# Electronics for photodetectors

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# (follow up with LTSpice simulation )

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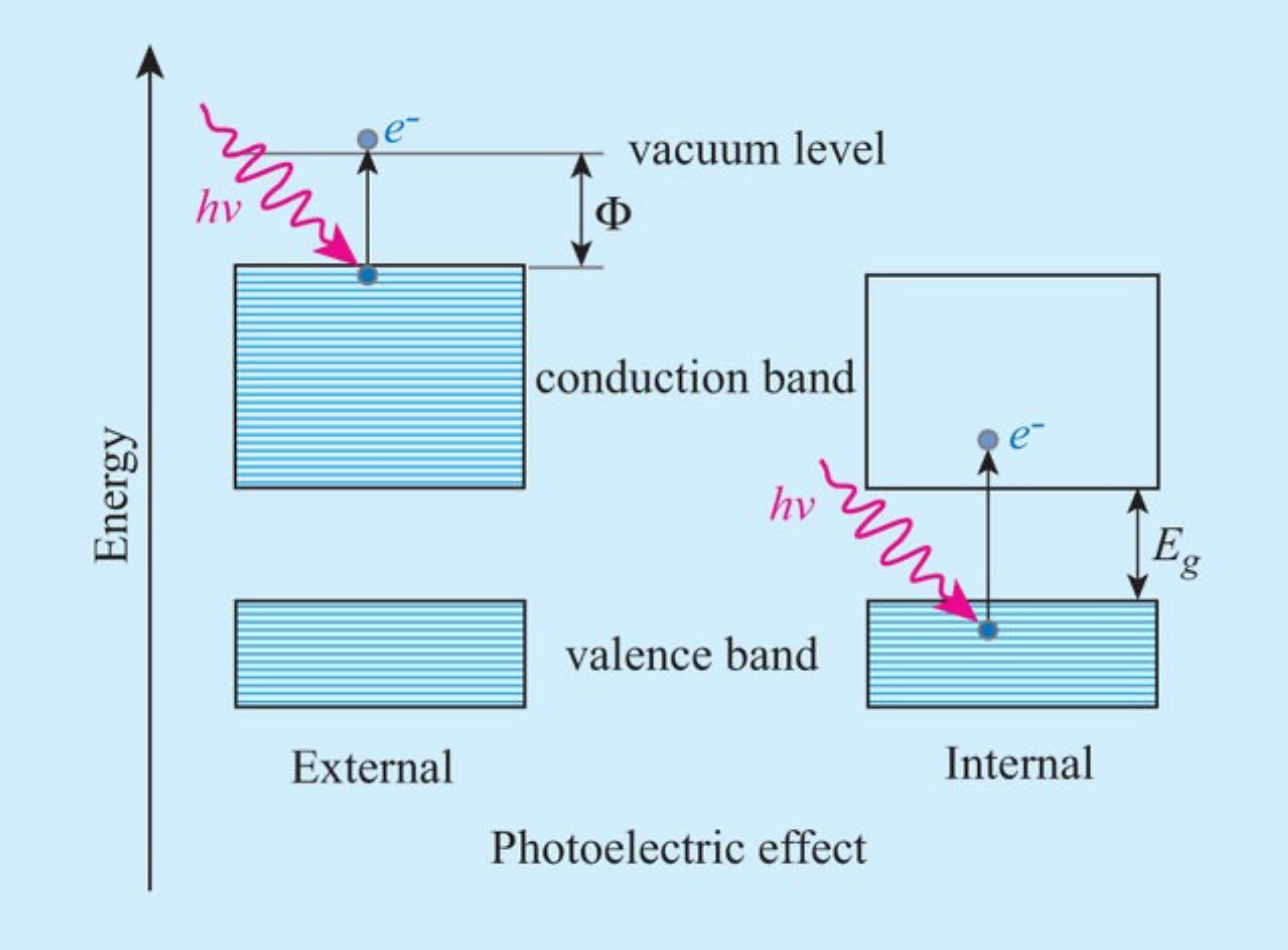
# General working principle: external/ internal photoelectric effect

"**External**":
photoelectron is ejected into free space (vacuum or air)




"**Internal**":
photoelectron is moved from valence band into the conduction band

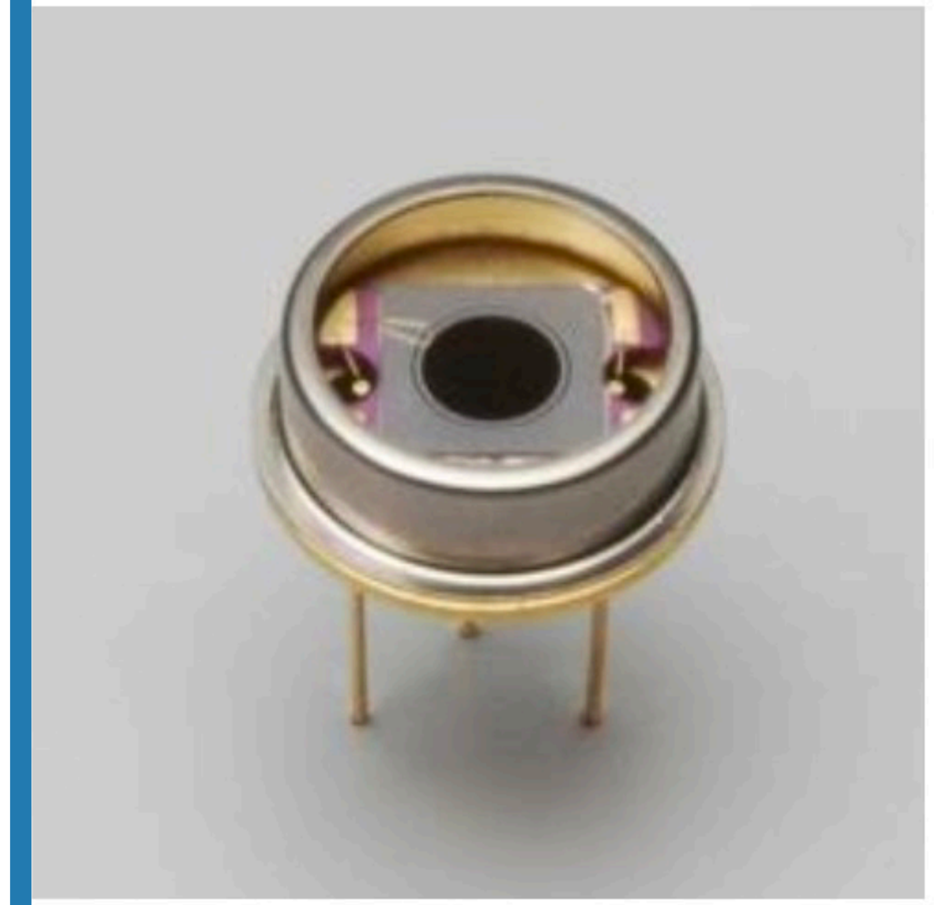
- Based on the **photoelectric effect**: **External** or **Internal**
- Need "*photosensitive*" materials (K, Na, Rb), which have high tendency to release electrons (or small *electronegativity*)
- Typically need to turn this *microscopic* "electron-emission" signal into the **macroscopic** level, eg. multiplication

# Different types of photodetectors

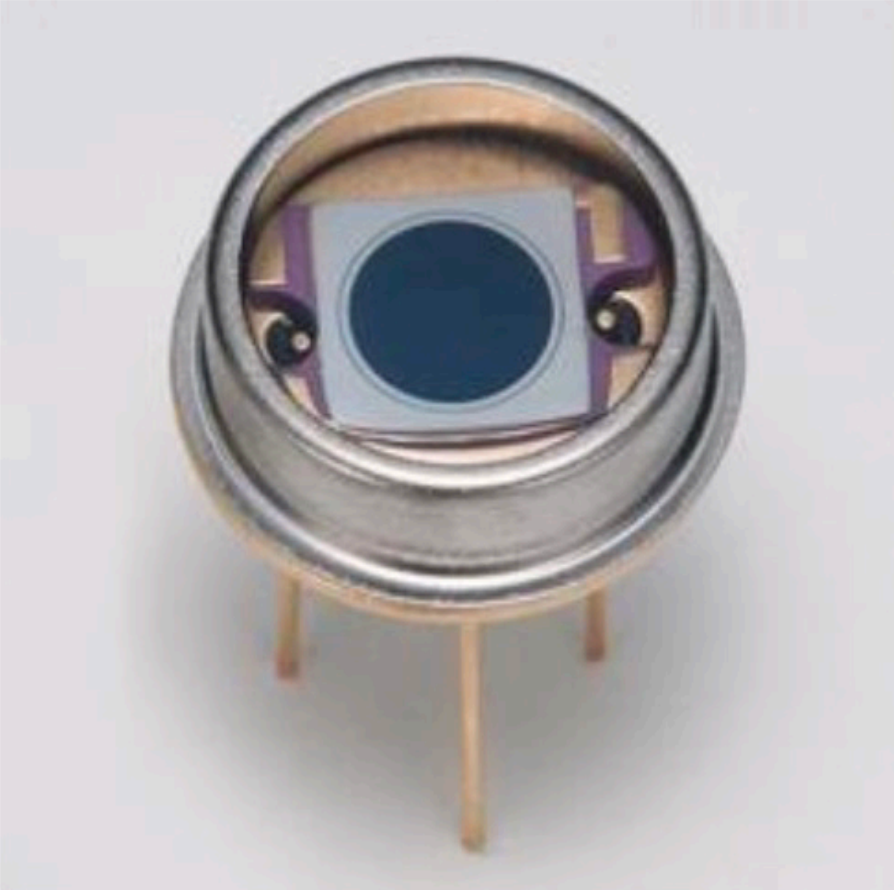
“EXTERNAL PHOTOELECTRIC ”

“INTERNAL PHOTOELECTRIC ”


PMT



PD



APD

SiPM

(Also called MPPC)

PMT – photomultiplier tube

APD – avalanche photodiode

PD – photodiode

SiPM – silicon photomultiplier

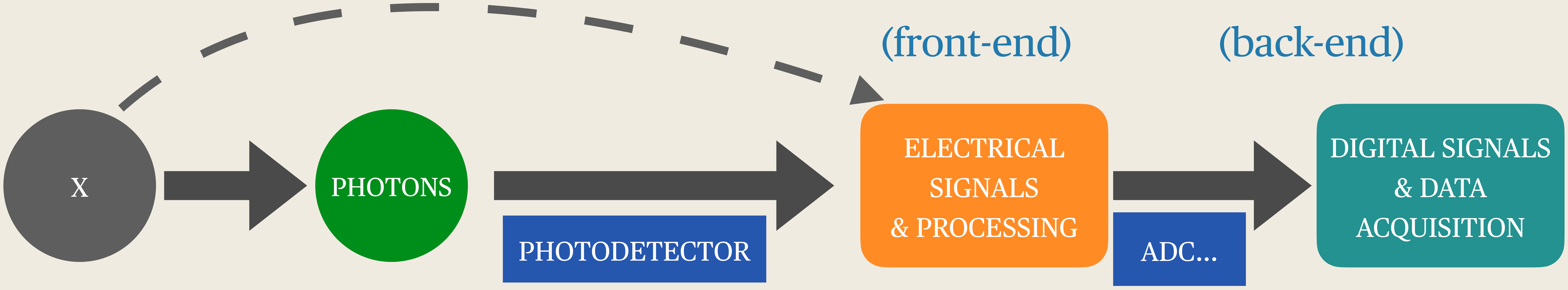
# Basic characteristics of photodetector

- **Spectral response:** *Range of wavelength can be detected *efficiently**
- ***Active* area:** *Part of detector is designed for producing photoelectron when light strikes on. PMT is typically larger than others*
- **Quantum efficiency (QE) and Photon detection efficiency (PDE)**:
  - QE: *probability for single photon coming into a "active" region and a photoelectron ejected.*

    $$QE = \frac{N_{p.e.}}{N_\gamma} \times 100\ \%$$

  - *PDE is probability for detectable output signal be generated by an incoming photon, normally smaller than QE, eg.* $PDE = QE \times R_{filling} \times P_{avalanche}$
- **Dark current:** *detectable output even in the completely dark (no light source )*
- **Intrinsic gain:** *No. of equivalent electron in the ouput given an incoming photon, PMT and SiPM are in order of* $10^6$
- **Dynamic range:** *ratio between the maximum and minimum detectable light intensities (with reasonably precise or good linearity)*
- **Response time:** *characterize how quickly it reacts to a strike of light (maybe confused from quantum point of view) and converts them into the electric signal.*
- ...

