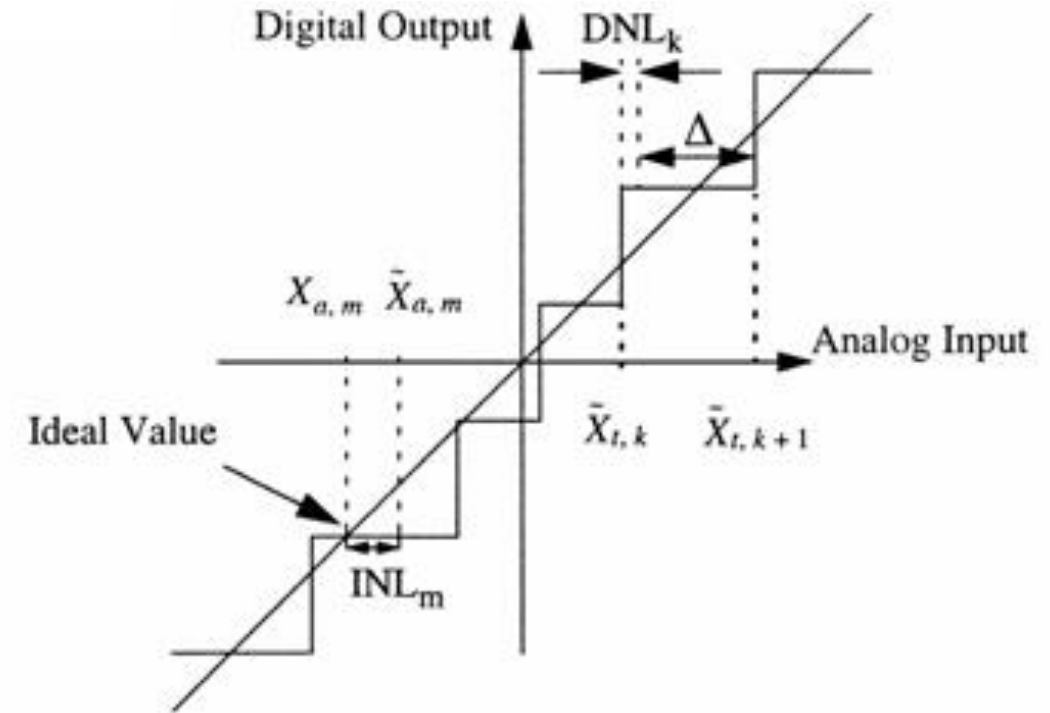
5.2.2 ADC – Real Case

- Non-idealities:
 - Differential non-linearity (DNL)
 - Integral non-linearity (INL)

$$DNL_j \equiv \frac{Width_{ACTUAL,j} - Width_{ID}}{Width_{IDEAL}}$$

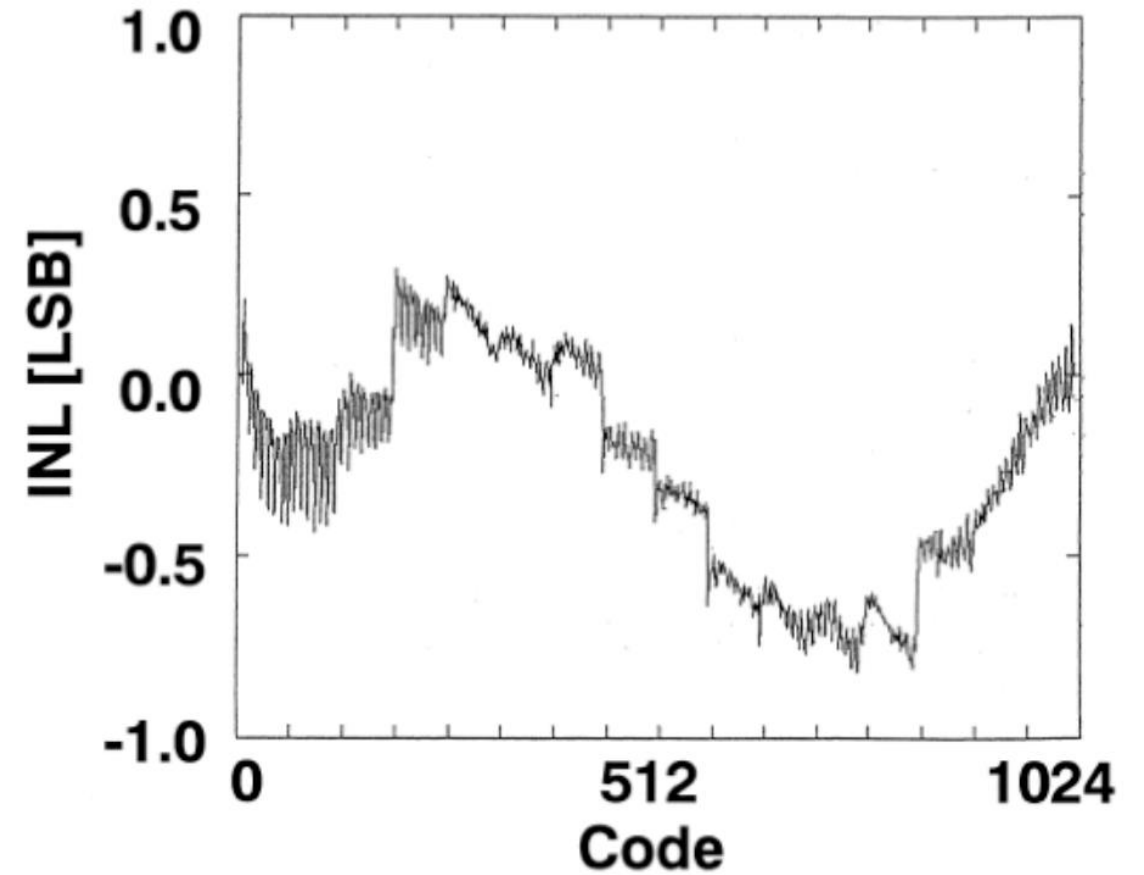
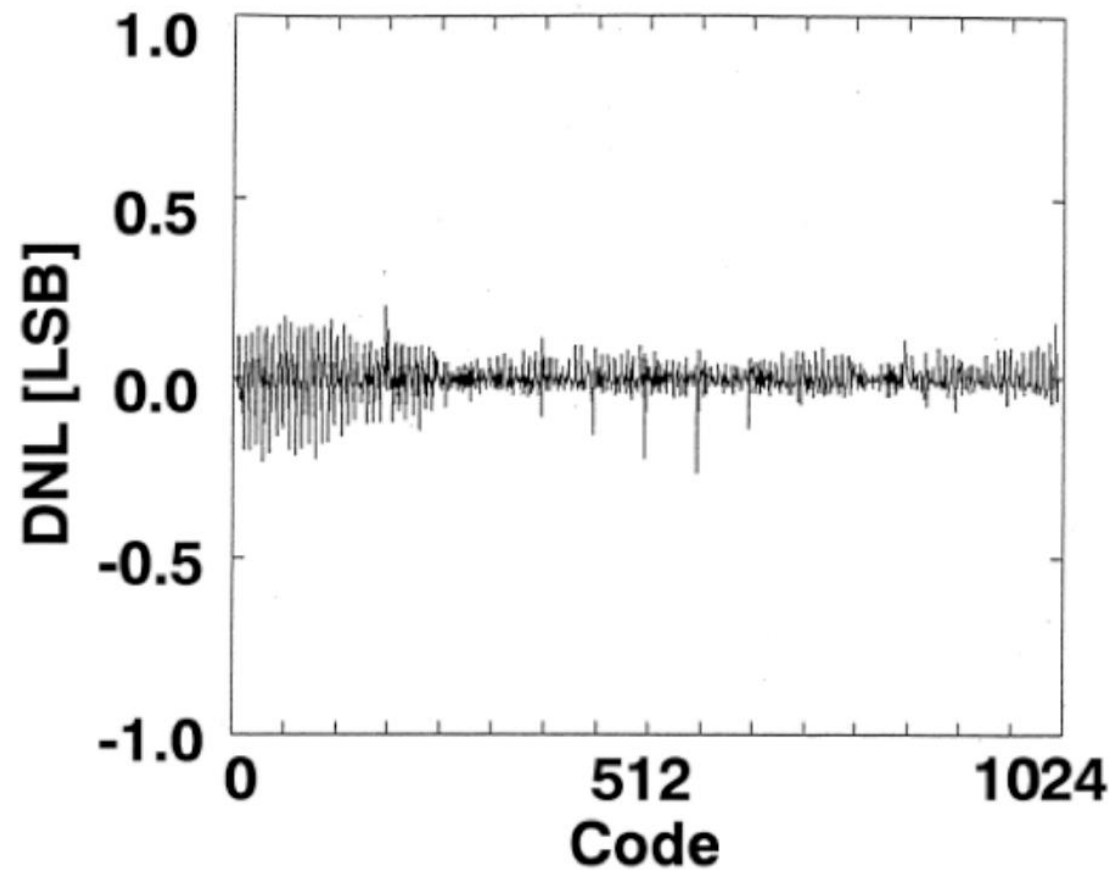
$$INL_j = \sum_{k=0}^{k=j} DNL_k$$

