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Oscilloscope analog front end

Lecture #3

Electronic measurements

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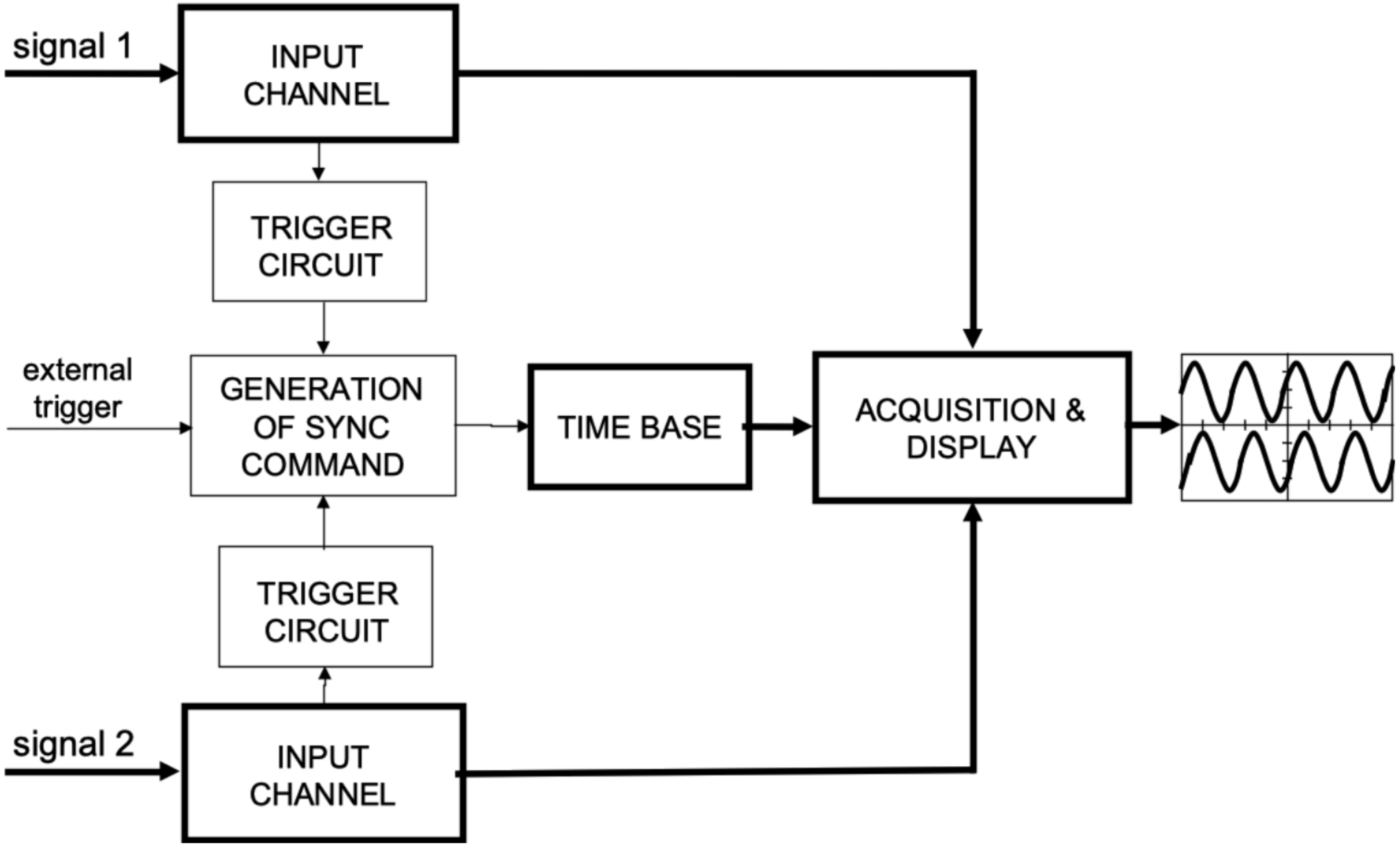
The oscilloscope



Input channel functions

- **Amplify or attenuate** the signal
- Realize a stable **input impedance**
- Provide a choice of **coupling modes**

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- Variable-gain amplifiers
- Attenuators
- Filters
- Coupling circuits

} Configured through the processors

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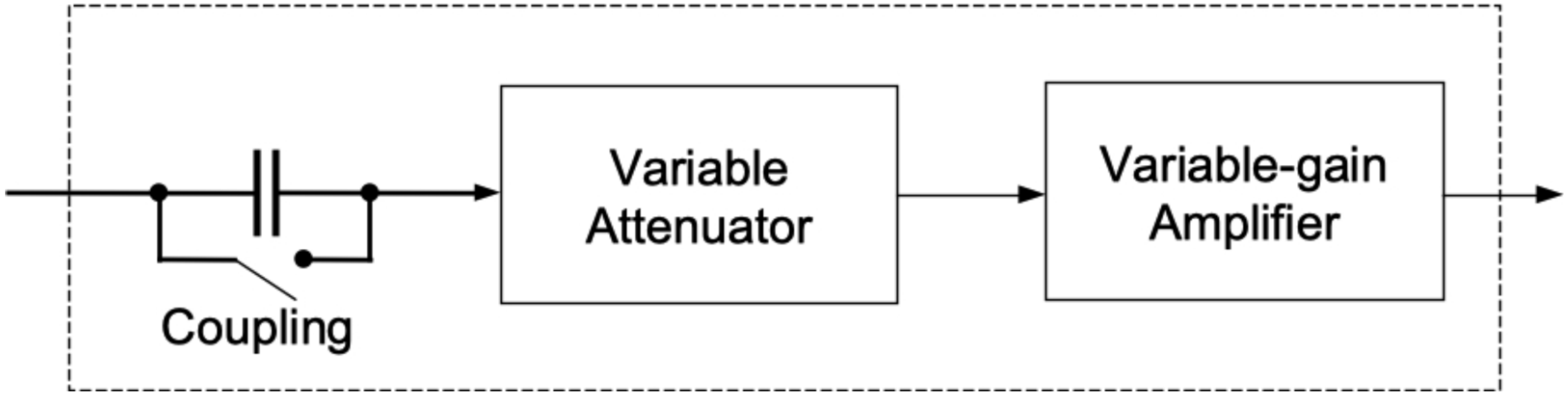
Signal conditioning

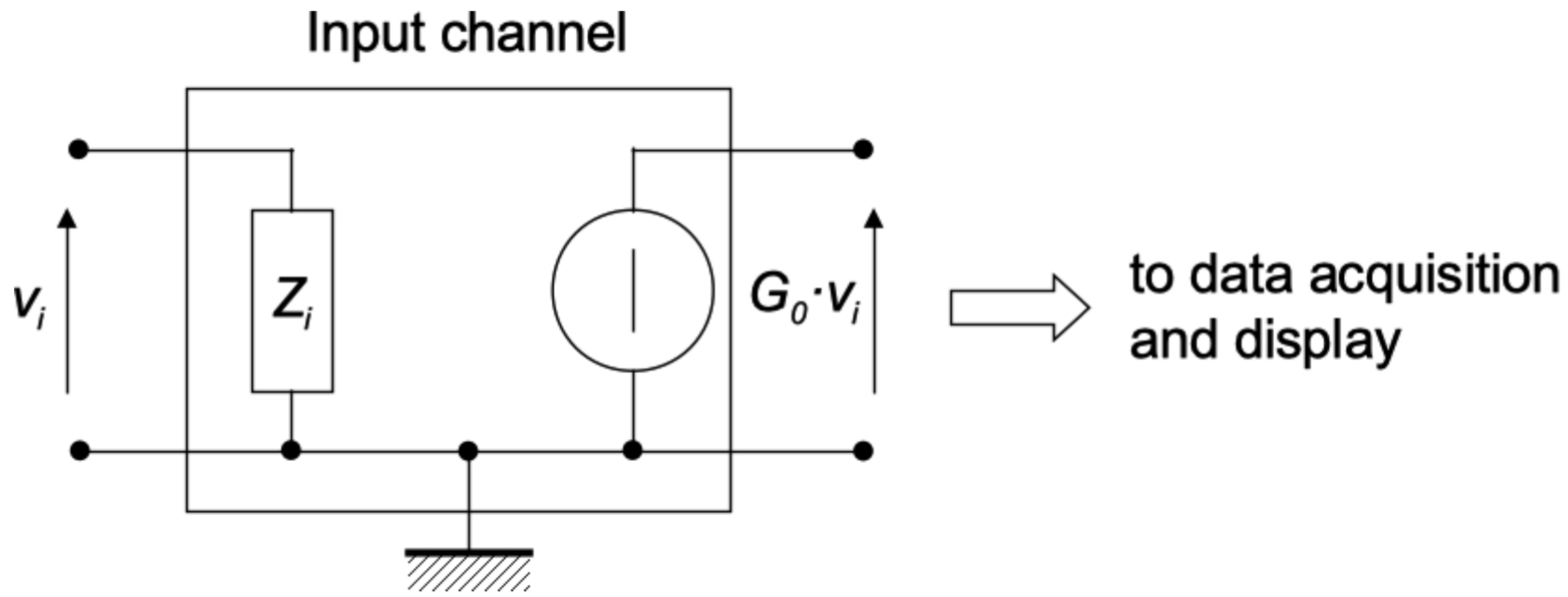
Input channel functions



- 2-4 channels
- **Simultaneous acquisition** of different signals
- **Common time reference**
- **Separate vertical scale settings**