# Photodetector for the radiation detection




- We have analog signal continuously streaming from photodetectors, then what to do next?
  - Do we want to RECORD it? Or just IGNORE it (eg. Because it's likely to be noise and is not interested at all) : **Triggering or signal conditioning**
  - What's kind of **INFORMATION of INTEREST** to be KEPT for further analysis?

# A bird view of triggering

Basic question: Do we know when the event/signal can happen?

- **Known timing**: eg. pulsing LED with synchronized function generator or neutrino from accelerator. Should keep electronic “open” for recording, otherwise event will be missed.
- **Unknown timing**: eg. Cosmic ray, radioactive decay…

2nd: How to decide to keep recording of signals?

- *Common*: Over some threshold. Expect signal has larger amplitude than background
- Some: keep record everything in a small fixed time then apply **software filtering** latter

3rd: If decided to record, then for how long? Few ns, us …

# Information of interest

Basically, we have three key information:

- **Counting or rate of events**
- **Signal time (*or peak time*)**
- **Signal amplitude (*pulse height  or charge* )**

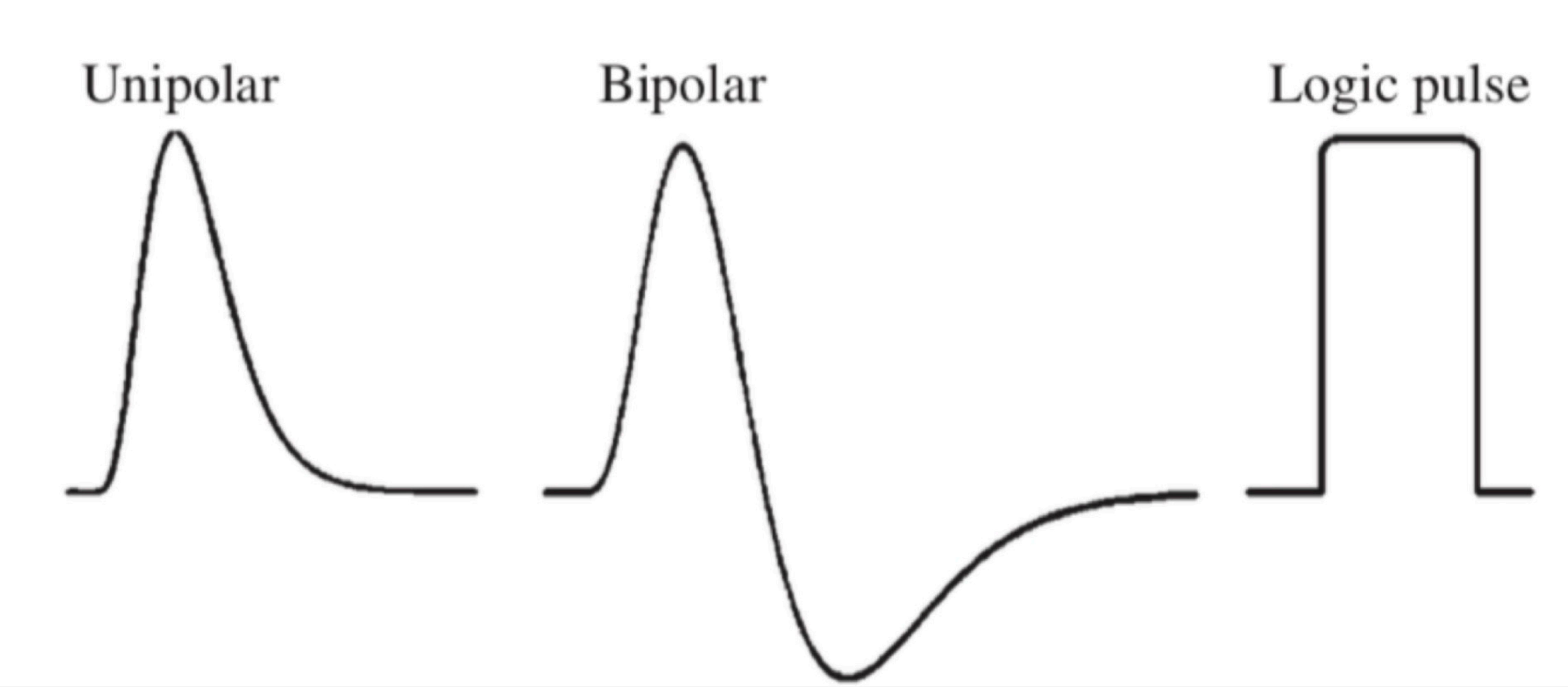
Why not everything?: Just too much to handle or costly sometimes…

**Information of interest to keep recording depend on the application**

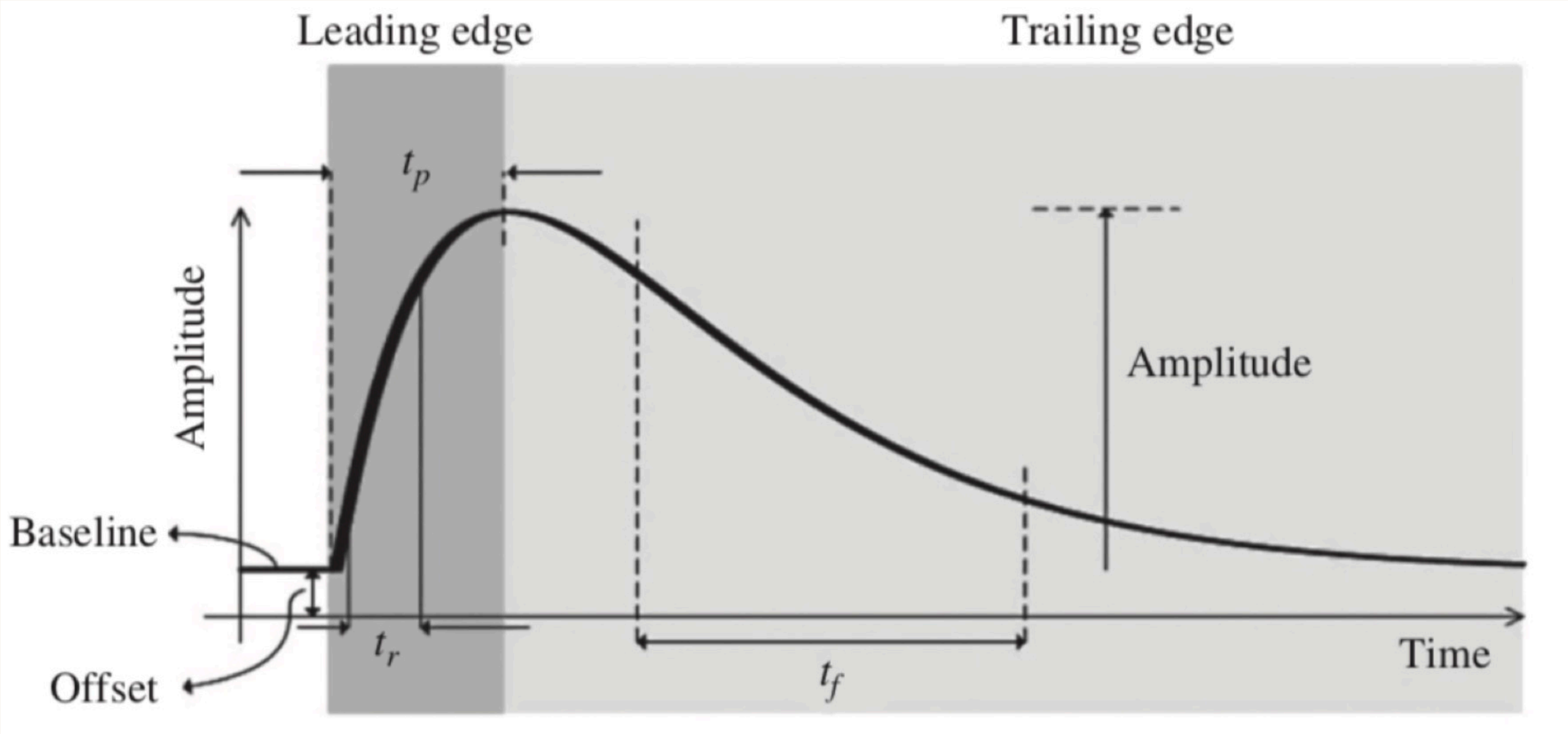
- Radiation monitor/survey: counting is sufficient
- LiDAR: Precise (few 100ps) signal time is vital
- Neutrino research: Both timing (*eg. when supernova happen…*) and signal amplitude (*eg. For reconstruct the neutrino energy for physics measurement*)
- …

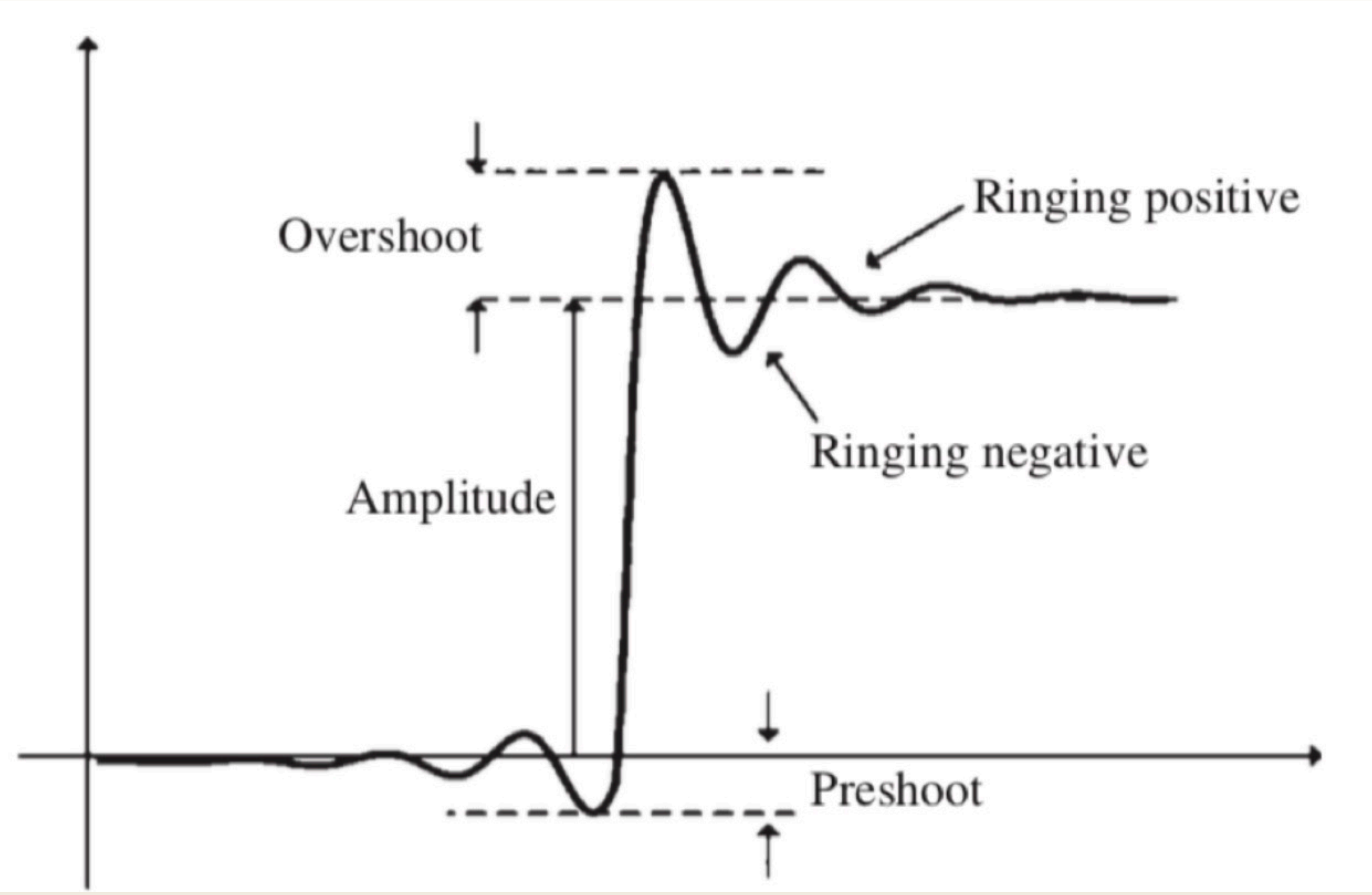
Ref: Super-Kamiokande triggering - Guillaume Pronost

# Pulse signal terminology




- Three types of pulse: Unipolar (positive or negative),  Bipolar, and Logic pulse

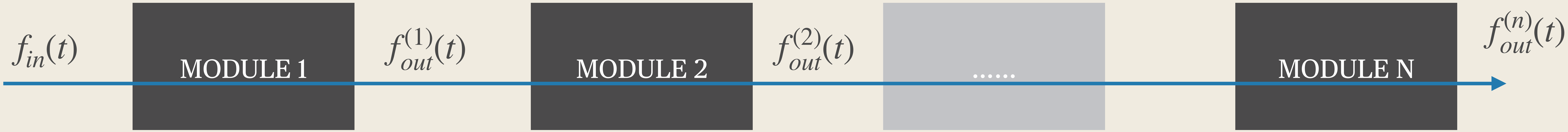



- Basically two dimensions of information: Amplitude and time.
  - **Amplitude**-related info: Peak or pulse height; baseline offset
  - **Time**-related info: Rising time, Falling time, peak position, pulse width
- Also **shape**-related info: Preshoot, Overshoot, ringing...

