نظم القياس الإلكترونية
Electronic Measurement Systems (EMS)

كلية الهندسة الكهربائية والالكترونية – جامعة حلب
د. أسعد كعدان

المحاضرتين 1-2 – مقدمة في القياسات ونظم القياس الإلكترونية

مصادر المحاضرة

- Electronic Instrumentation, Prof. Dr. Kofi Makinwa
  https://ocw.tudelft.nl/courses/electronic-instrumentation/
  - Lecture 1 - Measurement Science & Electronic Instrumentation
- Measurement Science, Dr. ir. Michiel Pertijs
  https://ocw.tudelft.nl/courses/measurement-science/
  - Lecture 1 - Introduction to Measurements and Measurement Systems

Mobile measurement system

image sensor

touch screen

GPS

microphone

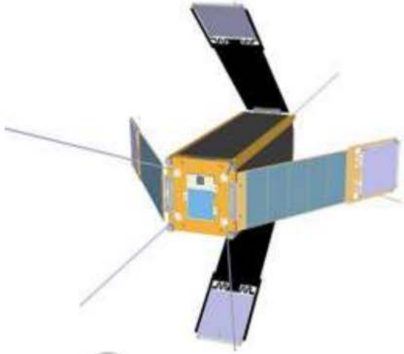
compass

acceleration sensor

rotation-sensor

Measurement science is everywhere!







The importance of measurements

- The numbers tell the tale!
- For scientists, measuring is *the* way to test a theory
- For engineers, measuring is *the* way to validate a design
- Measurement systems and sensors are the senses of the computer
- Measuring also implies: knowing what you *don't* know

"We have lots of information technology. We just don't have any information."

So, what is this course about?

Measurement Science:

Analyzing whether information on a parameter of interest (the *measurand*) has been (can be) obtained with sufficient quality, when considering interfering conditions and *specifications*.

Interfering with the measurand:

- Source loading by the measurement
- (Cross) sensitivity to undesired signals
- Electro-magnetic interference
- Many more…..

Electronic Instrumentation:

Designing a measurement instrument according to specifications

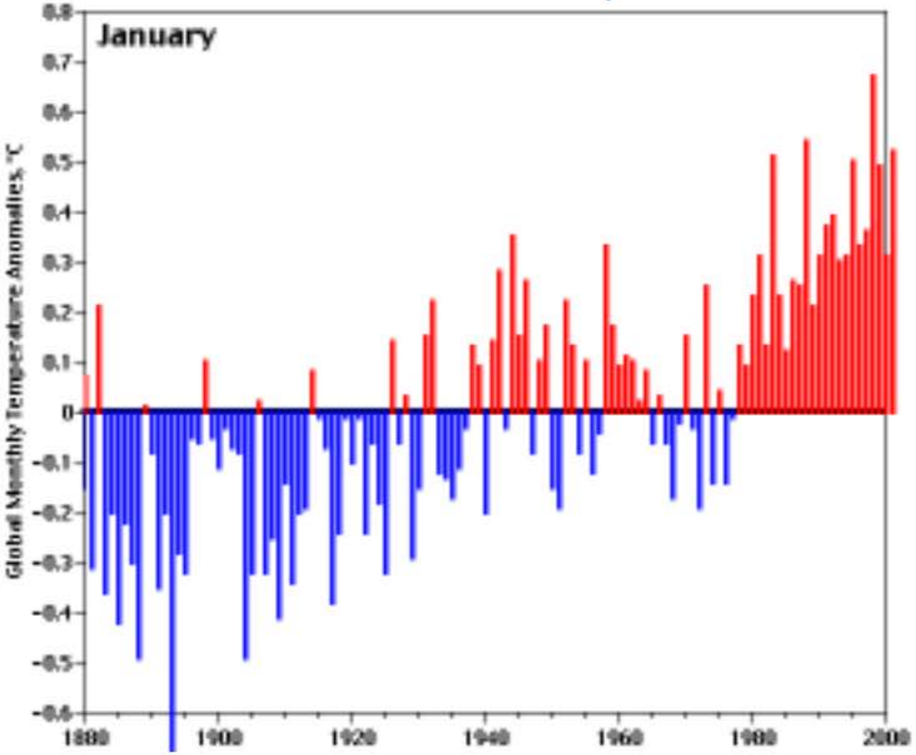
Specifications:
Imposed by measurement problem (= *problem specification*)
vs.
Offered by instrument (= *instrument specification*)
But there will be a ***Detection limit*** set by technology or by nature!

