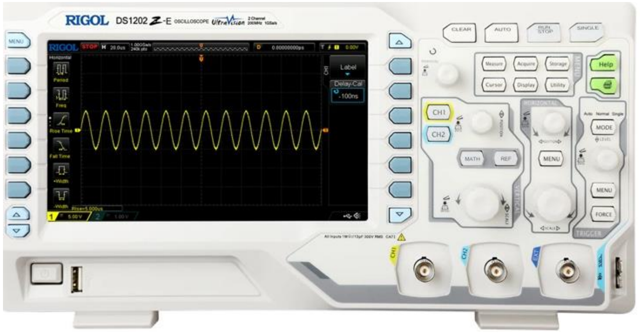
UNIVERSITÀ DEGLI STUDI DI PADOVA

Basic Laboratory Instrumentation

Lecture #2
Electronic measurements
Alessandro Pozzebon

Basic instrumentation

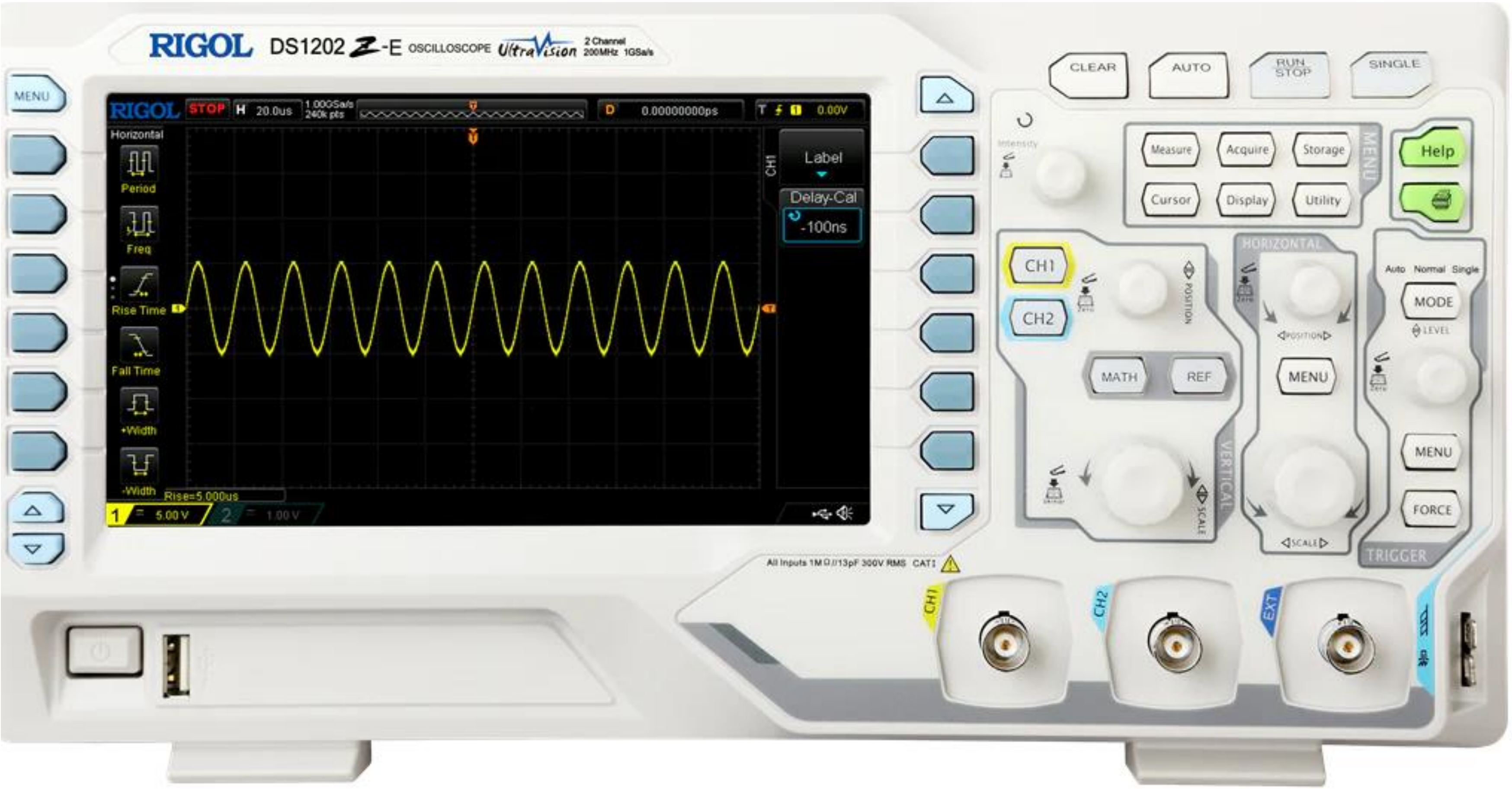
- Oscilloscope



- Signal Generator

- Digital multimeter

Oscilloscope



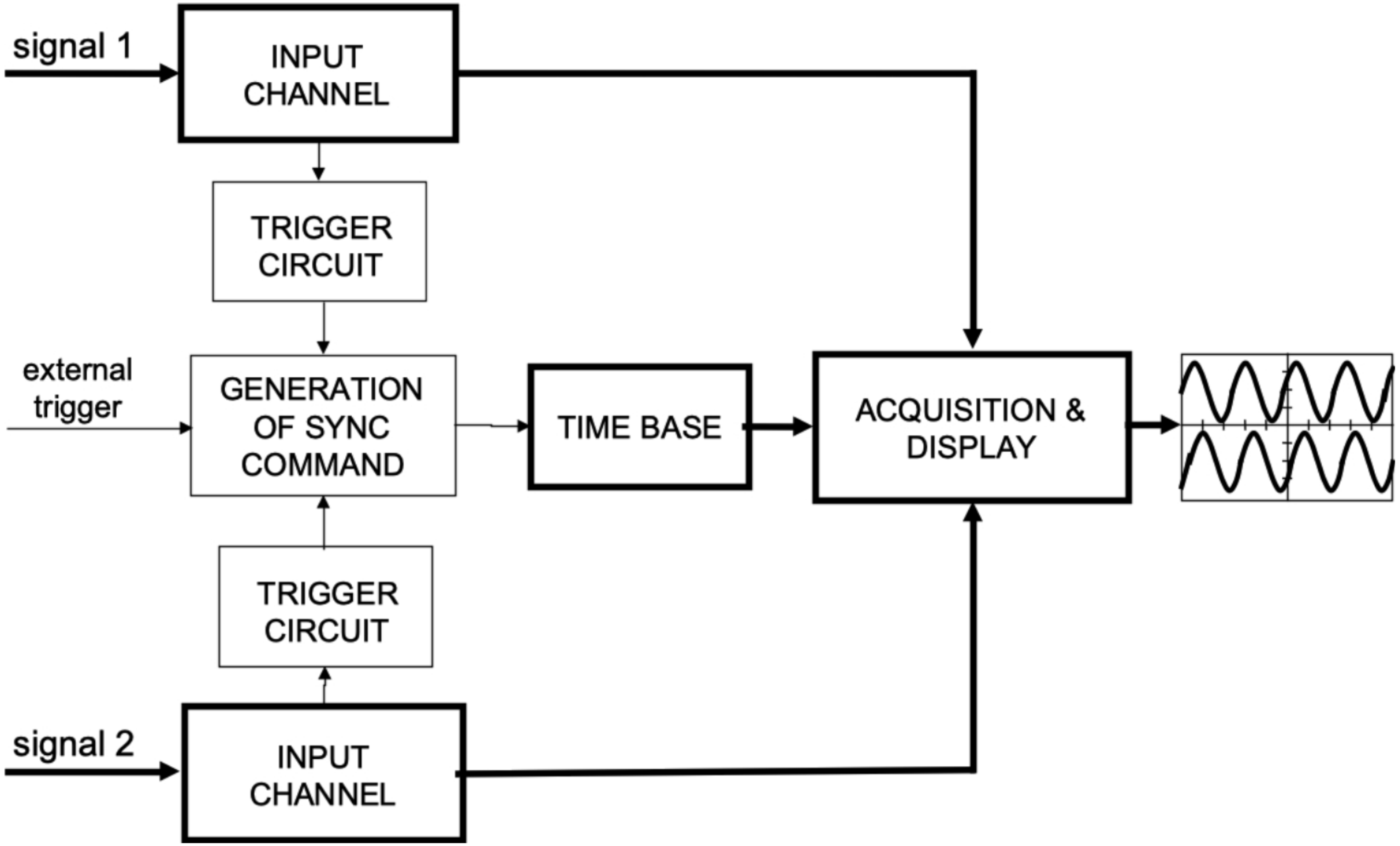
Oscilloscope

- **Waveform analysis**: the accurate measurement of signal behaviour
  - Observe
  - Measure
  - Compare
- **Diagnostics:** checking a system operation to detect possible anomalies and signal variations