# Signal processing

Typically presented as a series of signal processing modules, each of which have different functionality



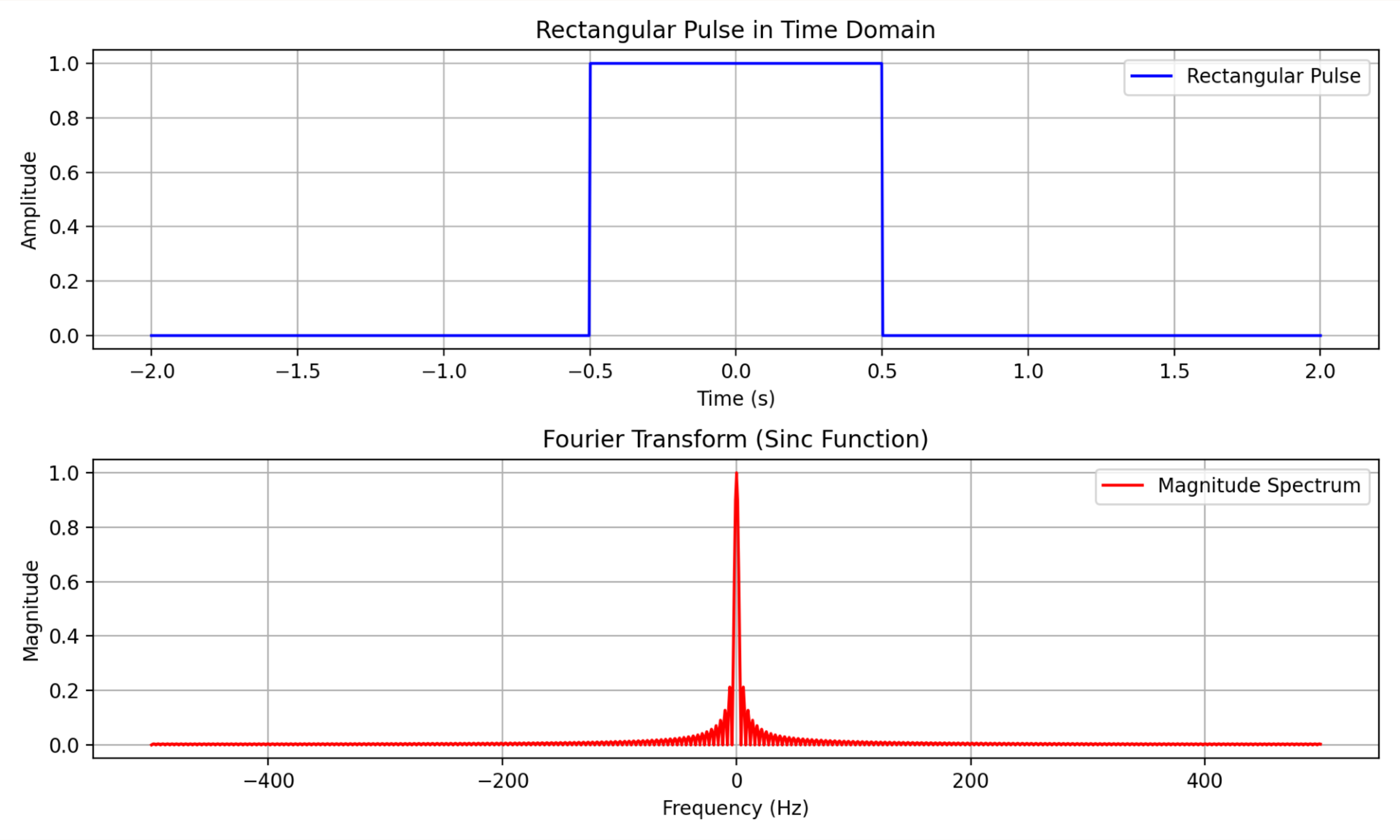

- Signal pulse shape is generally changed/distorted after passing each electronic modules
- Each electronic modules induces additional noise

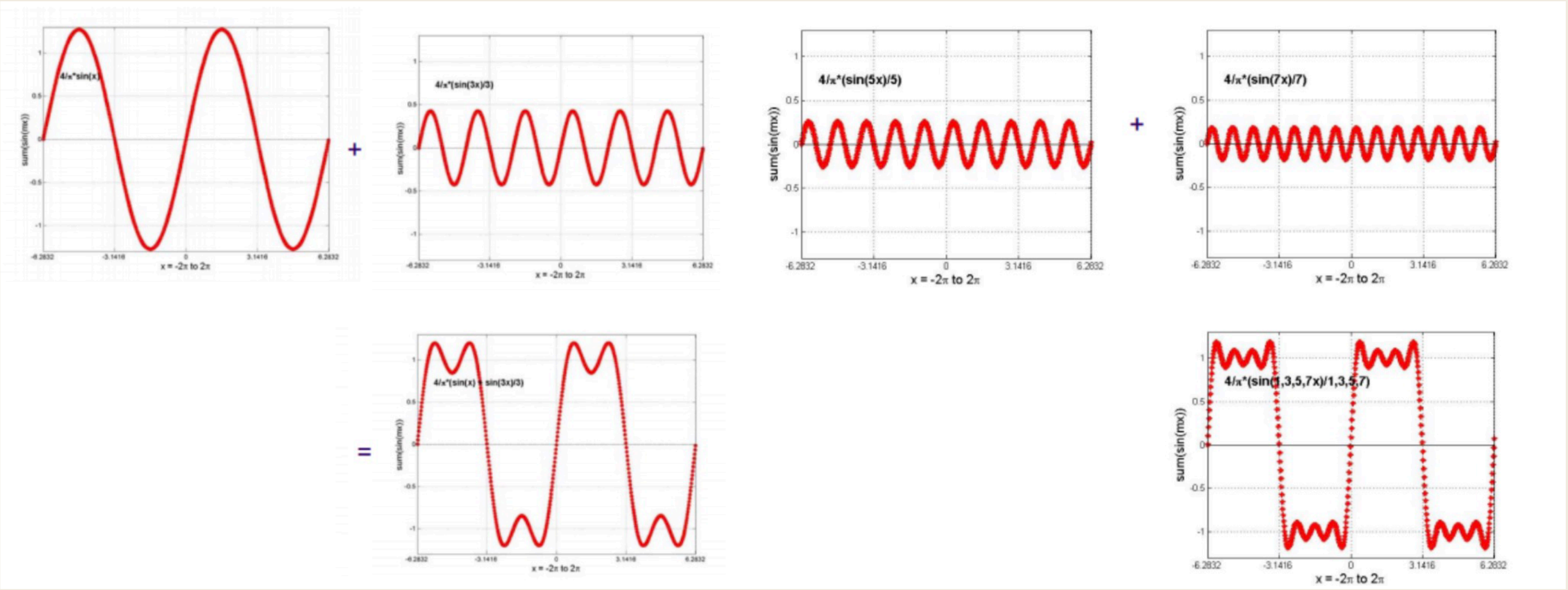
# Fourier transform: Time vs. Frequency Domain

Normally we picture the pulse as function of time but a more complete understanding of pulse change/distorted is using frequency representation

Mathematical background: Pulse form is superimposed of infinite sinusoidal components

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}F(\omega)e^{i\omega t}d\omega \rightarrow F(\omega)=\int_{-\infty}^{\infty}f(t)e^{-i\omega t}dt$$



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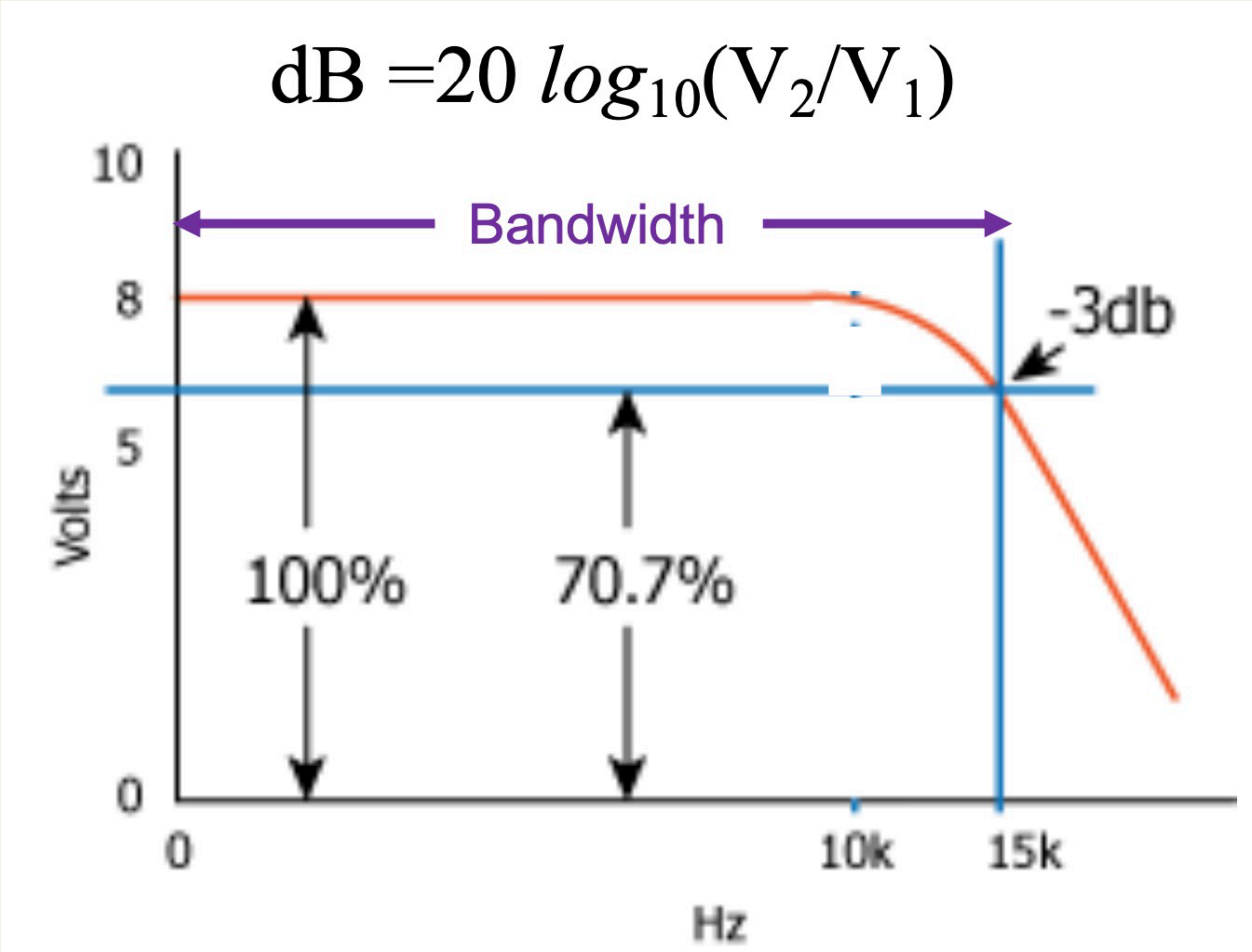
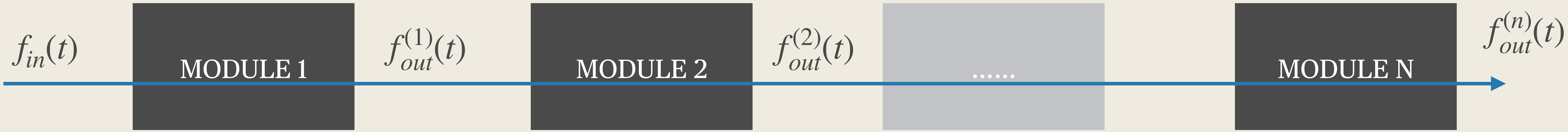
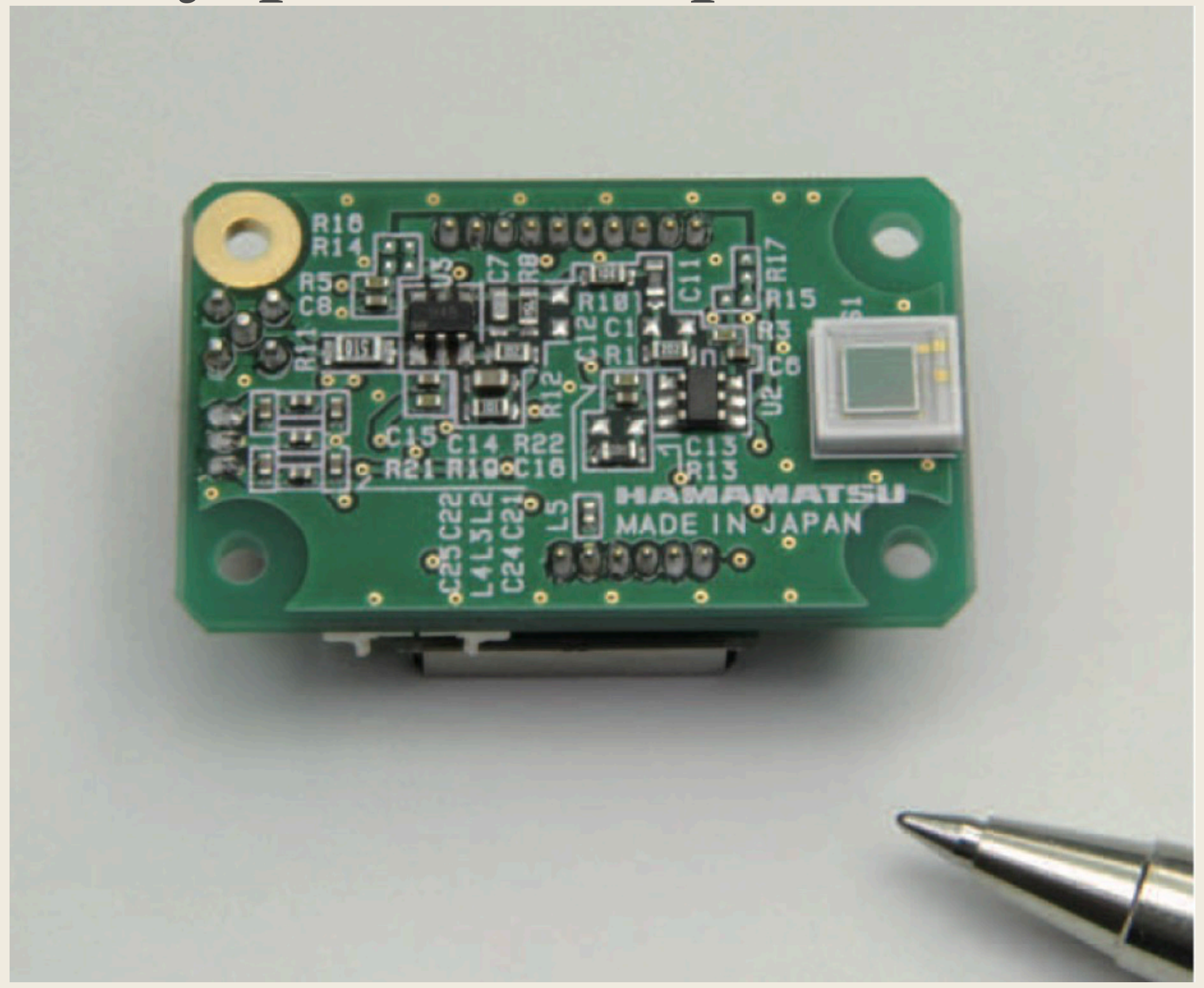


