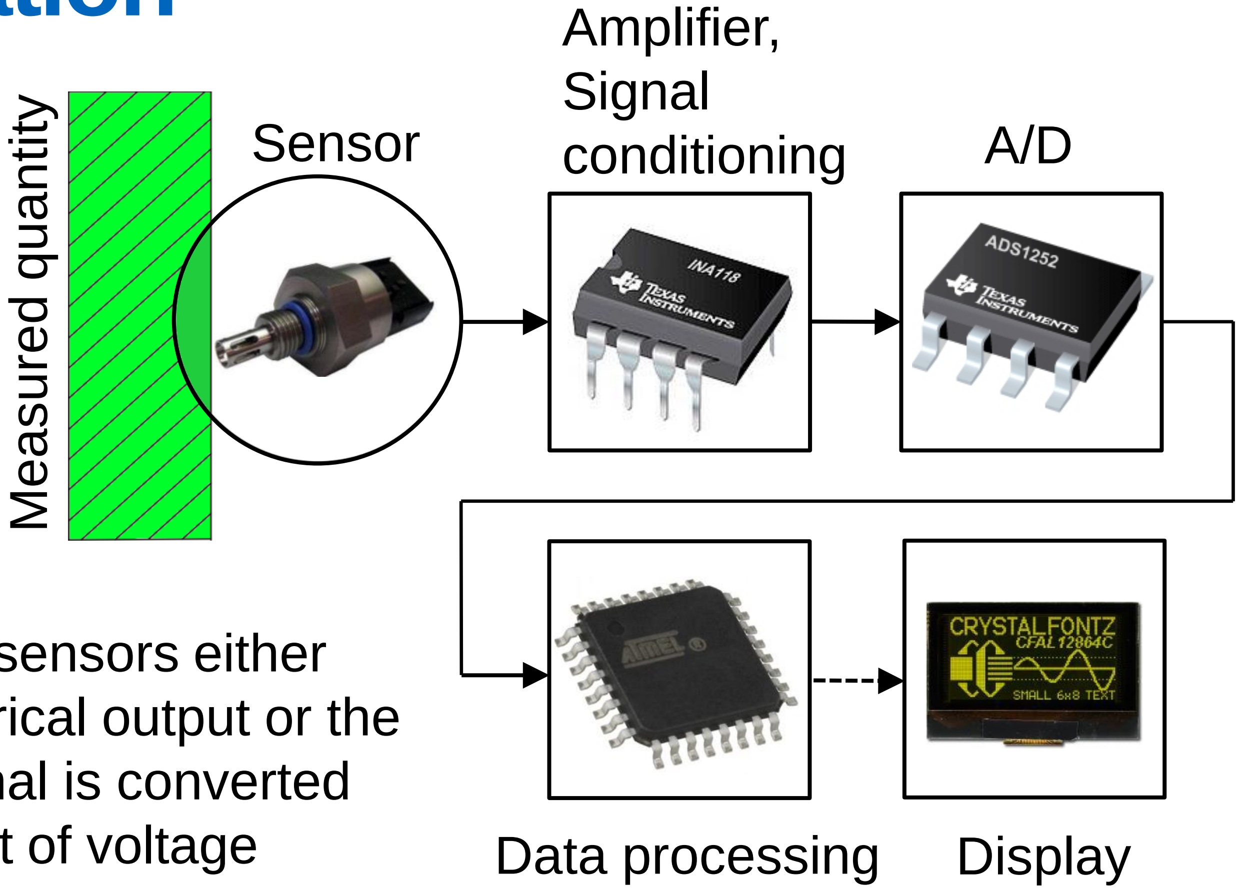
Aalto University

Electrical measurements

ELEC-E5710 - Sensors and Measurement Methods

Motivation



Measured quantity

Sensor

Amplifier, Signal conditioning

A/D

Data processing

Display

Almost all sensors either have electrical output or the output signal is converted into current of voltage

Content

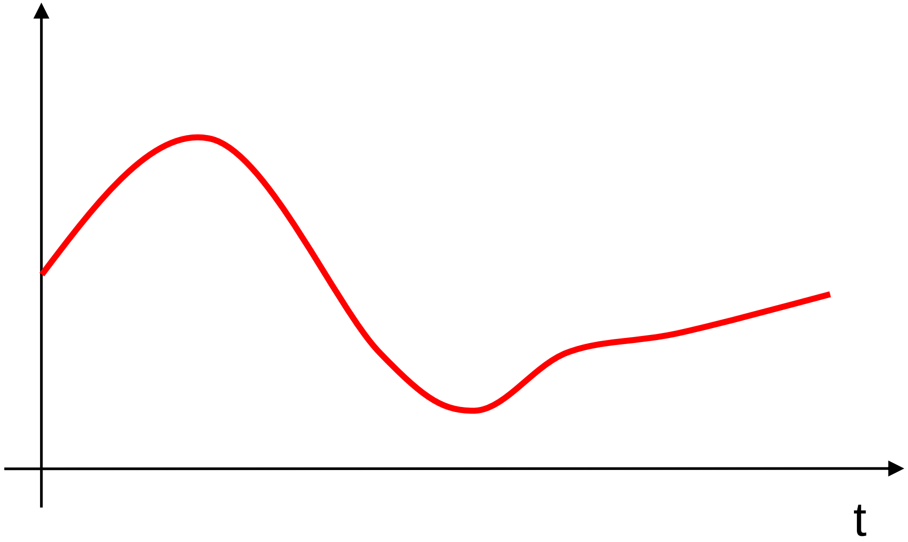
- **Voltage measurements**
  - Analog-to-digital conversion, voltage references
- **Current measurements**
  - Current-to-voltage conversion, current sense transformers
- **Resistance measurement**
  - Basic measurements, bridge circuits, linearization
- **Capacitance and inductance measurement**
  - Rise-time, attenuation based, bridge circuit, resonance, oscillation frequency

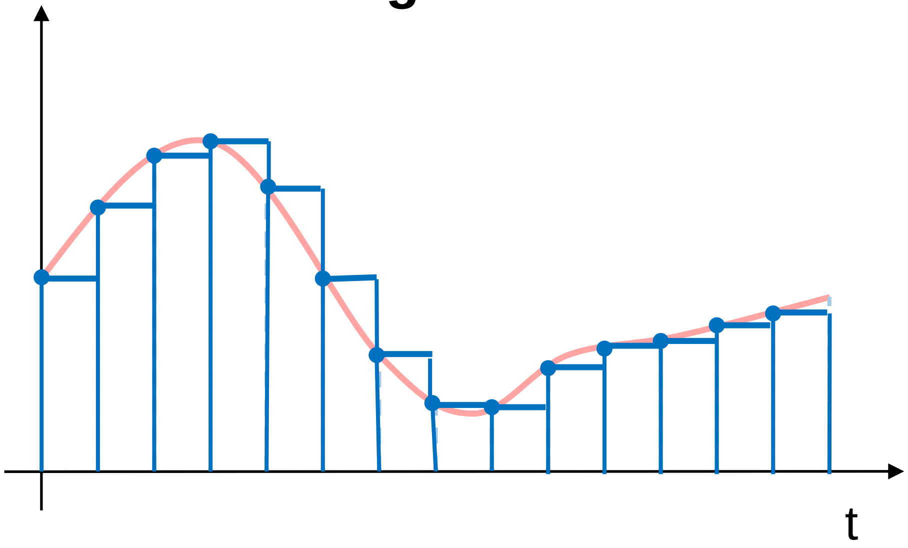
Handbook of Modern Sensors: chapter 5
Sensor Technology Handbook: chapter 4

Voltage measurements

Analog-to-digital conversion

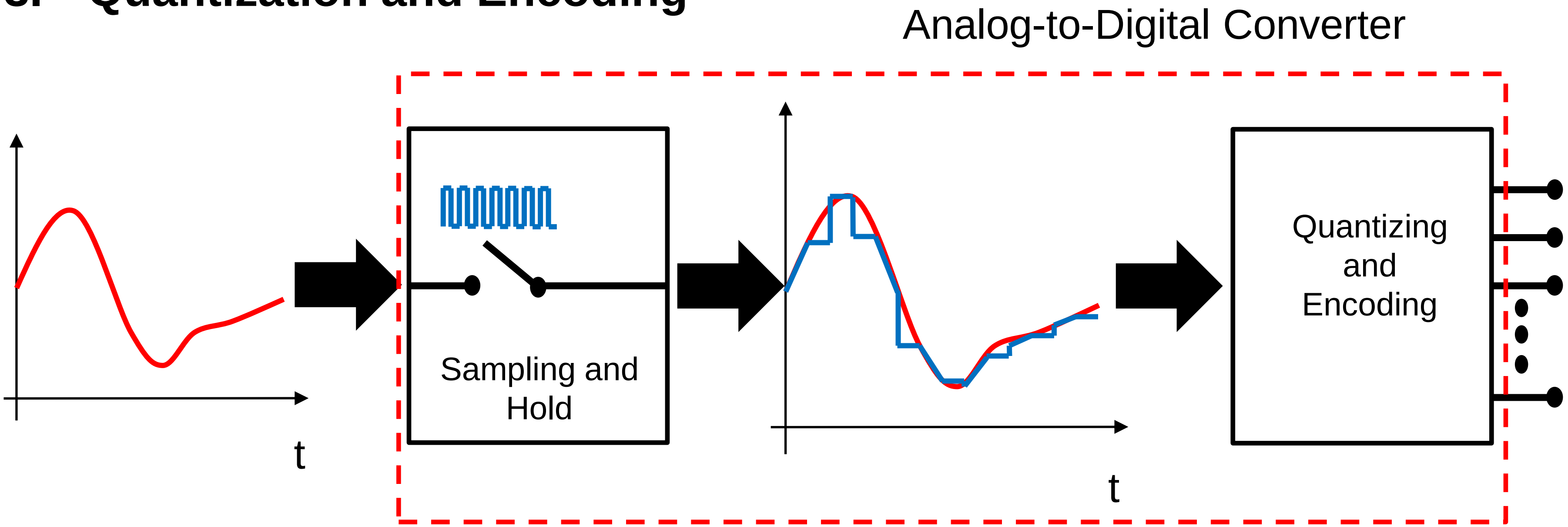
- Converting a signal from analog (continuous) to digital (discrete) form
- Link between the analog world of transducers and the digital world of signal processing and data handling





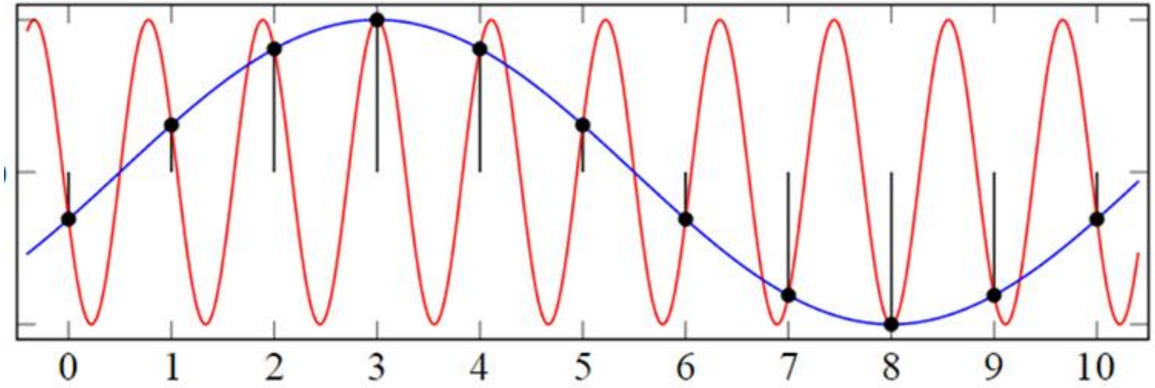
Main steps

1. **Signal conditioning:** amplification, filtering
2. **Sampling and holding**
3. **Quantization and Encoding**



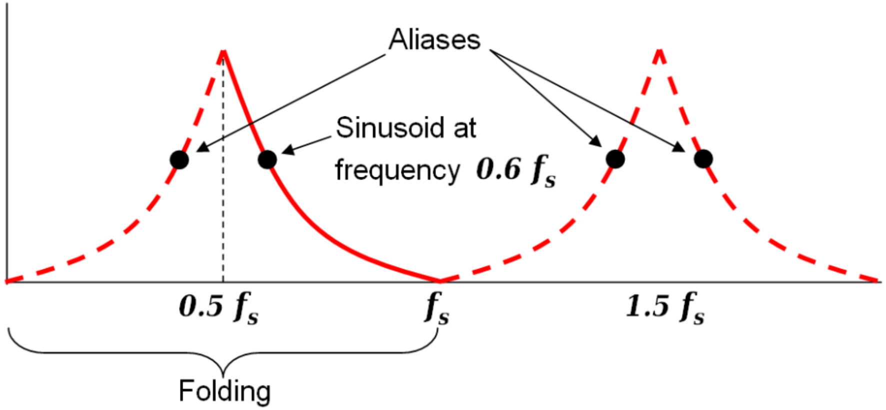
Sampling frequency

- **Nyquist sampling theorem**
  - Sampling frequency must be twice the maximum frequency component of the function being sampled
  - Otherwise harmful folding occurs
  - Anti-aliasing filter must be used before the converter