- Finite **observation interval**
  - Synchronization

- Simultaneous acquisition of **2-4 signals**

Oscilloscope
Functional scheme

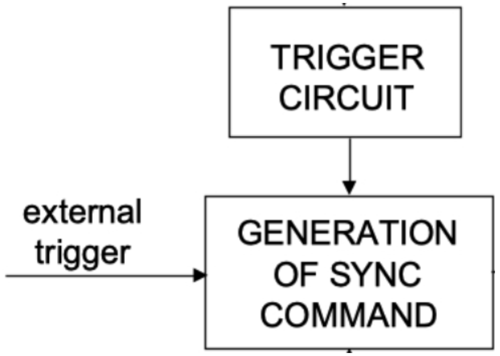


Oscilloscope
Functional scheme

- **Amplification and attenuation**
- **Bandwidth**
  - From less than 100 MHz to several GHz
- **Input impedance** → as high as possible
  - Parallel of a resistance R = 1 MΩ and a capacitance in the order of ten pF

Oscilloscope

Functional scheme



- Determine **reference points** to synchronize the instrument
- **Trigger event**: crossing of a preset voltage level
- **Synchronization command**: can combine multiple conditions and inputs
- **External trigger**

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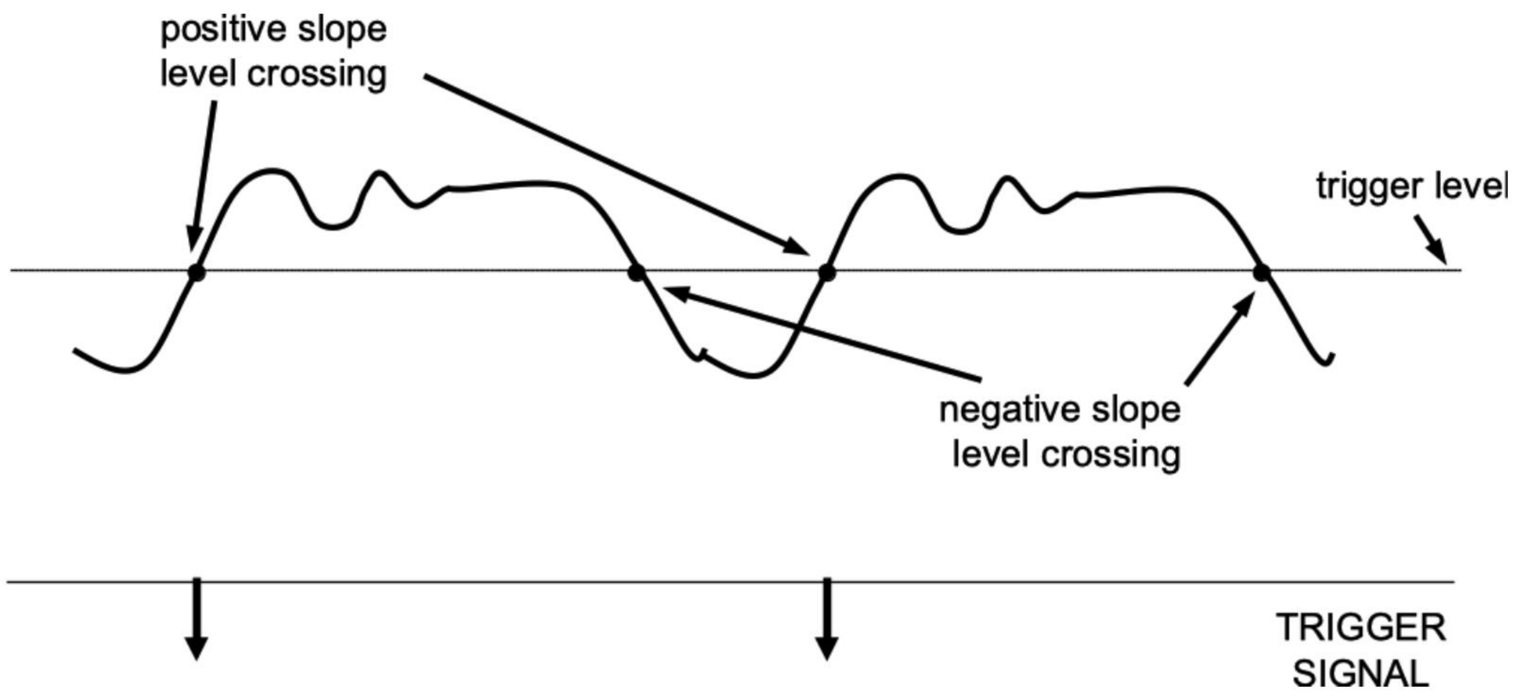
Oscilloscope
Functional scheme

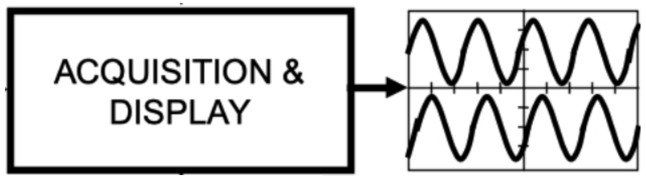


Oscilloscope
Functional scheme

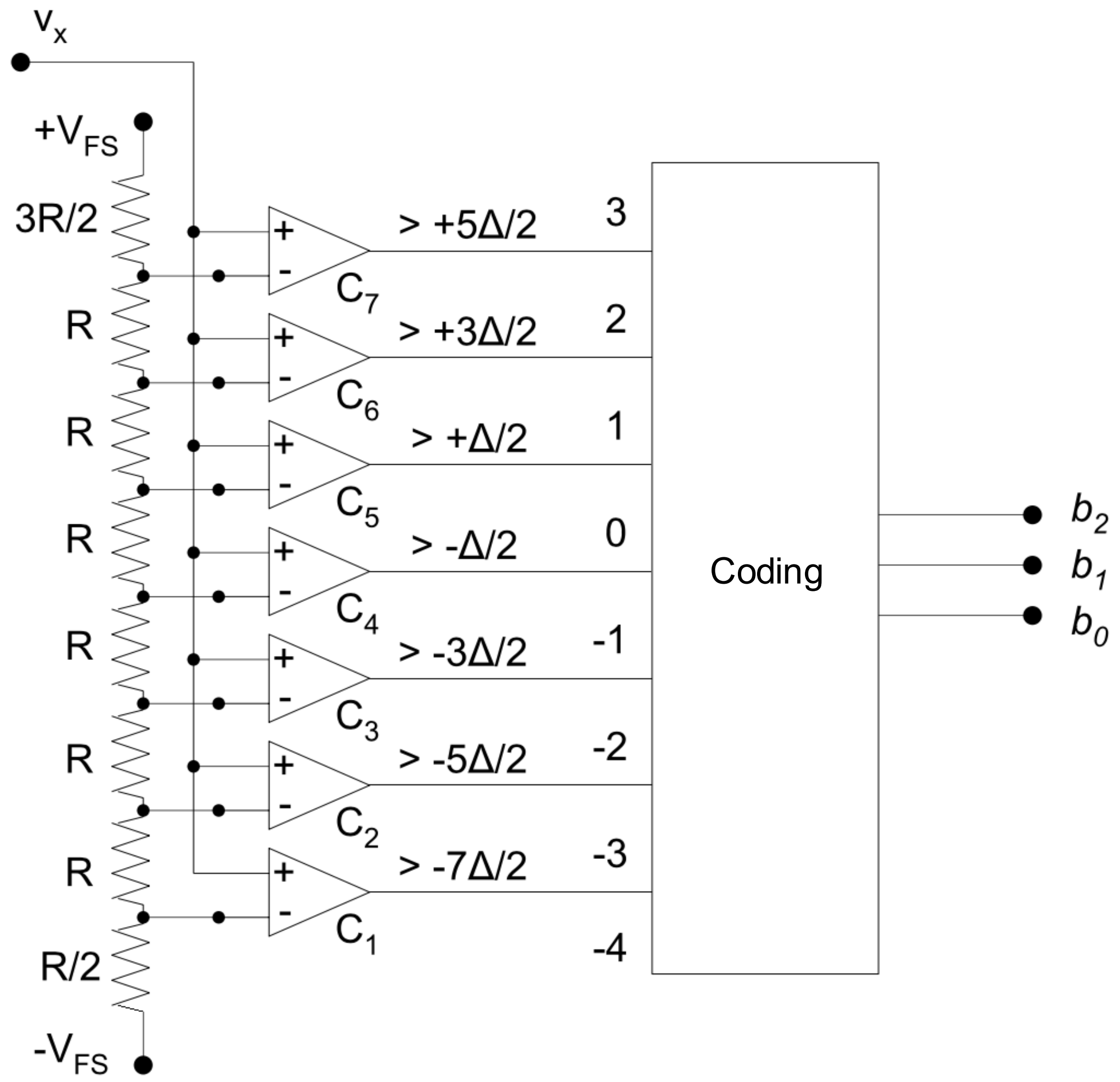
- **Internal time reference**
- Measurement of time intervals
- Observation interval length from **few ns to several s**
- **Calibrated** reference
- **Internal instrument clock**
- Crystal oscillator with relative uncertainty in the order of 10^{-4} to 10^{-6}