# Bandwidth limit for electronic components




Ideally, perfect response to all frequencies are desired but in any real electronic modules, bandwidth are limited



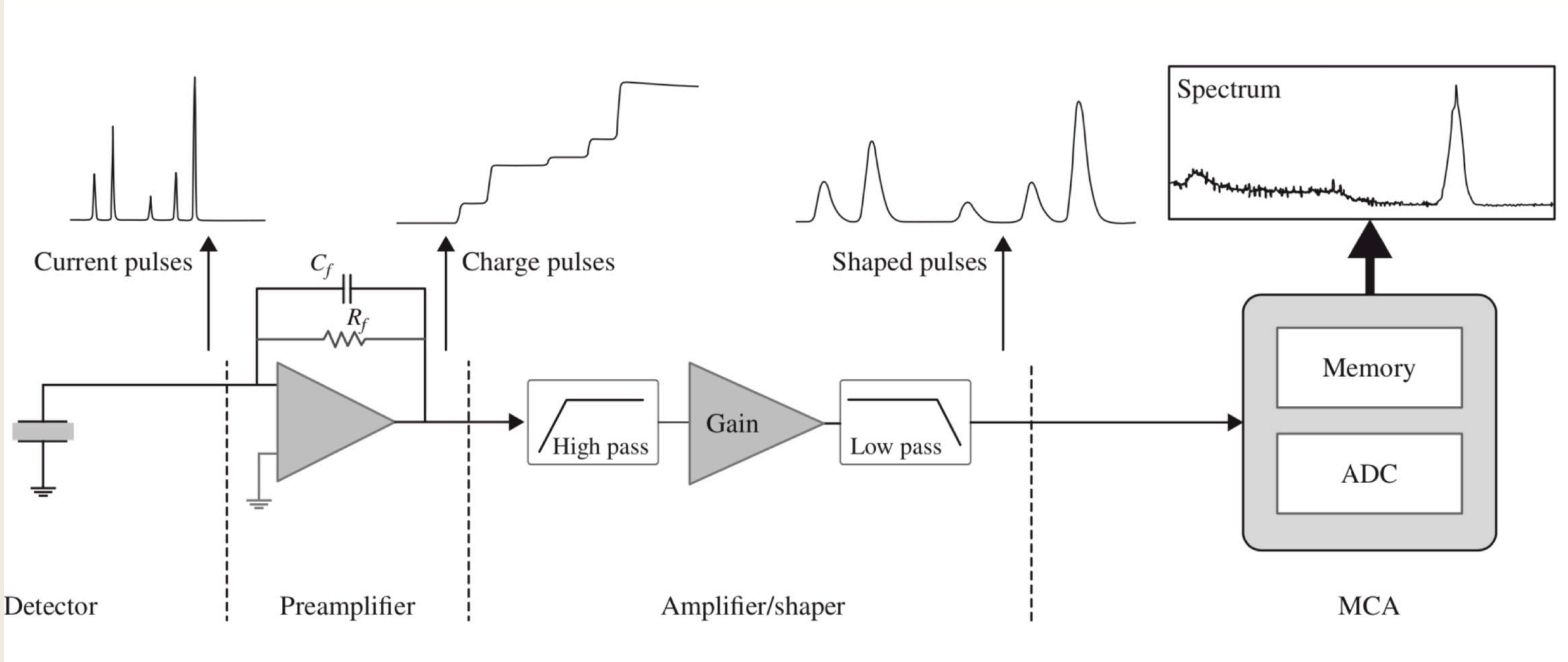

**Electrical and optical characteristics (Typ. Ta=25 °C, λ=λp, Vs=±5 V, unless otherwise noted)**

| Parameter | Symbol | Condition | C13365-1350SA Min. | C13365-1350SA Typ. | C13365-1350SA Max. | C13365-3050SA Min. | C13365-3050SA Typ. | C13365-3050SA Max. | Unit |
|---|---|---|---|---|---|---|---|---|---|
| Spectral response range | λ | | 270 to 900 | | | 270 to 900 | | | nm |
| Peak sensitivity wavelength | λp | | - | 500 | - | - | 500 | - | nm |
| Temperature stability of output voltage | - | Ta=25 ± 10 °C | - | - | ±5 | - | - | ±5 | % |
| Photoelectric sensitivity | - | | $0.7 \times 10^9$ | $1.0 \times 10^9$ | $1.3 \times 10^9$ | $0.7 \times 10^9$ | $1.0 \times 10^9$ | $1.3 \times 10^9$ | V/W |
| Cutoff frequency — High band | fc | -3 dB, sine wave | 3.5 | 5 | - | 3.5 | 5 | - | MHz |
| Cutoff frequency — Low band | fc | -3 dB, sine wave | DC | | | DC | | | - |
| Rise time | tr | 10% to 90%, 1 p.e. | - | 5 | - | - | 9 | - | ns |
| Noise equivalent power | NEP | Dark state | - | 0.5 | 1.0 | - | 1.2 | 2.0 | $fW/Hz^{1/2}$ |
| Minimum detection limit | - | Dark state | - | 1 | 2 | - | 2.7 | 4.5 | pW rms |
| Maximum output voltage | - | | - | 4.7 | - | - | 4.7 | - | V |

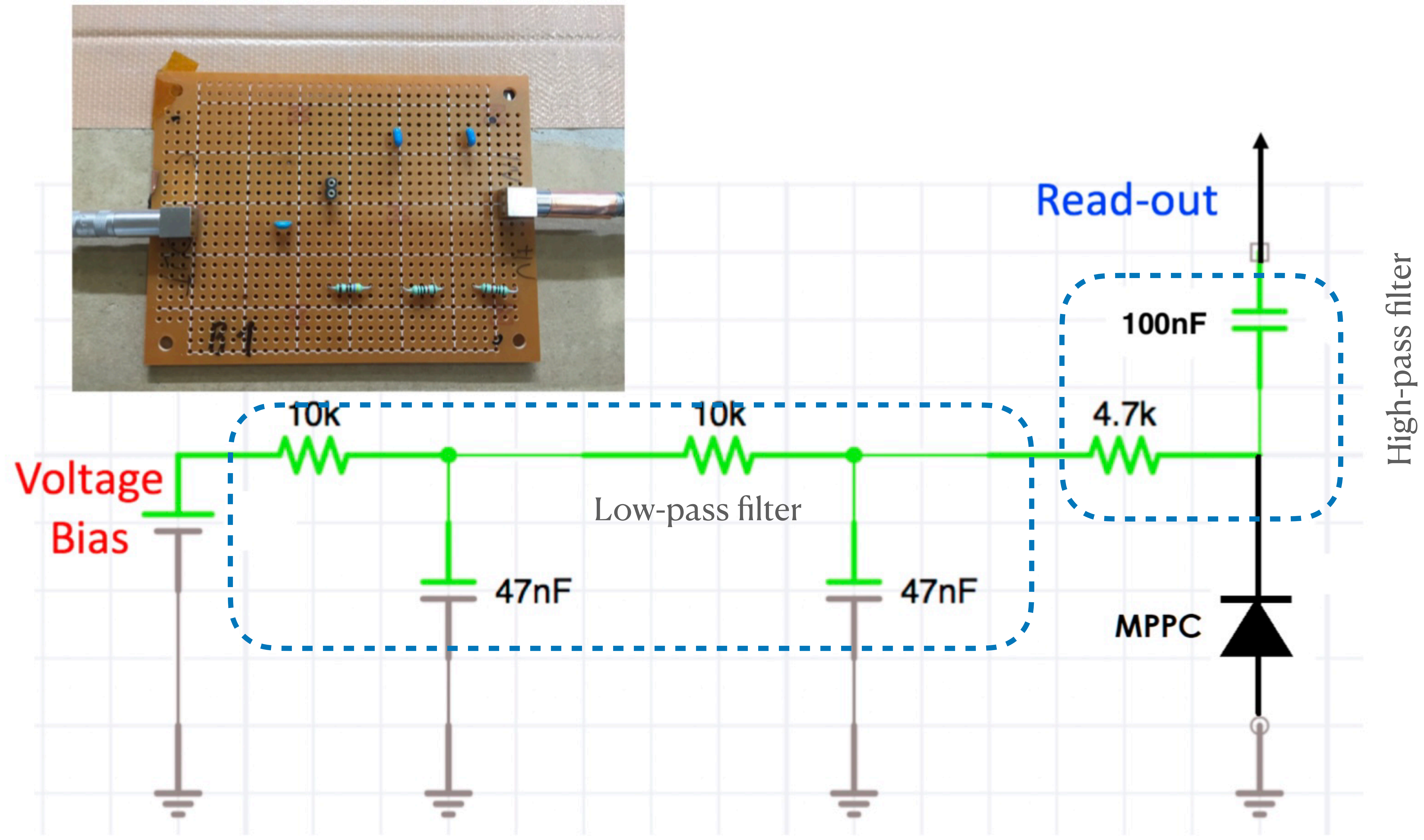
The C13365 series are optical measurement modules capable of detecting low level light. These modules consist of an MPPC, a signal amplifier circuit, a high-voltage power supply circuit, and a temperature compensation circuit. The photosensitive area is available in two sizes of 1.3 × 1.3 mm and 3 × 3 mm, and the signal output is analog. Modules operate just by connecting them to an external power supply (±5 V).