Input channel model

- **Voltage controlled generator**



- **Input impedance** Z_i
- **Frequency response** $G(f)$
- **Static gain** $G_0 = G(0)$
- Calibrated vertical scale factor $1/G_0$

Calibration through comparison with **known DC voltage levels**

Input impedance

- **Input impedance Z_i as large as possible**
- Parallel of a large resistance R_i and a small capacitance C_i
- $R_i = 10$ MΩ, $C_i = 10 - 20$ pF

- **Low frequencies** ⇒ $|Z_i| \cong R_i$ ⇒ Negligible loading effect
- **High frequencies** ⇒ Capacitive reactance ⇒ impedance drop

$$Z_i = R_i \frac{1}{1 + j\omega R_i C_i}$$

Input impedance

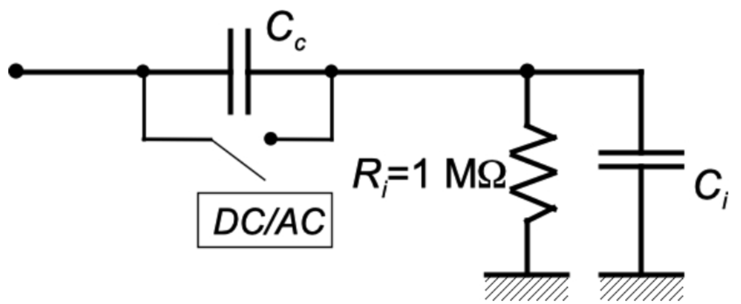
R_i = 1 MΩ and C_i = 15 pF

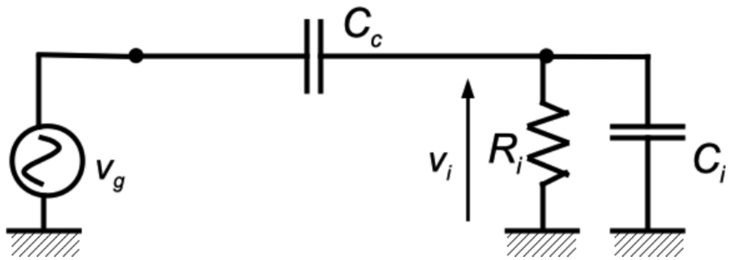
f	R_i	$\|X_i\|$	$\|Z_i\|$
0	1 MΩ	∞	1 MΩ
1 kHz	1 MΩ	10 MΩ	900 kΩ
1 MHz	1 MΩ	10 kΩ	10 kΩ
10 MHz	1 MΩ	1 kΩ	1 kΩ
100 MHz	1 MΩ	100 Ω	100 Ω

- **Lower input impedance** ⇒ larger current absorption at higher frequencies
- **High input impedance**: limited loading effect
- **50 Ω input impedance**: matched impedance ⇒ wavelength comparable to the physical size of circuits ⇓ avoid reflections

Coupling

- **Direct-current (DC) coupling**: the whole signal, including its DC component, is acquired
- **Alternating-current (AC) coupling**: only the alternating is acquired



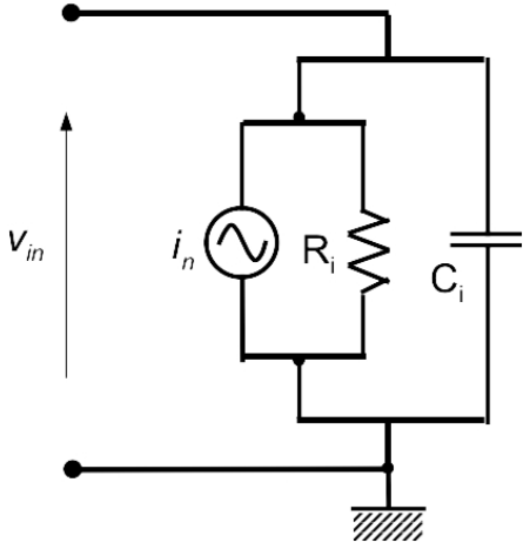


$$V_i(s) = V_g(s) \cdot \frac{j\omega R_i C_c}{1 + j\omega R_i (C_c + C_i)}$$

- **High pass filter**
- -3 dB cut-off frequency ~ 10 Hz
- C_c in the order of some tens of nF ⇒ $C_c \gg C_i$

Sensitivity and noise

- **Thermal noise:** random motion of electrons
- Power spectral density kT [W/Hz] (k Boltzmann constant = 1.38 x 10^{-23} J/K)
- Noise power is generated by an equivalent current source i_n in parallel to the "noiseless" input resistance R_{in}



$$S_{nn}(f) = \frac{4kT}{R_i}\ A^2/Hz$$

- **Noise voltage** v_{in} is produced by the noise current i_n flowing through the input impedance Z_i and is displayed as additive noise superposed on the measured signal

Sensitivity and noise

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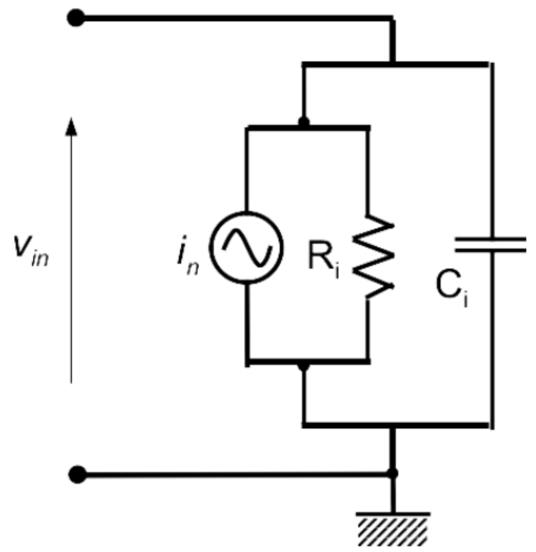
- Power spectral density kT [W/Hz] (k Boltzmann constant = 1.38 x 10^{-23} J/K)



$$S_{nn}(f) = \frac{4kT}{R_i}\ A^2/Hz$$

- **Input noise variance**

$$E\left[v_{in}^2\right] = \frac{4kT}{R_i} \cdot \frac{1}{2\pi} \int_0^{+\infty} \frac{R_i^2}{1 + \omega^2 (R_i C_i)^2} d\omega = 4kT \cdot \frac{1}{2\pi} \frac{\pi}{2 R_i C_i}$$

Sensitivity and noise

- $v_{in(RMS)} = \sigma_n = \sqrt{\frac{kT}{C_i}}$
- Determined by the the equivalent noise of the input RC circuit
- **Smaller levels of C_i lead to higher levels of noise**
- C_i = 10 pF and T = 300 K ⇒ $v_{in(RMS)} \cong 20\ \mu V$

- **Signal-to-Noise Ratio (SNR)**
  - Uniform probability density function for signals within the input voltage range ±V_{FS} ⇒ Variance $\sigma_S^2 = V_{FS}^2/3$
  - $SNR_{thermal} = \frac{V_{FS}^2}{3}\frac{C_i}{kT}$