Oscilloscope
Functional scheme

- **Digital Sampling Oscilloscope (DSO)**
- High speed data and acquisition system
- **Analog-to-Digital Converter (ADC)**
- Computing capabilities for **digital signal processing**
- Direct **measurements and signal analysis**



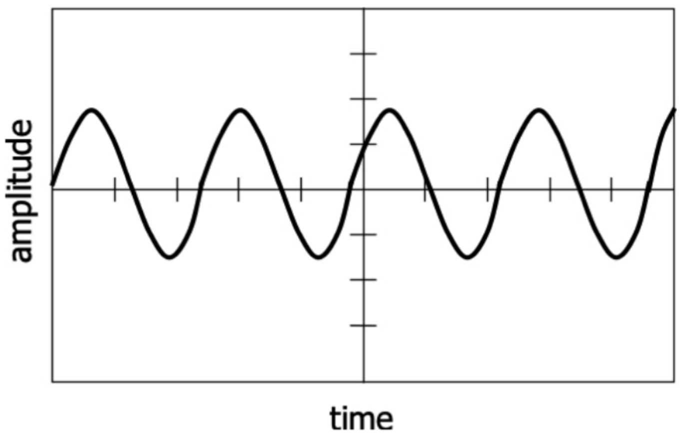
Flash ADC


vx
+VFS
3R/2
R
R
R
R
R
R
R/2
-VFS
+
-
C7
C6
C5
C4
C3
C2
C1
> +5Δ/2
> +3Δ/2
> +Δ/2
> -Δ/2
> -3Δ/2
> -5Δ/2
> -7Δ/2
3
2
1
0
-1
-2
-3
-4
Coding
b2
b1
b0

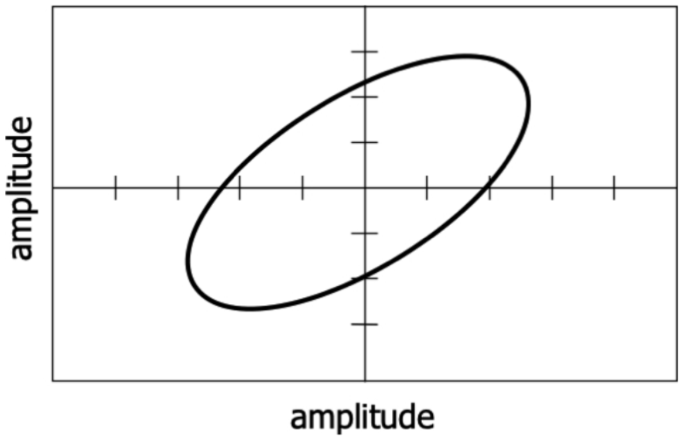
Oscilloscope:
visualization

- **x-t display** (voltage per division vs time per division)
  - Time base

- **x-y display** (voltage per division vs voltage per division)
  - Implicit time variable