$$DNL_j = INL_{j+1} - INL_j$$



INL = deviation of transfer curve from ideal (linear)

5.2.2 ADC – Real Case, Example



Source: A. Matzusawa

5.3 ADC architectures

- Divide yourself in small groups (2-3 ppl).
- Select two ADC architectures and explain them to your colleagues

Exercise 3: Choosing the right architecture

By group of 2-3 pick the right ADC and justify your choice.

Trait / Application

Matching ADC Type

1. Fastest possible conversion speed
2. Uses a binary search algorithm
3. Low power, moderate speed, good resolution
4. Uses an integrator and a counter
5. Requires one comparator per output level (2^n levels)
6. Often used in digital multimeters
7. Uses capacitor array for successive charge balancing
8. Best suited for audio applications (e.g., microphone)
9. Has the smallest latency
10. Balanced in speed, area, and resolution

Exercise 4: Group explanation

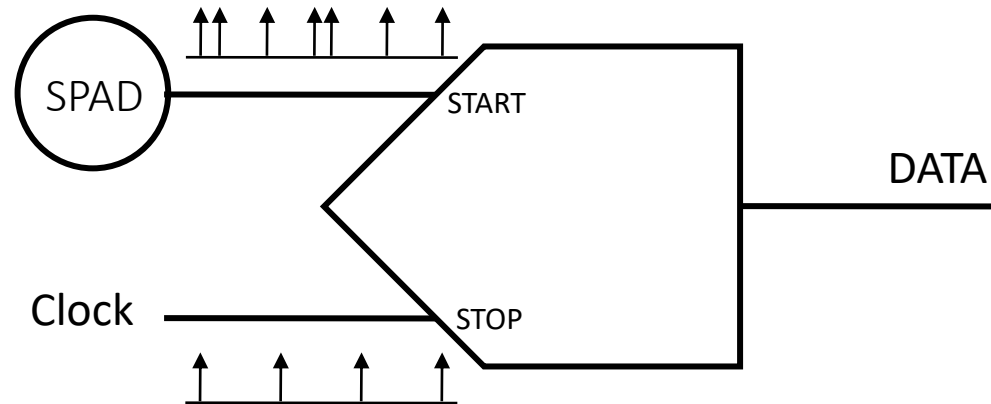
1. Divide yourself in small groups (2-3 ppl).
2. Discuss the following TDC-related Metrology techniques – code-density test and single-shot experiment – focusing on understanding what is happening.

5.3 TDC – Metrology: Optical Tests

A) (Code) Density test: free running SPAD (e.g. natural light source)*

B) Single-shot experiment (e.g. repetitive pulsed laser illumination):

- Histogram $\Delta t_i, i=[1...N]$ (Time-correlated single-photon counting – TCSPC)



*could also be done electrically

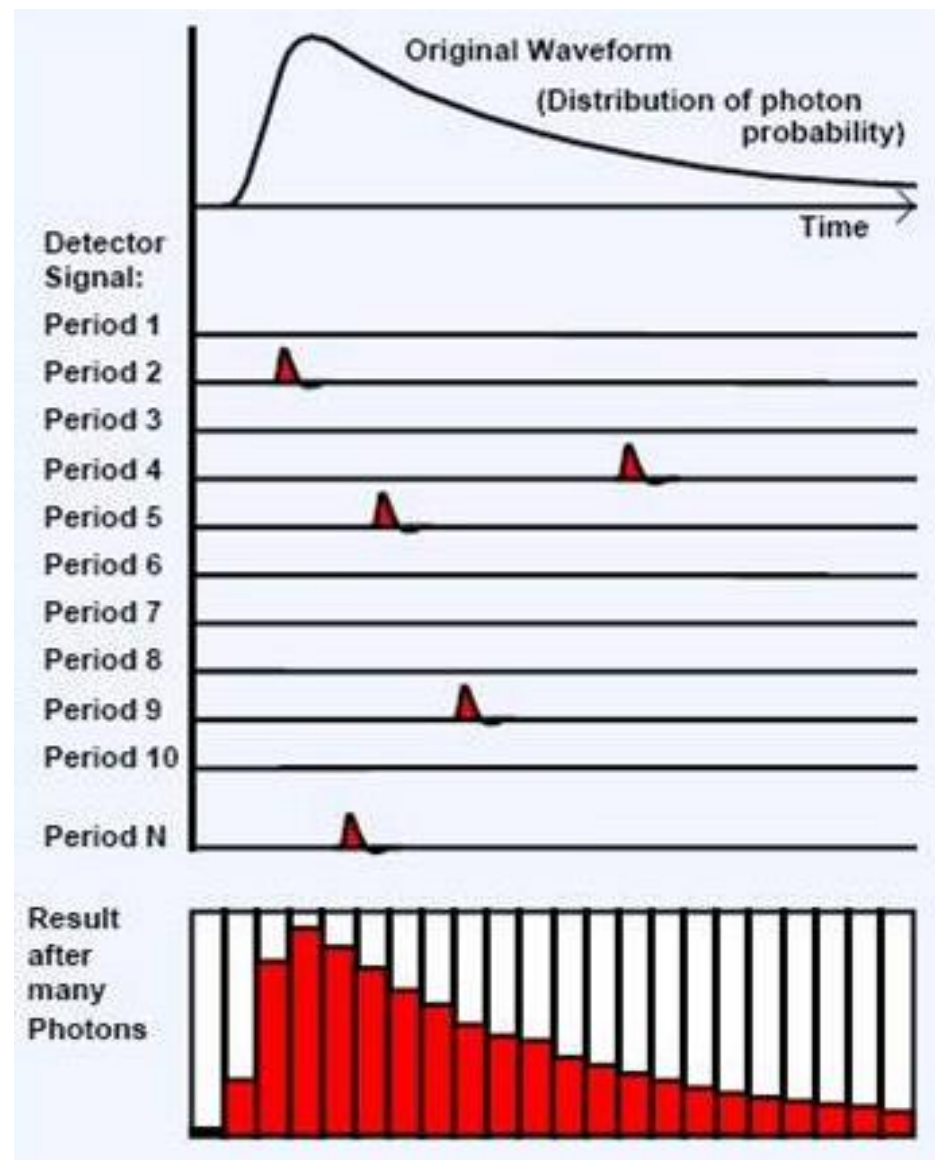
Homework

Homework 1-3 have already been discussed in previous classes and can be relevant to the exam.