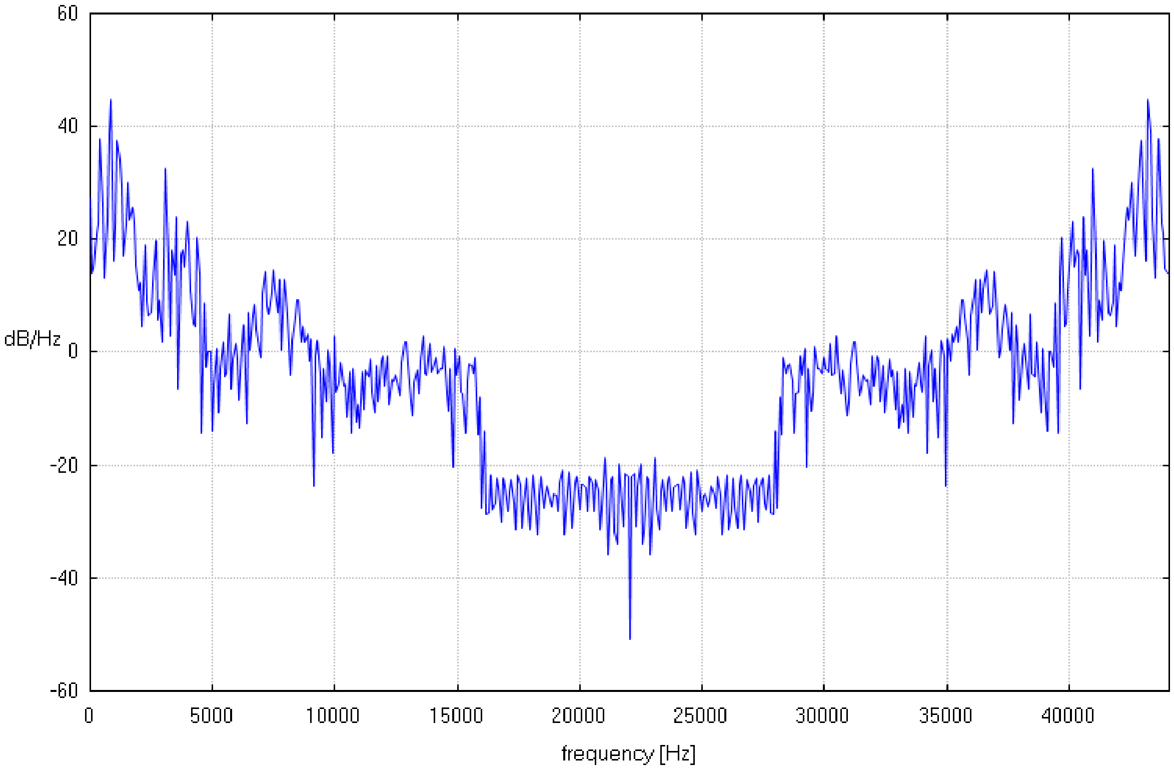


Aliasing and folding

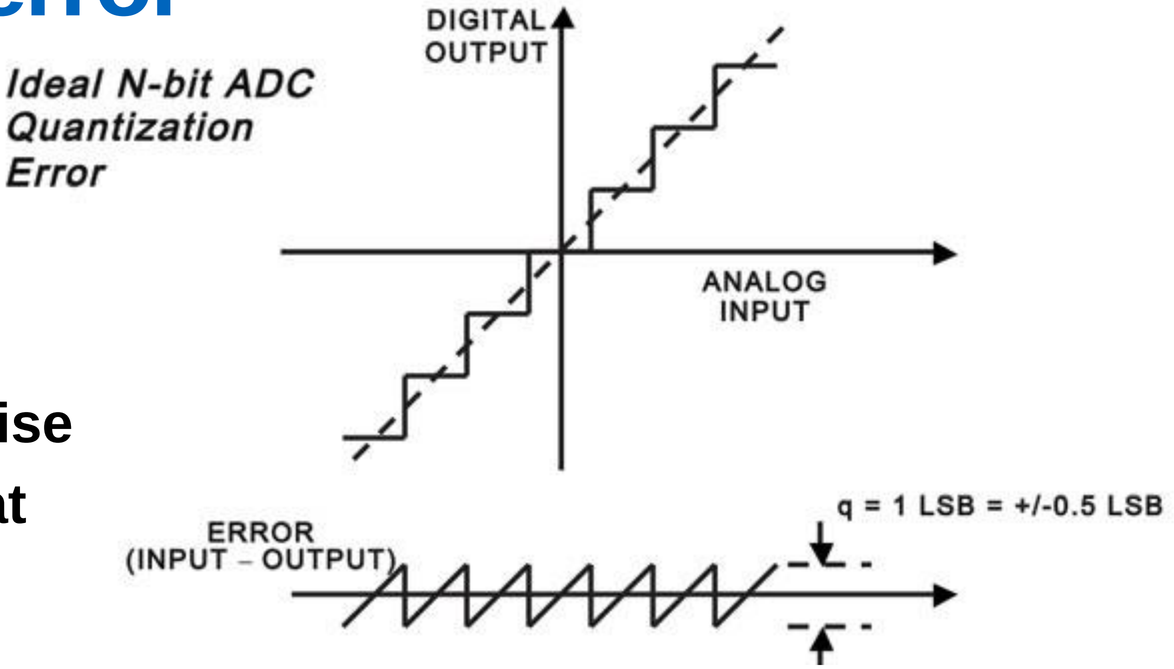
- **For sampling frequency *f*$_s$, all sinusoidals with the form** $\sin(2\pi(f+Nf_s)\,t+\varphi)$ **produce and identical set of samples**
  - $N = 0, \pm 1, \pm 2, \pm 3\ldots$
- **A sinusoidal signal having the frequency *f* has an infinite set of alias signals with freqencies** $|f+Nf_s|$
- **Folding of signal around** $0.5{*}f_s$, $1.5{*}f_s$, $2.5{*}f_s\ldots$
- **Signal must be limited to frequency range below** $f_s/2$
  - In practice: components above $f_s/2$ must be small



Fourier transform of audio signal sampled at 44.1 kHz

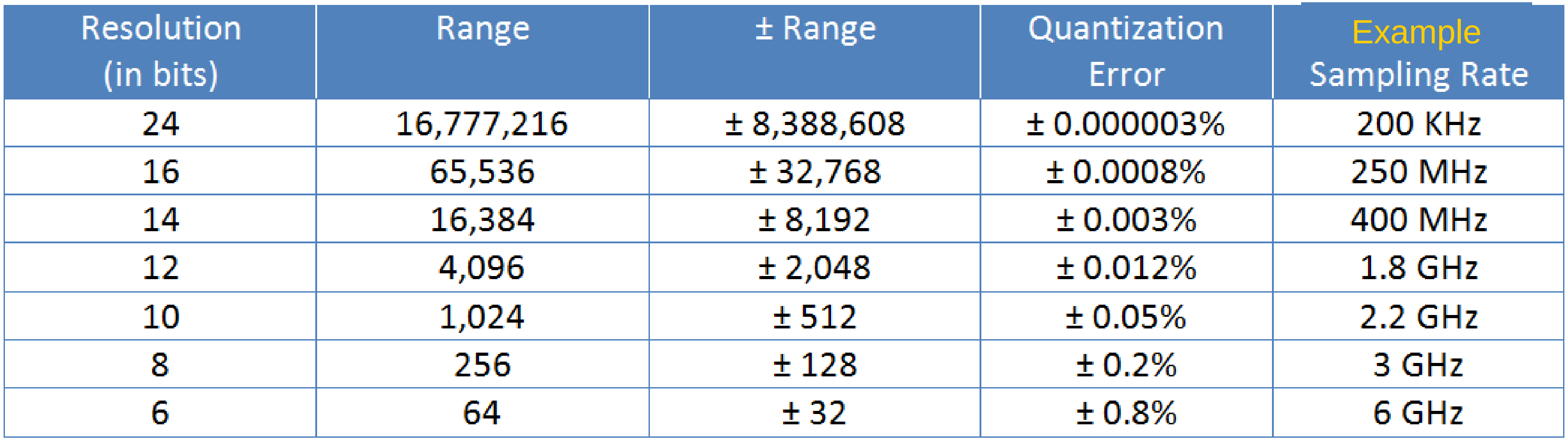


Quantization error



- Limited number of bits is seen as uniformly distributed error
- Effectively white noise
- Sinusoidal wave that utilized the whole dynamic range has $SNR = 20\log(2^N) + 1.76\ (\text{dB}) = 6.02N + 1.76\ (\text{dB})$
- Additional (analog) noise sources limit the practical SNR
  - Effective number of bits (noise free resolution) is smaller

Resolution and dynamic range



Resolution (in bits)	Range	± Range	Quantization Error	Example Sampling Rate
24	16,777,216	± 8,388,608	± 0.000003%	200 KHz
16	65,536	± 32,768	± 0.0008%	250 MHz
14	16,384	± 8,192	± 0.003%	400 MHz
12	4,096	± 2,048	± 0.012%	1.8 GHz
10	1,024	± 512	± 0.05%	2.2 GHz
8	256	± 128	± 0.2%	3 GHz
6	64	± 32	± 0.8%	6 GHz

- **For N bits, the dynamic range is given as $20 \cdot \log 2^N$ dB ≈ $6.02 \cdot N$ dB**

HMCAD5831LP9BE

v03.0818

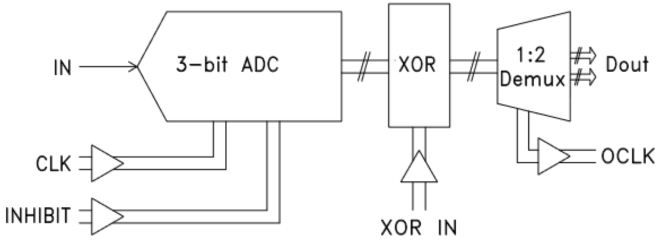
3-BIT 26 GSPS ANALOG-TO-DIGITAL CONVERTER W/ OVERRANGE, INHIBIT, AND 1:2 DEMUX

Typical Applications

The HMCAD5831LP9BE is ideal for:

- Ultra Wideband Phased Arrays
- Radio Astronomy
- Serial Data Links
- Test Equipment for Link Diagnostics
- Spectrometers

Functional Diagram



Features

- 20 GHz Input Bandwidth
- Full Flash Architecture with Ultra-Low Latency
- Over/Under Range Bit
- Data Inhibit Function
- Data XOR Function
- 1:2 Demux Output
- Programmable Differential CML Output Swing
- 64 Lead Plastic 9 x 9 mm SMT Package: 81 mm²

General Description

The HMCAD5831LP9BE is a wideband 3-bit analog-to-digital converter with over/under range bit. The converter operates at typical speeds of up to 26 GSPS under typical conditions with a Nyquist input. Reference ladder end voltages are set externally by the user allowing the user to customize input common mode and swing levels. ADC outputs can be forced to

AK5522

Differential Input Stereo 32-bit ΔΣ ADC with Excellent PSRR

1. General Description

The AK5522 is a 32-bit, from 8kHz to 192kHz sampling A/D converter for line and microphone inputs of digital audio systems. It achieves 108dB dynamic range and 98dB S/(N+D) while keeping low power consumption performance. Four types of digital filters are integrated and selectable according to the sound quality preference.

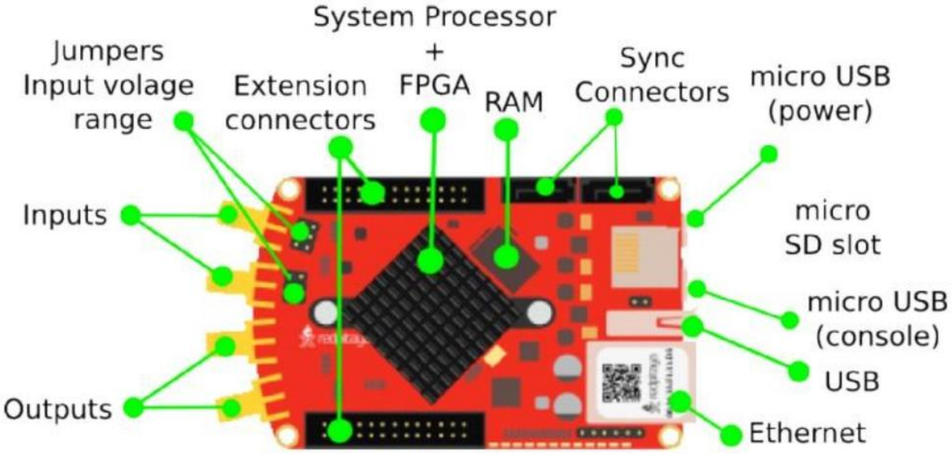
The AK5522 has great power supply rejection ratio, (PSRR), and common mode rejection ratio, (CMRR), enabling to maintain sufficient characteristics when connecting USB bus power or DCDC converter output as a power supply. It is suitable for applications with noisy power supply such as USB audio interface, wireless speakers and car audio equipment.

In addition, the AK5522 integrates a regulator with high PSRR for DAC power supply. Using the AK5522 with a DAC such as the AK4432 or the AK4452, it is enable to bring maximum DAC performance even in a poor power supply condition. Moreover, the AK5522 integrates low-jitter PLL circuit that generates a master clock for DAC from LRCK or BICK. It provides a low-EMI solution by avoiding unnecessary drawing of the master clock that has high frequency, on the board.

The AK5522 helps reducing components and a mounting space with these features for environmental noise.

STEMLab 125-14

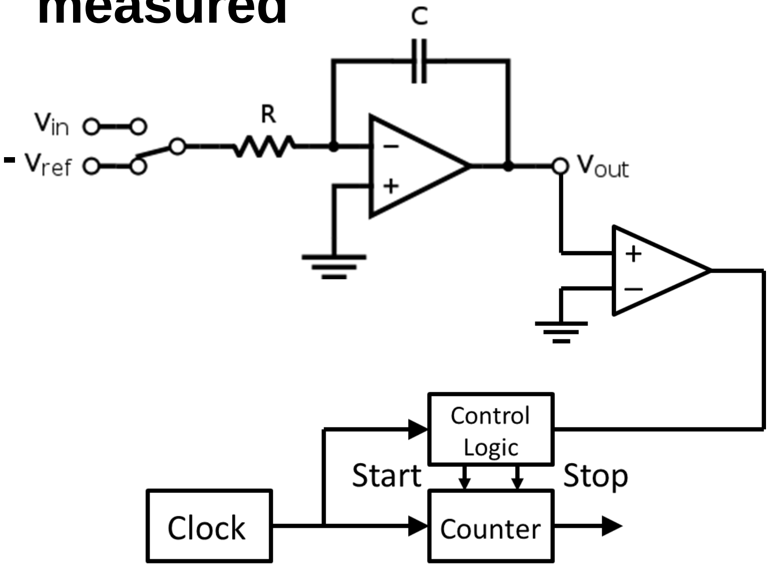
		STEMLAB 125-14
RF inputs	RF input channels	2
	Sample rate	125 MS/s
	ADC resolution	14 bit
	Input impedance	1MOhm/10pF
	Full scale voltage range	+-20 V
	Absolute max. Input voltage range	30V
	Input ESD protection	Yes
	Overload protection	Protection diodes