Application to real-world measurement problems

Starts with a measurement problem.

Is there global warming ?

"Of course, *everyone* knows that !
Just look at the *measured* temperatures"



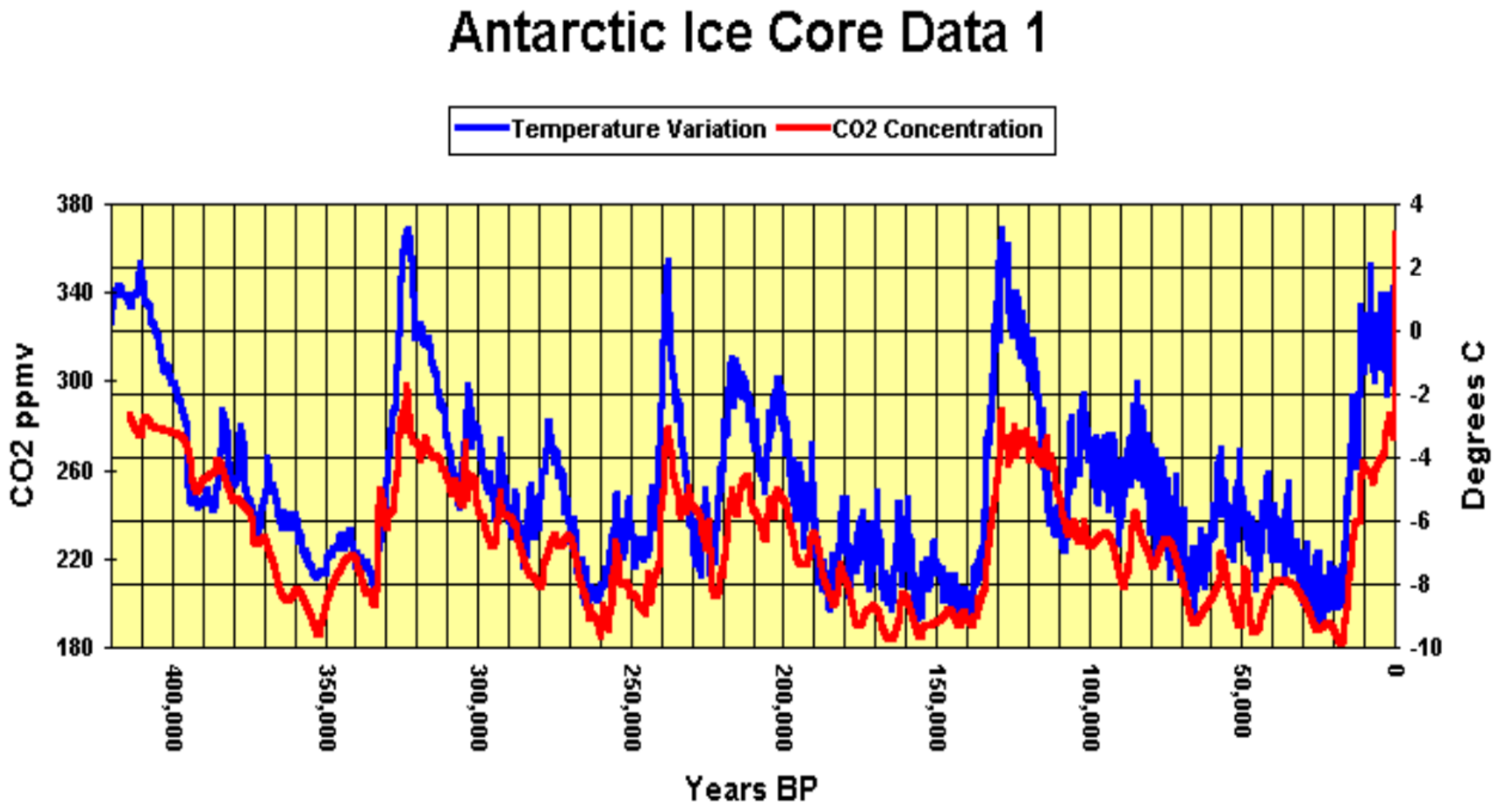
"Act now, or would you like this to happen……."