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/c13365_series_kacc1227e.pdf

# Example of electronic components for energy spectroscopy

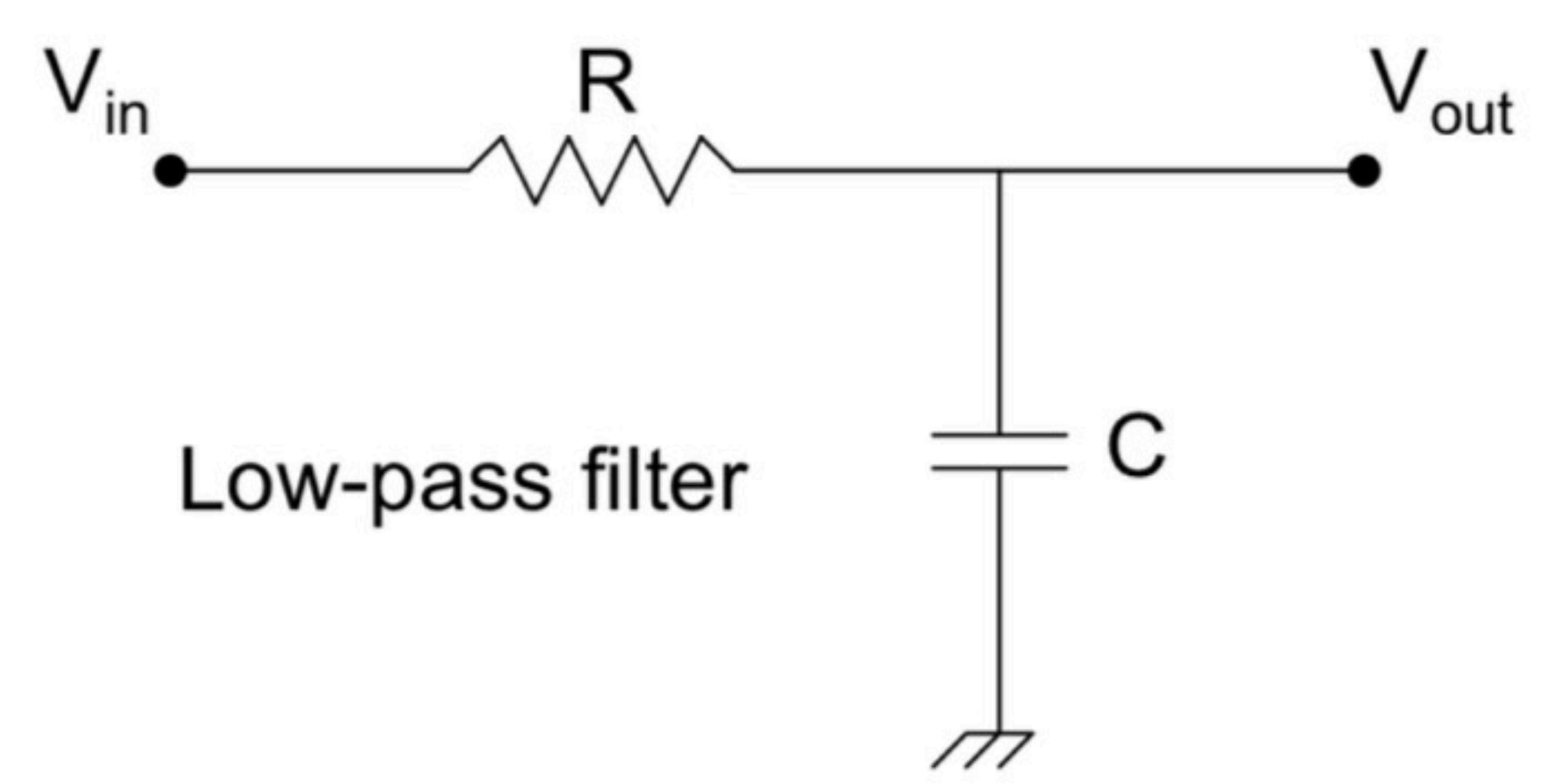


# Low-pass filter and high-pass filter



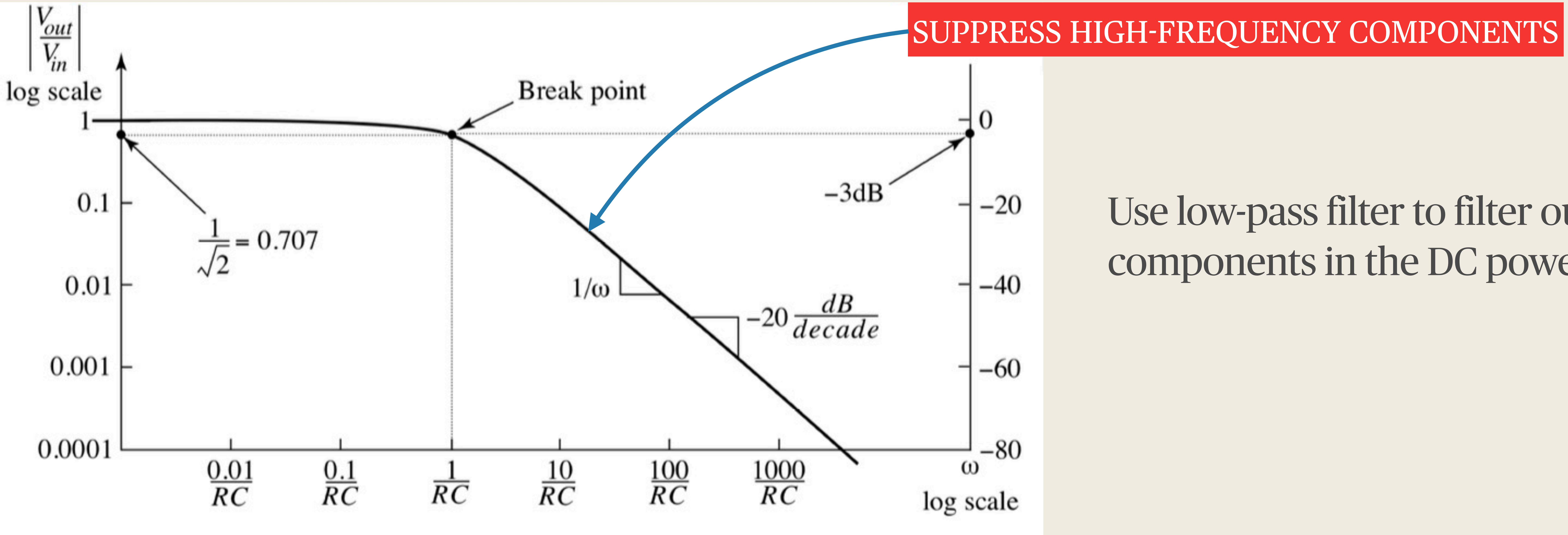

A MPPC readout circuit used practically for the characteristic measurements

# Low-pass filter or integrating circuit



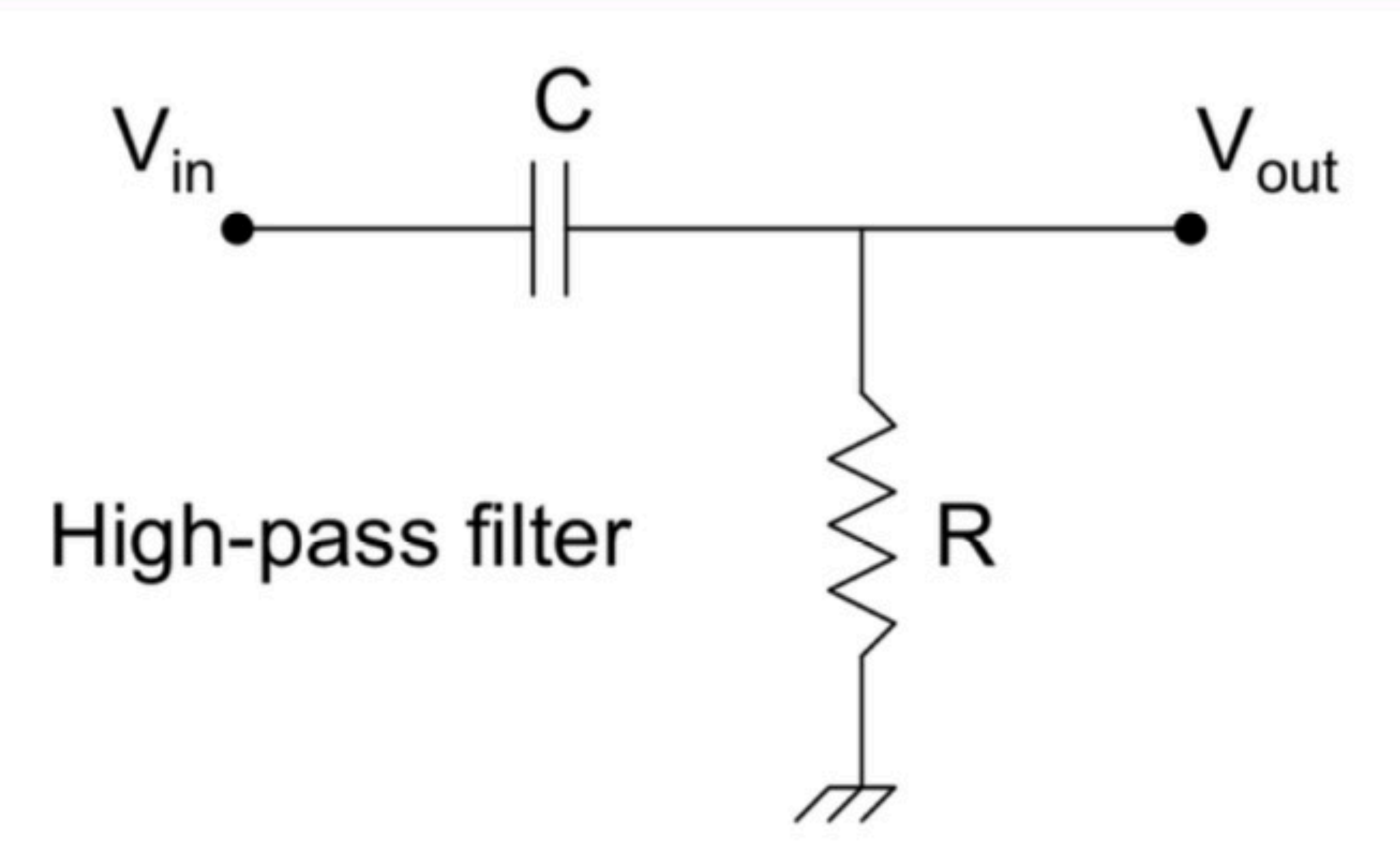

$$\frac{V_{out}}{V_{in}} = \frac{1/j\omega C}{R + 1/j\omega C} = \frac{1}{1 + j\omega RC}$$