Homework 1: Design and analysis of a FLIM System

- Design and analyse a simple Fluorescence Lifetime Imaging (FLIM) system, based on the discussion during the class (TDC application examples, Section 5.3.9):
 - a) Estimate the overall system parameters (e.g. fluorophore type, typical process timescales, detector and excitation source). How do their variances add?
 - b) Which is the PDF/CDF of the fluorescent sample?
 - c) How can you estimate the fluorescence lifetime from i) a timestamp histogram, ii) a series of timestamps?
 - d) Which is the standard deviation of the fluorescence lifetime and how does it get better with increasing sample size?
 - e) Suppose that there are two fluorophores with different lifetimes (e.g. 2 and 4 ns) and that your measurement system is ideal (negligible measurement error). How many measurements are necessary to differentiate them (rough estimate)?
- *Hint:* Use a Time-Correlated Single-Photon Counting (TCSPC) approach

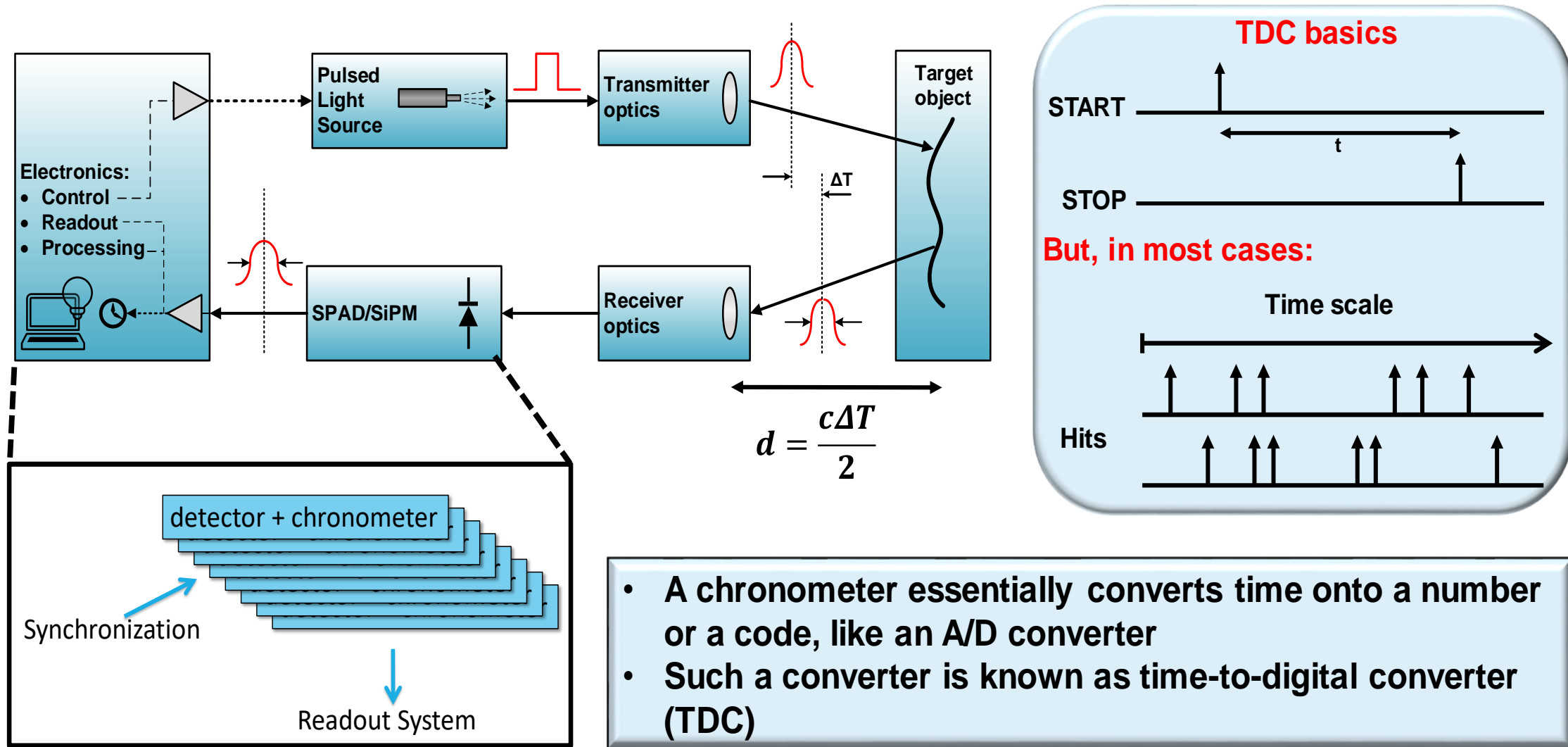
Homework 1: Reminder: TCSPC Principle



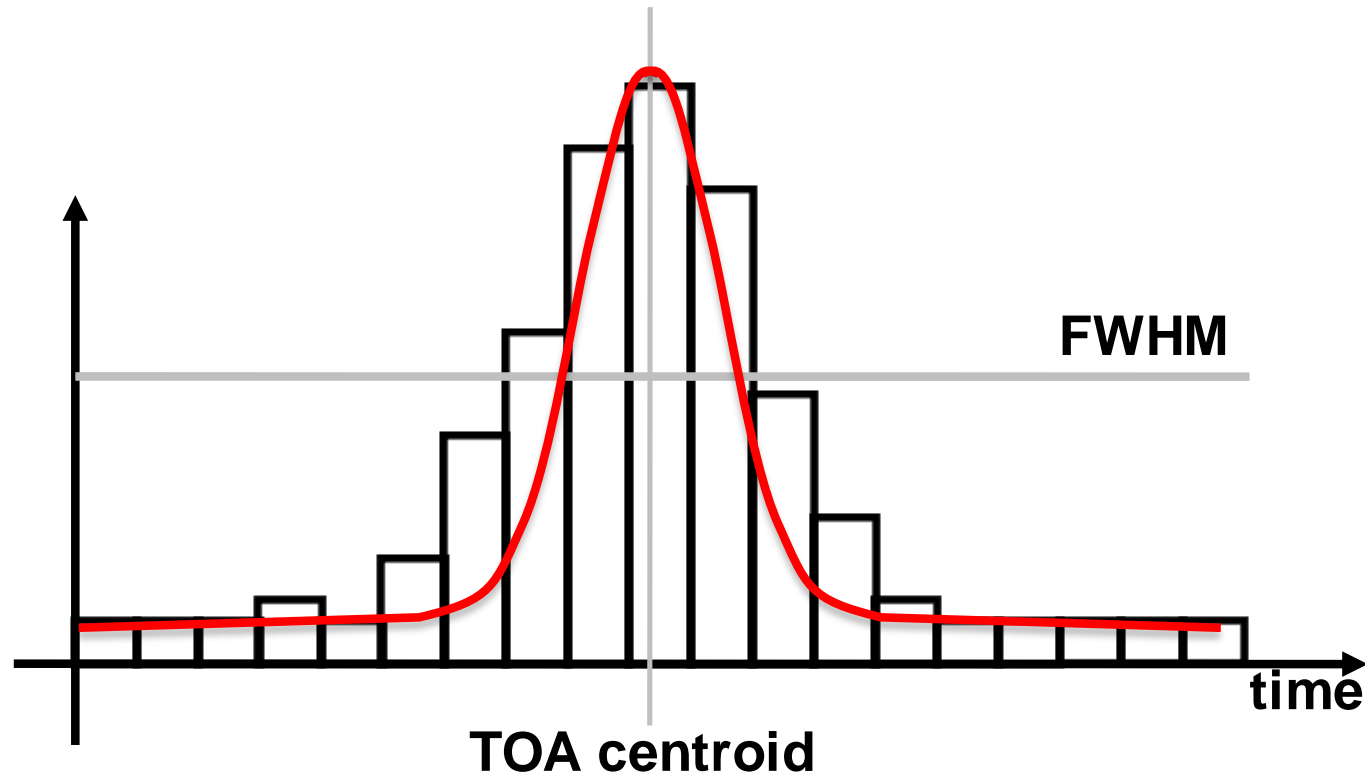
Homework 2: Design and analysis of a LIDAR system