TU Delft
Delft University of Technology

Uncertainties in measuring global warming

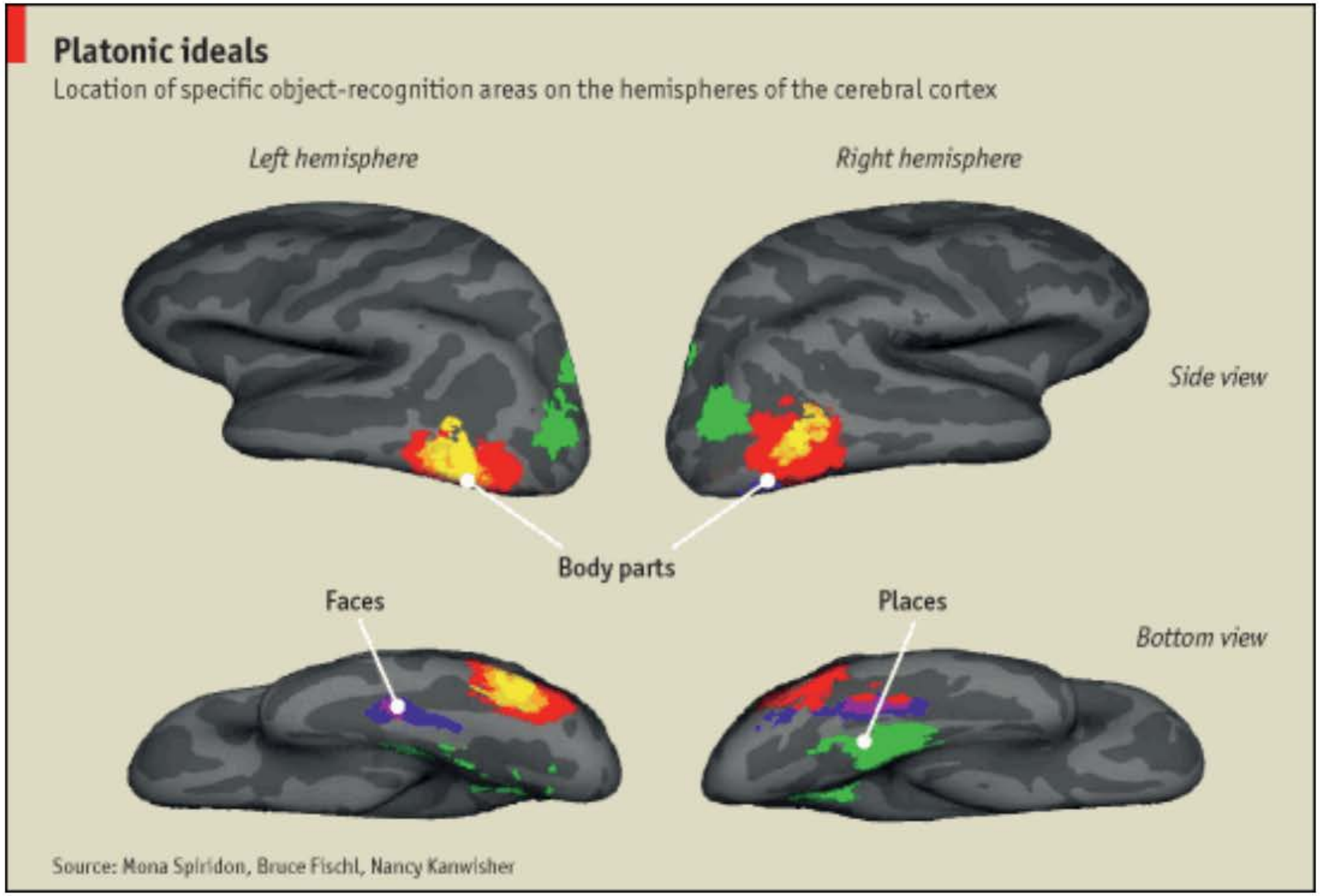
ET8.017
El. Instr.