Dynamic characteristics

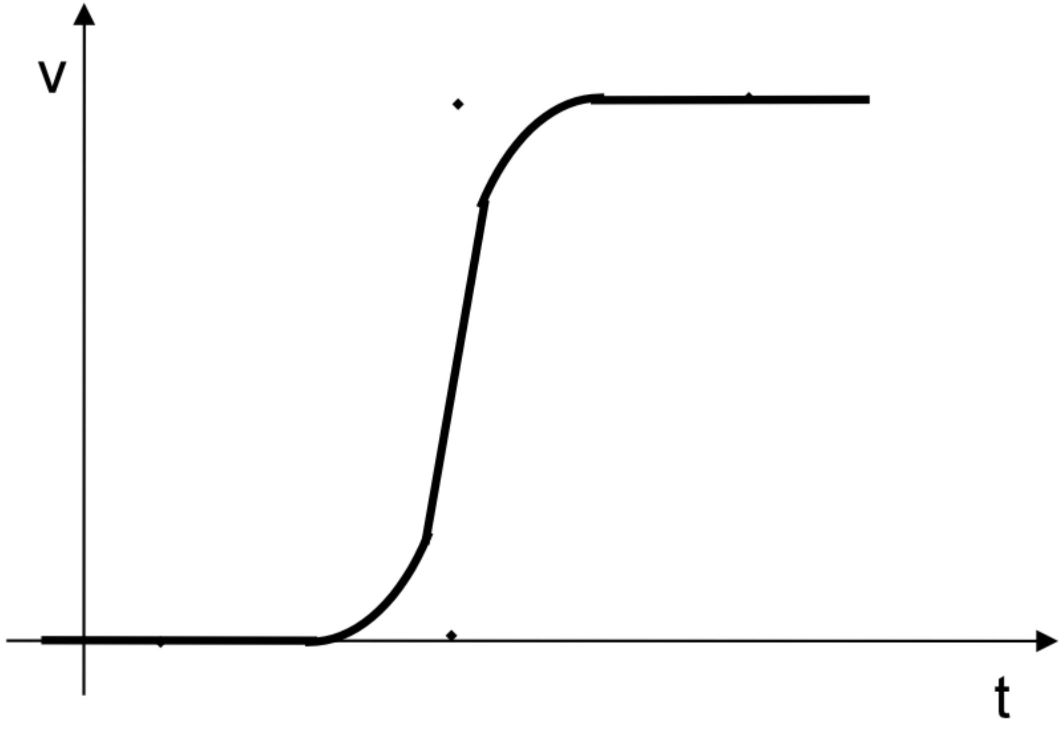
- **Flatness:** maximum deviation of $|G(f)|$ from the DC value

$$\text{flatness} = \frac{max_j|G(f)-G(0)|}{G(0)}$$

- **Non distortion conditions**
- Linear frequency response with:
  - **Constant magnitude**
  - **Linear phase (constant group delay)**

Dynamic characteristics:
Step response

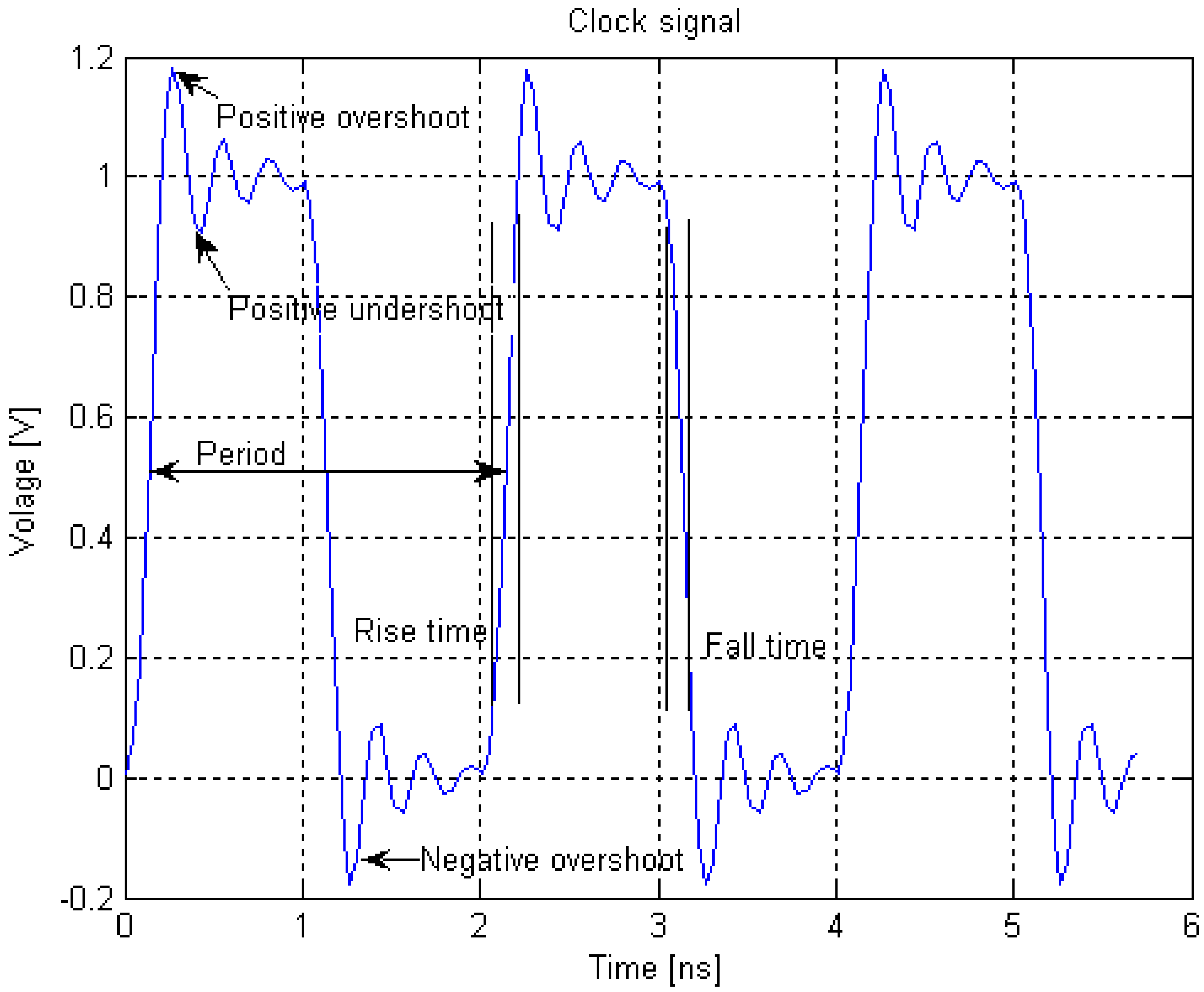
- Faithful waveform reproduction in the time domain
- **Step response:**
  - Shortest possible rise time
  - No overshoot



- Follow any voltage variation **avoiding the creation of artifacts**
- Linear system with Gaussian impulse response

$$g(t) = A \cdot e^{-(t-\tau_0)^2}$$

Dynamic characteristics: Step response



Dynamic characteristics: Rise time

- Signals with sharp edges (**digital signals or clock signals**)
- Edge not distorted
  - **Significant high-frequency contributions**
  - **Instrument bandwidth limitations**
- **Rise time:** time required for the transition between two levels

Dynamic characteristics: Rise time

- **T_r:** oscilloscope rise time
- **T_v:** visualized rise time
- **T_s:** signal rise time
- Relative deviation from T_s:

$$\frac{T_v - T_s}{T_s}$$

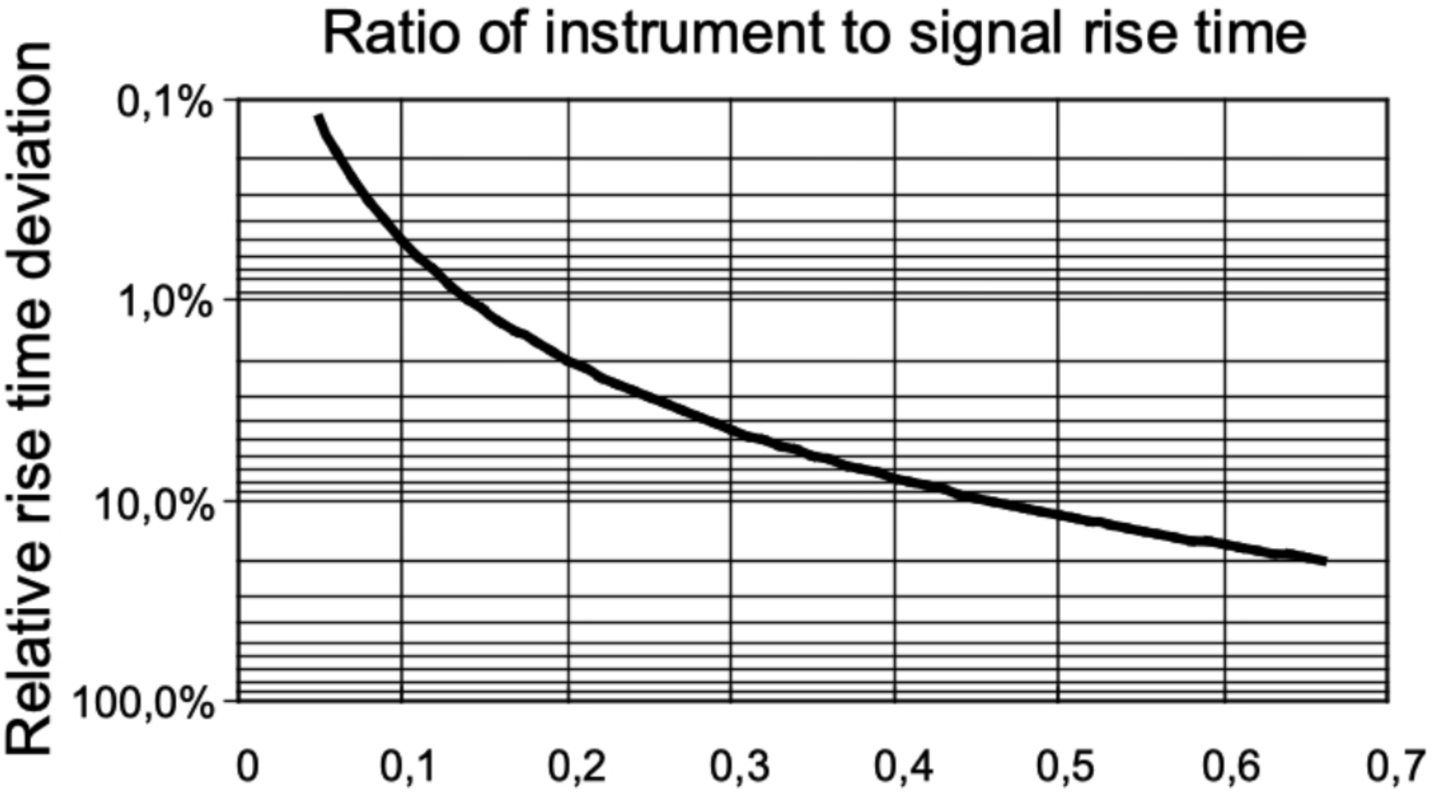
$$T_v \cong \sqrt{T_s^2 + T_r^2}$$

- To make the difference from T_v negligible, $T_r \ll T_s$

Dynamic characteristics:
Rise time

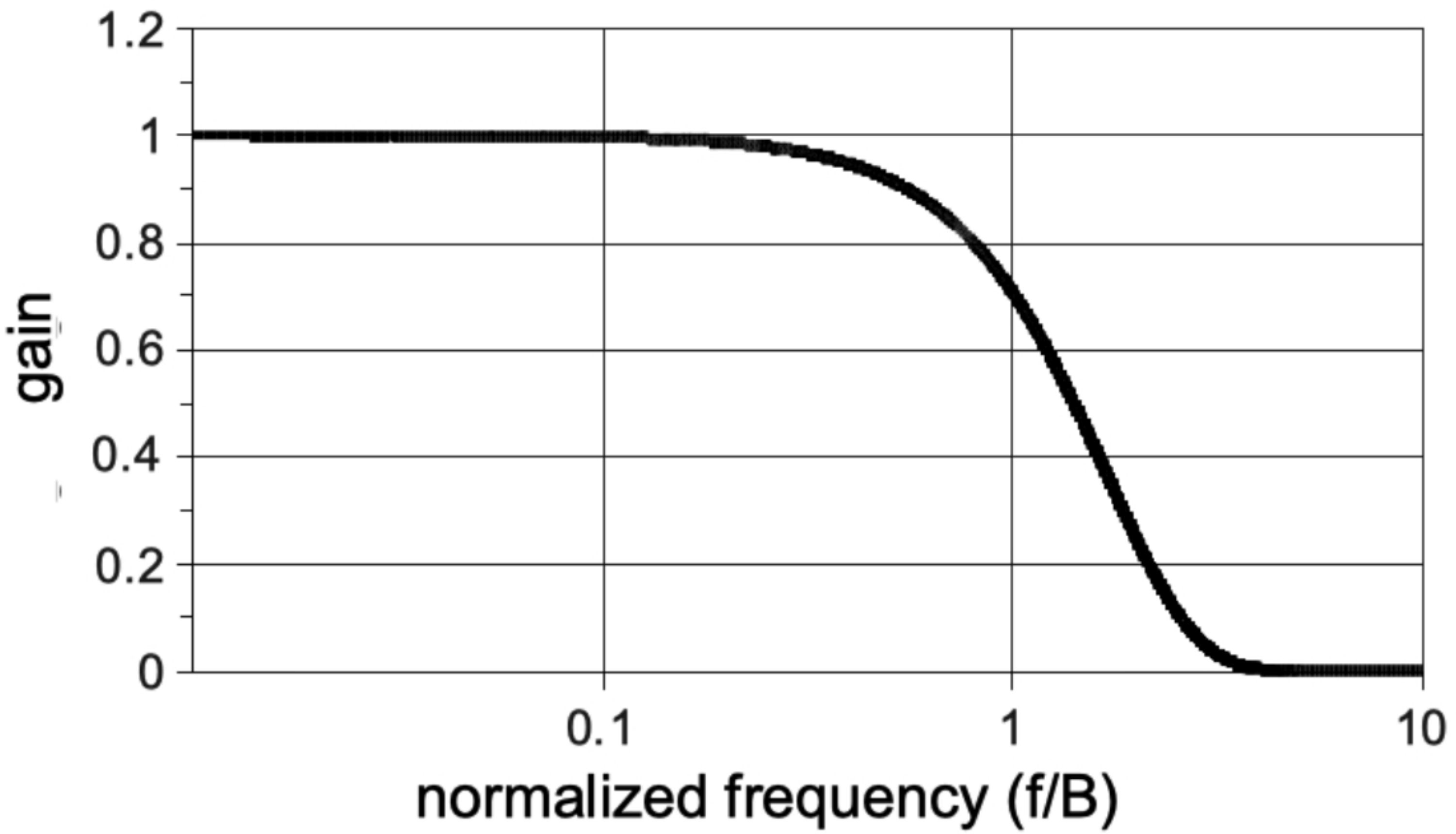
$$\frac{T_r}{T_s}$$

$$\frac{T_v - T_s}{T_s}$$



Frequency response

- B ⇒ -3 dB bandwidth ⇒ attenuation about 30%

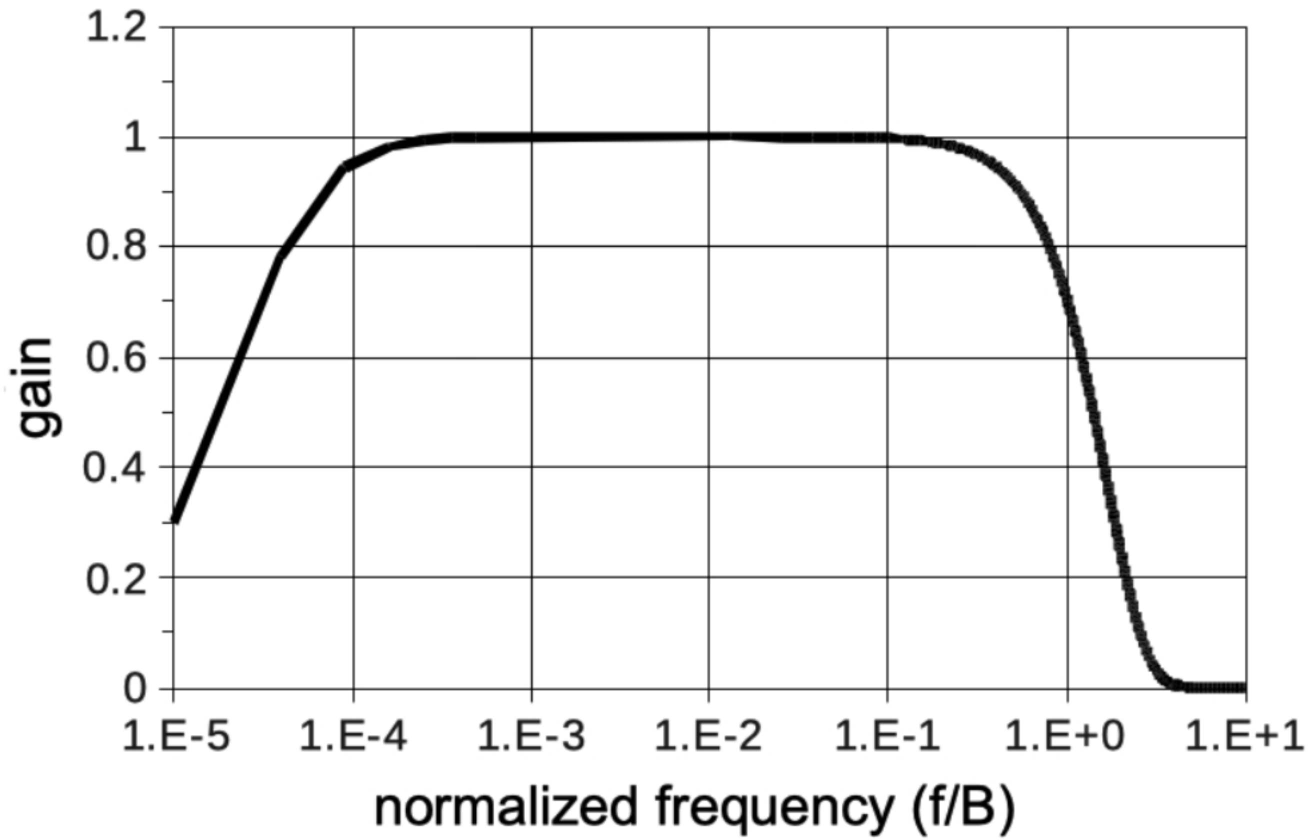


$$T_r \cong \frac{0.35}{B}$$

Frequency response

- The frequency response may present some ripple ⇒ flatness
- Two parallel paths for **broad band amplification**
  - **DC-coupled** low-frequency
  - **AC-coupled** high-frequency (cross-over frequency around 1 kHz)
- Output noise **higher** for higher-gain circuits → Different vertical scale factor, different noise level

Frequency response with AC coupling



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Oscilloscope probes

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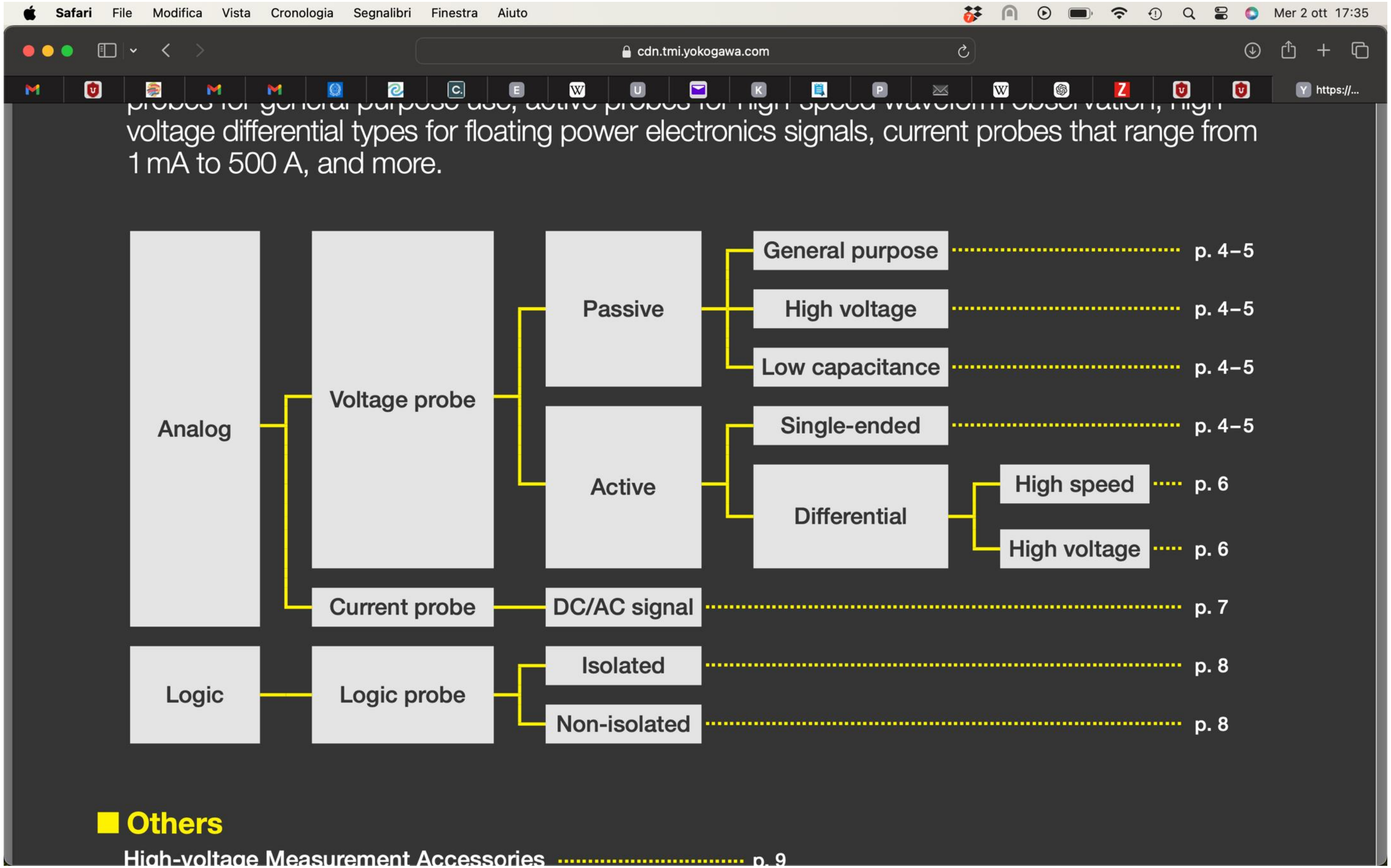
Oscilloscope probes



Oscilloscope probes

- **Connections are circuits** with their own parameters
- Connections may alter the circuit behaviour (**Loading effect**)
- Length is comparable to the wavelength ⇒ **Transmission lines**

- **Probe**: device enabling to **pick up the signal of interest** and take it to the input connectors of the measuring instrument
- **A pair of conductors, a coaxial cable and a BNC connector**
  - Reduce the loading effect
  - Avoid signal distortion
  - Enable contact with test points

Oscilloscope probes

- Cable length ⇒ **Propagation effects**
- Propagation speed $v = 1/\sqrt{\epsilon\mu} = \frac{c}{\sqrt{\epsilon_r}}$
- **Polyethylene** ⇒ $\epsilon_r = 2.3 \Rightarrow v \cong 2 \times 10^8$ m/s
- 1 m cable ⇒ 200 MHz sinewave
- Up to **few MHz** the cable can be described by a **lumped-parameter** electrical network

- **Coaxial cables capacitance** C_c: 0.5-2 pF/cm
- In parallel with the instrument input impedance