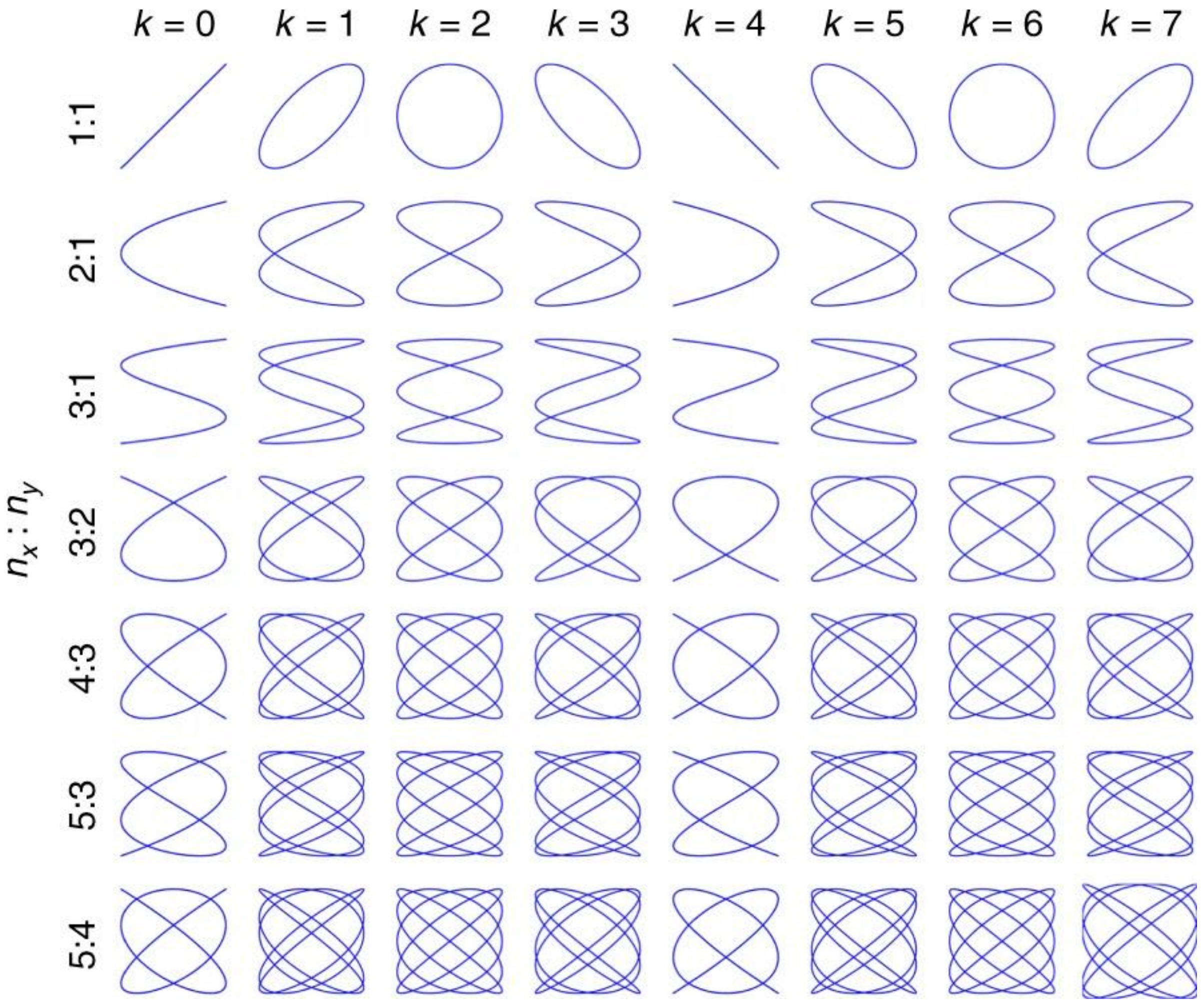
(a) amplitude versus time display



(b) XY display

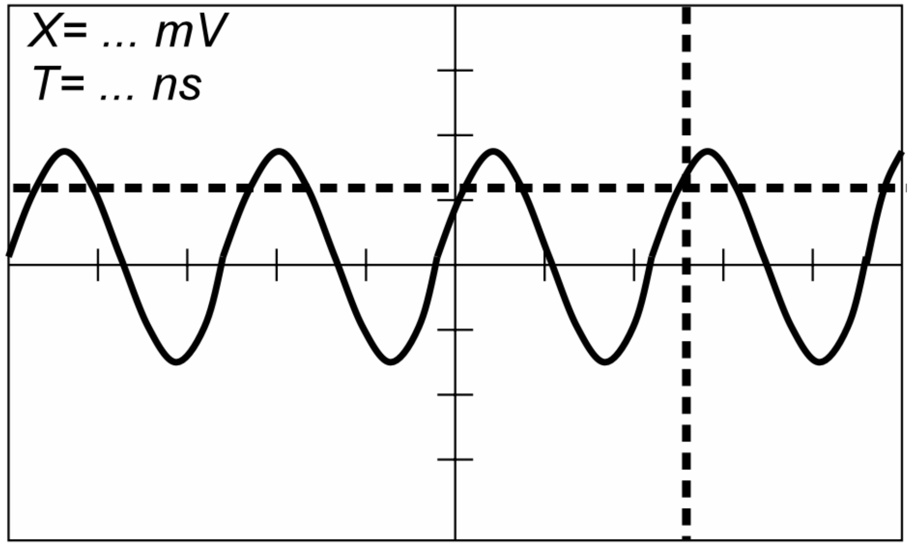
Oscilloscope:
visualization

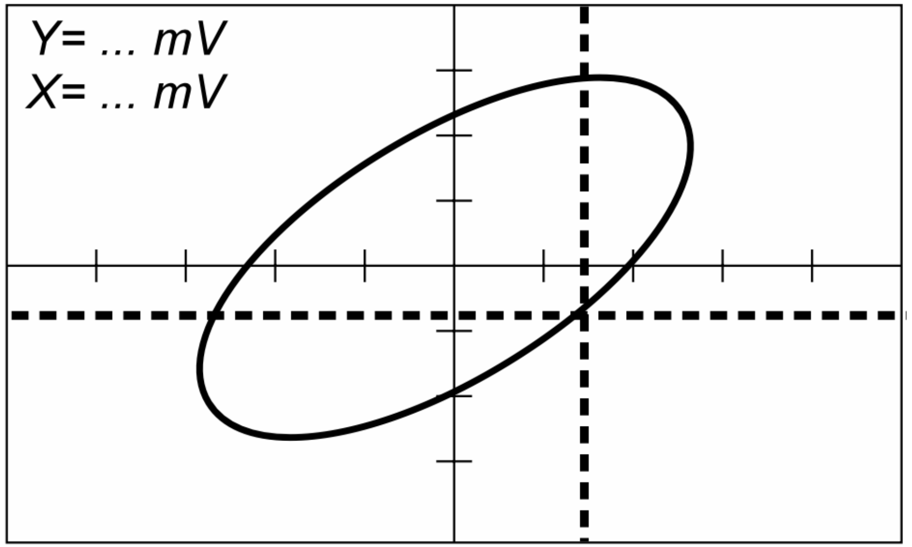
Lissajous curves



Oscilloscope:
visualization

- **Grid** (divisions)
- **Cursors**
- **Scale factors** (voltage per division, time per division)





Oscilloscope:
Measurement accuracy

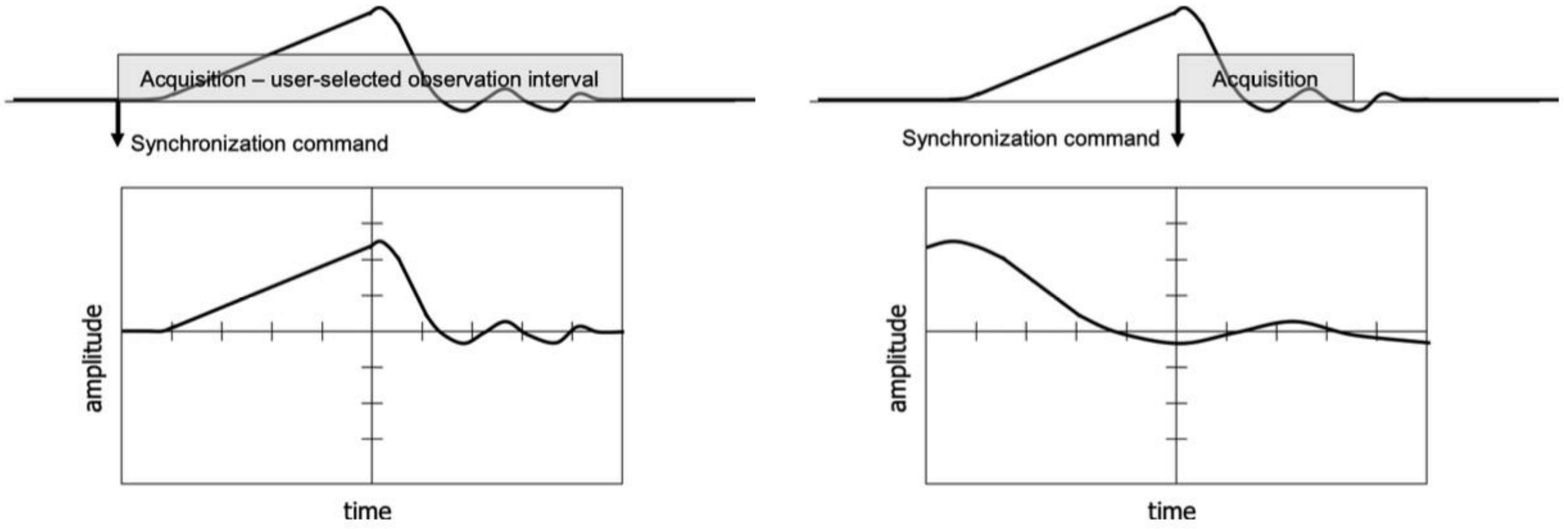
- **Amplitude uncertainty:**
    - **Lower bound → ADC resolution**
    - 2^b quantization levels for a b bit ADC
    - **Input range** → height of the oscilloscope grid
    - **Uncertainty: 1/ 2^b of the full scale value** → lower than 1%
    - **Noise and calibration uncertainty** → around 1%

- **Time base uncertainty:**
    - Reciprocal of the **instrument memory depth**: N samples → 1/N uncertainty
    - Further limited by graphical resolution → 600 x 1000 pixels, 1/1000 resolution
    - **Clock uncertainty**

Oscilloscope:
Operating cycle

- **Horizontal scale factor** → set observation interval length
- **Vertical scale factor** → set the amplitude scale
- **Trigger** → Synchronize signal acquisition

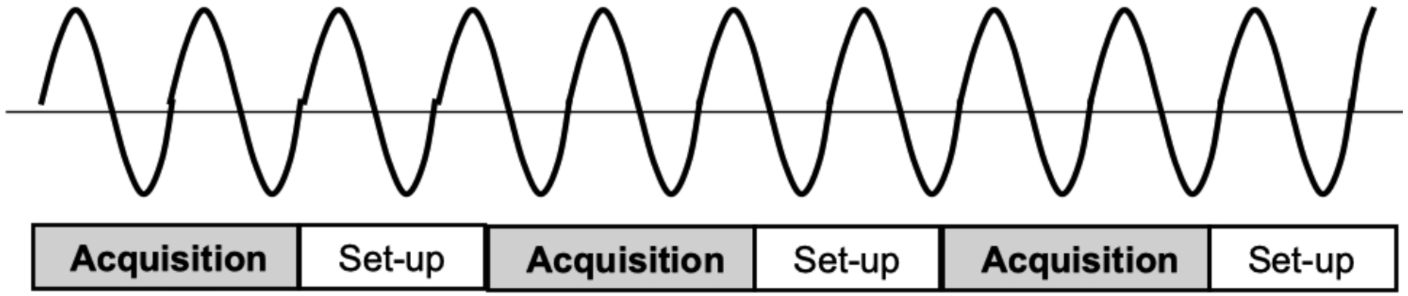
Non repetitive signal → acquisition is triggered by a synchronization command

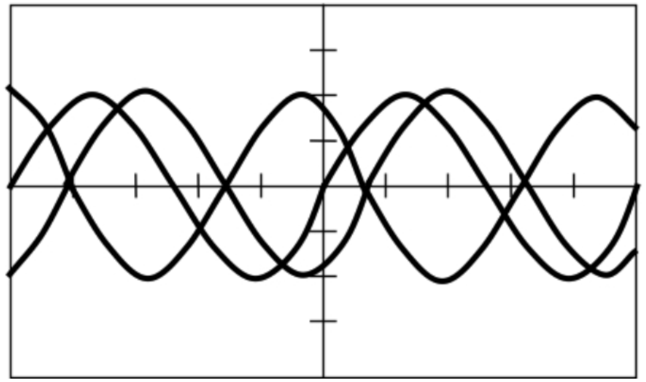


Oscilloscope:
Operating cycle

Periodic signal → trace constantly updated

- **Acquisition phase** t_A
- **Setup-up phase** t_B
  - Minimum interval = $t_A + t_B$