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$




Use low-pass filter to filter out the AC components in the DC power supply

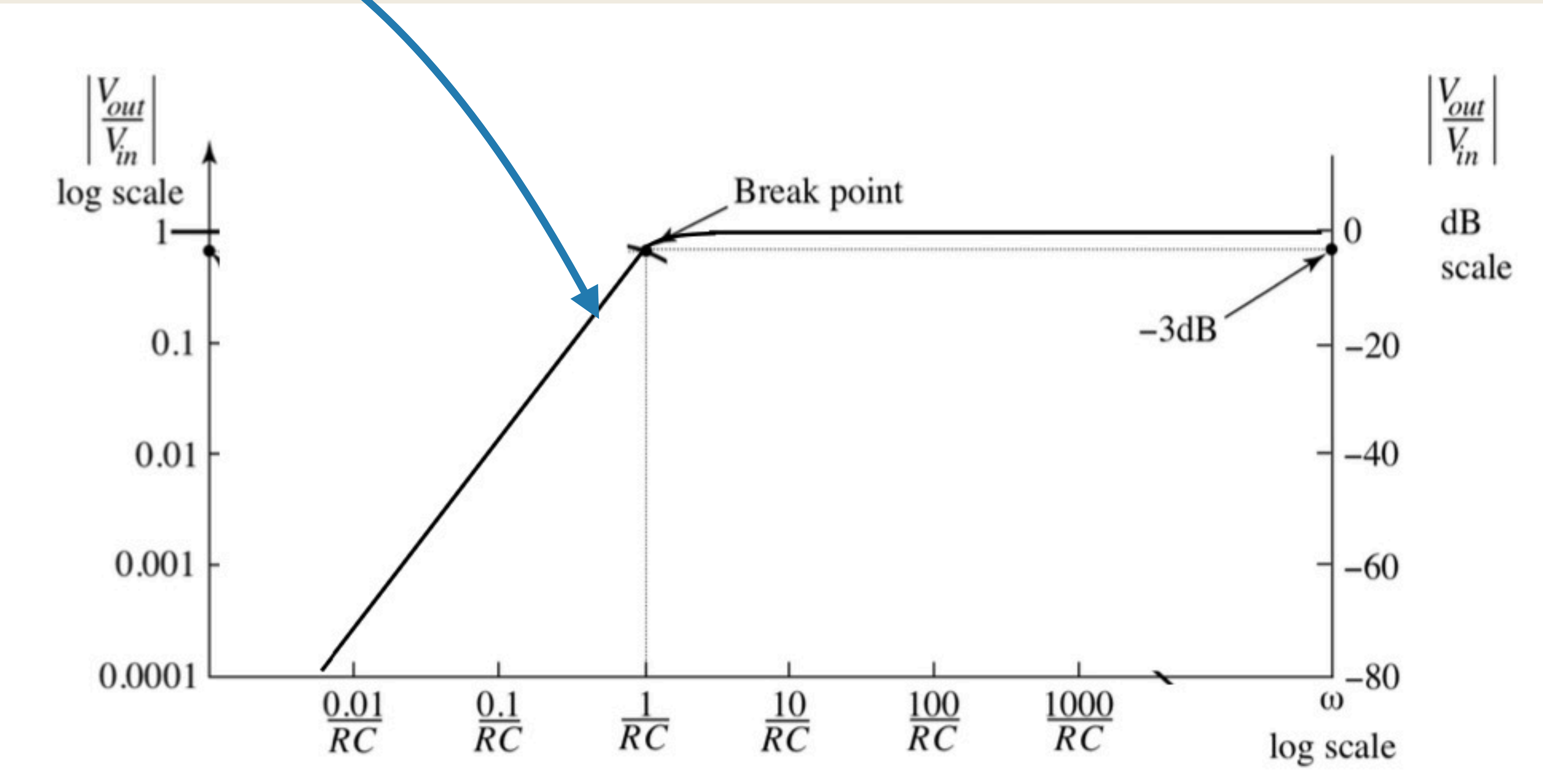
# High-pass filter or differentiating circuit



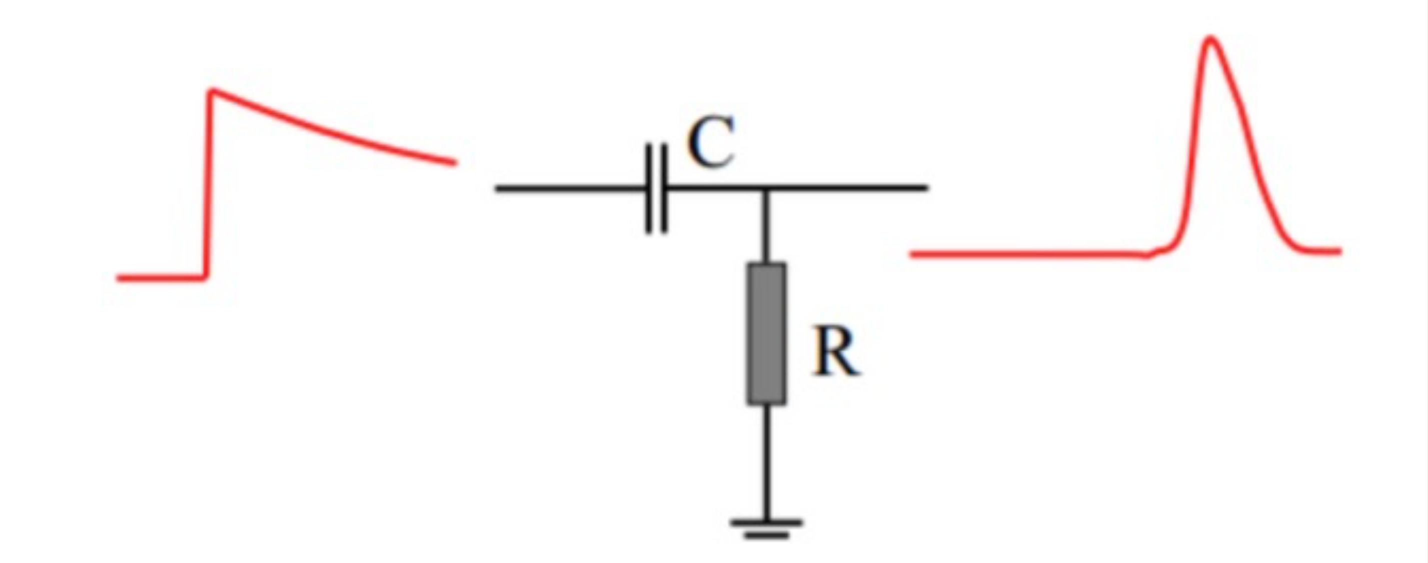

$$\frac{V_{out}}{V_{in}} = \frac{R}{R + 1/j\omega C}$$

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}}$$

SUPPRESS LOW-FREQUENCY COMPONENTS



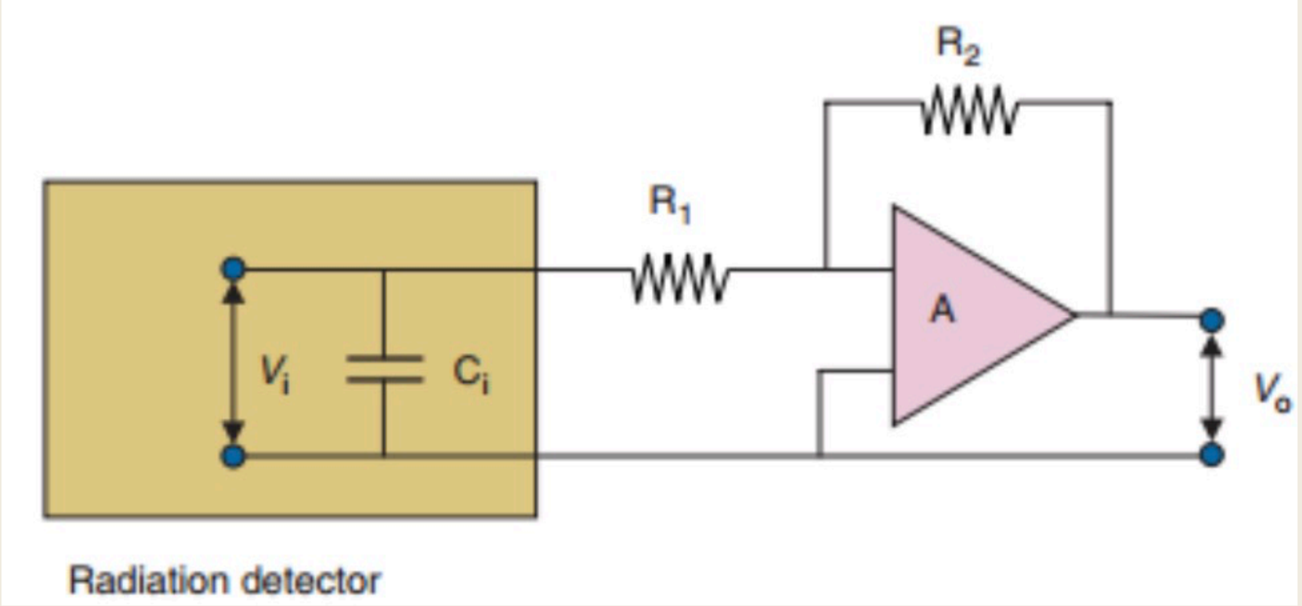

Eg. Shorten the trailing edge



# Pre-amplifier

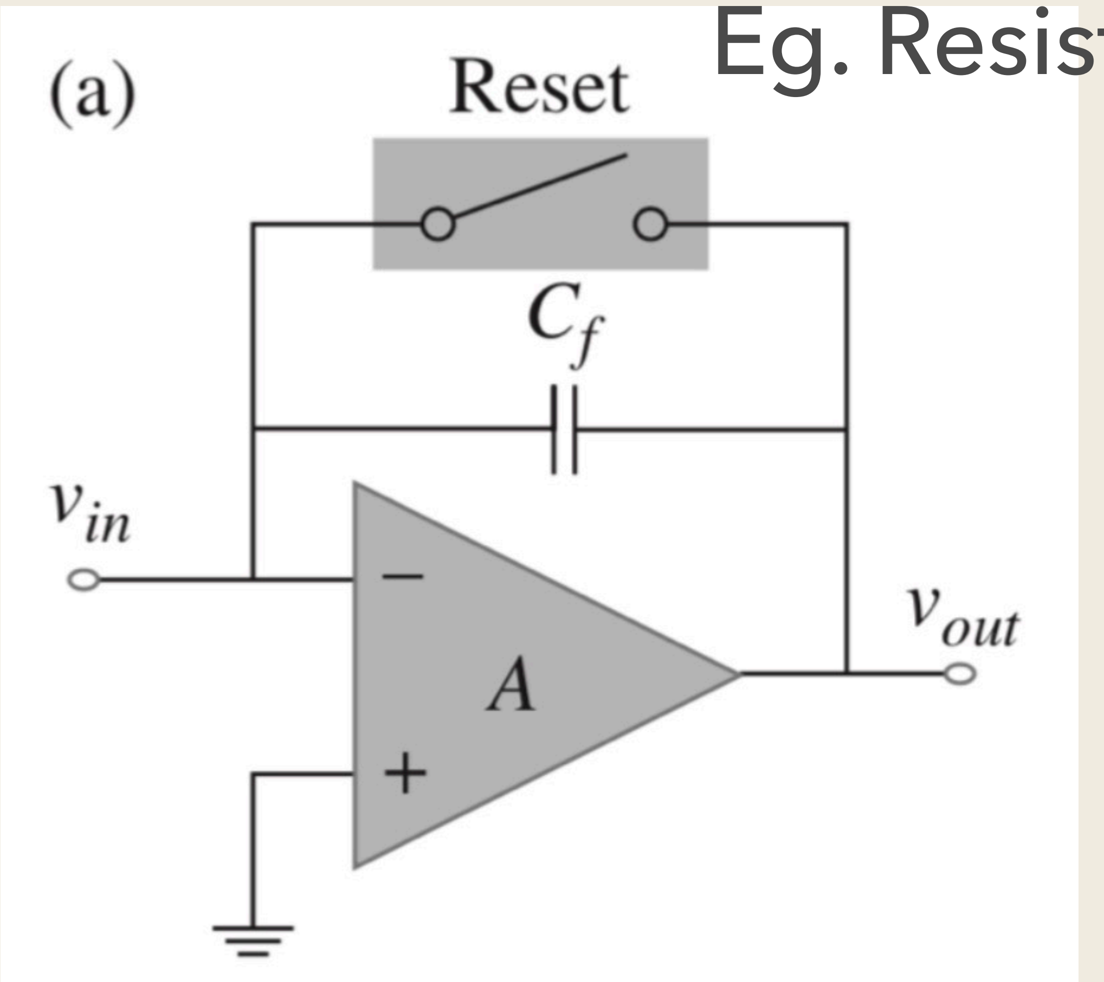
***Amplify what?***

- **Current-sensitive:** simple version is what we do during this hardware camp, just connected with 50Ohm-attached coaxial cable $V_{out}[V] = 50 \cdot I_{in}[A]$
- **Voltage-sensitive:** Signal depends on the detector's capacitance




$$V_{out} = -\frac{R_2}{R_1} V_{in} = -\frac{R_2}{R_1} \frac{Q}{C_{in}}$$

- **Charge-sensitive**




Eg. Resistor for discharge

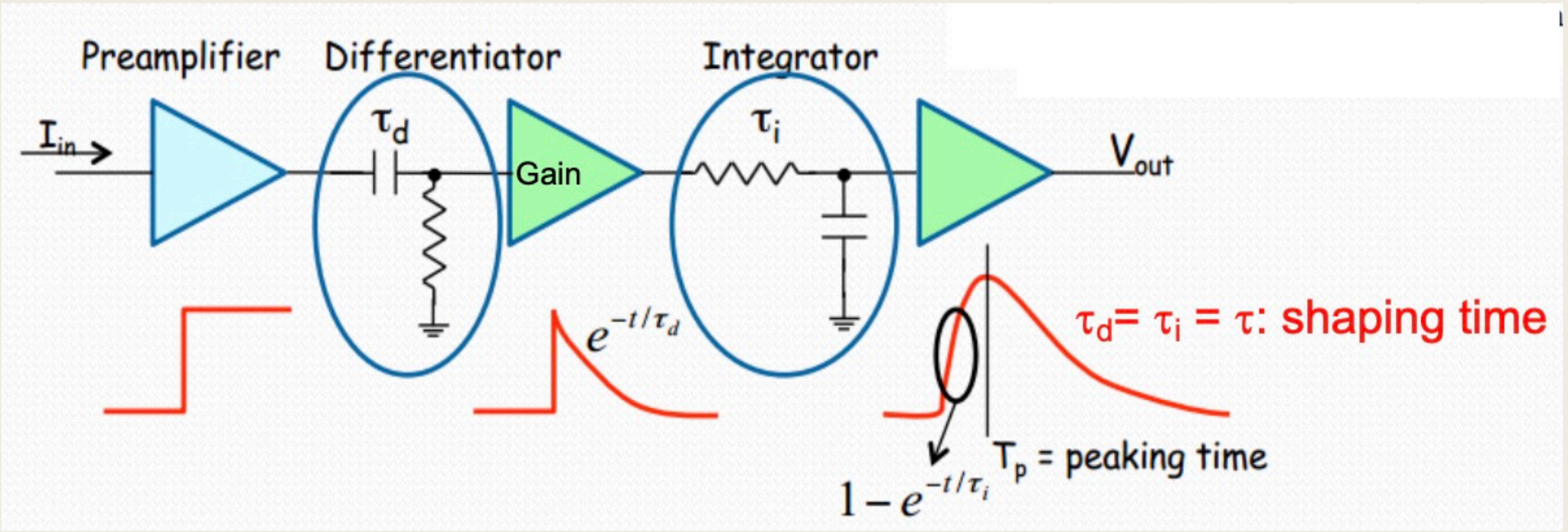
$$V_{out} \approx \frac{Q}{C_f}$$

# Main amplifier (or shaping amplifier or shaper )

Amplify for what?