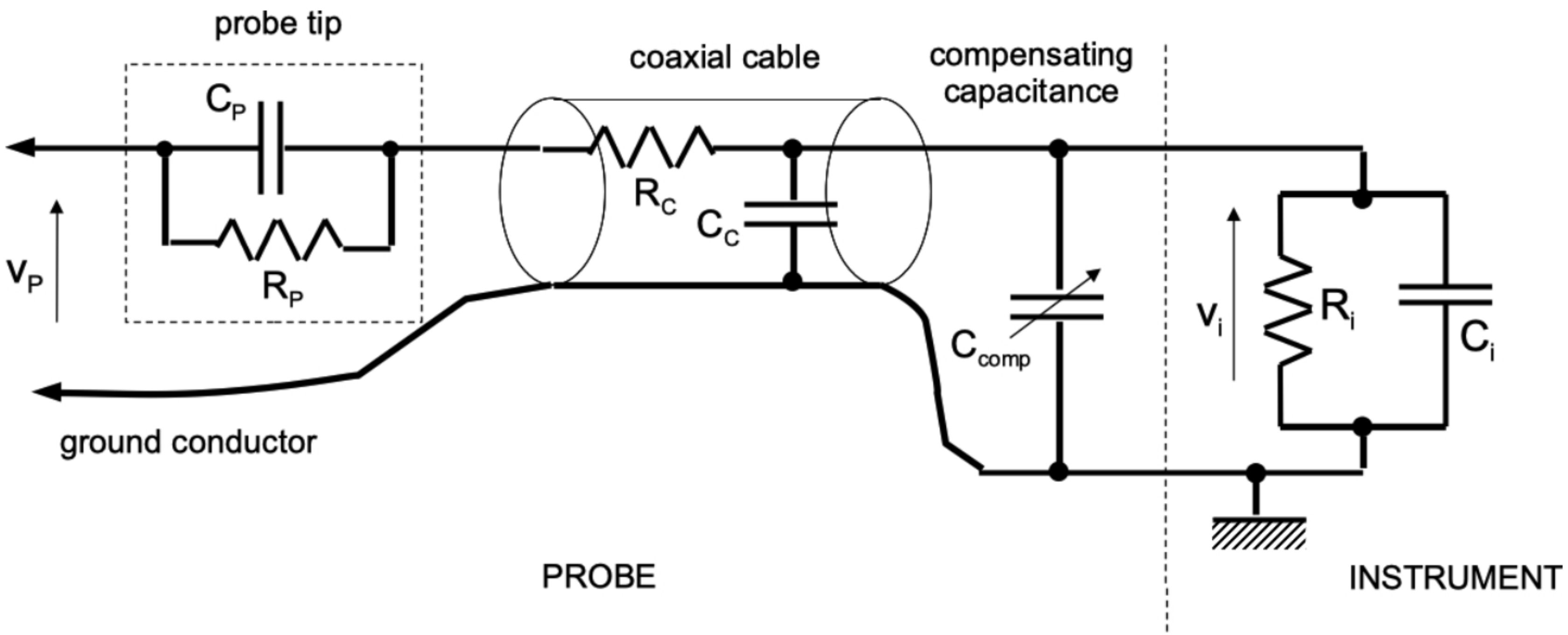
Passive probes

- A tip containing a **parallel RC network**
- A connector body, that contains a **variable capacitor**, placed in parallel to the BNC connector linking the probe to the oscilloscope
- A **coaxial cable** from the tip to the connector body

- **Attenuation factor**: ratio between the voltage v_x at the signal source and the voltage v_i at the oscilloscope input
- Typical factor **10**

Passive probes

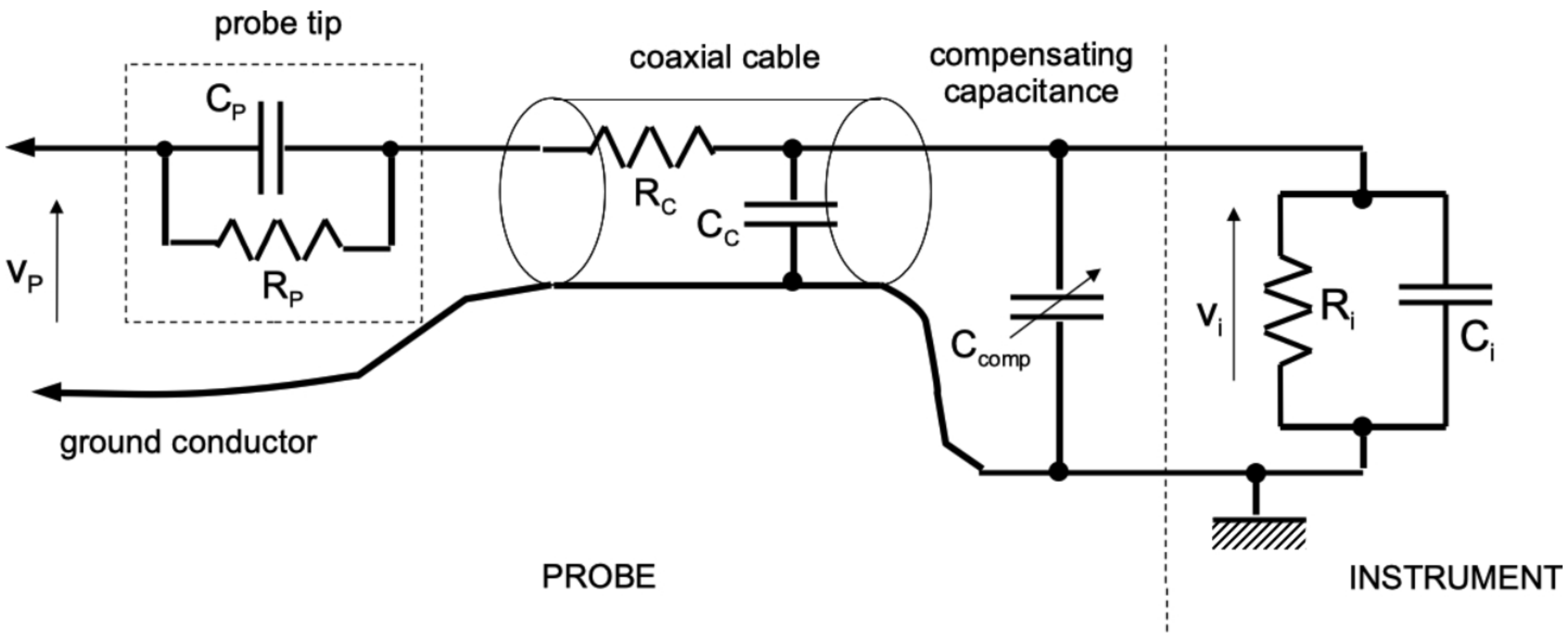
- **Probe tip**: C_p and R_p in parallel
- **Coaxial cable**: small R_c and C_c in series
- **Compensation capacitance** C_{comp}



Passive probes

- **Parallel**:
  - Oscilloscope input capacitance C_i
  - Cable capacitance C_c
  - Compensation capacitance C_{comp}

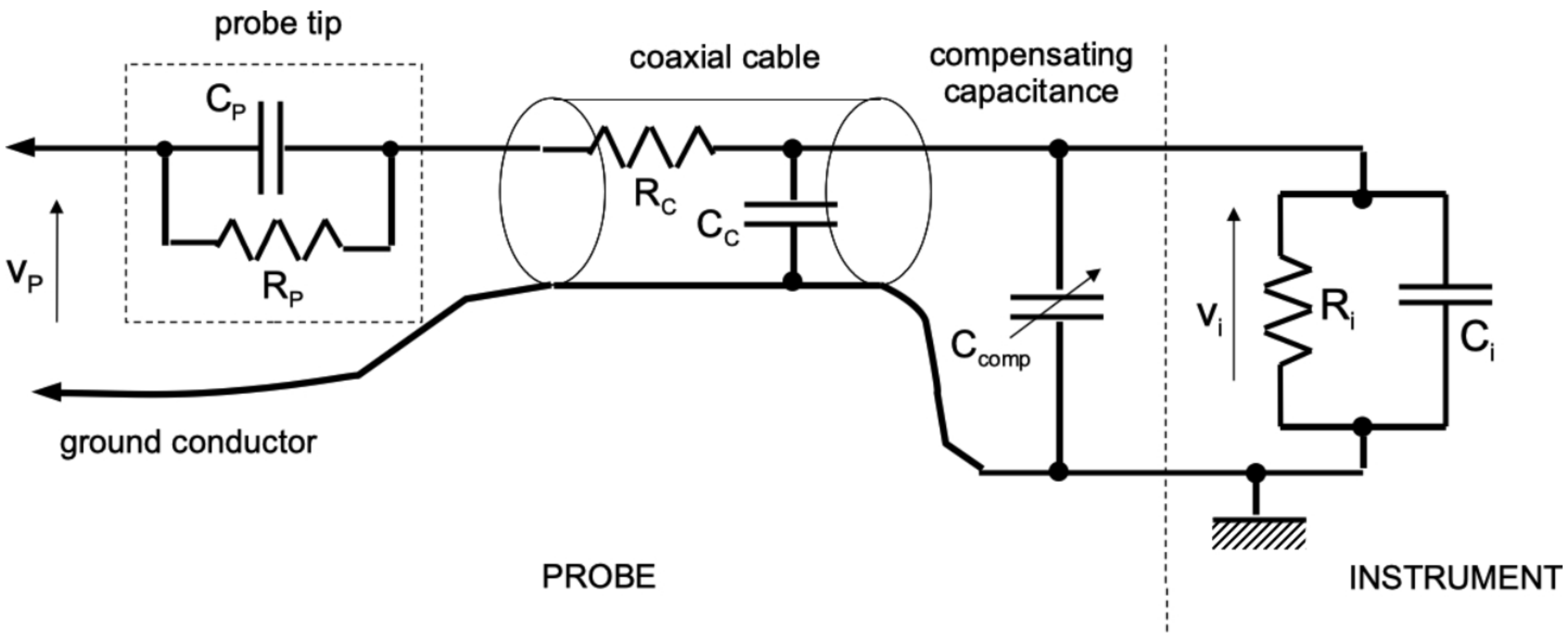
} $C_{i(eq)}$ (R_C Neglectable)



Passive probes

- **Series**:
  - Parallel in the probe tip
  - $Z_{i(eq)}$ (parallel of $C_{i(eq)}$ and R_i)