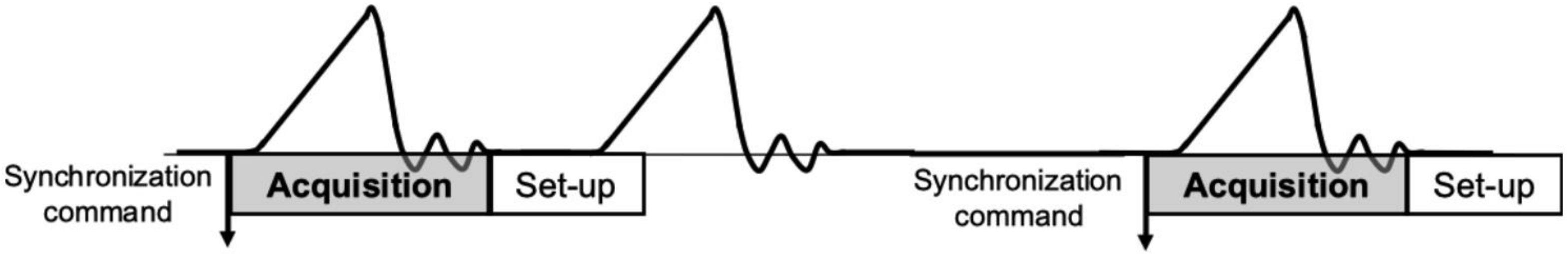




Oscilloscope:
Operating cycle

Periodic signal → trace constantly updated

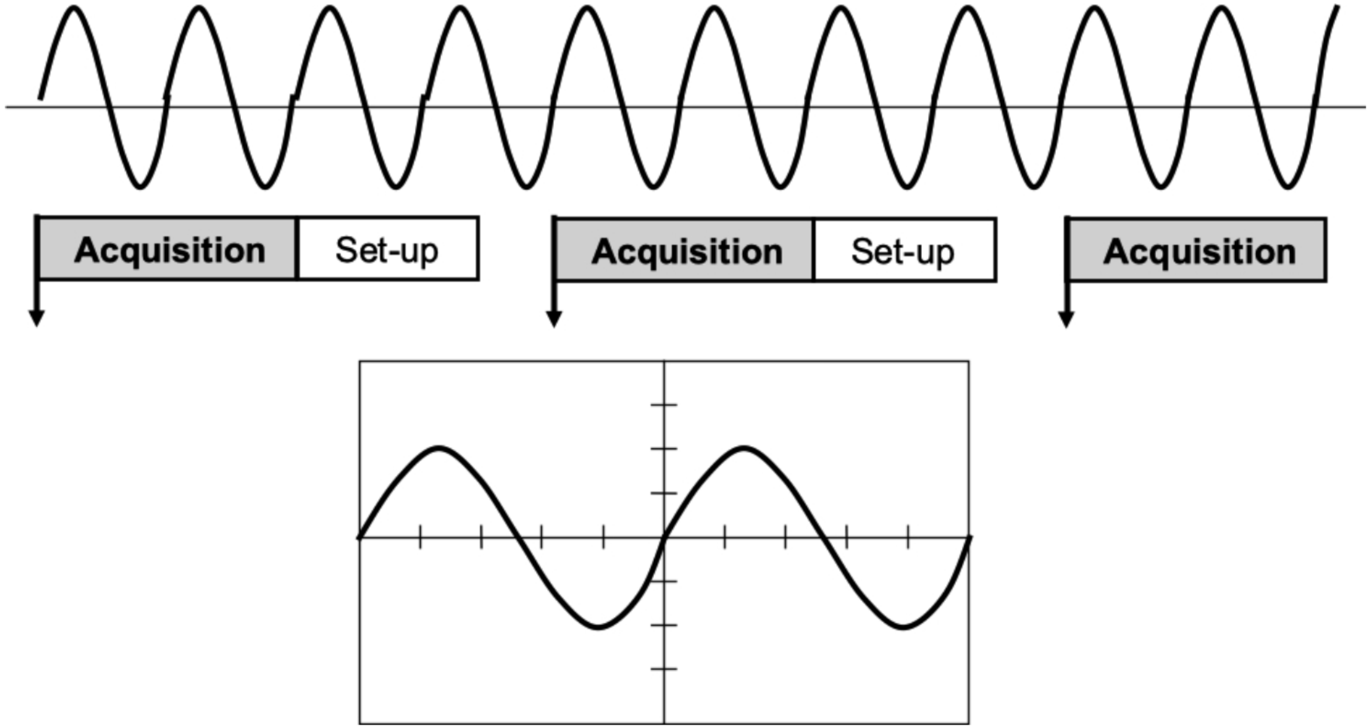
- **Acquisition phase** t_A
- **Setup-up phase** t_B
  - Minimum interval = $t_A + t_B$
- **Wait phase** t_c



Oscilloscope:
Operating cycle

Periodic signal → trace constantly updated

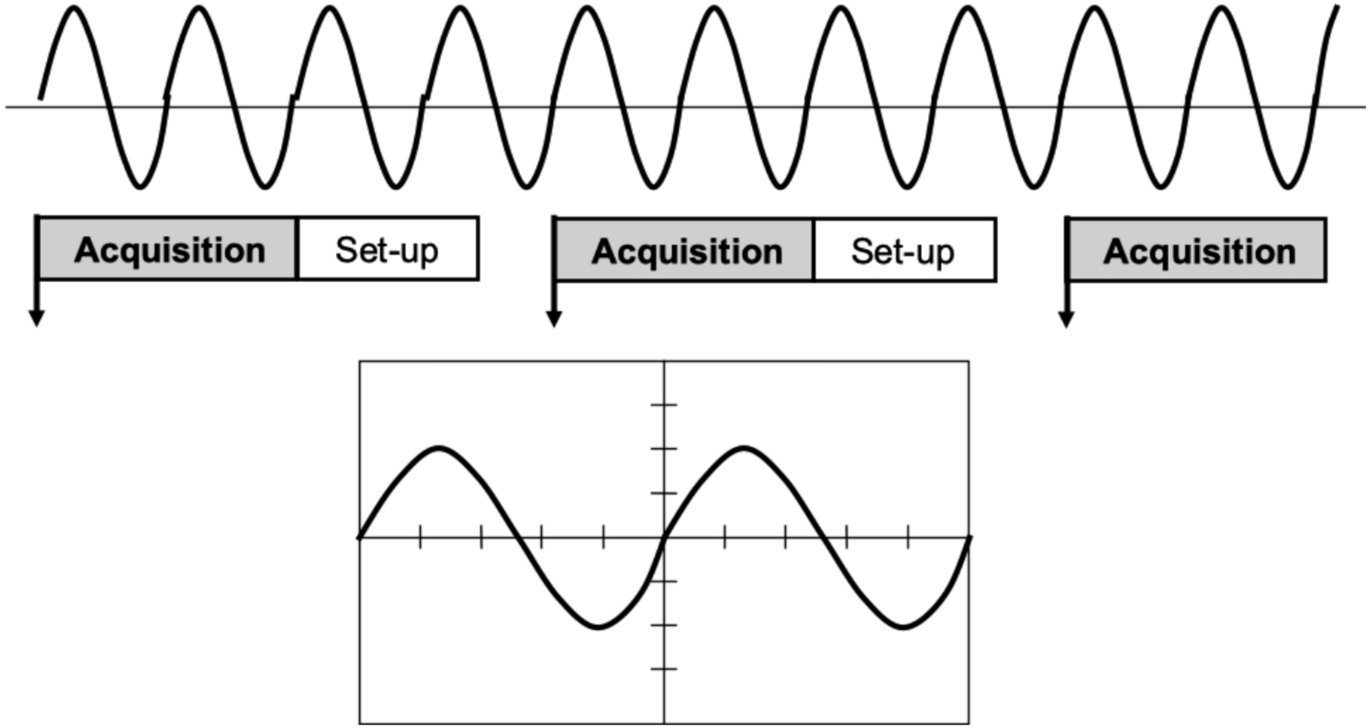
- **Acquisition phase** t_A
- **Setup-up phase** t_B
  - Minimum cycle length = $t_A + t_B$
- **Wait phase** t_c
  - Total cycle length = $t_A + t_B + t_C$
- **Signal period** T
  - $t_A + t_B + t_C = MT$ with $M \in \mathbf{Z}$



Oscilloscope:
Operating cycle

Periodic signal → trace constantly updated

- **Signal period** T
  - $t_A + t_B + t_C = MT$ with $M \in \mathbf{Z}$
- **Trace update rate**
  - $1/ t_A + t_B + t_C$
- **Acquisition efficiency**
  - $0 < t_A / t_A + t_B + t_C < 1$



Signal generator

Signal generator

- **Test inputs for measurements**
- **Different waveforms** according to the specific test

- **Analog signals** → different waveforms (multi-sine combinations)
- **Digital signals** → transitions between two levels

- **Linear systems → Sinewaves**
  - Same frequency as the input
  - Different amplitude and phase

Signal generator

- **Sinewave generator**
  - Adjustable amplitude and frequency
  - Low harmonic content
  - Stable output frequency
  - Stable output amplitude
  - Limited number of low level spurious components