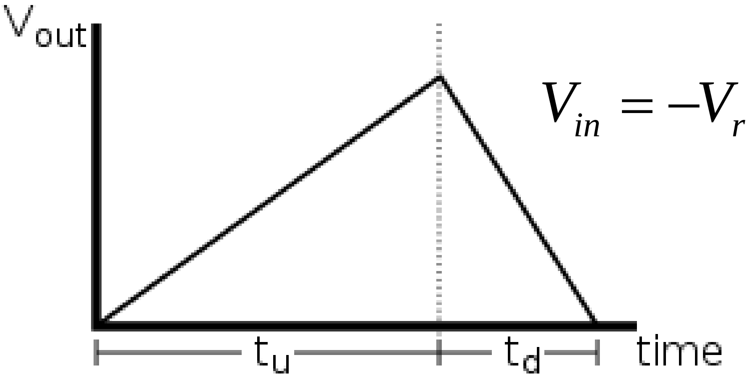


Different types of analog-to-digital converter

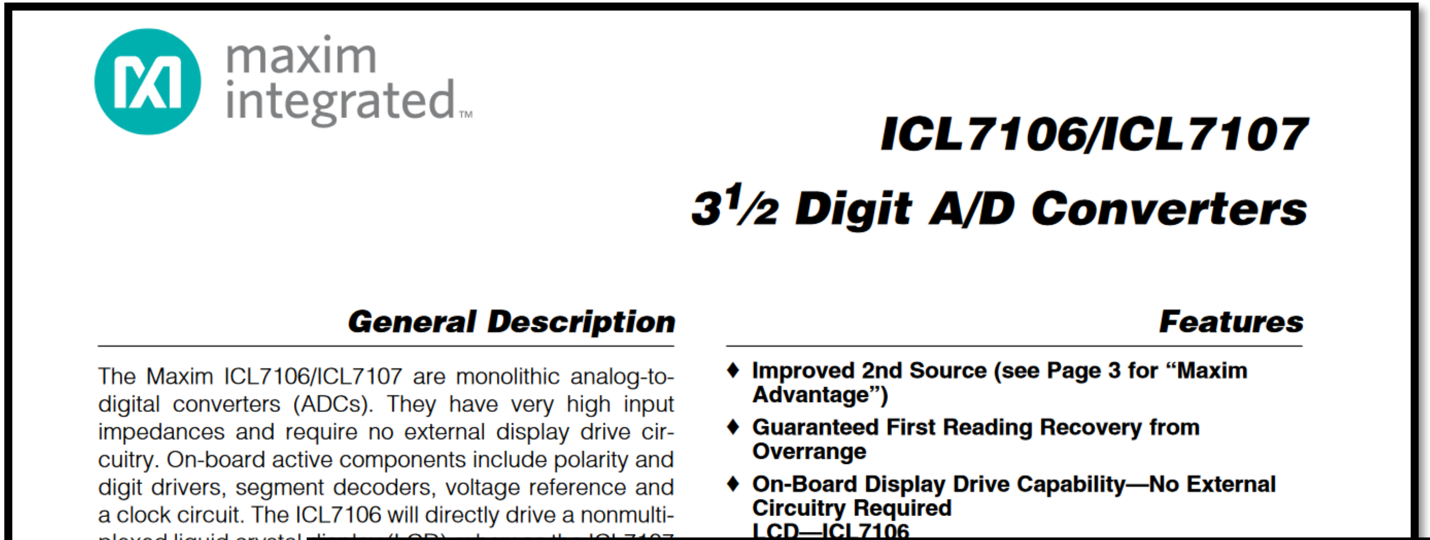
Dual Slope Converter

- **High resolution, linear, accurate, limited bandwidth (DC signals)**
- **Input signal is integrated for fixed time t_u**
- **Discharge with known opposite polarity V_{ref}, discharge time measured**





$$V_{in} = -V_{ref}\frac{t_d}{t_u}$$



maxim integrated

ICL7106/ICL7107

3½ Digit A/D Converters

General Description

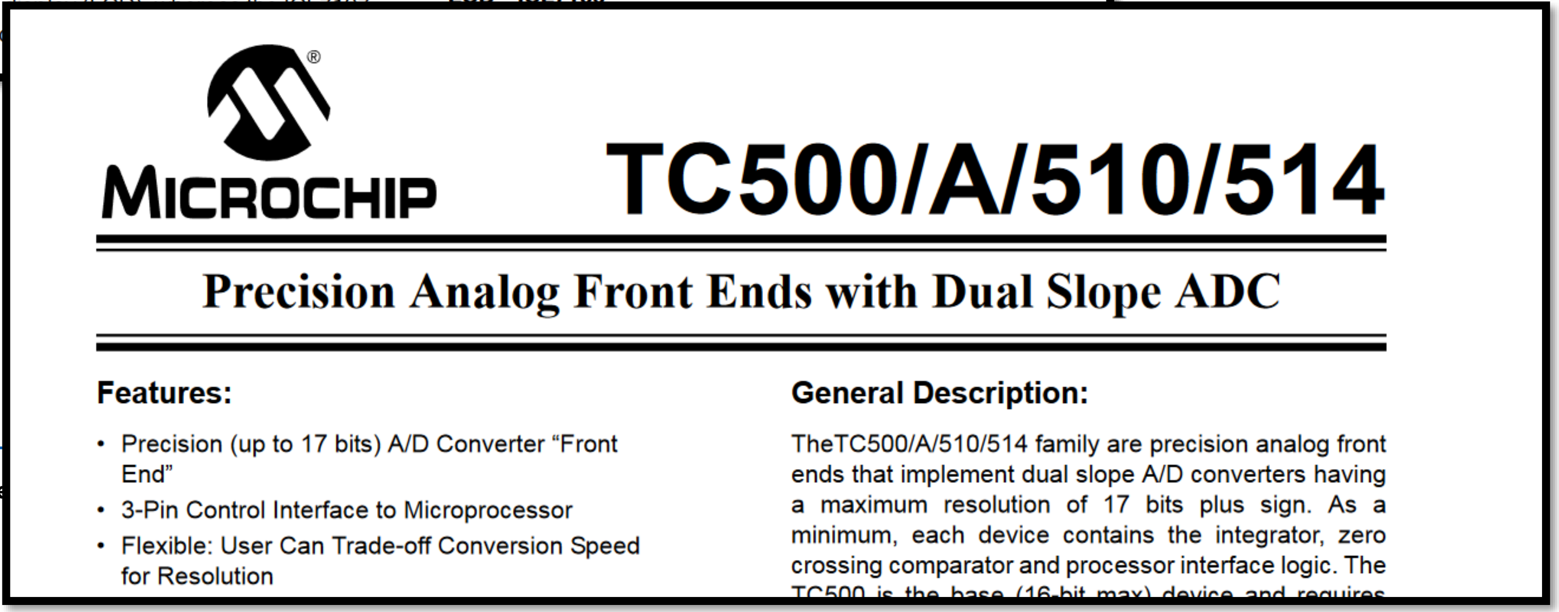
The Maxim ICL7106/ICL7107 are monolithic analog-to-digital converters (ADCs). They have very high input impedances and require no external display drive circuitry. On-board active components include polarity and digit drivers, segment decoders, voltage reference and a clock circuit. The ICL7106 will directly drive a nonmultiplexed liquid crystal

will directly drive a

(LED) display.

Features

- **Improved 2nd Source (see Page 3 for "Maxim Advantage")**
- **Guaranteed First Reading Recovery from Overrange**
- **On-Board Display Drive Capability—No External Circuitry Required**
  LCD—ICL7106



MICROCHIP

TC500/A/510/514

Precision Analog Front Ends with Dual Slope ADC

Features:

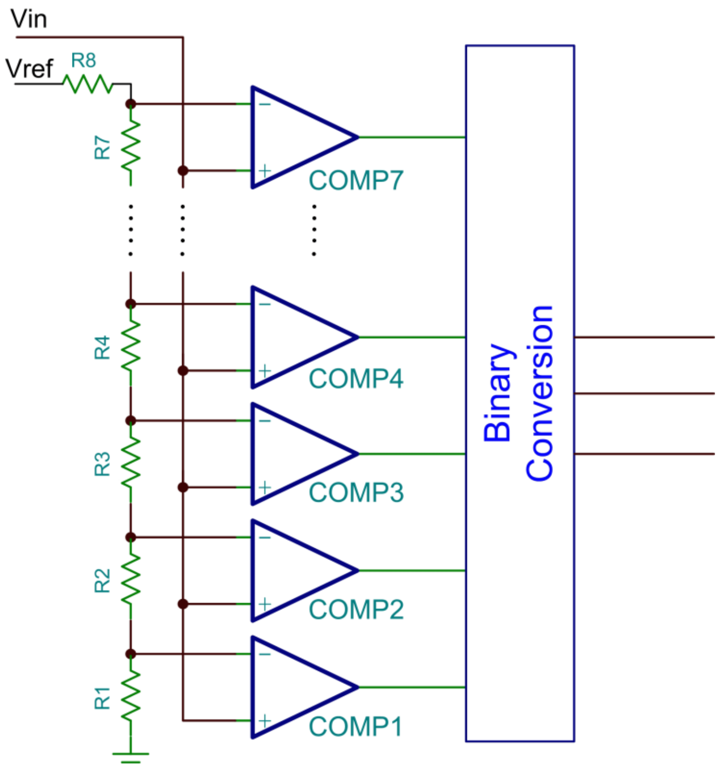
- Precision (up to 17 bits) A/D Converter "Front End"
- 3-Pin Control Interface to Microprocessor
- Flexible: User Can Trade-off Conversion Speed for Resolution

General Description:

TheTC500/A/510/514 family are precision analog front ends that implement dual slope A/D converters having a maximum resolution of 17 bits plus sign. As a minimum, each device contains the integrator, zero crossing comparator and processor interface logic. The

Flash Converter

- **Fastest available converter**
- **All bits are converted in parallel**
- **Encoding based on highest comparator acticating**
- **$2^N - 1$ comparators**
- **Expensive**
- **Limited number of bits**



8-Bit, 2.2Gsps ADC with Track/Hold Amplifier and 1:4 Demultiplexed LVDS Outputs

General Description

The MAX109, 2.2Gsps, 8-bit, analog-to-digital converter (ADC) enables the accurate digitizing of analog signals with frequencies up to 2.5GHz. Fabricated on an advanced SiGe process, the MAX109 integrates a high-performance track/hold (T/H) amplifier, a quantizer, and a 1:4 demultiplexer on a single monolithic die. The MAX109 also features adjustable offset, full-scale voltage (via REFIN), and sampling instance allowing multiple ADCs to be interleaved in time.

The innovative design of the internal T/H amplifier, which has a wide 2.8GHz full-power bandwidth, enables a flat-frequency response through the second Nyquist region. This results in excellent ENOB performance of 6.9 bits. A fully differential comparator design and decoding circuitry reduce out-of-sequence code errors (thermometer bubbles or sparkle codes) and provide excellent metastability performance (10^{14} clock cycles). This design guarantees no missing codes.

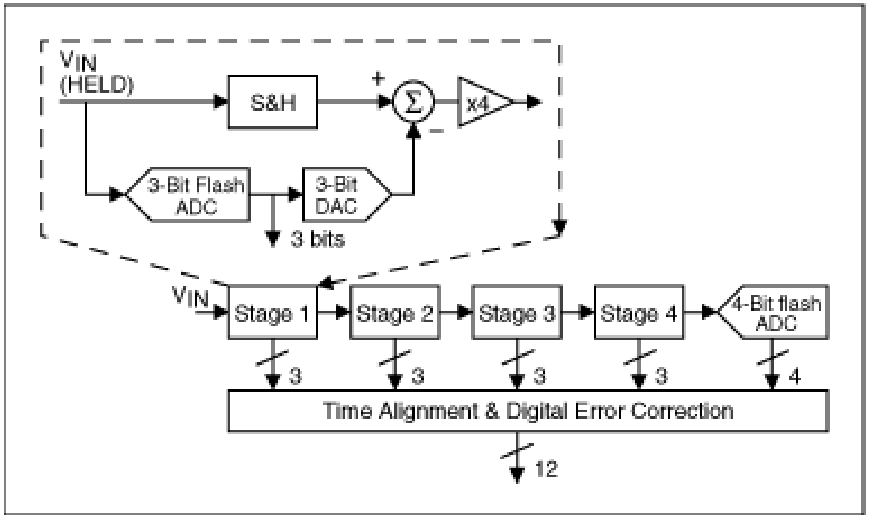
The analog input is designed for both differential and single-ended use with a 500mV$_{P-P}$ input-voltage range. The output data is in standard LVDS format, and is demultiplexed by an internal 1:4 demultiplexer. The

Features

- **Ultra-High-Speed, 8-Bit, 2.2Gsps ADC**
- **2.8GHz Full-Power Analog Input Bandwidth**
- **Excellent Signal-to-Noise Performance**
  - **44.6dB SNR at f_{IN} = 300MHz**
  - **44dB SNR at f_{IN} = 1600MHz**
- **Superior Dynamic Range at High-IF**
  - **61.7dBc SFDR at f_{IN} = 300MHz**
  - **50.3dBc SFDR at f_{IN} = 1600MHz**
  - **-60dBc IM3 at f_{IN1} = 1590MHz and f_{IN2} = 1610MHz**
- **500mV$_{P-P}$ Differential Analog Inputs**
- **6.8W Typical Power Including the Demultiplexer**
- **Adjustable Range for Offset, Full-Scale, and Sampling Instance**
- **50Ω Differential Analog Inputs**
- **1:4 Demultiplexed LVDS Outputs**
- **Interfaces Directly to Common FPGAs with DDR and QDR Modes**