- Design and analyse a simple Light Detection and Ranging (LIDAR) time-of-flight system, based on the discussion during the class (TDC application examples, Section 5.3.9):
 - a) Estimate the overall system parameters (target distance, characteristics such as reflectivity, background light, illuminator, detector, time-stamping electronics).
 - b) What is the typical PDF of the backscattered light?
 - c) How is it influenced by the precision of the individual components?
 - d) How can you increase the measurement precision? And its accuracy?
 - e) Suppose that you need to operate at a distance of up to 10 m. Which maximum laser pulse repetition rate can you use?

Homework 2: Reminder: 5.3.9 TDC Application Example: Time-of-Flight System



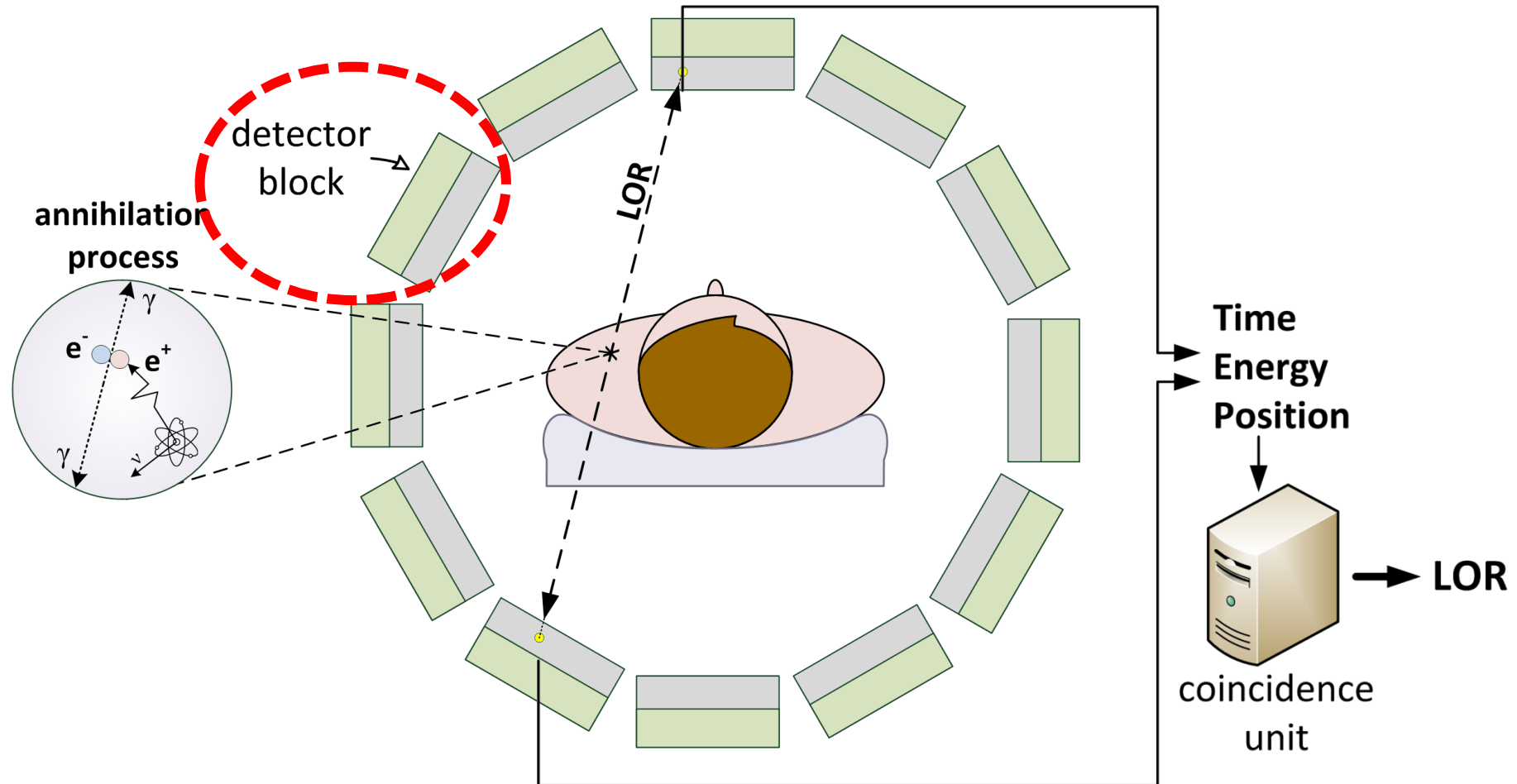
Homework 2: Reminder: 5.3.9 TDC Application Example: Time-of-Flight System