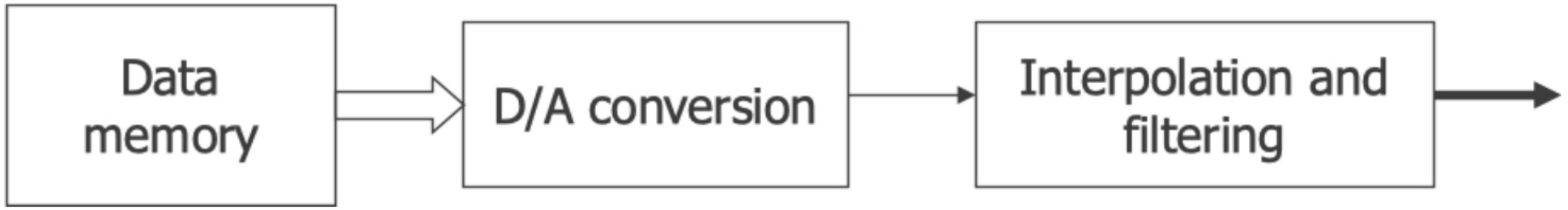
- **Specialized laboratory equipment**

Signal generator

- **Waveform generator**
  - **Different generable signals**: sinusoidal, triangular, square and ramp waveforms

- More flexibility, less accuracy…

- **Sampling Shannon theorem** → continuous-time reconstruction (band limited signal)
- **Digital Samples → Analog samples → Interpolation - Low-pass filtering**



Signal generator

- **Arbitrary Waveform Generator (AWG)**
  - Signal stability
  - Good frequency and amplitude resolution
  - Low harmonic distortion
  - Easy generation of complex waveforms

  - **Digital memory** for the writing of samples related to arbitrary waveforms
  - **Common waveforms stored permanently** → faster standard operations (changing amplitude and frequency)

Signal generator

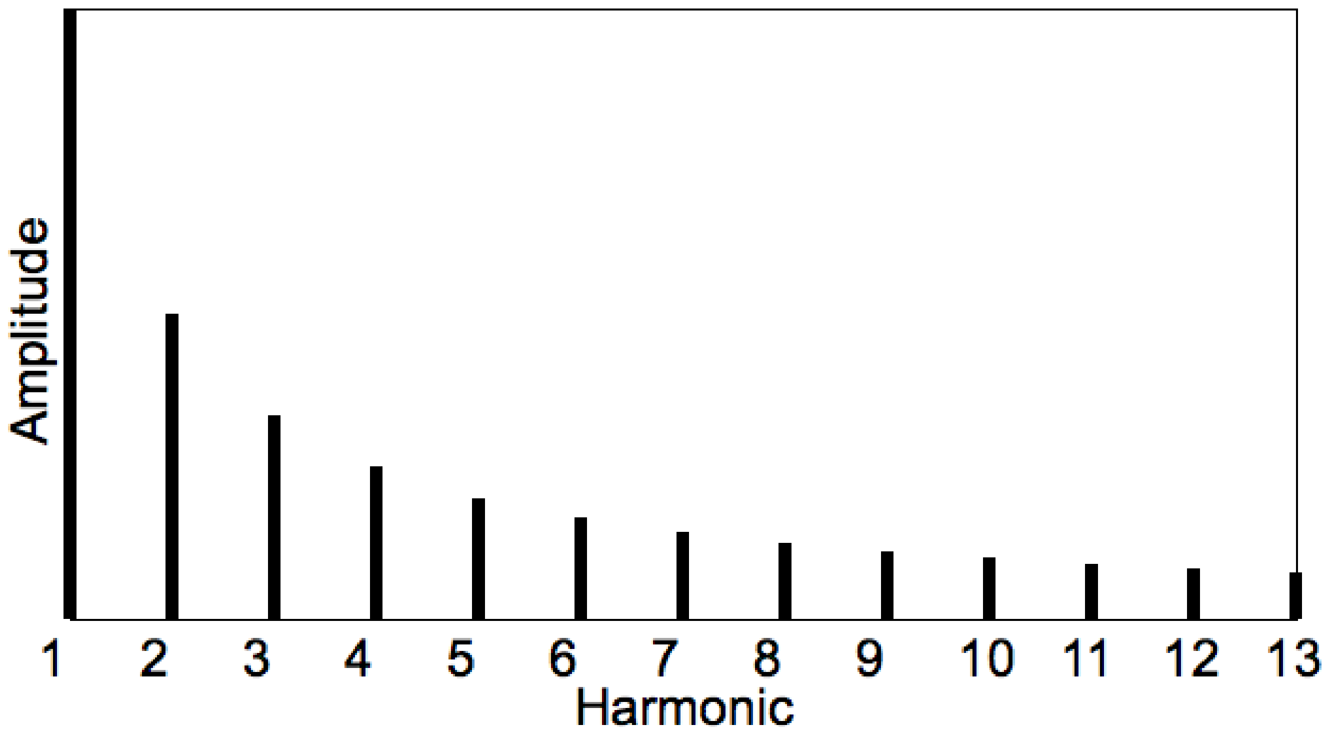
- **Arbitrary Waveform Generator (AWG)**
  - Voltage source
  - 50 Ω output impedance → adaptation to the characteristic impedance of coaxial cables
  - Actual voltage indication only in case of maximum power transfer ($R_G = R_L$)

  - Connection of an AWG to the oscilloscope → **High impedance load**

Test waveforms

Sinewave

- **Spectrum composed of a single spectral line** (with its frequency image)
- Possible harmonic components



Test waveforms

Sinewave

- **Spectrum composed of a single spectral line** (with its frequency image)
- Possible harmonic components
- **Total Harmonic Distortion (THD)**: typical values < -70 dB

$$\frac{\sqrt{V_{RMS\_2}^2 + V_{RMS\_3}^2 + \cdots}}{V_{RMS\_1}}$$

- **Signal to Noise and Distortion (SINAD)**: typical values > 70 dB

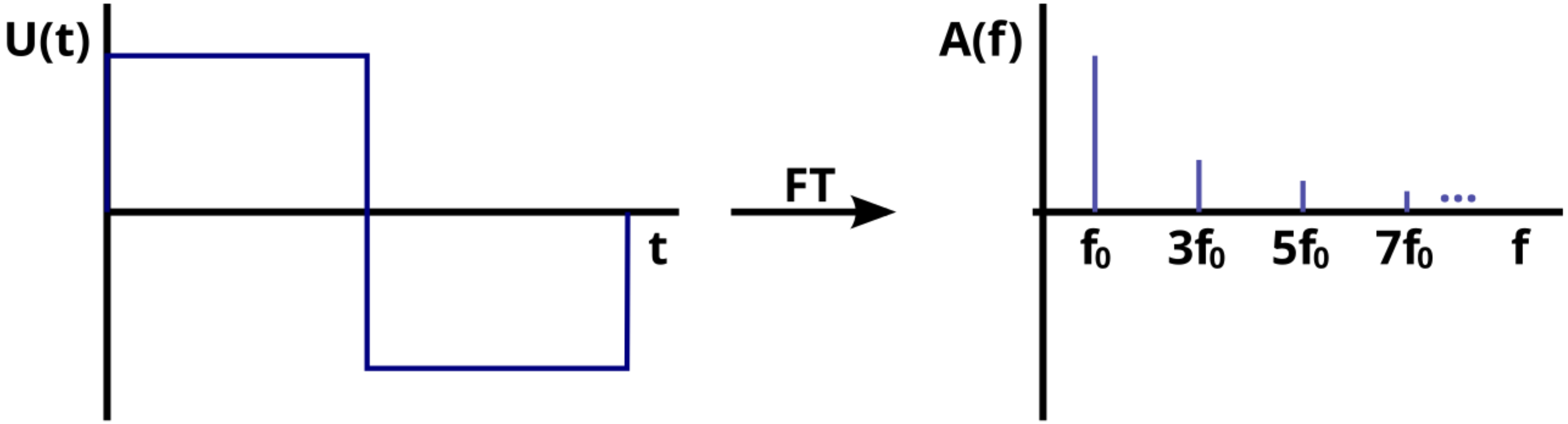
$$\frac{V_{RMS\_1}}{\sqrt{V_{RMS\_2}^2 + V_{RMS\_3}^2 + \cdots + N}}$$

Test waveforms

Square Wave

- Spectral lines at the **fundamental frequency and its integer multiples** (harmonics)
- Fundamental frequency and harmonic components at **odd multiples**

$$\left|\frac{A_k}{A_1}\right| = \begin{cases} \frac{1}{k} & \text{for } k \text{ odd} \\ 0 & \text{for } k \text{ even} \end{cases}$$