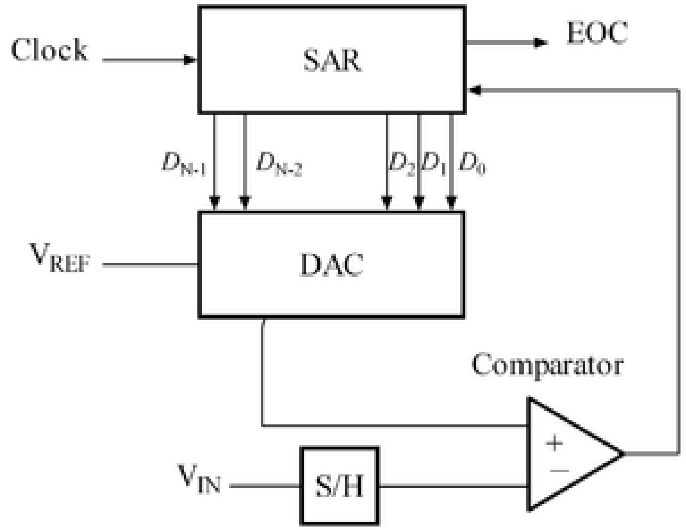
Pipeline Converter

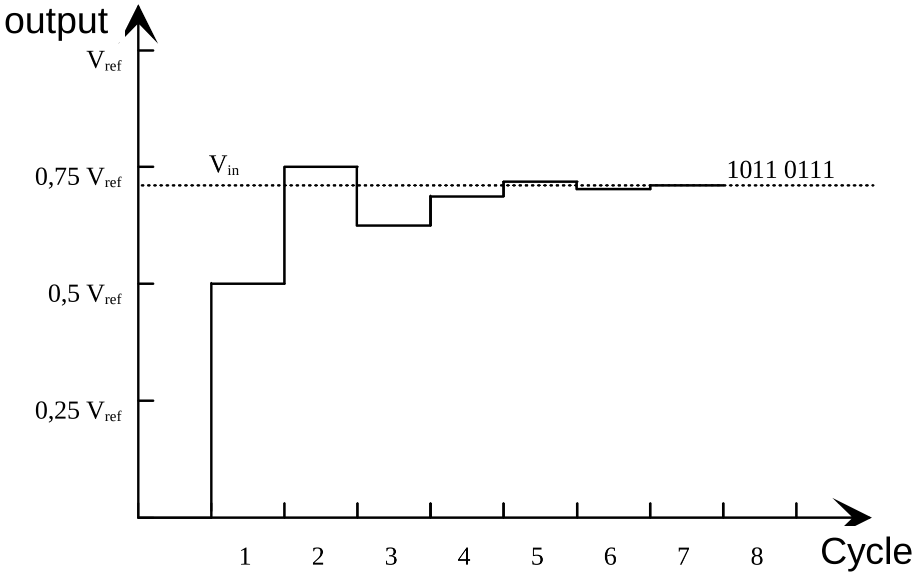
- First stage resolves first *N* bits
- Residual is calculated, multiplied and passed to next stage
- Pipeline: when a stage finishes processing a sample, it can then start processing the next sample



Successive approximation register (SAR)

- Iterative method to convert signal bit by bit, starting from most significant bit (MSB)
- Non-linearity issues, sensitive to electrical interference





LINEAR TECHNOLOGY

LTC2344-18

Quad, 18-Bit, 400ksps/ch Differential SoftSpan ADC with Wide Input Common Mode Range

FEATURES

- **400ksps per Channel Throughput**
- **Four Simultaneous Sampling Channels**
- **±4LSB INL (Maximum, ±4.096V Range)**
- **Guaranteed 18-Bit, No Missing Codes**
- **Differential, Wide Common Mode Range Inputs**
- **Per-Channel SoftSpan Input Ranges:**
  ±4.096V, 0V to 4.096V, ±2.048V, 0V to 2.048V
  ±5V, 0V to 5V, ±2.5V, 0V to 2.5V
- **95dB Single-Conversion SNR (Typical)**
- **–114dB THD (Typical) at f_{IN} = 2kHz**
- **102dB CMRR (Typical) at f_{IN} = 200Hz**
- **Rail-to-Rail Input Overdrive Tolerance**
- Guaranteed Operation to 125°C
- Integrated Reference and Buffer (4.096V)
- SPI CMOS (1.8V to 5V) and LVDS Serial I/O

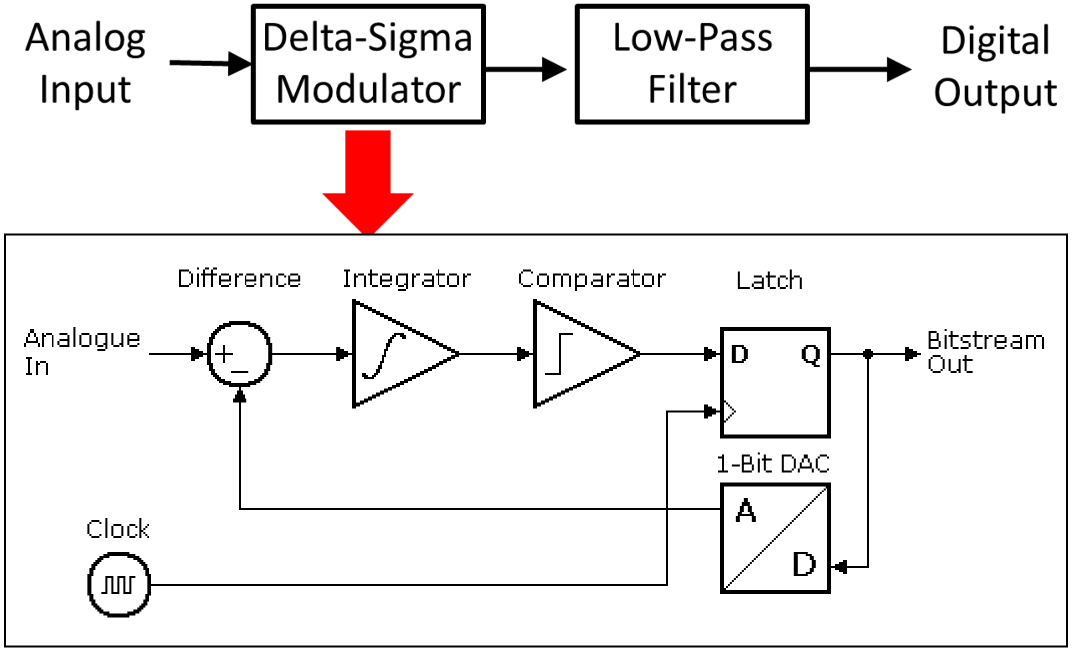
DESCRIPTION

The LTC®2344-18 is an 18-bit, low noise 4-channel simultaneous sampling successive approximation register (SAR) ADC with differential, wide common mode range inputs. Operating from a 5V supply and using the internal reference and buffer, each channel of this SoftSpan™ ADC can be independently configured on a conversion-by-conversion basis to accept ±4.096V, 0V to 4.096V, ±2.048V, or 0V to 2.048V signals. Individual channels may also be disabled to increase throughput on the remaining channels.

The wide input common mode range and 102dB CMRR of the LTC2344-18 analog inputs allow the ADC to directly digitize a variety of signals, simplifying signal chain design. This input signal flexibility, combined with ±4LSB INL, no missing codes at 18 bits, and 95dB SNR, makes the LTC2344-18 an ideal choice for many applications

Delta-Sigma Converter

- **Modulator outputs a stream of ones and zeros**
- **The density of "ones" at the modulator output is proportional to the input signal**
- **Highly oversampled**
- **ADC with highest resolution**



ADS126x 32-Bit, Precision, 38-kSPS, Analog-to-Digital Converter (ADC) with Programmable Gain Amplifier (PGA) and Voltage Reference

1 Features

- Precision, 32-bit, ΔΣ ADC
- Auxiliary 24-Bit, ΔΣ ADC (ADS1263)
- Data Rates: 2.5 SPS to 38400 SPS
- Differential Input, CMOS PGA
- 11 Multifunction Analog Inputs
- High-Accuracy Architecture
  - Offset Drift: 1 nV/°C
  - Gain Drift: 0.5 ppm/°C
  - Noise: 7 nV_{RMS} (2.5 SPS, Gain = 32)
  - Linearity: 3 ppm
- 2.5-V Internal Voltage Reference
  - Temperature Drift: 2 ppm/°C
- 50-Hz and 60-Hz Rejection
- Single-Cycle Settled Conversions
- Dual Sensor Excitation Current Sources
- Internal Fault Monitors
- Internal ADC Test Signal
- 8 General-Purpose Input/Outputs

3 Description

The ADS1262 and ADS1263 are low-noise, low-drift, 38.4-kSPS, delta-sigma (ΔΣ) ADCs with an integrated PGA, reference, and internal fault monitors. The ADS1263 integrates an auxiliary, 24-bit, ΔΣ ADC intended for background measurements. The sensor-ready ADCs provide complete, high-accuracy, one-chip measurement solutions for the most-demanding sensor applications, including weigh scales, strain-gauge sensors, thermocouples, and resistance temperature devices (RTD).

The ADCs are comprised of a low-noise, CMOS PGA (gains 1 to 32), a ΔΣ modulator, followed by a programmable digital filter. The flexible analog front-end (AFE) incorporates two sensor-excitation current sources suitable for direct RTD measurement.

A single-cycle settling digital filter maximizes multiple-input conversion throughput, while providing 130-dB rejection of 50-Hz and 60-Hz line cycle interference.

The ADS1262 and ADS1263 are pin and functional compatible. These devices are available in a 28-pin TSSOP package and are fully specified over the –40°C to +125°C temperature range.

Comparison of ADCs

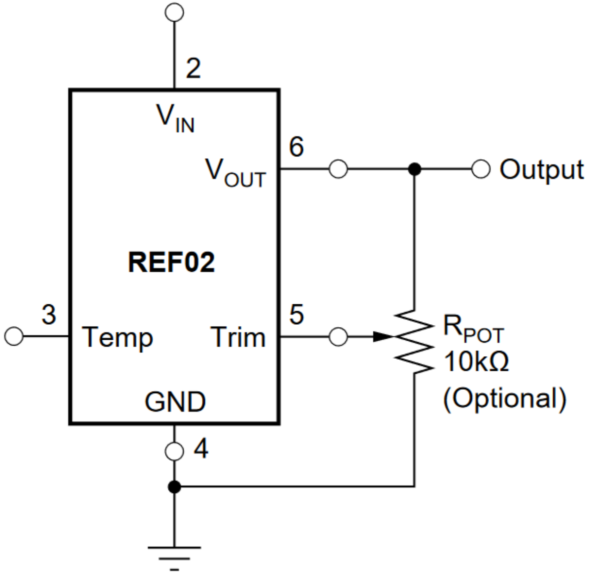
Type	Speed (relative)	Cost (relative)	Resolution (bits)
Dual Slope	(Very) slow	Low – Med	12-18
Flash	Very Fast	High	3-12
Pipeline	Fast	Med	8-16
Successive Approx	Medium – Fast	(Very) Low	8-16
Sigma – Delta	Slow – Fast	Low	12-32

- **Matter of optimization: Resolution, sampling rate, noise, price, etc…**

Voltage references

Voltage references

- **Important part of ADC, ultimately limiting the accuracy**
- **Typically temperature compensated zener reference**
- **Can be external or internal**
- **Important parameters**
  - Initial accuracy
  - Temperature stability
  - Drift rate
  - Noise
  - Supply (and load) regulation



Examples of voltage references

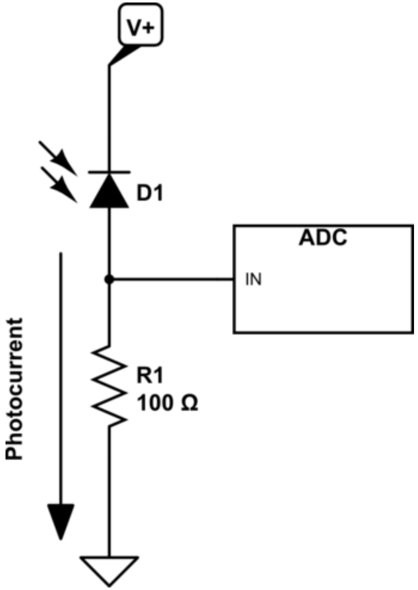
Typical perform values are given

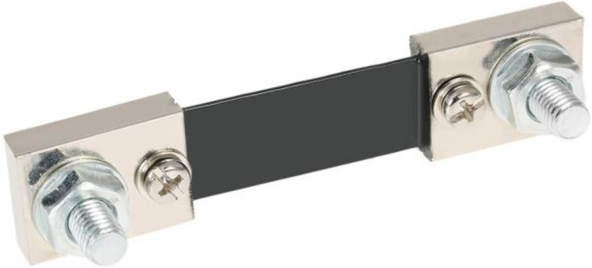
IC	Initial accuracy	Temperature dependence	Long term stability	Price
TL431	0.5%	4 ppm/°C	?	0.1 €
ADR380	0.2%	3 ppm/°C	70 ppm / 1000 h	1.5 €
REF3240	0.01%	4 ppm/°C	55 ppm / 1000 h	5 €
LM399	2 %	0.5ppm/°C	8 ppm / $\sqrt{1000\ \mathrm{h}}$	10 €
LTZ1000	~2 %	0.05 ppm/°C	0.03 ppm / $\sqrt{1000\ \mathrm{h}}$	50 €

Current measurements

Shunt resistor

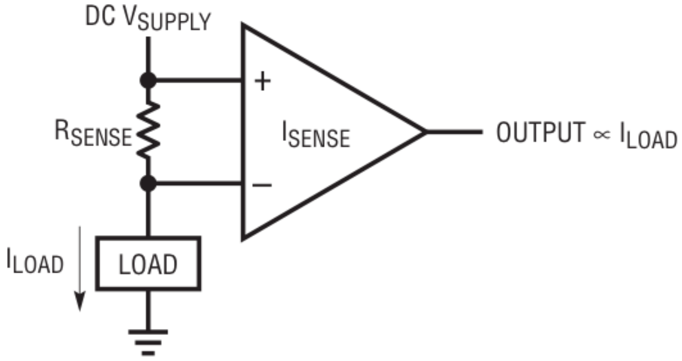
- **Simplest approach: resistor is used to convert current to voltage → $U = R \cdot I$**
- **Disadvantages**
  - The voltage seen by the source changes as a function of current → nonlinearities
  - *Small currents:* sensitive to load of the external circuitry
  - *High currents:* without amplification, power losses become significant ($U = R \cdot I^2$) or the output voltage is low
  - → Actice circuits

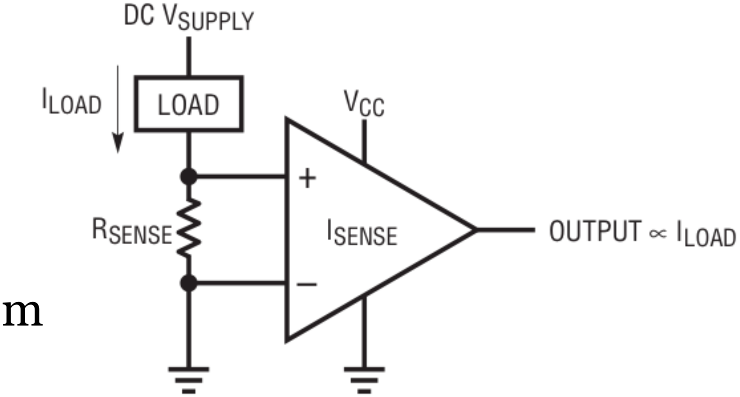




Current sense amplifier

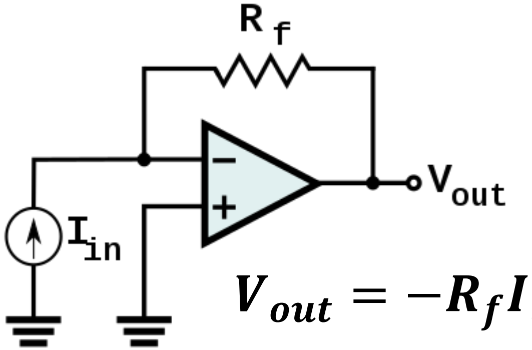
- **High-side measurement**
  - Current is monitored directly from the source
  - High immunity to ground disturbance
  - Easy to detect load short to ground
  - High supply voltage can be problematic
- **Low-side measurement**
  - Common mode voltage ~0
  - Easier in terms of component selection
  - Load short to ground is undetected
  - Possible issues with ground loops
  - Can be noisy if multiple loads are driven from common supply