Homework 3: Design and analysis of a PET System

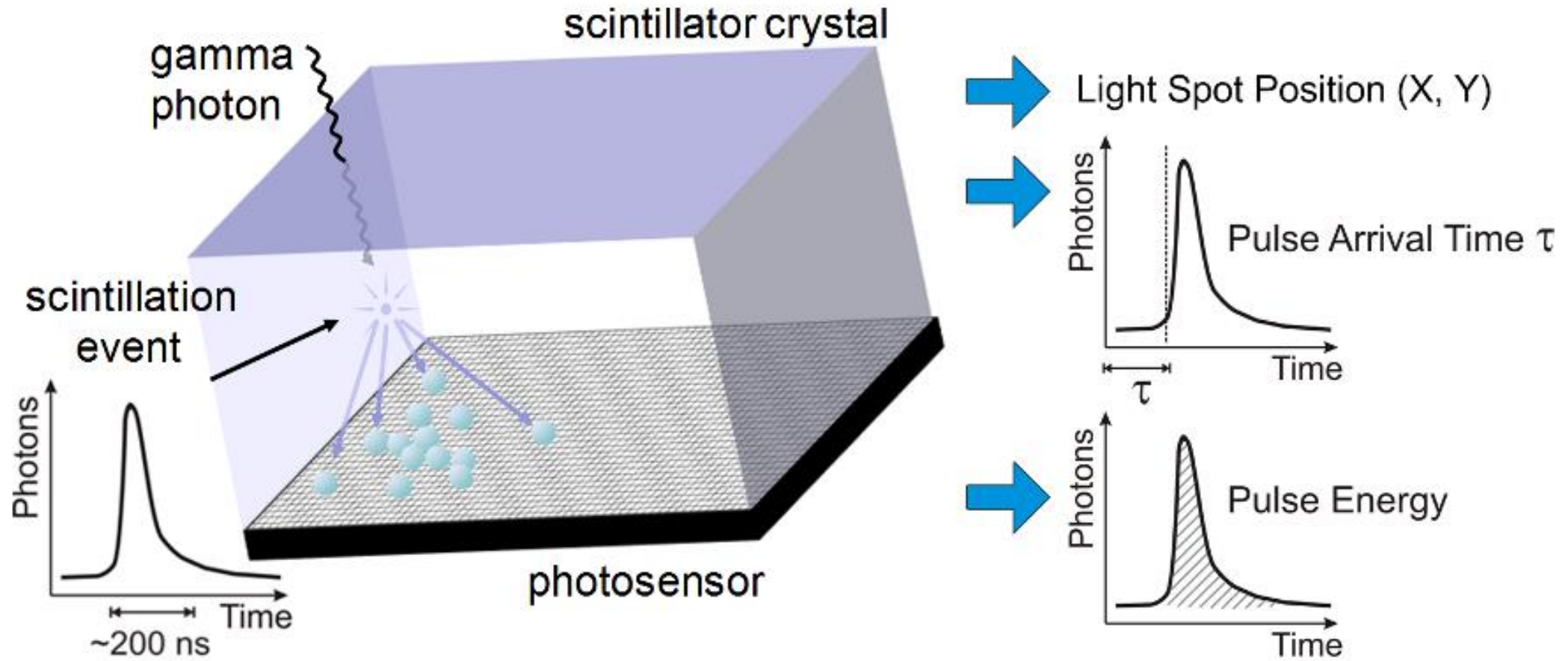
- Design and analyse a simple Positron Emission Tomography (PET) system:
 - a) How does the system work (in general terms)?
 - b) How does the photodetector module, coupled to a scintillator, work? Which main parameters must be estimated?
 - c) Which is the typical PDF of the scintillation light?
 - d) How much time does the scintillation light take to travel from the point of impact in the crystal to the photodetector?
 - e) Provide some examples of overall time of arrival estimators (estimation theory).

Homework 3: Design and analysis of a PET System



 GE Discovery IQ, Nov 2016

Homework 3: Design and analysis of a PET System



Homework 4: Design case study

Homework 4: Amplifier frequency response (1)

- For any electronic circuit we can derive a transfer function $A(s)$ by small-signal analysis to give


$$A(s) = \frac{N(s)}{D(s)} = \frac{a_0 + a_1 \cdot s + a_2 \cdot s^2 + \dots + a_m \cdot s^m}{1 + b_1 \cdot s + b_2 \cdot s^2 + \dots + b_n \cdot s^n}$$

Where a_0, a_1, \dots, a_m and b_1, b_2, \dots, b_n are constants.

- Very often the transfer function contains poles only (or the zeros are unimportant). In this case we can factor the denominator to give

$$A(s) = \frac{K}{\left(1 - \frac{s}{p_1}\right) \left(1 - \frac{s}{p_2}\right) \dots \left(1 - \frac{s}{p_n}\right)}$$

Where K is a constant and p_1, p_2, \dots, p_n are the poles of the transfer function.

 Paul R. Cova, "Analysis and design of analog integrated circuits, 5th edition."

Homework 4: Amplifier frequency response (2)

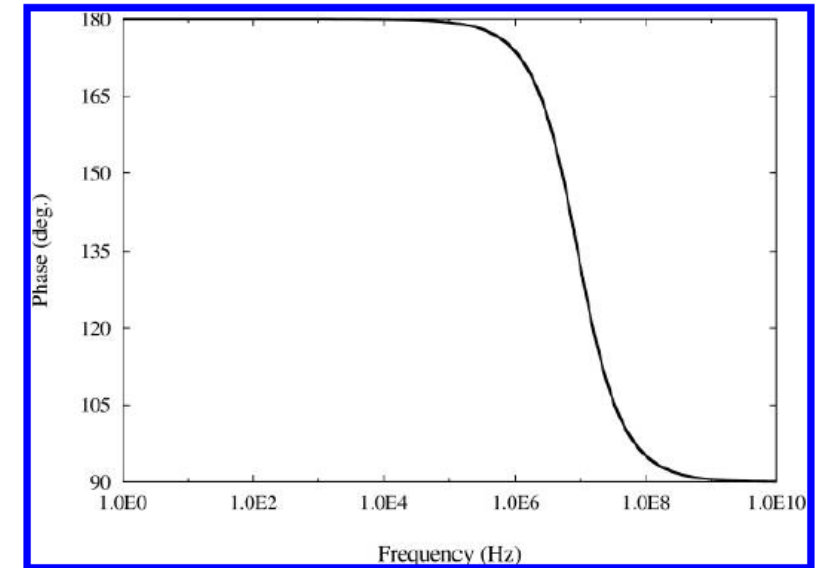
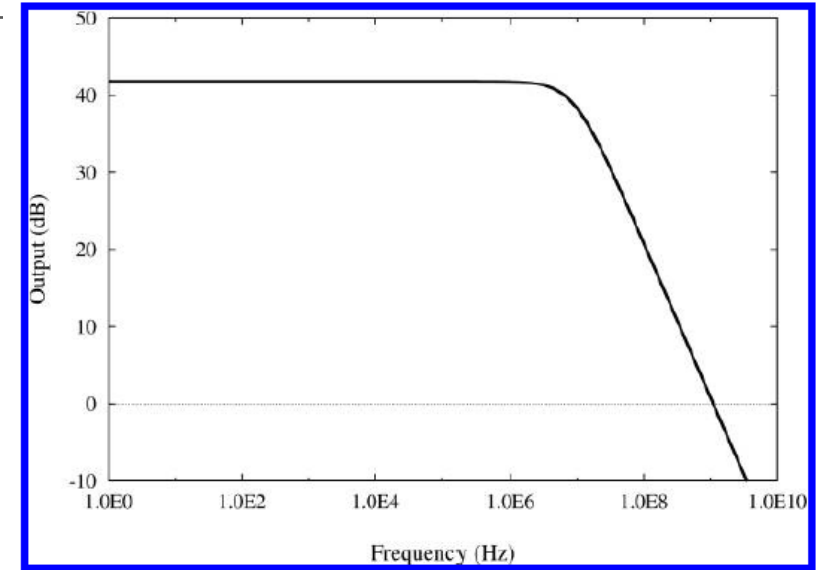
- An important case occurs when one pole is dominant. That is, when $|p_1| \ll |p_2|, |p_3|, \dots$
- The gain magnitude in the frequency domain can be approximated as

$$|A(j\omega)| \simeq \frac{K}{\sqrt{1 + \left(\frac{\omega}{p_1}\right)^2}}$$

This approximation can accurately predict the -3-dB frequency at least until $\omega \simeq |p_1|$, and we can write