Test waveforms

Square Wave

- Spectral lines at the **fundamental frequency and its integer multiples** (harmonics)
- Fundamental frequency and harmonic components at **odd multiples**

$$\left|\frac{A_k}{A_1}\right| = \begin{cases} \dfrac{1}{k} & \text{for } k \text{ odd} \\ 0 & \text{for } k \text{ even} \end{cases}$$

- Asymmetries in the lengths of level → duty cycle D not 50%

$$\left|\frac{A_k}{A_1}\right| = \frac{1}{k}\frac{\sin \pi k D}{\sin \pi D}$$

- In general D ≅ 0.5 → $\mathrm{D} = \frac{1}{2}(1 + 2\delta)$

$$\left|\frac{A_k}{A_1}\right| = \begin{cases} \dfrac{1}{k} & \text{for } k \text{ odd} \\ \pi\delta & \text{for } k \text{ even} \end{cases}$$

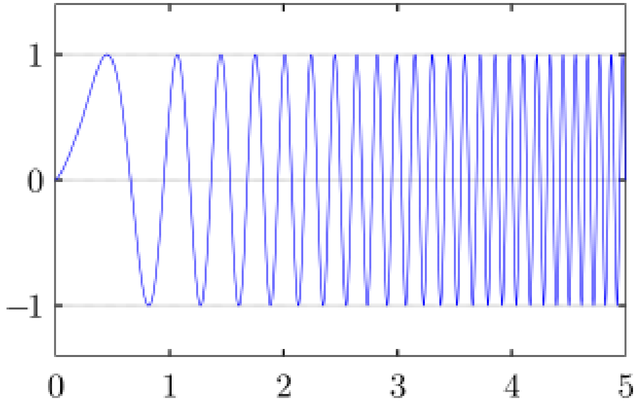
Test waveforms

Frequency sweep or chirp

- **Sinewave whose frequency varies linearly with time in a certain interval**

$$f(t) = f_1 + \frac{f_2 - f_1}{T_{sweep}} t \quad \text{with } 0 \leq t \leq T_{sweep}$$

- Spectrum with constant amplitude for $f_1 \leq f \leq f_2$
- Measuring the **system response G(f)** for a certain frequency interval. |Y(f)| proportional to |G(f)|



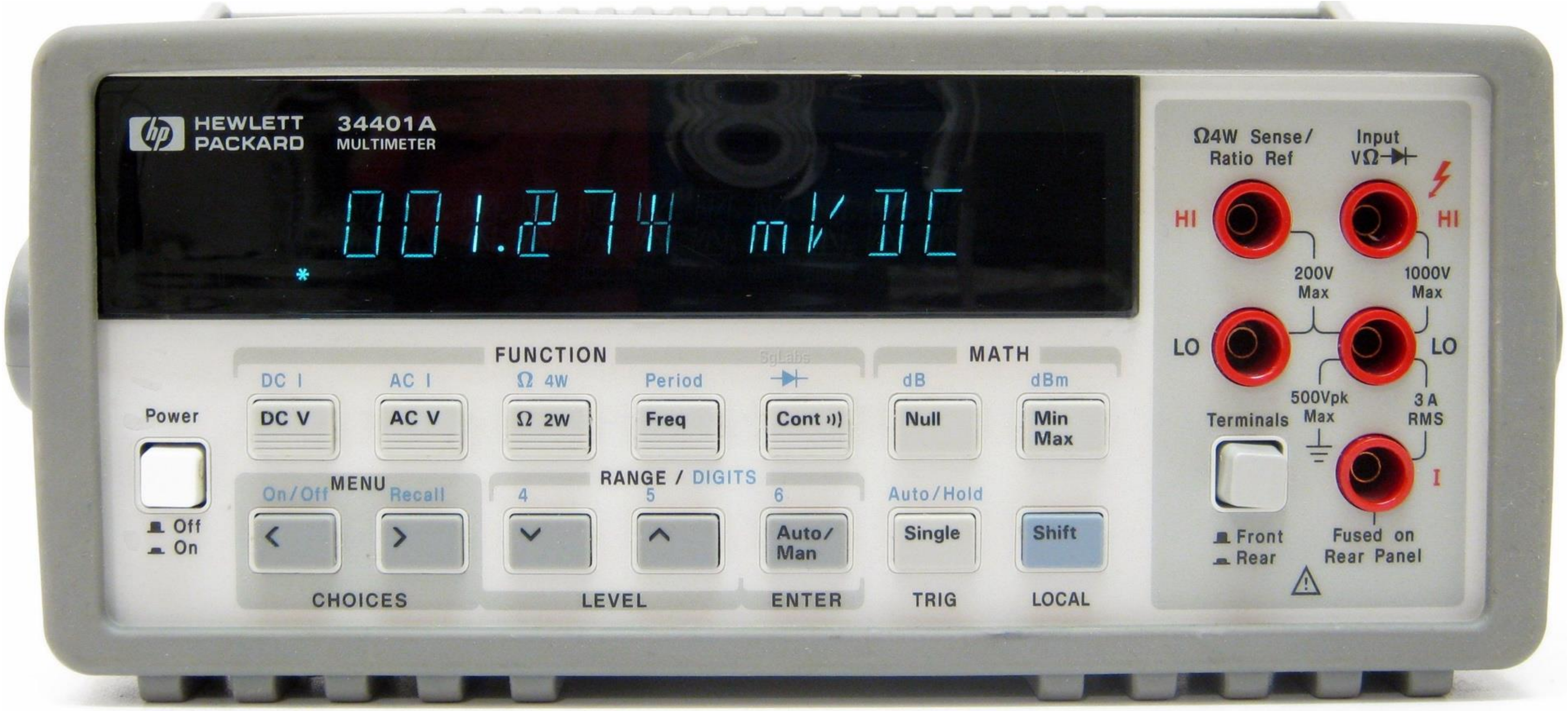
Test waveforms

Synchronization output

- **Two levels signal**: the rising edge of a steep transition coincides with the start of a signal period
- Zero mean sinewave → Zero crossing
- Maximum possible slope

- **‘Sync’ output → Oscilloscope ‘external trigger’**

Digital multimeter (DMM)



DMM

- **Measurements of:**
  - DC and AC voltage
  - DC and AC current
  - Resistance
- High resolution ADC (up to 24 bits or higher)
- **3 or 5 inputs**
  - Positive voltage
  - Negative voltage
  - Current
  - Ω-sense terminal
- Different measurement ranges

DMM resolution

- **Resolution:** *smallest change in a quantity being measured that causes a perceptible change in the corresponding indication*
- ±1 variation in the least significant digit
- Same quantity of the measured quantity → same measurement unit

- **Relative resolution**

$$\frac{\Delta_X}{X_M}$$

$$\frac{\Delta_X}{X_{FS}}$$

DMM number of digits

- **Resolution → Number of digits → Uncertainty**
- D decimal digits → $10^D - 1$ maximum displayed value → $\frac{1}{10^D}$ resolution relative to full scale
- 4-digit DMM → 10^{-4} resolution relative to full scale value
- Typical full scale values: (0.3, 3, 30, 300), (0.2, 2, 20, 200)
- Still D digits, but the the most significant is not employed to display the maximum value
- $(D-1)+\frac{1}{2}$ DMMs (e.g., $3^1/_2$, $5^1/_2$, $6^1/_2$, $8^1/_2$)

DC voltage measurements

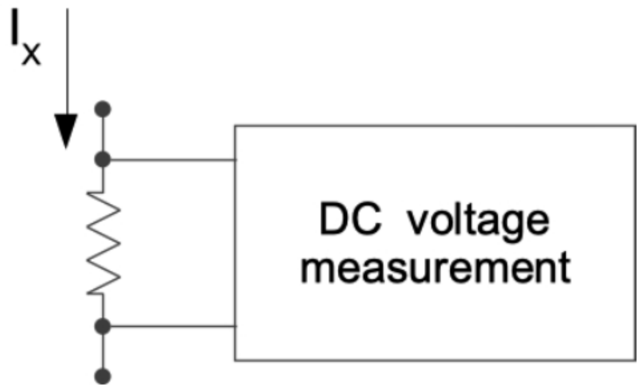
- **Wide range of values** → attenuators/amplifiers
- **Autorange**
- **Input resistance** R_{in} = 10 MΩ
- **Differential** input configuration with floating ground
- **Offset errors** → offset compensation
- **Autozero** (Active by default)