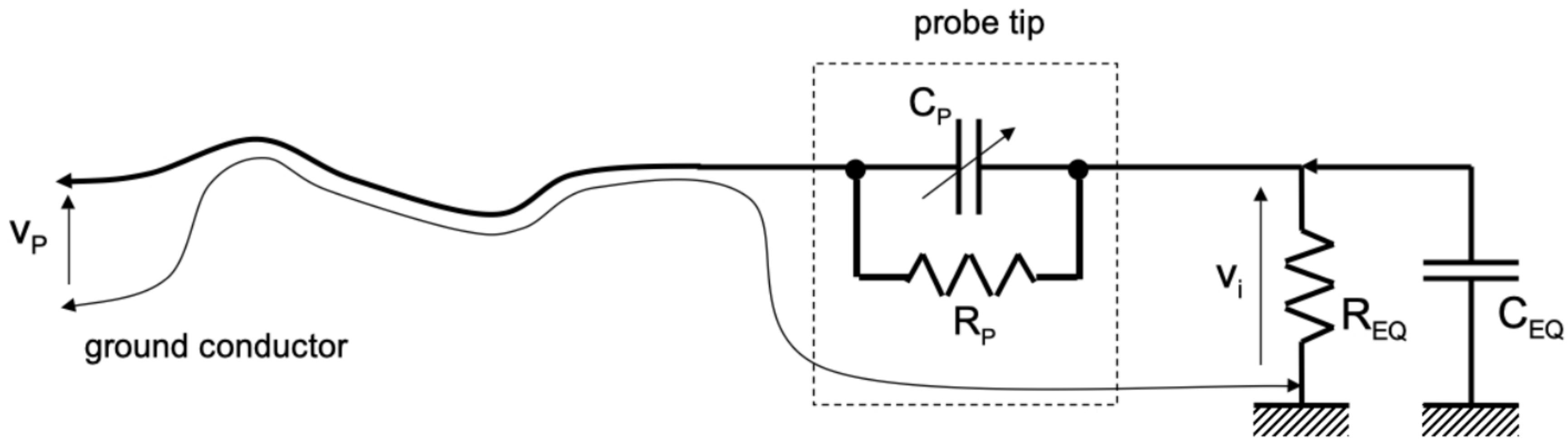
- Constant input $\Rightarrow v_i = v_p \frac{R_i}{R_i + R_p}$
- $R_p = 9R_i$



Passive probes

- **Probe impedance** $Z_p(s) = R_p \frac{1}{1+sR_pC_p}$
- **Input impedance** $Z_{i(eq)}(s) = R_i \frac{1}{1+sR_iC_{i(eq)}}$

$$\frac{1}{\alpha_{probe}} = \frac{R_i \frac{1}{1+sR_iC_{i(eq)}}}{R_p \frac{1}{1+sR_pC_p} + R_i \frac{1}{1+sR_iC_{i(eq)}}}$$



Passive probes

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- **Input impedance** $Z_{i(eq)}(s) = R_i \frac{1}{1+sR_iC_{i(eq)}}$

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$$R_P C_P = R_i C_{i(eq)}$$

$$\alpha_{probe} = \frac{R_P + R_i}{R_i}$$

→ Independent of frequency

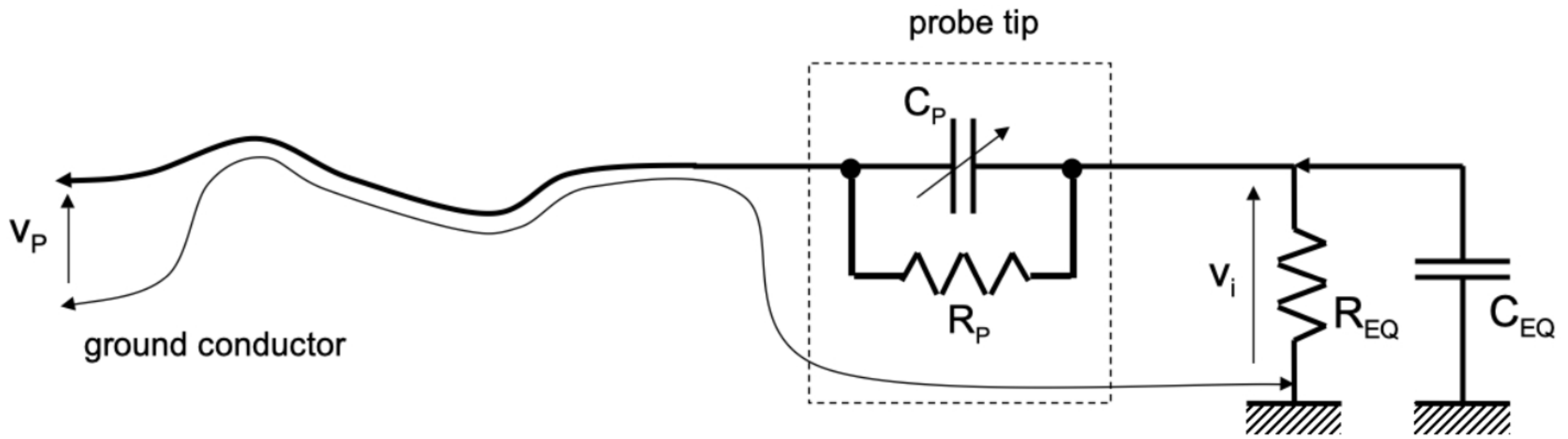
Passive probes

- **Equivalent impedance:**

$$Z_{EQ}(s) = R_p \frac{1}{1 + sR_pC_p} + R_i \frac{1}{1 + sR_iC_{i(eq)}}$$

- **Compensation condition satisfied:**

$$Z_{EQ}(s) = (R_p + R_i) \frac{1}{1 + s(R_p + R_i)\frac{C_{i(eq)}}{\alpha_{probe}}}$$



Passive probes

- **Equivalent impedance**:

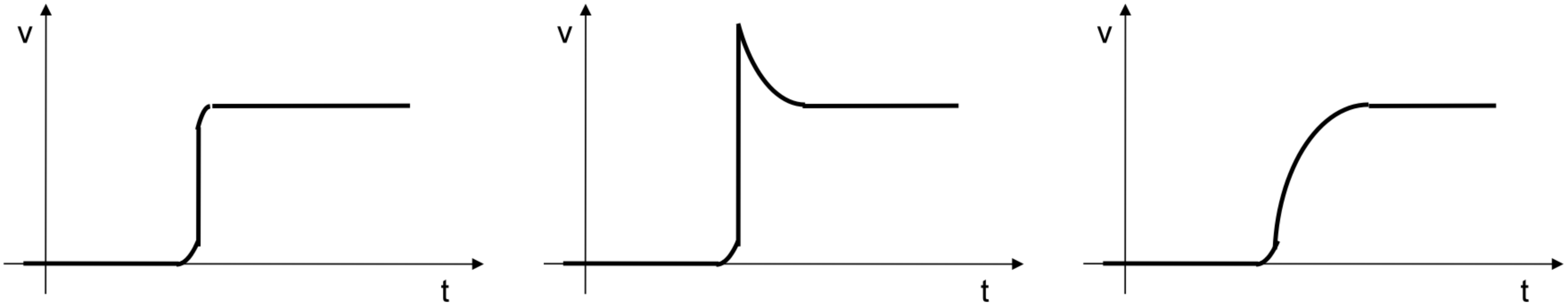
$$Z_{EQ}(s) = R_p \frac{1}{1 + sR_pC_p} + R_i \frac{1}{1 + sR_iC_{i(eq)}}$$

- **Compensation condition satisfied**:

$$Z_{EQ}(s) = (R_p + R_i) \frac{1}{1 + s(R_p + R_i)\dfrac{C_{i(eq)}}{\alpha_{probe}}}$$

- $R_{EQ} = R_p + R_i = R_i \cdot \alpha_{probe}$
- $C_{EQ} = \dfrac{C_{i(eq)}}{\alpha_{probe}}$