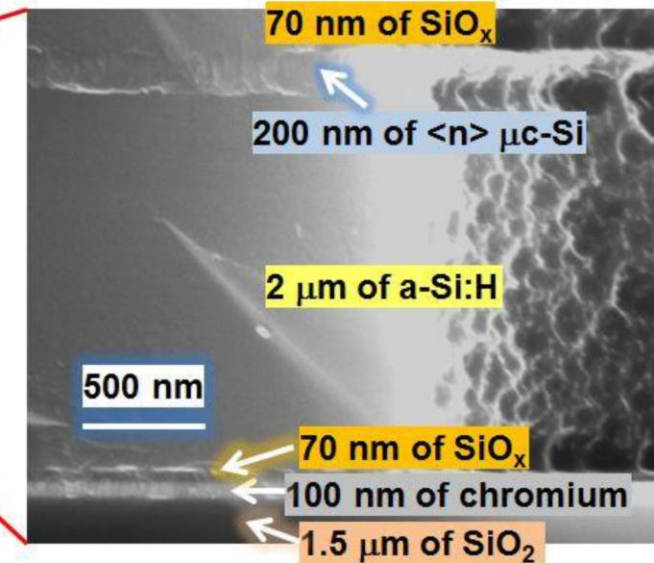
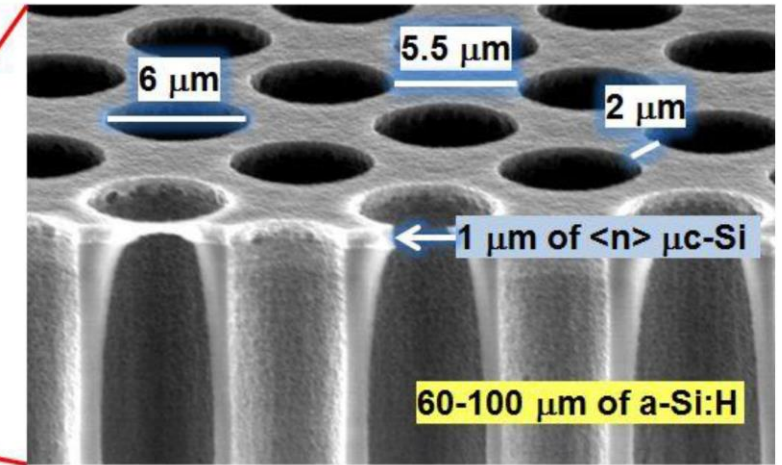
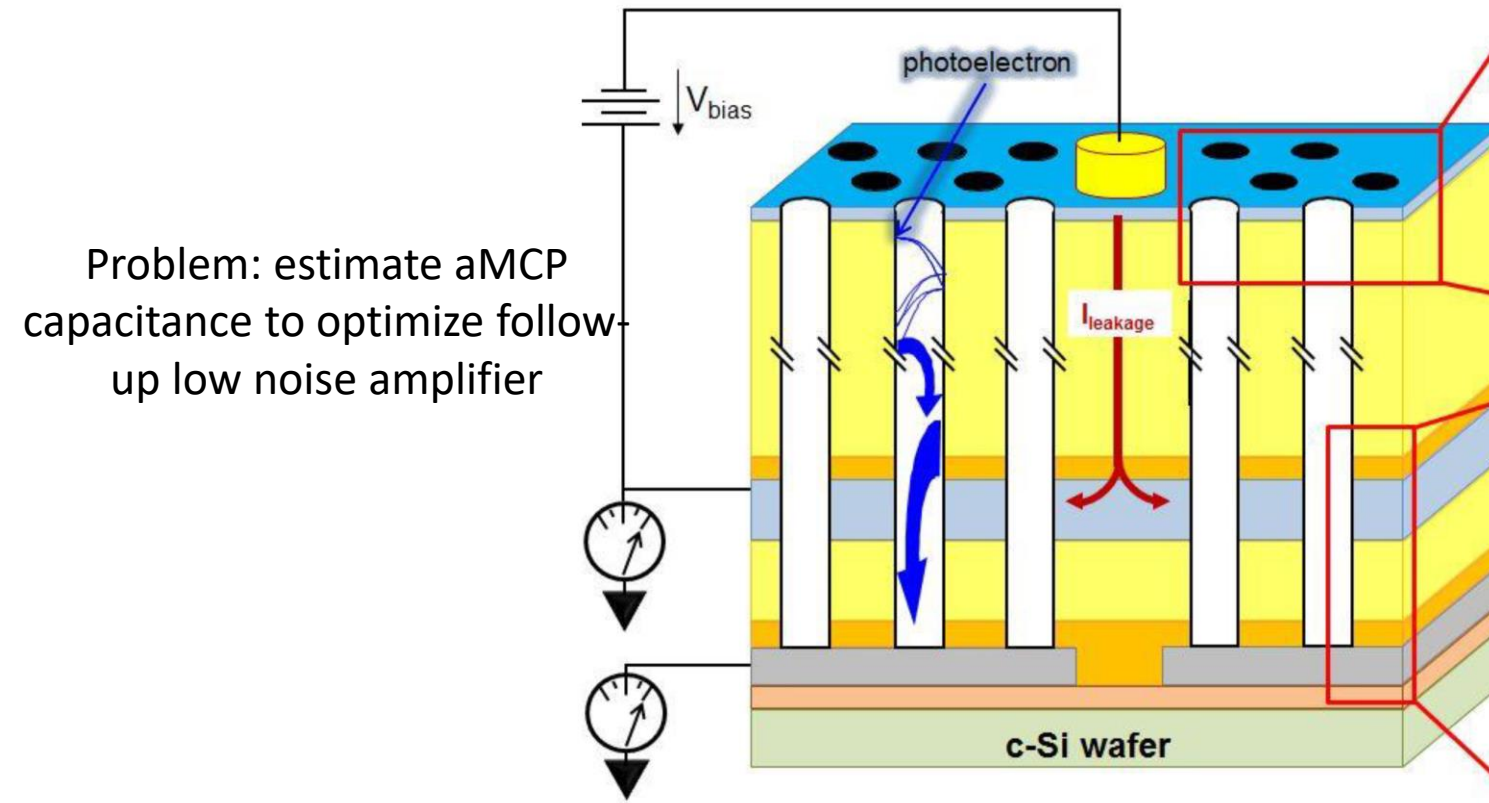
$$\omega_{-3dB} \simeq |p_1|$$

📖 Paul R. Cova, "Analysis and design of analog integrated circuits, 5th edition."