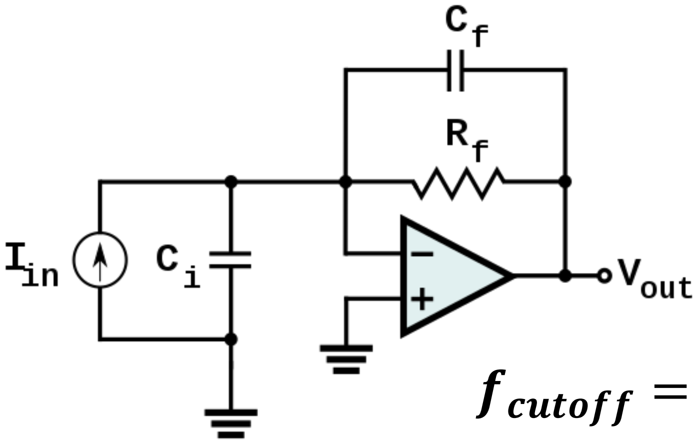


Transimpedance amplifier (TIA)

- Active current-to-voltage converter
- Typically implemented using an operational amplifier
- May contain additional amplification stages
- Practical range from sub-femtoamperes to few milliamperes

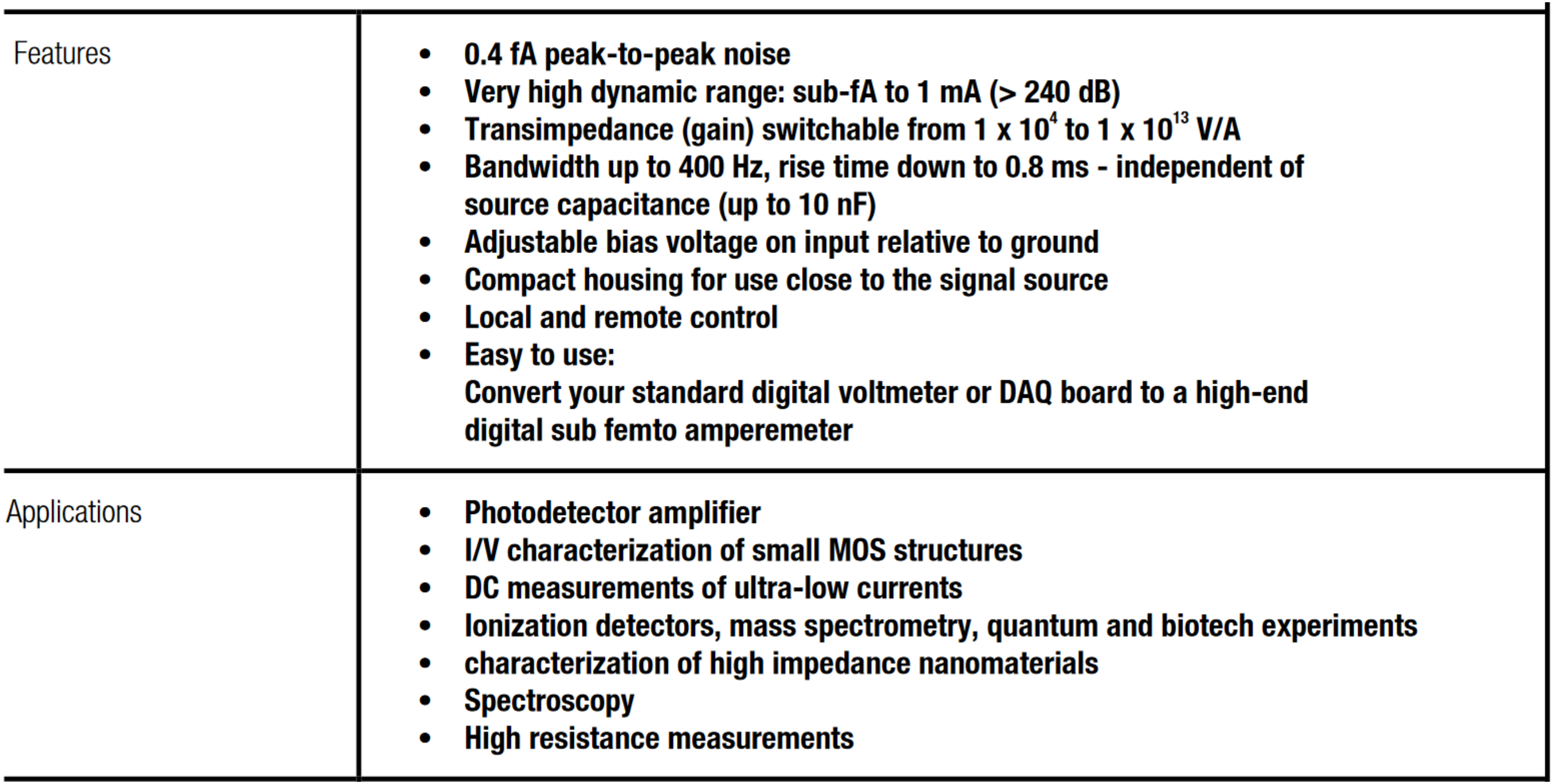


$$V_{out} = -R_f I_{in}$$



$$f_{cutoff} = \frac{1}{2\pi R_f C_f}$$

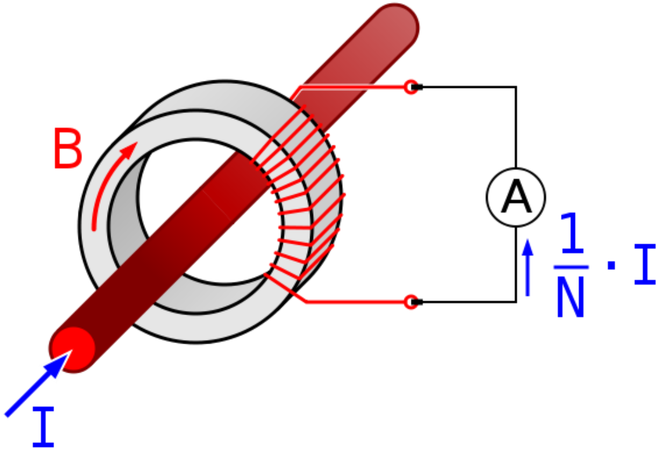
Variable Gain
Sub Femto Ampere Current Amplifier



Features	• 0.4 fA peak-to-peak noise • Very high dynamic range: sub-fA to 1 mA (> 240 dB) • Transimpedance (gain) switchable from 1 x 10^4 to 1 x 10^{13} V/A • Bandwidth up to 400 Hz, rise time down to 0.8 ms - independent of source capacitance (up to 10 nF) • Adjustable bias voltage on input relative to ground • Compact housing for use close to the signal source • Local and remote control • Easy to use: Convert your standard digital voltmeter or DAQ board to a high-end digital sub femto amperemeter
Applications	• Photodetector amplifier • I/V characterization of small MOS structures • DC measurements of ultra-low currents • Ionization detectors, mass spectrometry, quantum and biotech experiments • characterization of high impedance nanomaterials • Spectroscopy • High resistance measurements

Current transformer

- A transformer optimized for current sensing
- Typically frequency range 50 Hz to 1 Mhz, RF models up to GHz
- Typically in high current applications (1A to 1 kA)
- Output measured for example with TIA

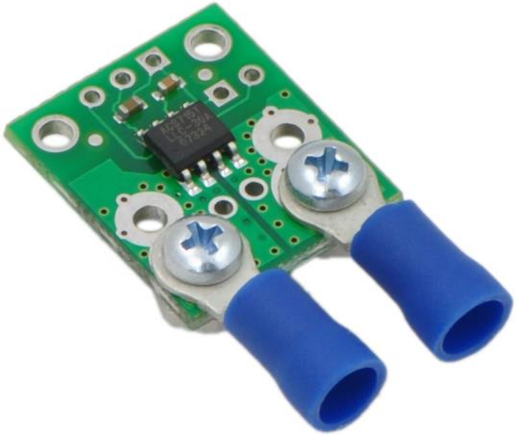


Modifying the transformer ratio

1:300 **1:150** **1:100**

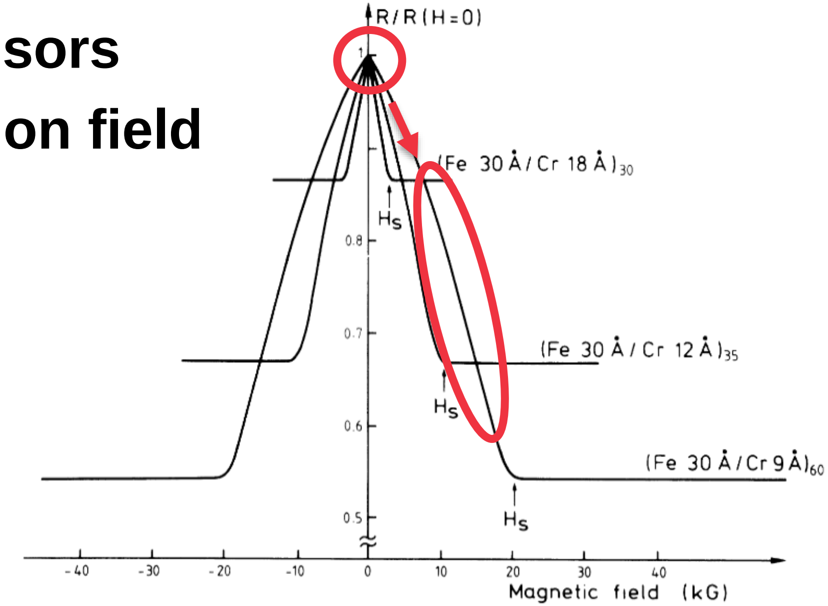
Hall effect current sensor

- **Utilizes the Hall effect to convert current to voltage**
  - Perpendicular current and magnetic field induce potential difference
- **Suitable from DC to >100 kHz**
- **Suffers from significant drift → compensation needed**



Magnetoresistive current sensor

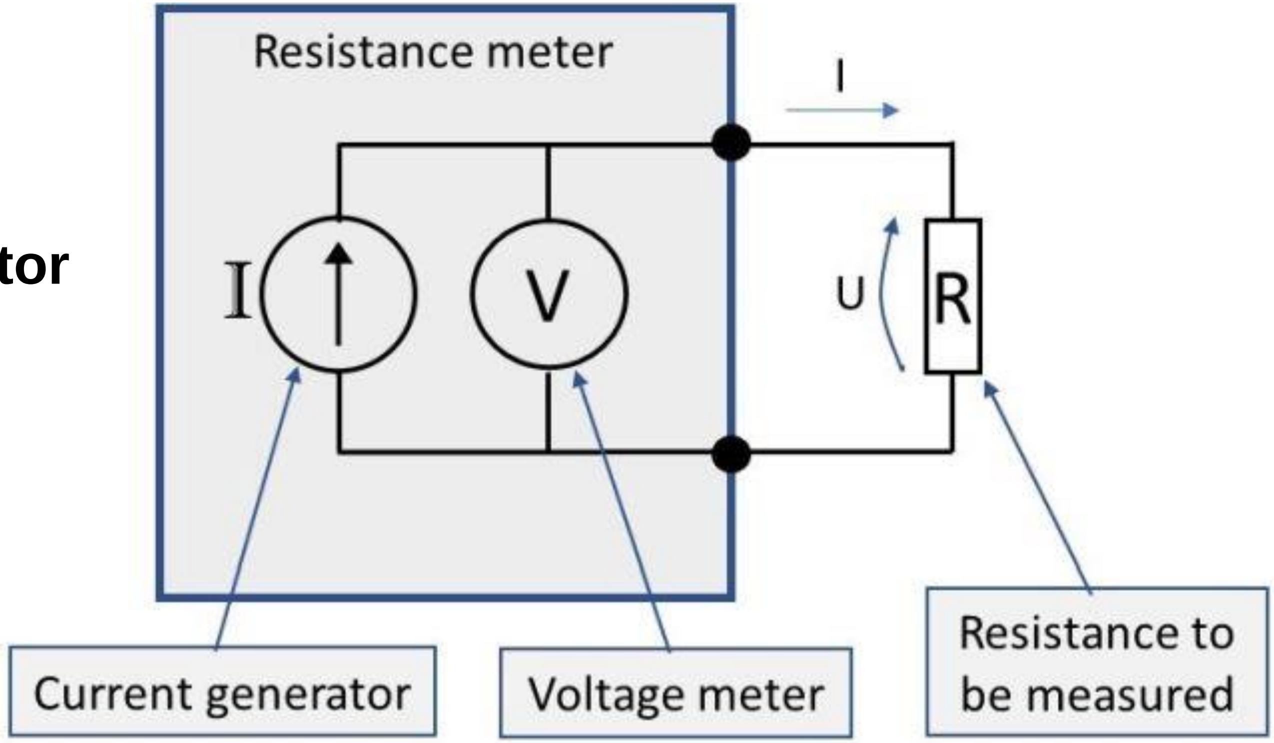
- Magnetoresistance: the change of electrical resistance under externally-applied magnetic field
- Somewhat similar usage as with Hall effect sensor
- Improved accuracy over Hall sensors
- Limited linear range, compensation field needed for linear region operation