Drilling down to 3623 m in the Antarctic ice at Vostoc (equivalent to about 420 kyr BP with 4-6 kyr delay). Samples analyzed for:
- CO_2 by gas chromatography
- Temperature by measuring ^{18}O and Deuterium concentration
- Dust particle concentration.



How to access the measurand?

Medical application

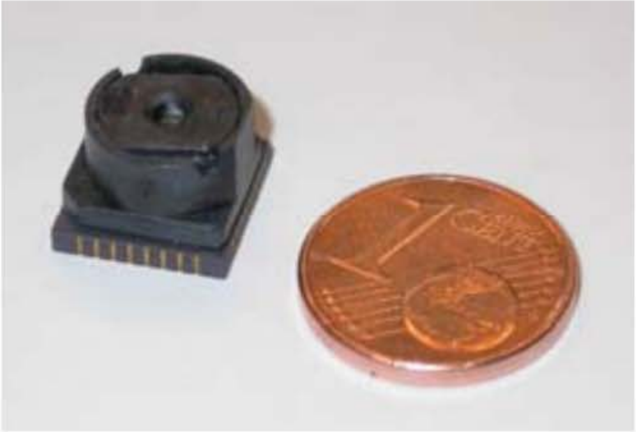


TU Delft
Delft University of Technology

We need (smart) sensors!

ET8.017
El. Instr.

Sensor ⟷ *analog* ⟷ Interface electronics ⟷ digital



Smart sensor

- Analog-to-digital conversion ⇒ Interface electronics
- Smart sensor = Sensor system in a package

(MEMS) Sensors in our Cars

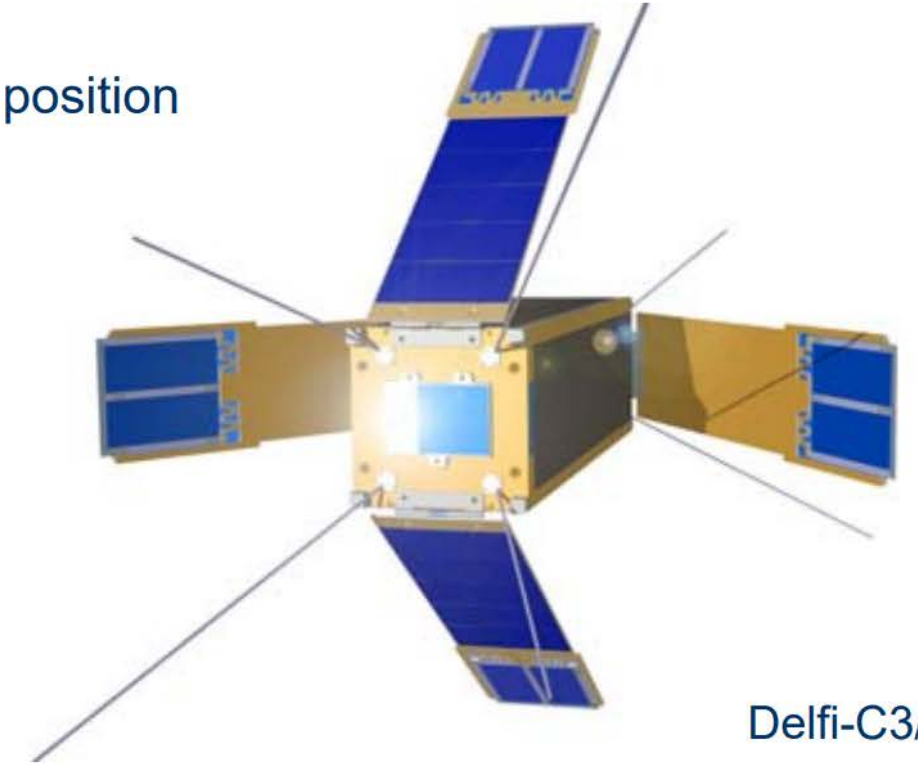
Automotive application – airbag crash detection