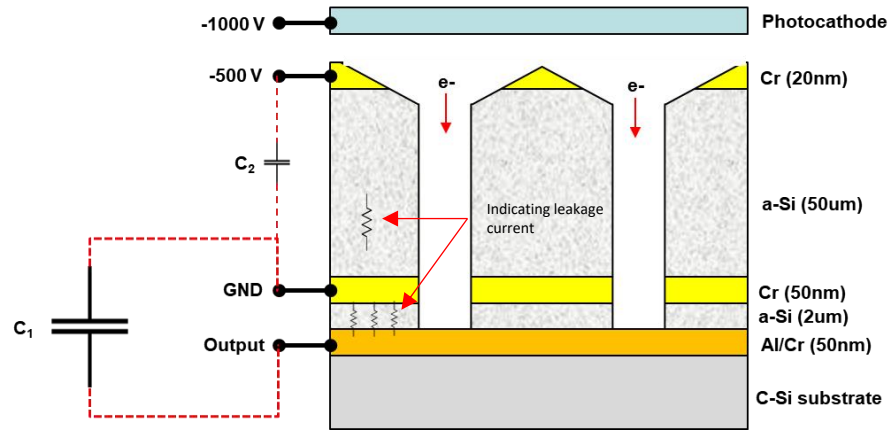


Homework 4: Design case study

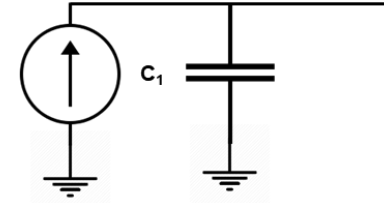
Rendering and microscopic (SEM) view of an a-Si:H based Multi-Channel Plate (aMCP)



Homework 4 : Design case study



Cross-section view of the aMCP channels

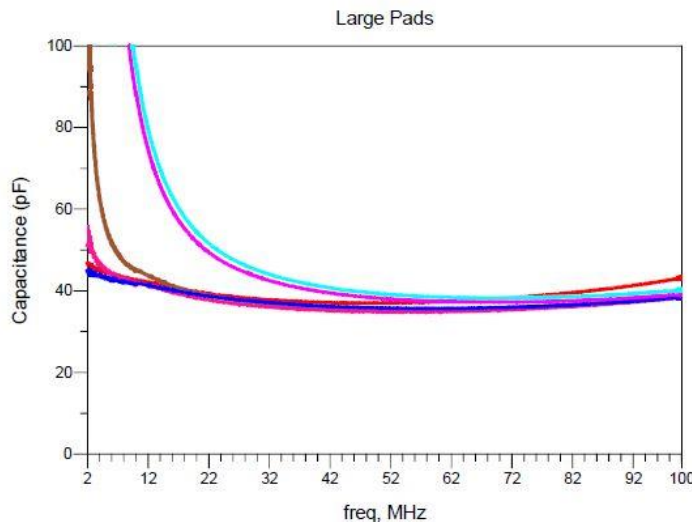


Simplified electrical model of AMCPs

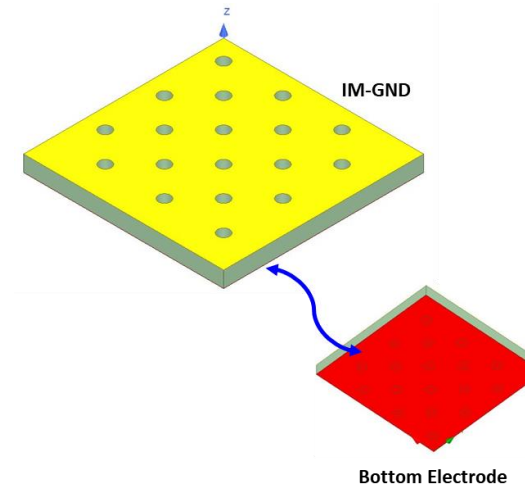
$$C = \epsilon_r \epsilon_0 \frac{A}{d}$$

$$\epsilon_r \rightarrow \sim 12 \text{ for a-Si:H}^*$$

Estimation of AMCP capacitance via parallel plate capacitor
($\sim 960 \times 960 \mu\text{m}^2$) $\rightarrow C_1 \sim 45.5 \text{ pF}$



vs. Experimental results
(notice a few broken channels)

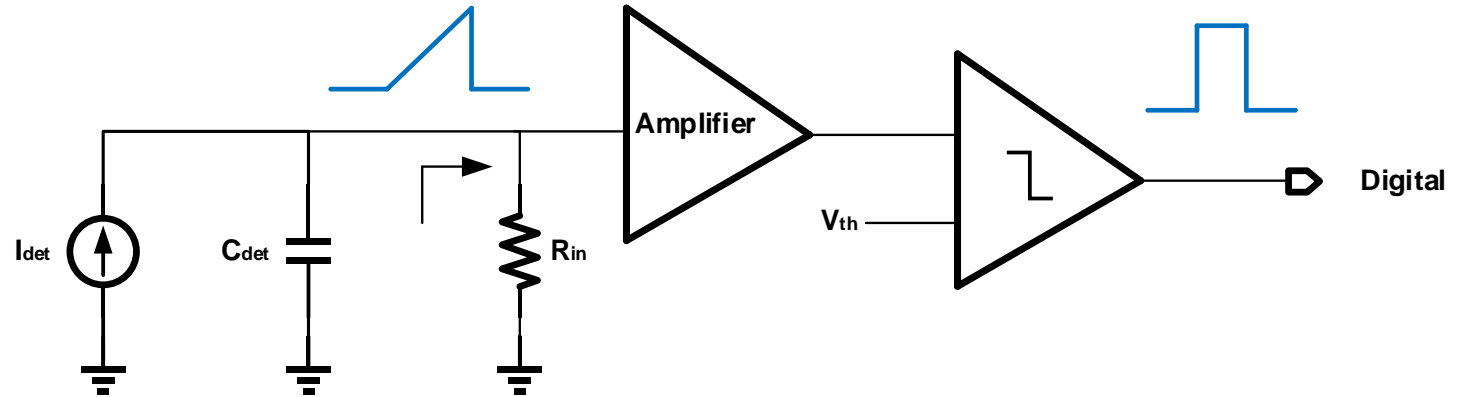


vs. ANSYS simulation
 $\rightarrow C_1 = 49.37 \text{ pF}$

Homework 4 : Design case study

- Example of detector specifications:

$$\begin{aligned}Q_{in} &= 3000 \text{ e-} / 10000 \text{ e-} \\C_{det} &= 2 \text{ pF} \\t_{coll} &= 10 \text{ ps}\end{aligned}$$

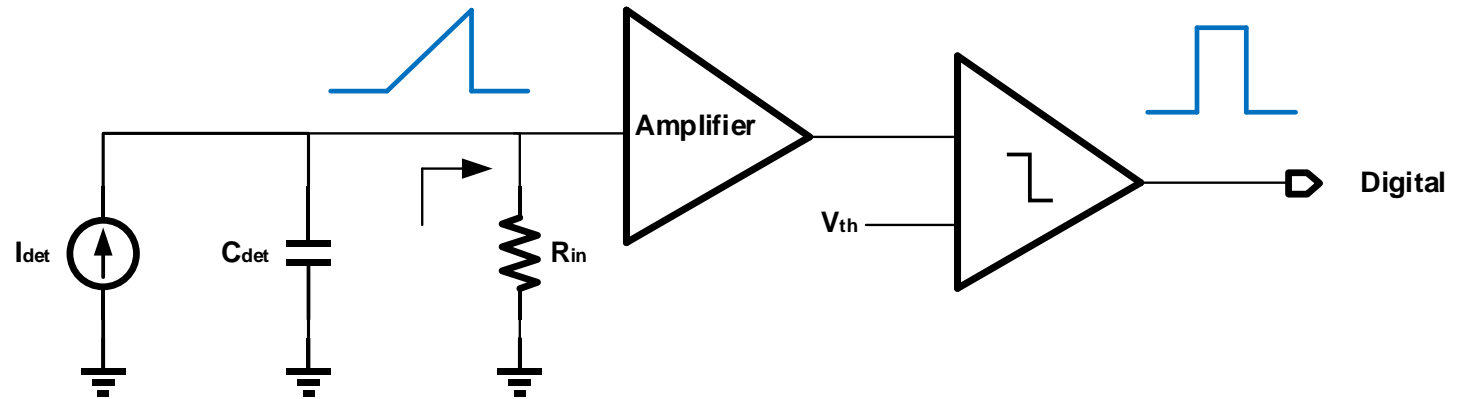


- *Exercise:* Estimate the pre-amplifier specifications:
 - a/ DC gain
 - b/ -3 dB bandwidth
- *Hint 1:* We always cover the worst case scenario when designing a read-out circuit.
- *Hint 2:* Assume a targeted rise time $t_{rise} = 30 \text{ ps}$ at the input of the comparator.