- **Scale up but keep the relative height of the pulse signal**
- **Improve signal-to-noise ratio**
- **Reduce the pileup effect**

**Side impact: Increase the rising time.**

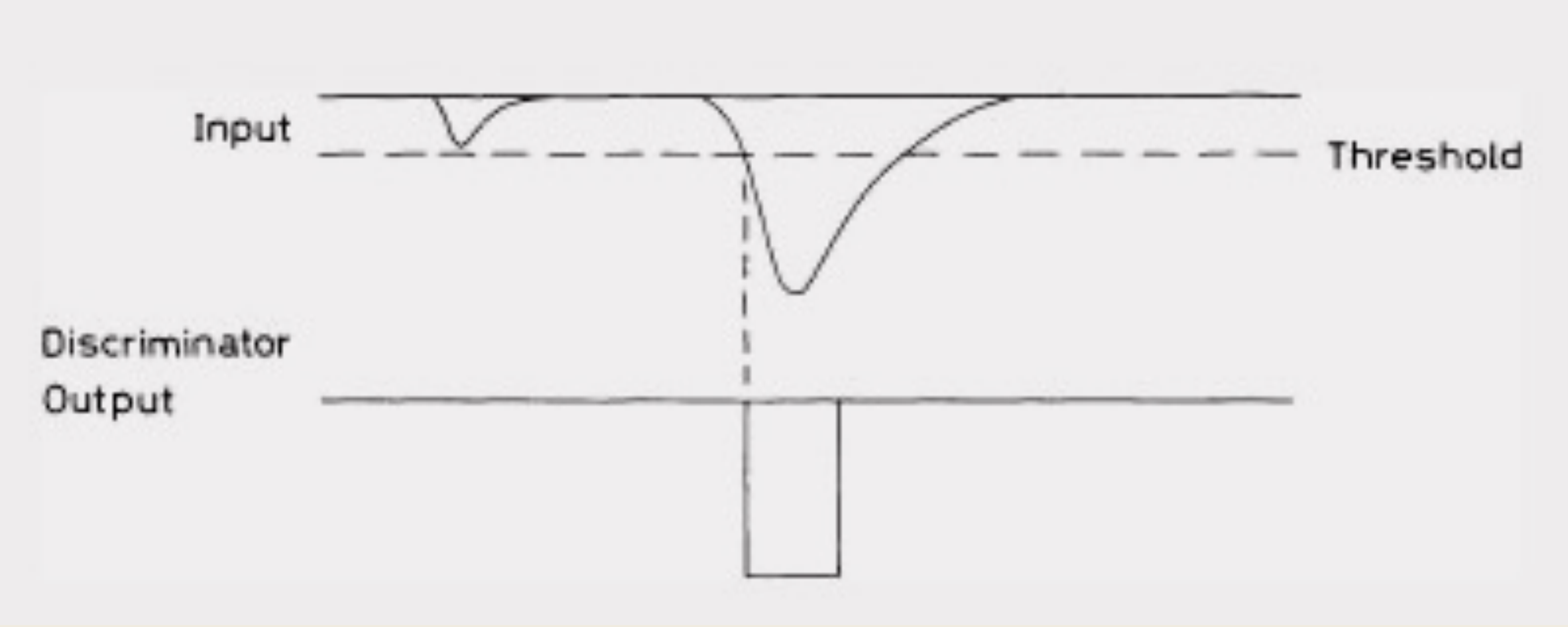



SIMPLE SHAPER CR-RC

# Discriminator

Purpose: to tell “yes” by issuing a logical pulse to incoming signal which satisfies the “discriminated” condition

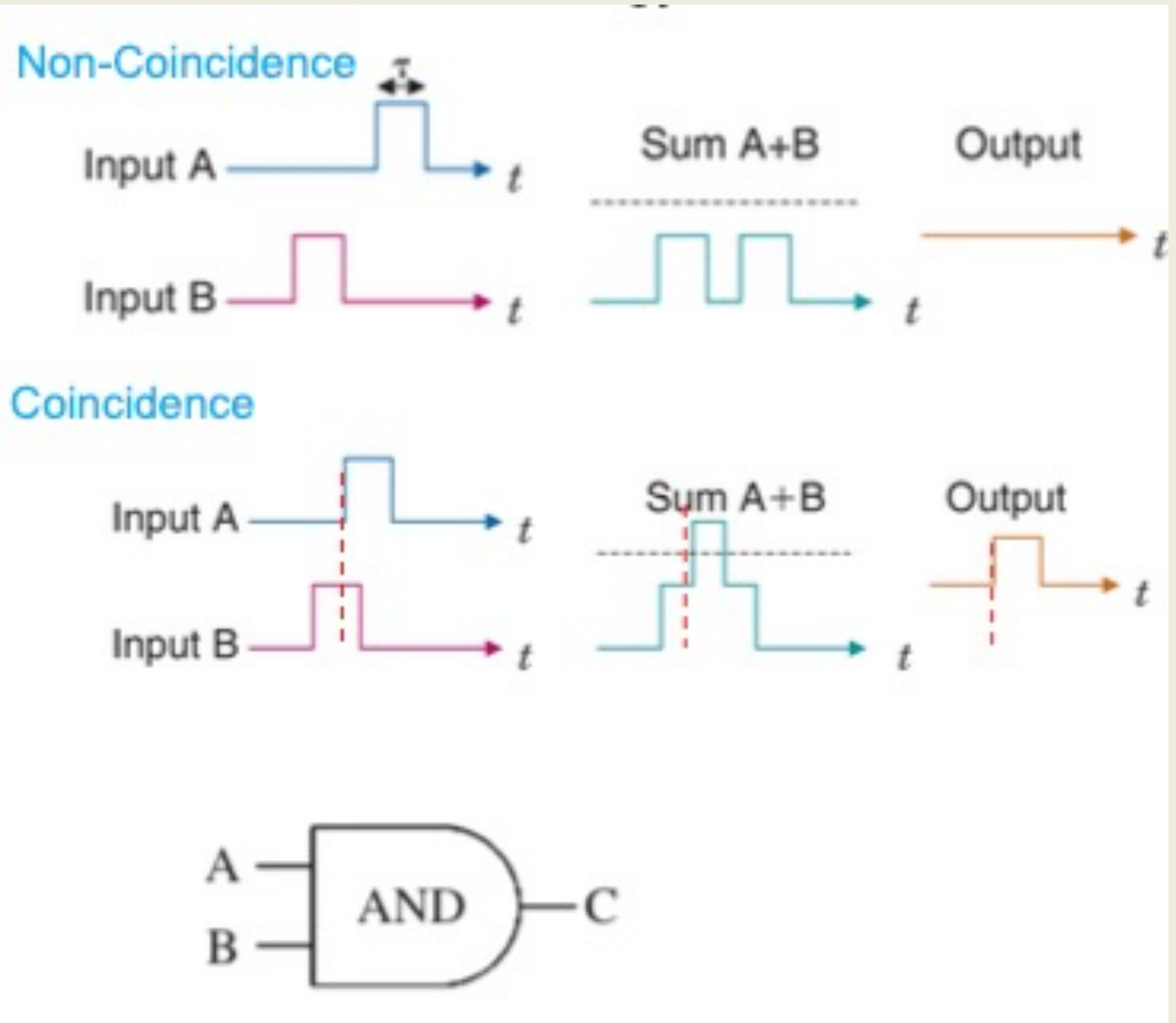
- It’s kind of simple analog-to-digital converter
- Key is method of triggering, eg. edge triggering; slope...(Ref. Your digital oscilloscope provides various options for triggering )
- The output is typically used for counting and conditional triggering



# Coincidence Unit

It's very powerful tool for finding the signal among the sea of the noise

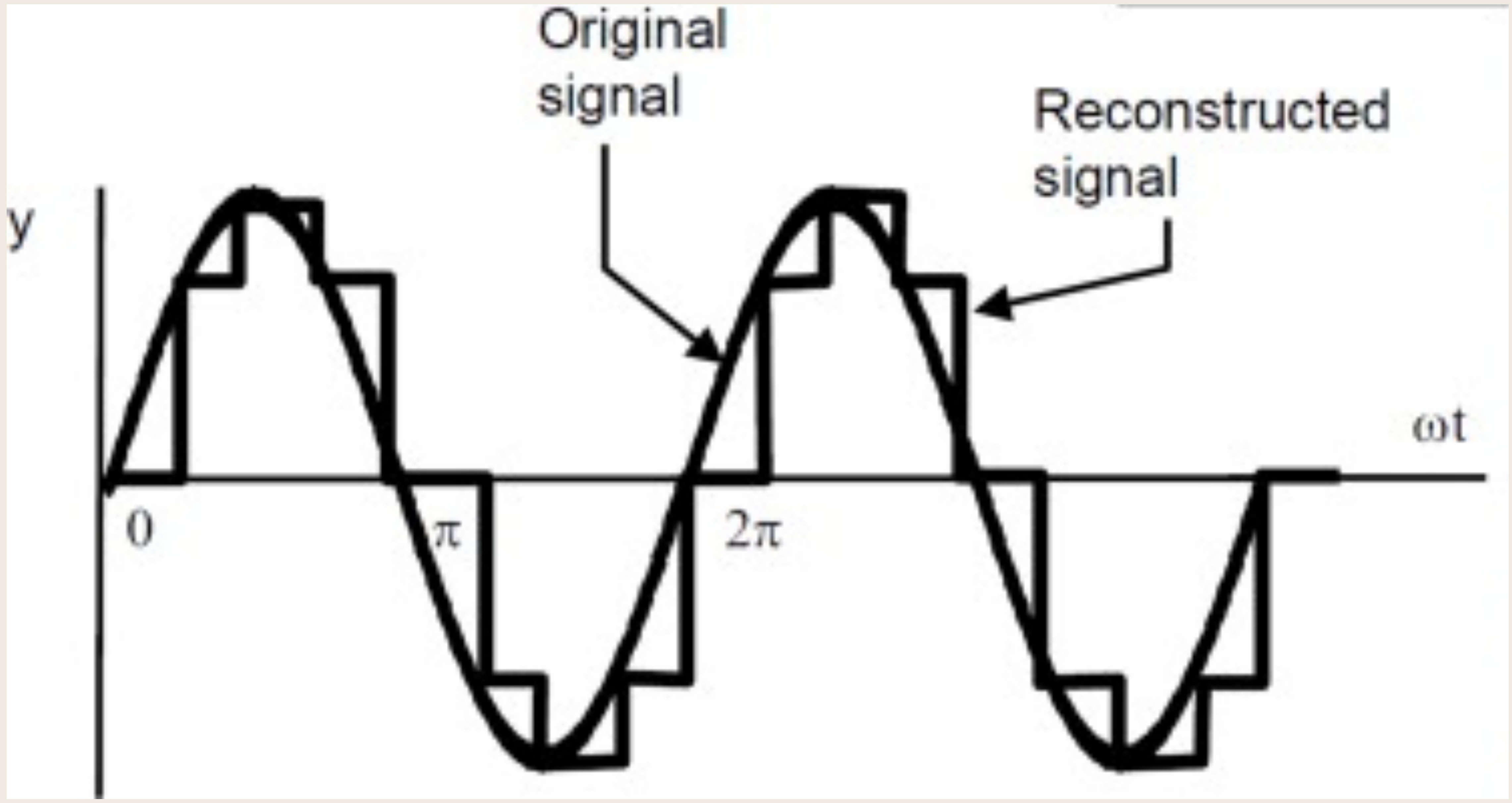
**Walther Bothe** shared the Nobel Prize for Physics in 1954 "for his discovery of the method of coincidence and the discoveries subsequently made by it".
**Bruno Rossi** invented the electronic coincidence circuit for implementing the coincidence method.