DC current measurements

- **Current shunt**

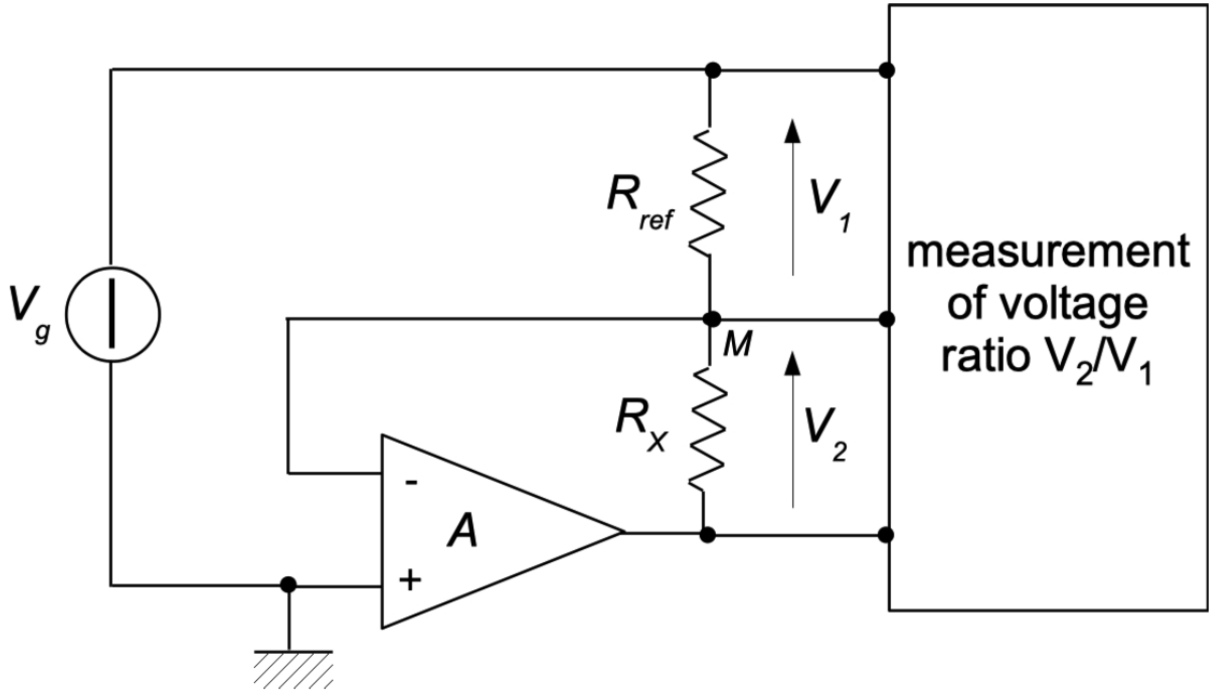
$$I_M = \frac{V_M}{R_{shunt}}$$

- Interruption of a circuit line
- Shunt resistance **as low and as constant as possible**



Resistance measurements

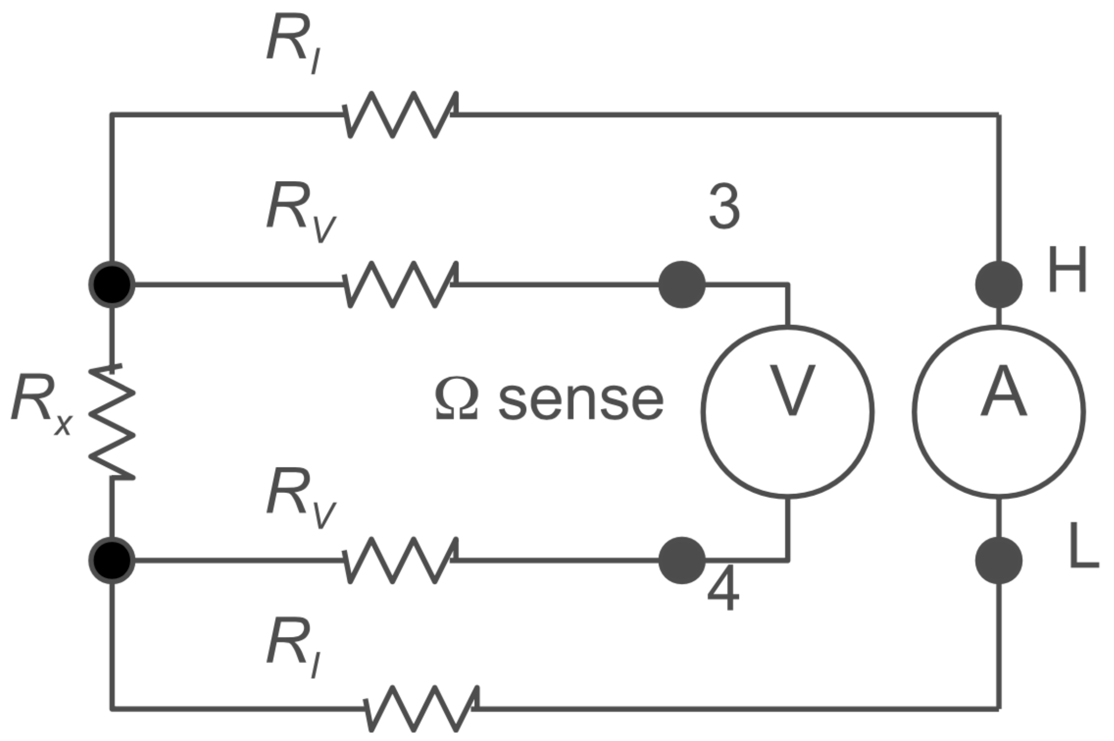
- **Test current injection**



$$R_X = \frac{V_1}{V_2} R_{ref}$$

4-wire resistance measurements

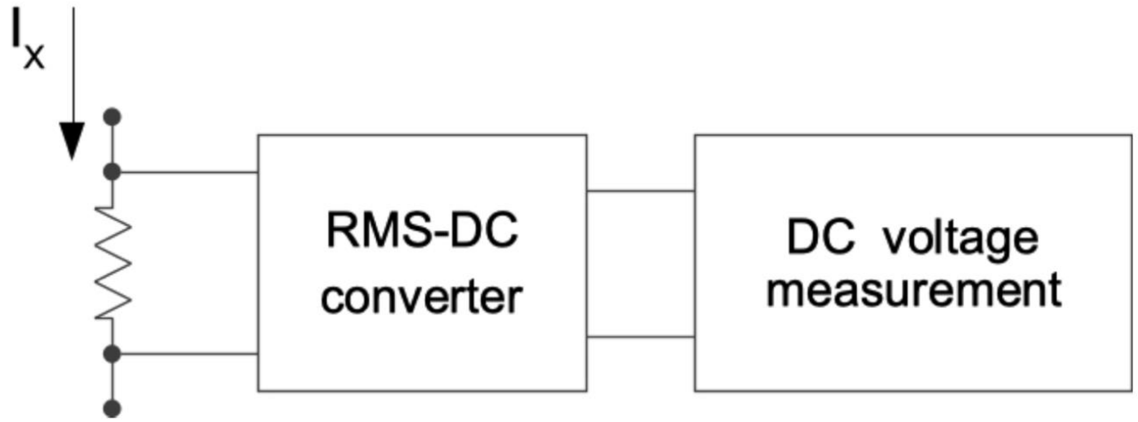
- Avoiding the effects of **contact and conductor resistances** (some tens of mΩ)



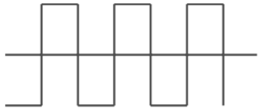
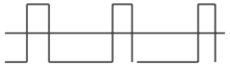
$$R_X = \frac{V_{34}}{I_{HL}} \text{ with } I_{34} = 0$$

AC measurements

- AC voltage and current **Root Mean Square (RMS) value**
- Value of a corresponding DC voltage or current that produces the same **active power** on a resistor
- AC-coupled multimeter
- Other parameters:
  - Peak value X_{PK}
  - Conventional mean value X_M
  - Form Factor (FF) → X_{RMS}/X_M
  - Crest Factor (CF) → X_{PK}/X_{RMS}



AC measurements

$x(t)$				D = duty cycle 
X_{RMS}	$\frac{A_0}{\sqrt{2}}$	$\frac{A_0}{\sqrt{3}}$	A_0	$2A_0\sqrt{D(1-D)}$
X_m	$\frac{2A_0}{\pi}$	$\frac{A_0}{2}$	A_0	$4A_0[D(1-D)]$
X_{pk}	A_0	A_0	A_0	$2A_0\left(\frac{1}{2}+\lvert D-\frac{1}{2}\rvert\right)$
FF	$\frac{\pi}{2\sqrt{2}} \simeq 1.11$	$\frac{2}{\sqrt{3}} \simeq 1.15$	1	$\frac{1}{2\sqrt{D(1-D)}}$
CF	$\sqrt{2}$	$\sqrt{3}$	1	$\frac{\frac{1}{2}+\lvert D-\frac{1}{2}\rvert}{\sqrt{D(1-D)}}$

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