Homework 4: Design case study

$$\begin{aligned}Q_{in} &= 3000 \text{ e-} / 10000 \text{ e-} \\C_{det} &= 2 \text{ pF} \\t_{coll} &= 10 \text{ ps}\end{aligned}$$

- a/ DC gain



$$V_{in,min} = \frac{Q_{in,min}}{C_{det}} = 0.25 \text{ mV}$$

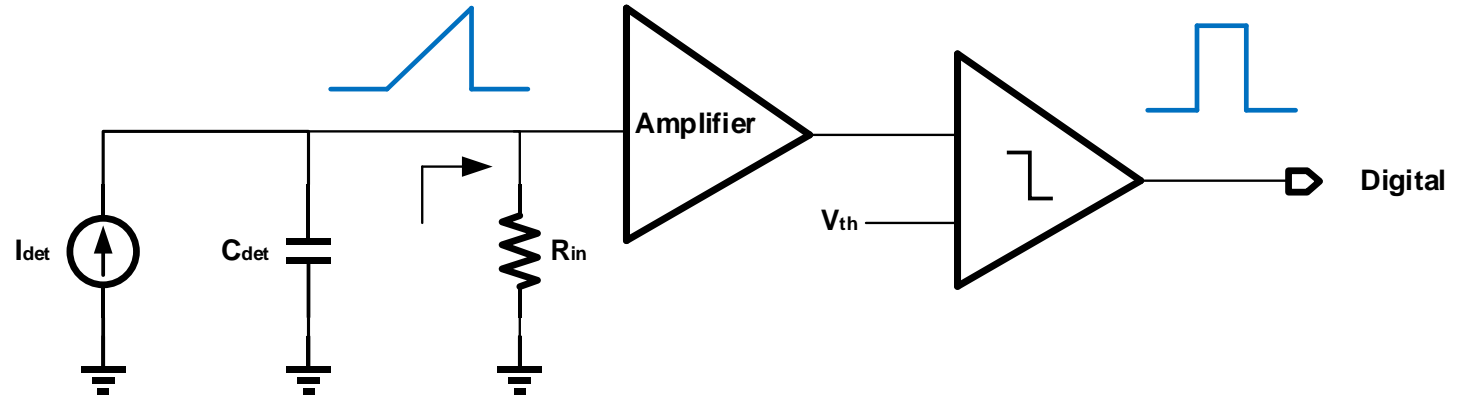
$$V_{out,min} = 1.5 \cdot V_{th,cmp}$$

$$A_{v,min} = \frac{V_{out,min}}{V_{in,min}} \approx 120$$

$$A_{v,min(dB)} = 20 \log(120) \approx 42 \text{ dB}$$

Homework 4: Design case study

$$\begin{aligned}Q_{in} &= 3000 \text{ e-} / 10000 \text{ e-} \\C_{det} &= 2 \text{ pF} \\t_{coll} &= 10 \text{ ps}\end{aligned}$$



- b/ -3 dB bandwidth

In case the collection time t_{coll} is smaller than the input RC constant, the rise time is higher than the collection time.

- The collected charges are integrated on the detector capacitance.

Homework 4: Design case study

$$\begin{aligned}Q_{in} &= 3000 \text{ e-} / 10000 \text{ e-} \\C_{det} &= 2 \text{ pF} \\t_{coll} &= 10 \text{ ps}\end{aligned}$$

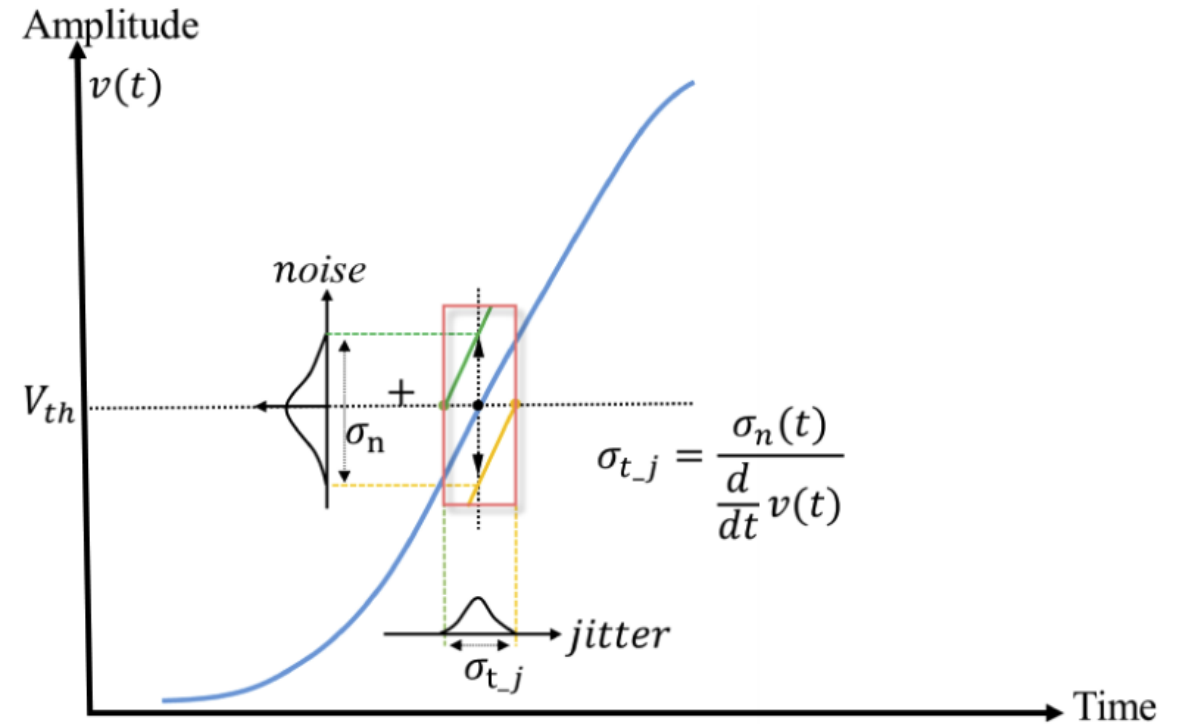
In order to make the comparator less sensitive to noise, the slope at its input should be as steep as possible (ideally $t_{rise} = t_{coll}$).


For our analysis:

$$t_{rise} = 30 \text{ ps}$$

$$f_{-3dB} \approx \frac{0.33}{t_{rise}}$$

$$f_{-3dB} \approx 11 \text{ GHz}$$



 J. Yang, G. Gu, W. Qian, K. Ren, D. Lu, J. Zhang, P. Guo, Q. Gao, M. Wan, and Q. Chen, "Pulsed light time-of-flight measurement based on a differential hysteresis timing discrimination method," Opt. Express 28, 23554-23568 (2020).