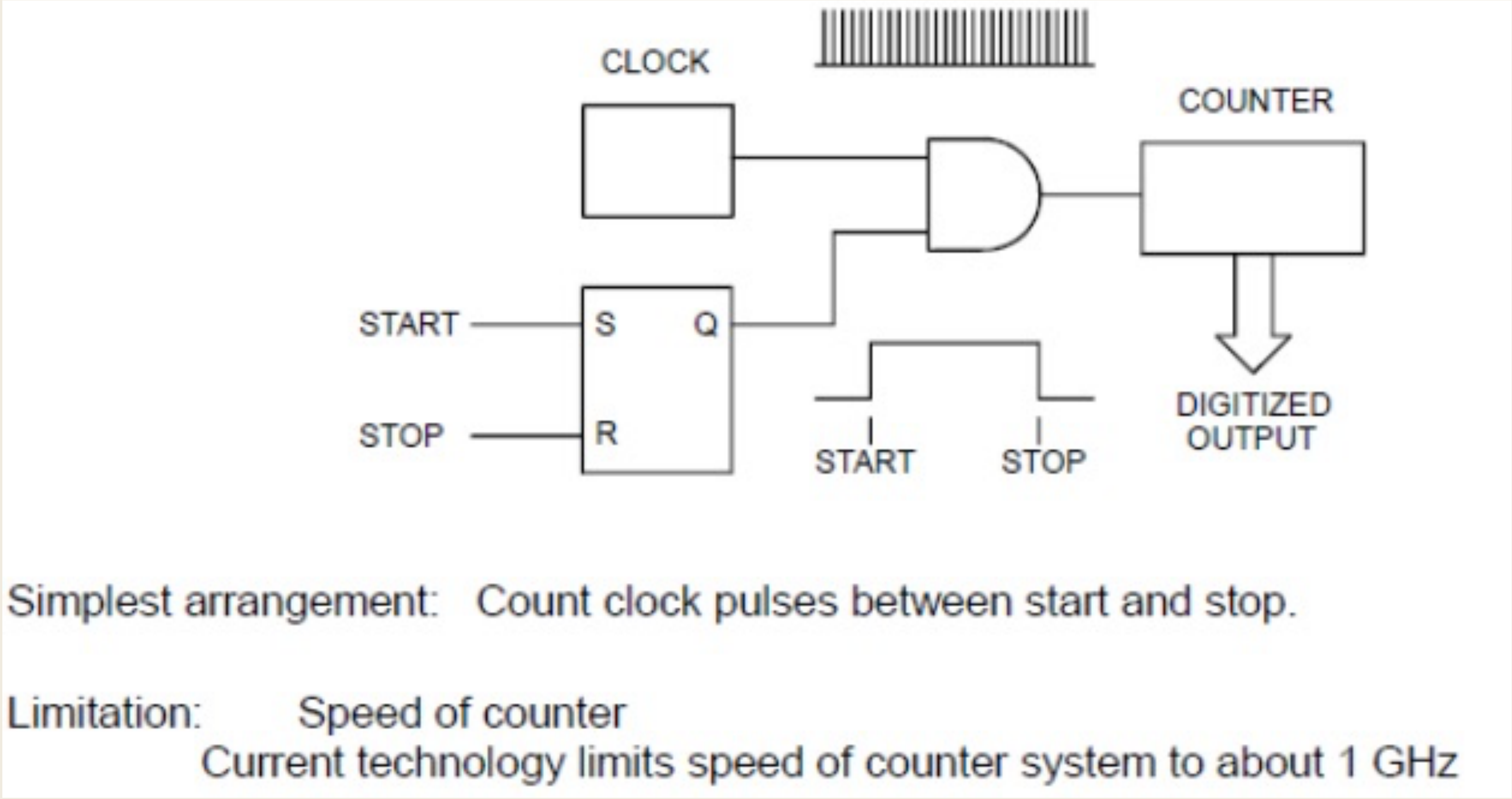



Your oscilloscope used during this camp can perform a task as Coincidence Unit with so-called "pattern" triggering.

# Analog-to-digital (ADC) and Time-to-Digital (TDC) module

ADC: to measures the analog signal pulse height and converts that value to the digital number



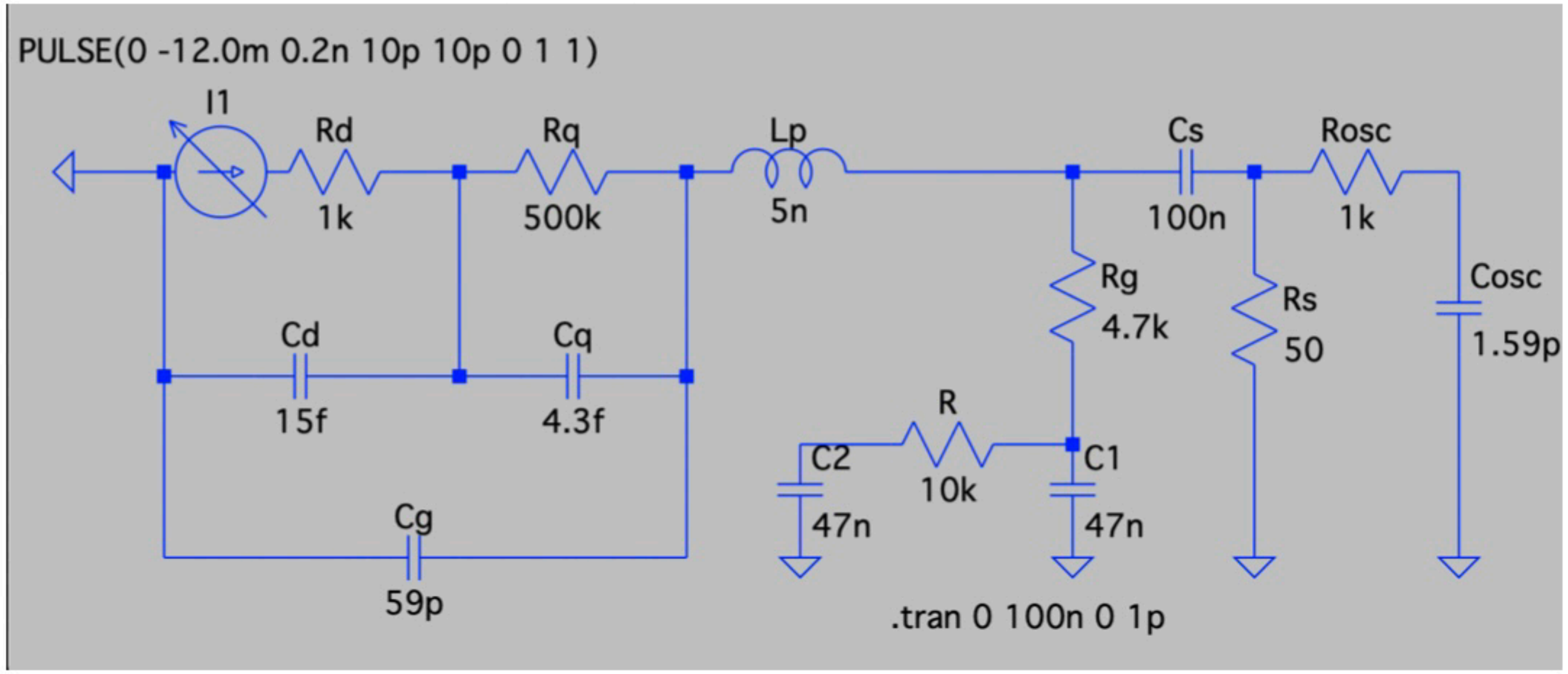

TDC: to covert the time intervals into a digital output

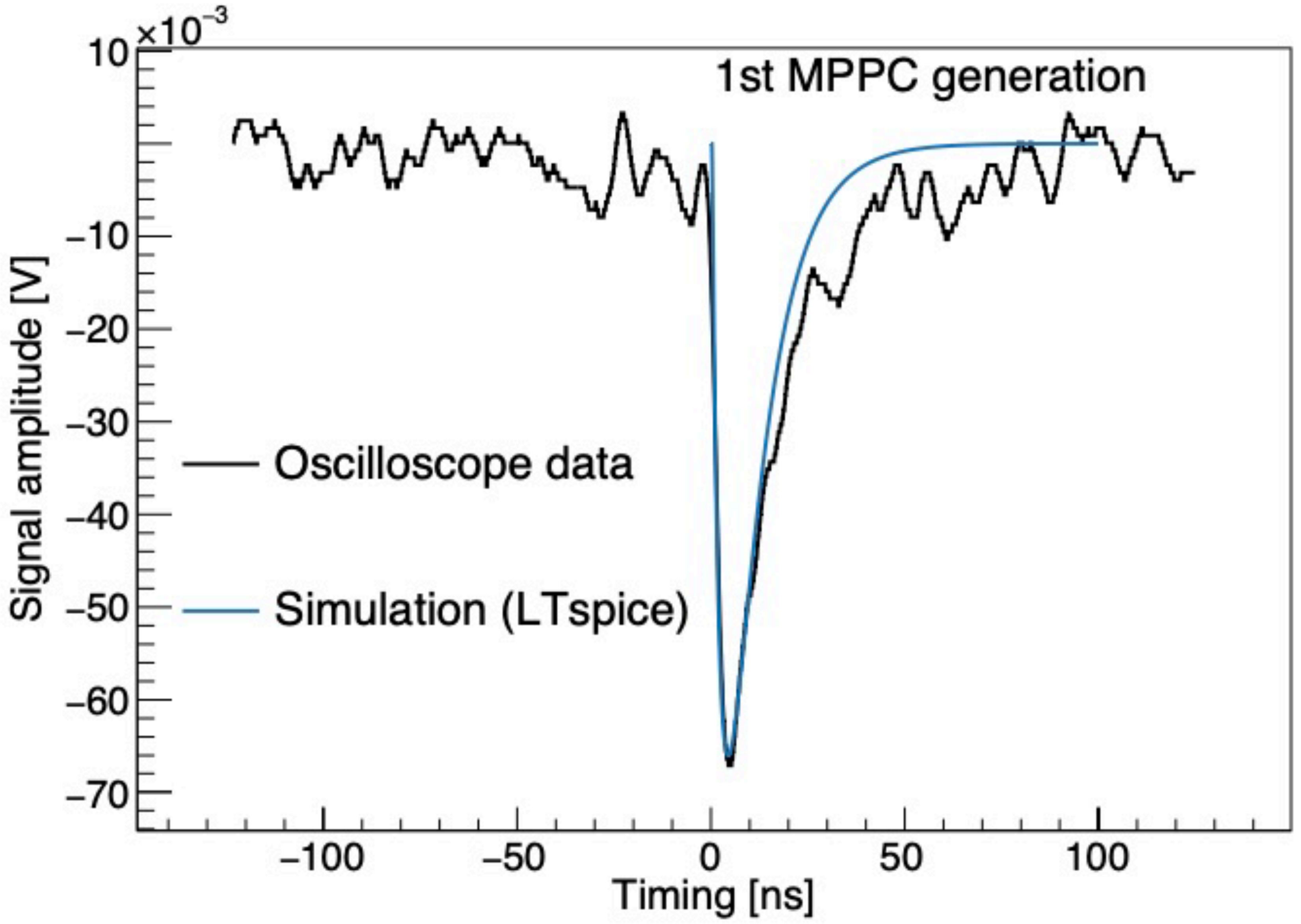
# Mini-conclusion

- *Diverse electronic components with numerous functionalities*
- *To dive deeply into this field, need times but still widely opening (personal impression)*
- *When, What, How to record the information of interest depends on specific applications.*
- *They are essential to harness the power of photodetectors*

# Move to electronic simulation section

# Signal vs. simulation




Left: Equivalent circuit of MPPC with 100 $MHz$ bandwidth of oscilloscope included

# Reference

- *Techniques for Nuclear and Particle Physics Experiments: A how-to approach, Ch14 (also 11, 12, 13): Electronics for Pulse Signal Processing, Dr. William R. Leo*