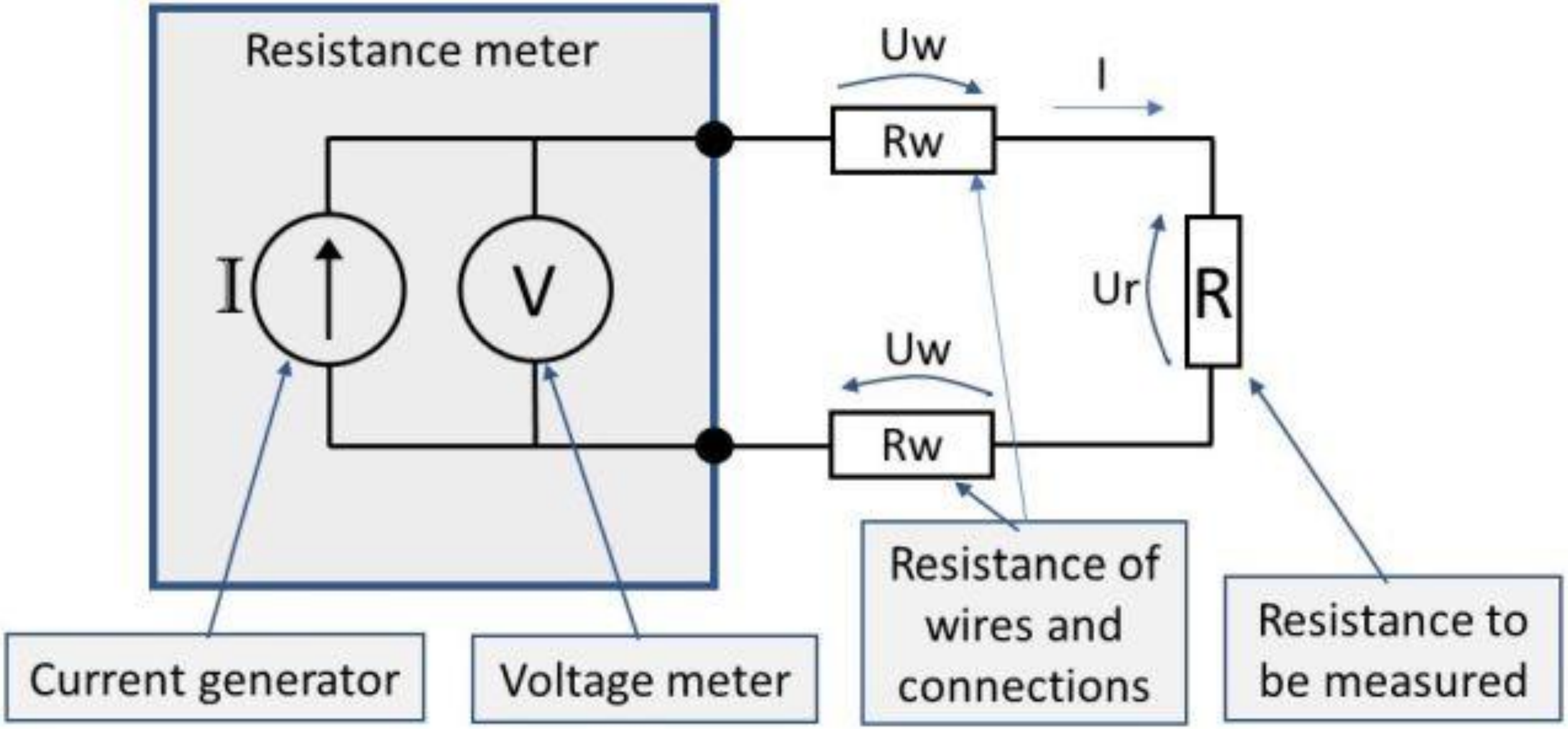
Resistance measurements

Typical resistance measurement

- **Typically resistance is measured with current generator and voltage source**

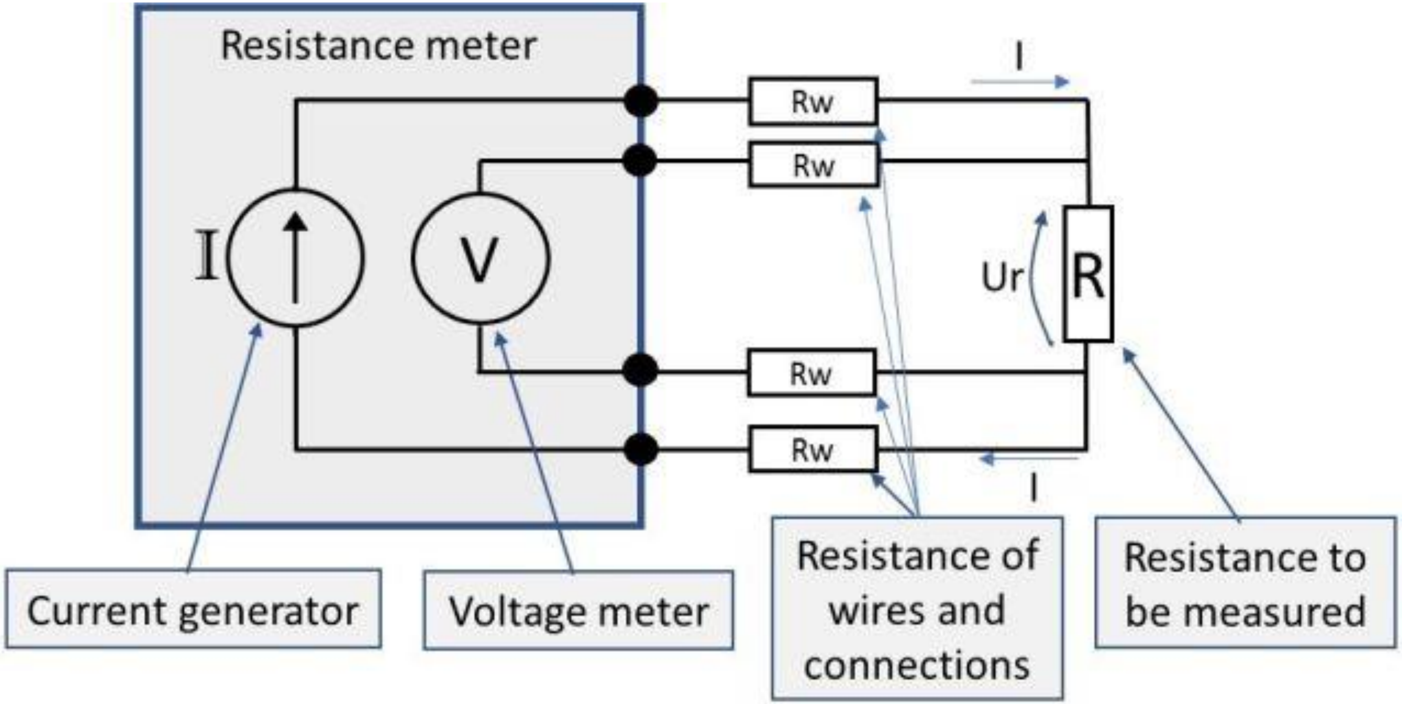


2-wire measurement



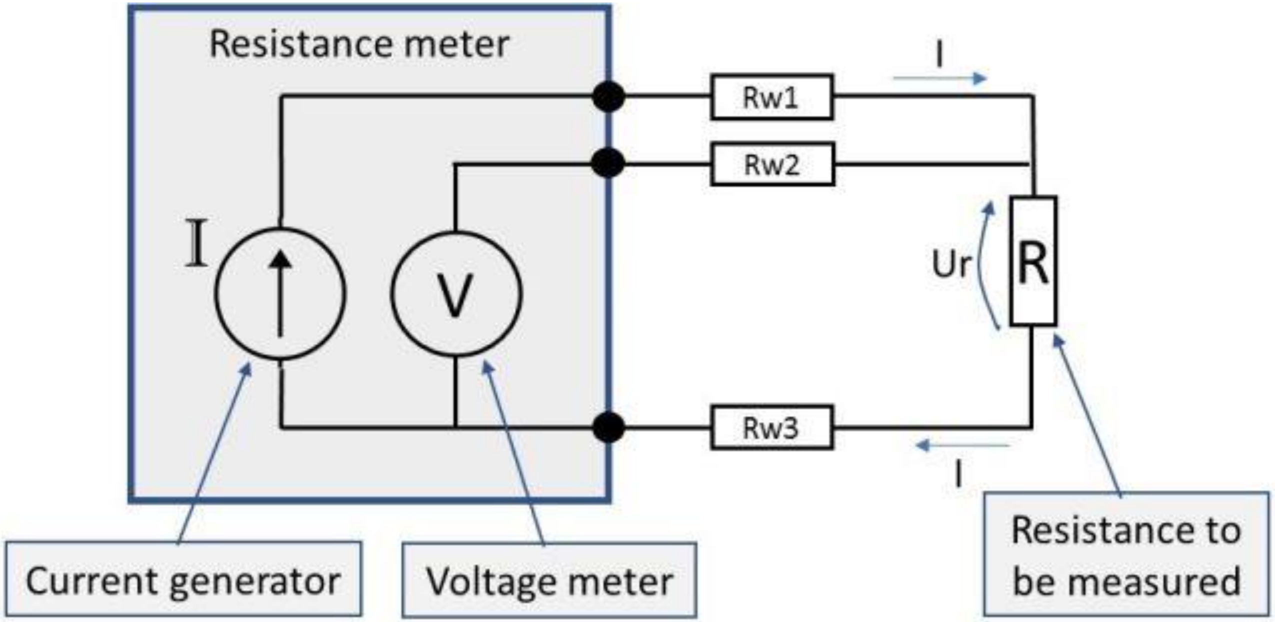
4-wire measurement

- **Eliminates the effect of wire resistances**

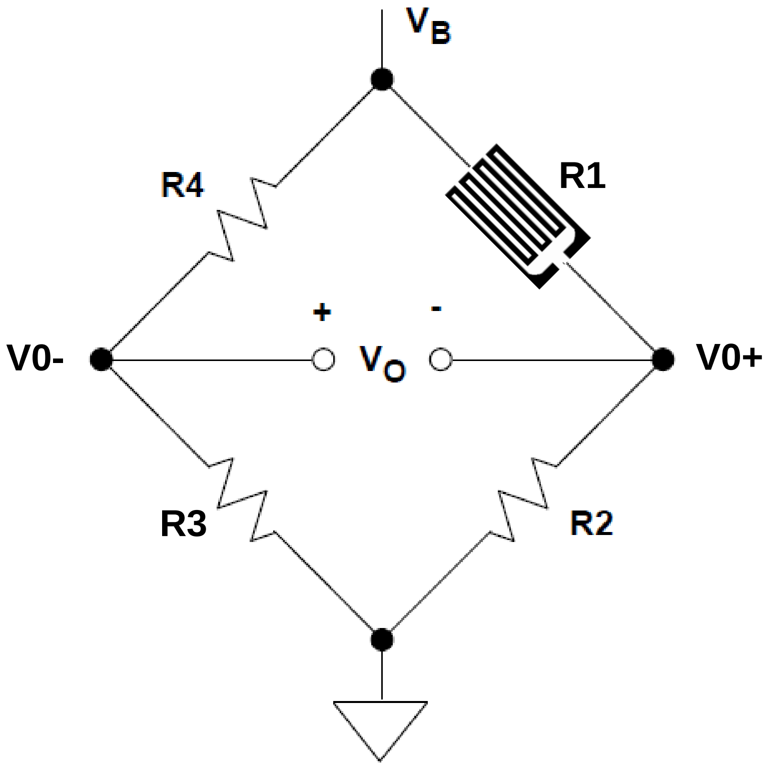


3-wire measurement

- **Assumes identical resistance in all wires**
- **Industry standard in many applications**

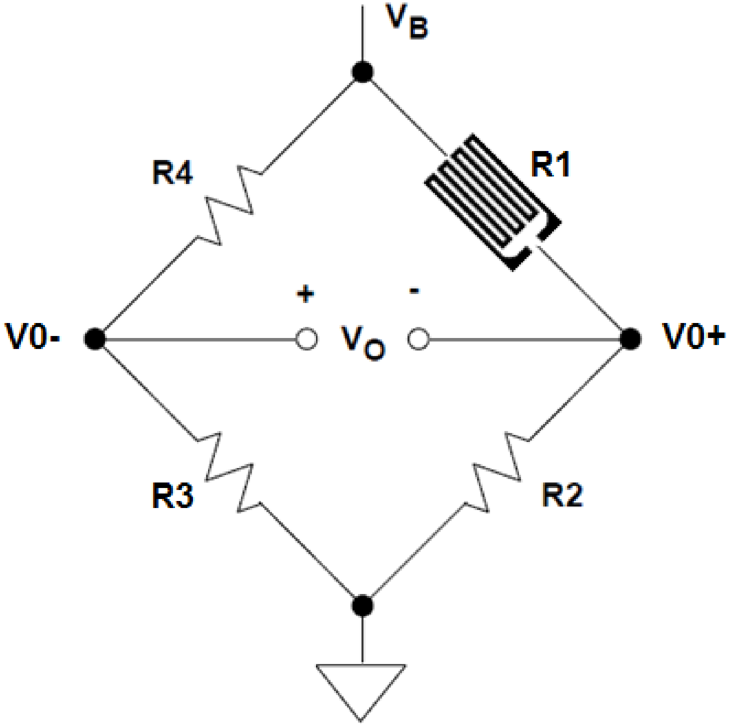


Wheatstone bridge



- For detecting small changes of resistance (PT temperature sensor, strain gauge etc.)
- Change in resistance causes imbalance in the circuit → Voltage over the bridge
- Minimum of one sensor → linear up to 5% change in resistance
- Adding sensors will improve linearity and sensitivity