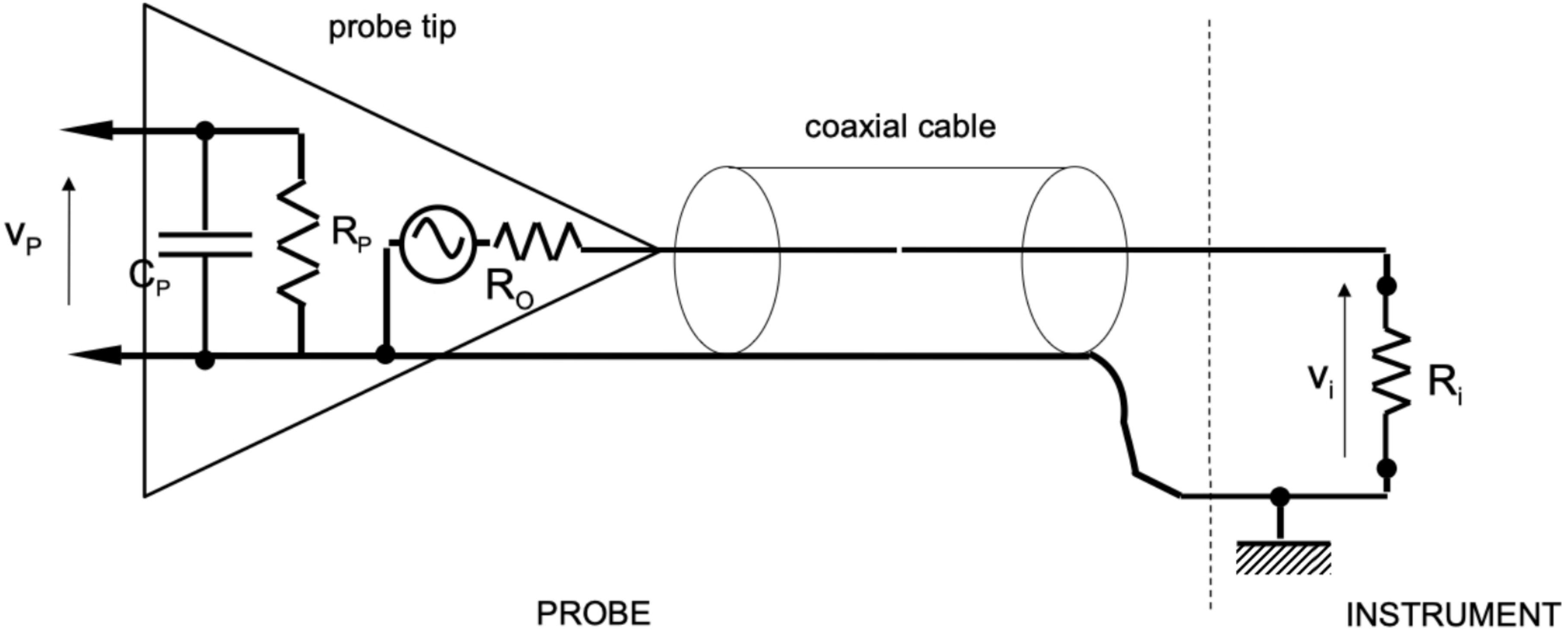
Passive probes



(a) compensated probe; (b) over-compensated probe; (c) under-compensated probe;

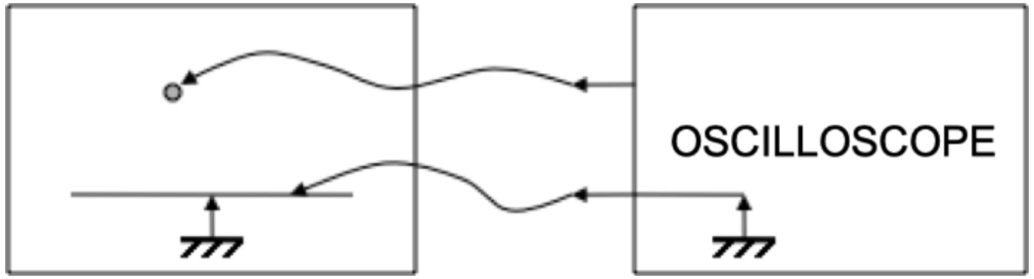
- **Over-compensated**: C too high → Limited attenuation of the high order harmonics
- **Under-compensated**: C too small → Larger attenuation of the high order harmonics

Active probes

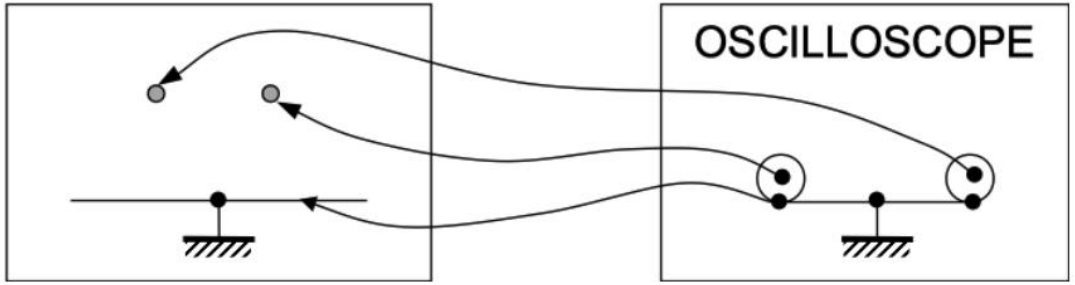


Pseudo-differential measurement

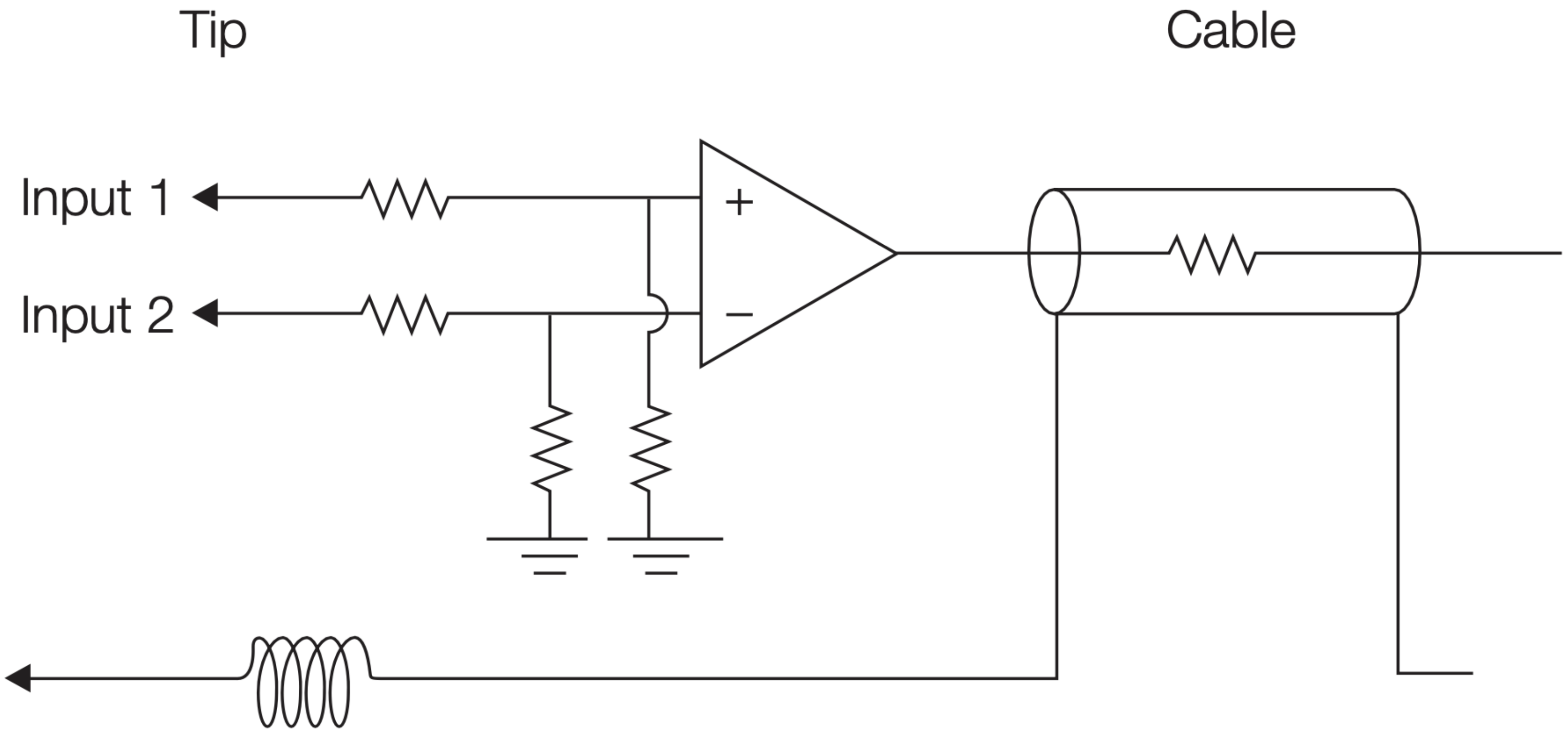
- Oscilloscopes feature a **single-ended input** with the ground reference connected to earth



- **Pseudo-differential measurement**: measure the "voltage to ground" of the two points independently, then determine their difference



Differential probes



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