Wheatstone bridge equations



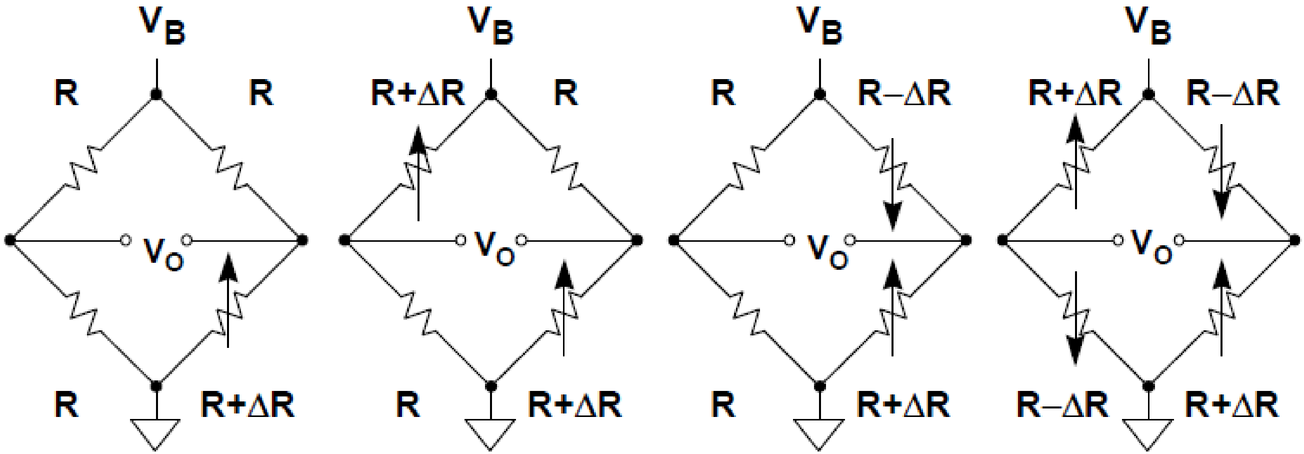
Voltage divider rule gives:

$$V_O = V_{O+} - V_{O-} = V_e\left(\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_4}\right)$$

With equal nominal resistances:

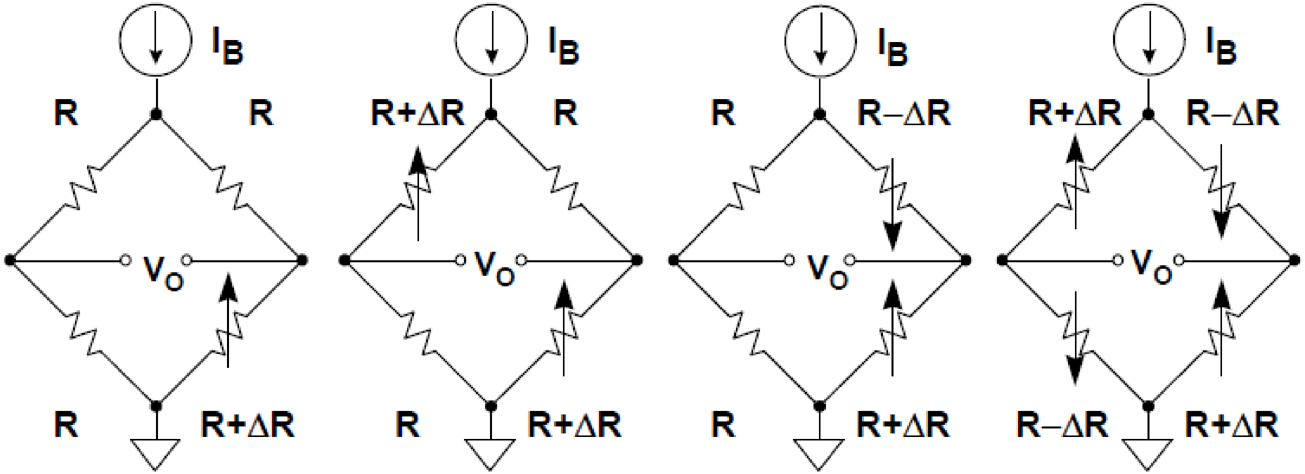
$$V_O \approx V_e\left(\frac{\Delta R_1 - \Delta R_2 + \Delta R_3 - \Delta R_4}{4R}\right)$$

OUTPUT VOLTAGE AND LINEARITY ERROR FOR CONSTANT VOLTAGE DRIVE BRIDGE CONFIGURATIONS



V_O:	$\frac{V_B}{4}\left[\frac{\Delta R}{R+\frac{\Delta R}{2}}\right]$	$\frac{V_B}{2}\left[\frac{\Delta R}{R+\frac{\Delta R}{2}}\right]$	$\frac{V_B}{2}\left[\frac{\Delta R}{R}\right]$	$V_B\left[\frac{\Delta R}{R}\right]$
Linearity Error:	0.5%/%	0.5%/%	0	0
	(A) Single-Element Varying	(B) Two-Element Varying (1)	(C) Two-Element Varying (2)	(D) All-Element Varying

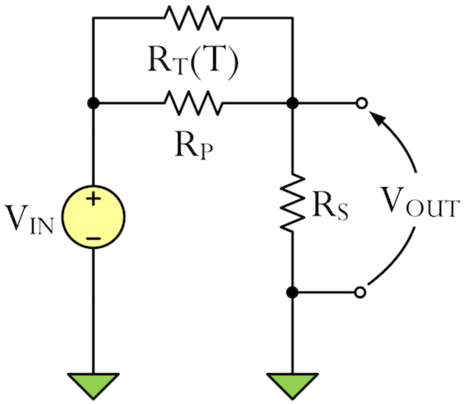
OUTPUT VOLTAGE AND LINEARITY ERROR FOR CONSTANT CURRENT DRIVE BRIDGE CONFIGURATIONS

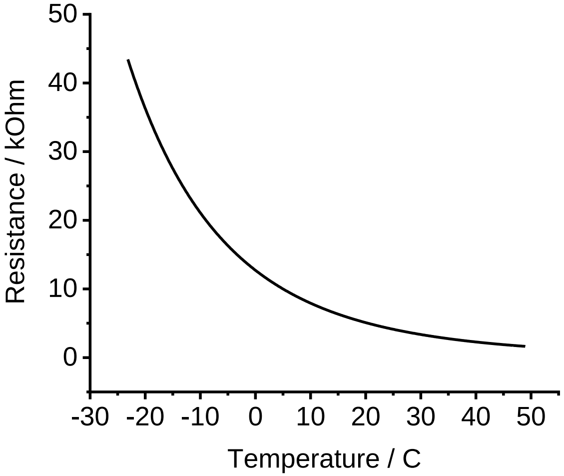


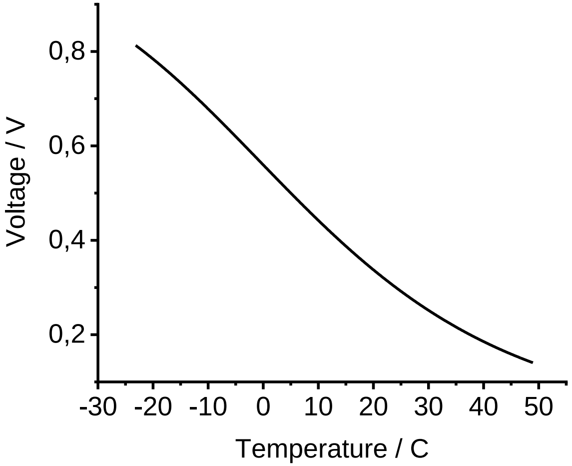
V_O:	$\frac{I_B R}{4}\left[\frac{\Delta R}{R+\frac{\Delta R}{4}}\right]$	$\frac{I_B}{2}\left[\Delta R\right]$	$\frac{I_B}{2}\left[\Delta R\right]$	$I_B\left[\Delta R\right]$
Linearity Error:	0.25%/%	0	0	0
	(A) Single-Element Varying	(B) Two-Element Varying (1)	(C) Two-Element Varying (2)	(D) All-Element Varying

Linearization

- **Many sensors have exponentially changing resistance**
  - NTC temperature sensors, photoresistors, resistive humidity sensors etc.)
- **Simple resistive divider based circuits are often used to linearized these sensors**



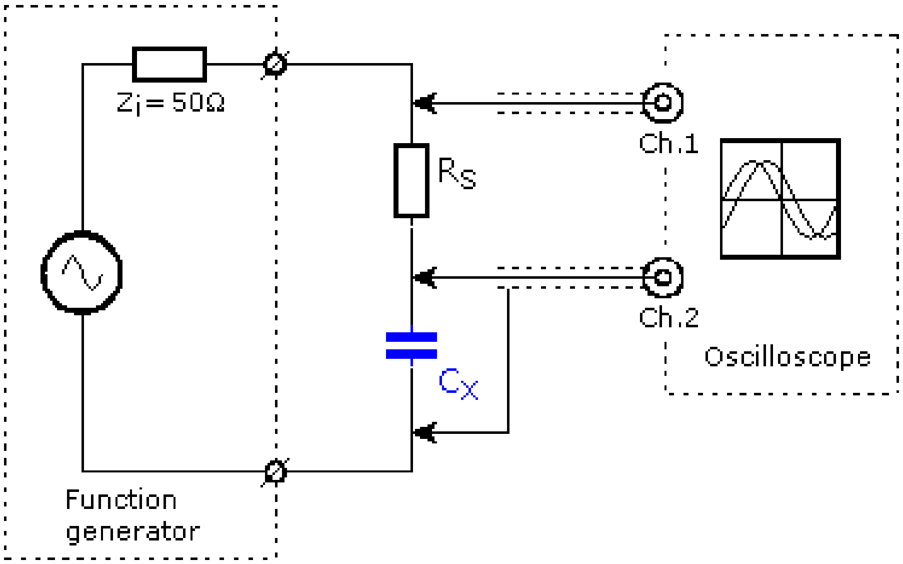


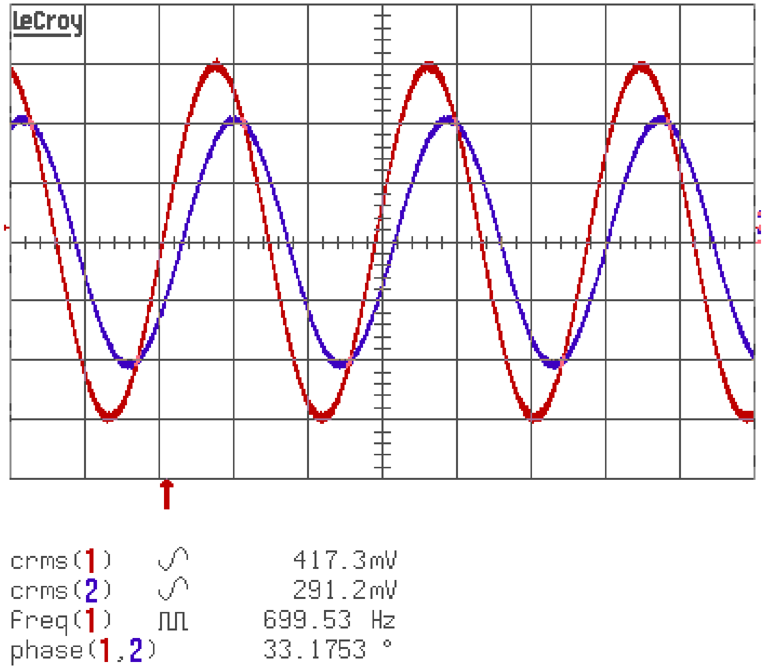


Capacitance and inductance measurements

Aalto University

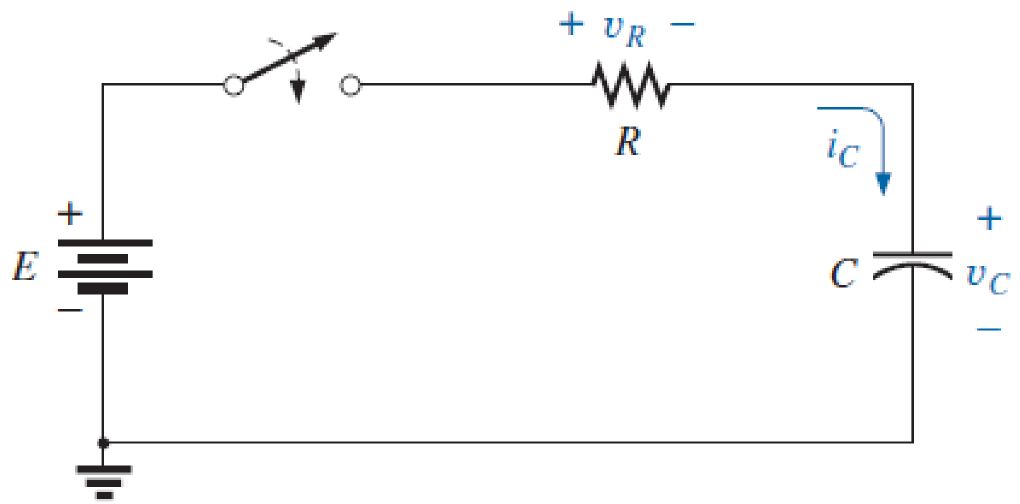
Measure attenuation / phase shift

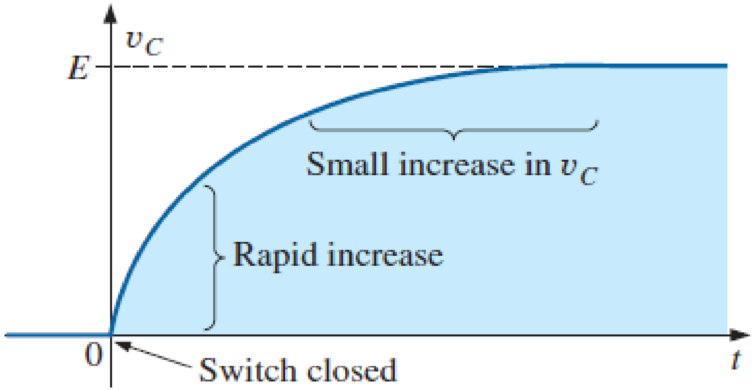




```
crms(1)   ∿      417.3mV
crms(2)   ∿      291.2mV
Freq(1)   ⎍⎍    699.53 Hz
phase(1,2)      33.1753 °
```

Measurement of time constant

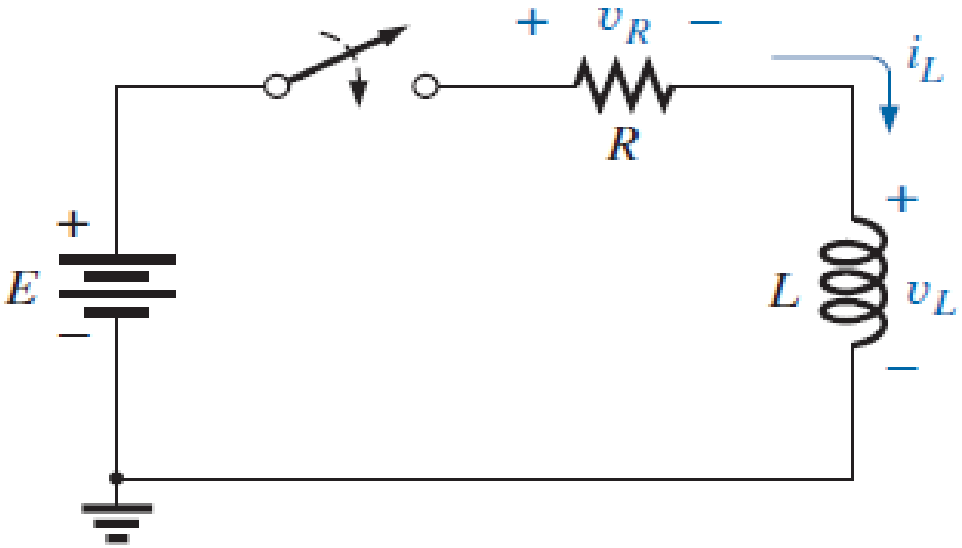


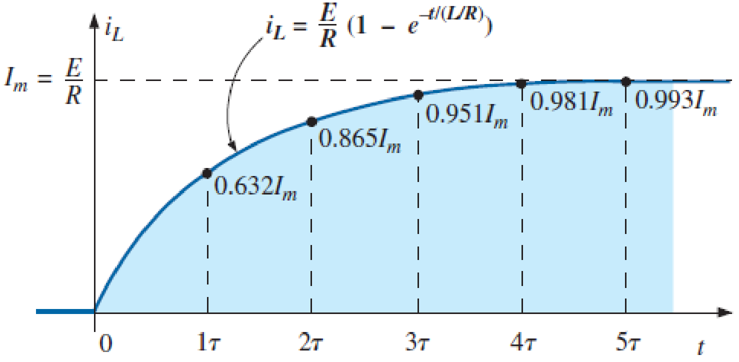


$$\boxed{v_C = E(1 - e^{-t/\tau})}$$

$$\boxed{\tau = RC}$$

Measurement of time constant

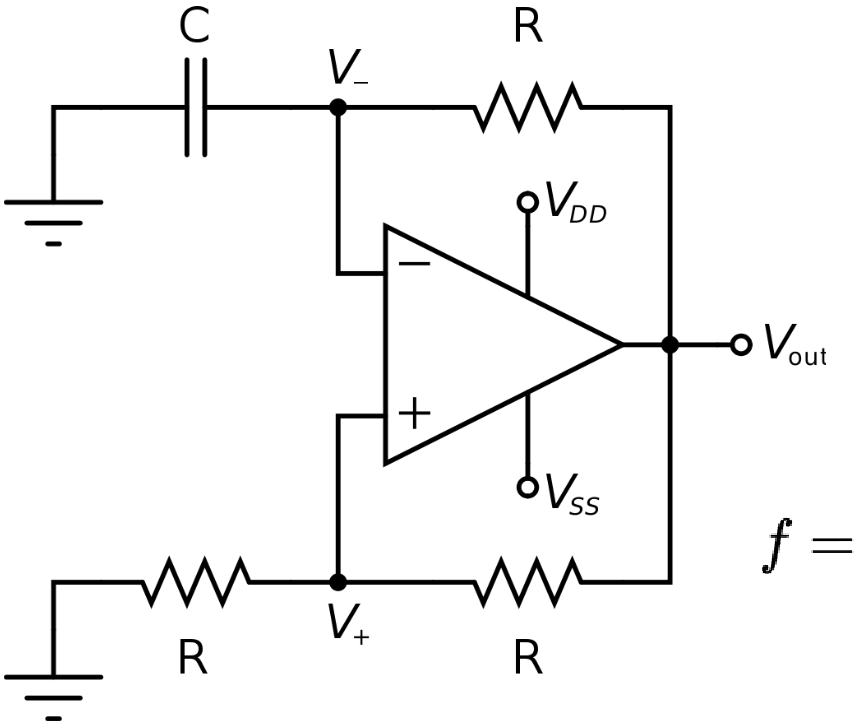




$$\boxed{v_R = E(1 - e^{-t/\tau})}$$

$$\boxed{\tau = \frac{L}{R}}$$

Oscillator based

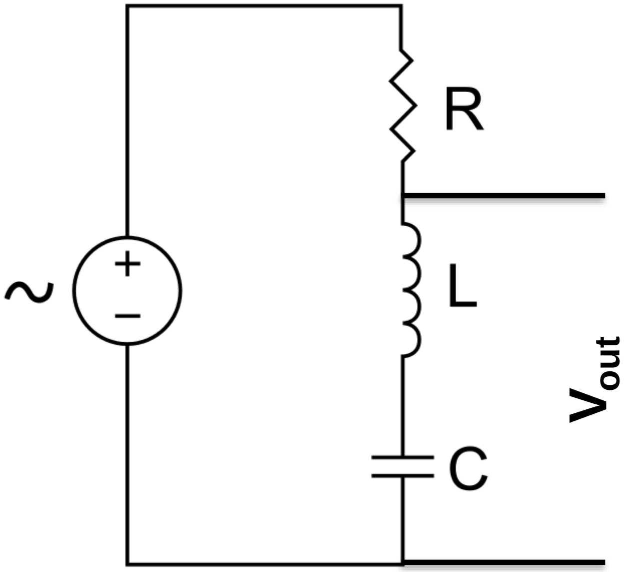


- **Countless oscillator circuits exist where *f* ∝ 1/*C*, *f* ∝ R *or f* ∝ L**
- **Practical approach in many sensor applications**

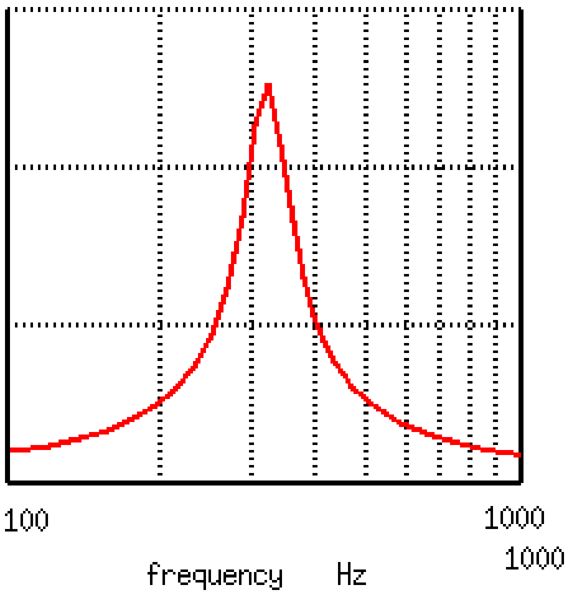
$$f = \frac{1}{2\ln(3)RC}$$

Resonance

Sweeping frequency



Output amplitude



Peak at resonant frequency

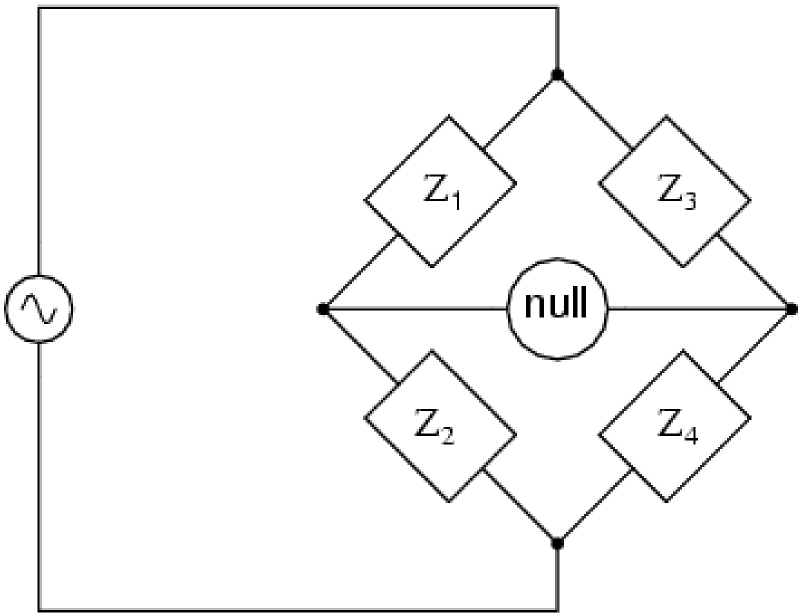
$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

AC bridge circuits

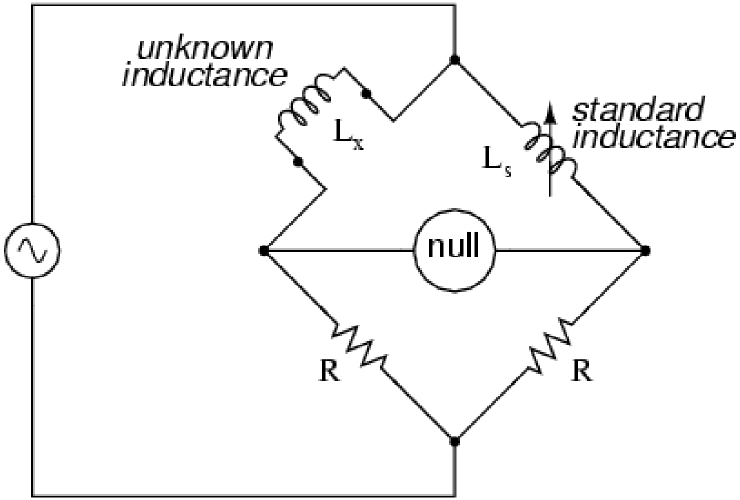
- **Based on the Whetsone bridge**
- **Complex impedances and AC source**
- **Balanced bridge:**

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

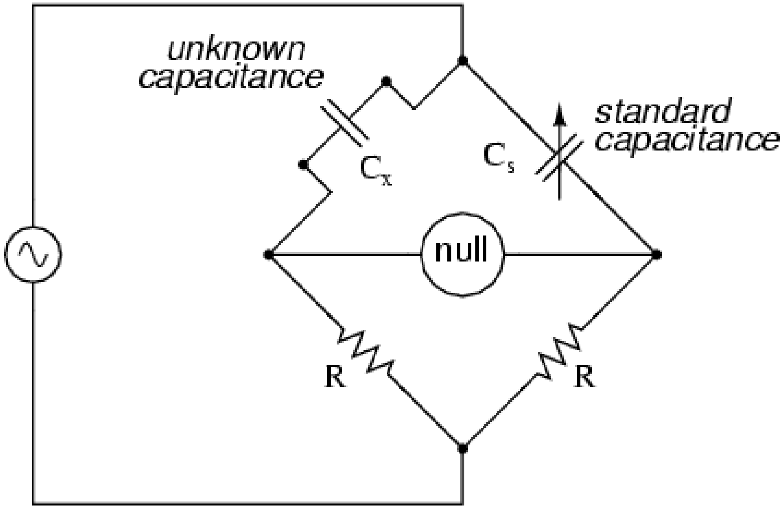
General impedance bridge



C and L bridge measurements



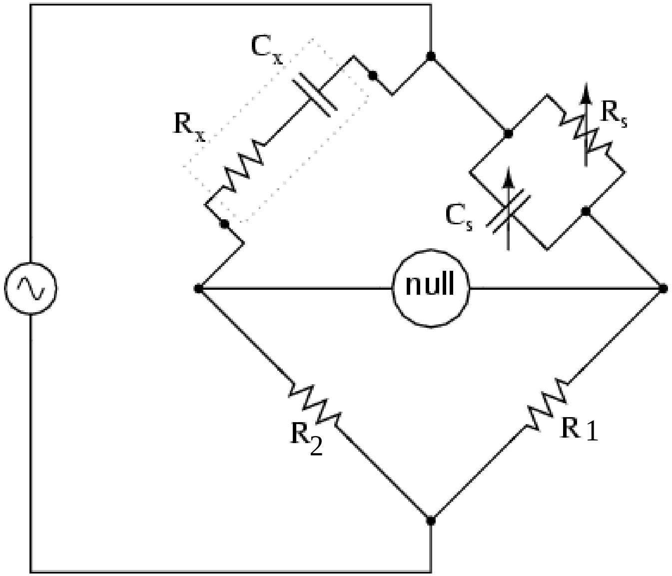
inductance



capacitance

Wien bridge

- **Bridge design that takes into account the series resistance of the measured capacitance**



$$R_s = \frac{R_1}{R_2}\left(R_x + \frac{1}{\omega^2 R_x C_x^{\ 2}}\right)$$

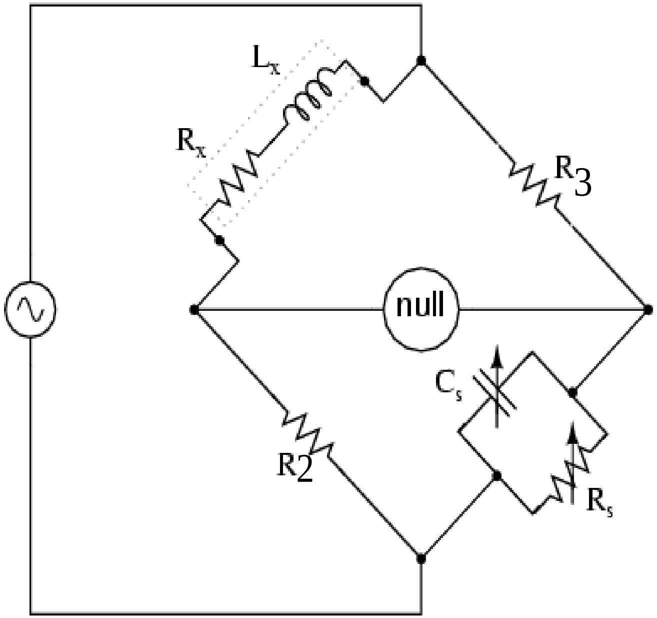
$$C_s = \frac{R_2}{R_1}\left(\frac{1}{1+\omega^2 R_x^{\ 2} C_x^{\ 2}}\right) C_x$$

$$R_x = \frac{R_2}{R_1}\left(\frac{R_s}{1+\omega^2 R_s^{\ 2} C_s^{\ 2}}\right)$$

$$C_x = \frac{R_1}{R_2}\left(C_s + \frac{1}{\omega^2 R_s^{\ 2} C_s^{\ 2}}\right)$$

Maxwell bridge

- **Bridge design that takes into account the series resistance of the measured inductance**



$$R_x = \frac{R_2 R_3}{R_s}$$

$$L_x = R_2 R_3 C_s$$

Next week

- **Frequency measurements**
- **Noise issues**
  - Noise sources
  - Noise reduction techniques
- **Measuring low signal levels**
  - Special amplifiers
  - Switched integrators
  - Lock-in amplification
  - Statistical approaches
  - Case examples