Airbag should only operate
when needed ⇒ crash sensor

Also for:
- side impact
- Non-passengers

Sensors in Space

Measuring satellite position



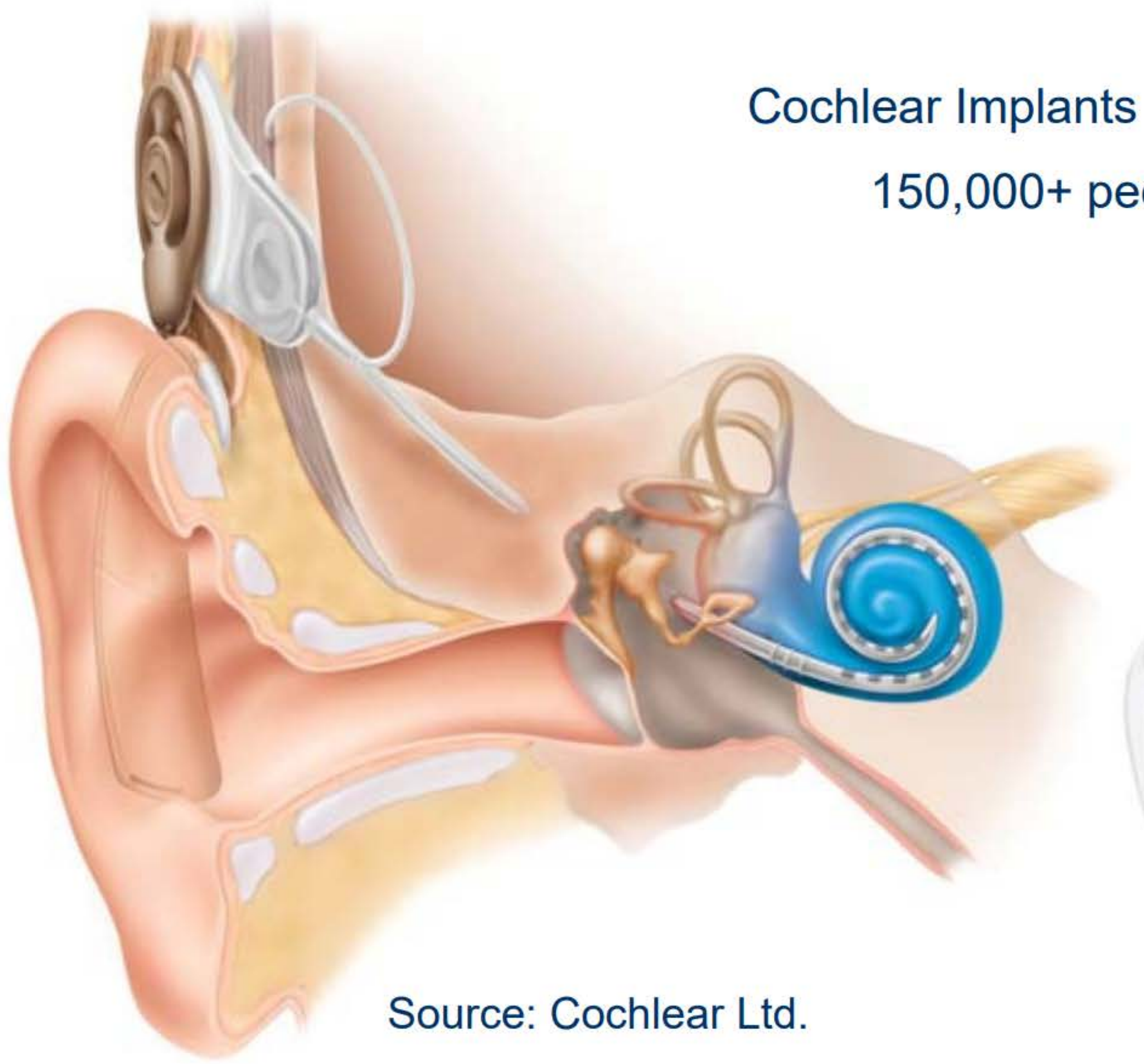
Delfi-C3/MISAT

Purpose:
- Solar panel position control
- Antenna directional control
- Satellite attitude control

Sensors in our Bodies

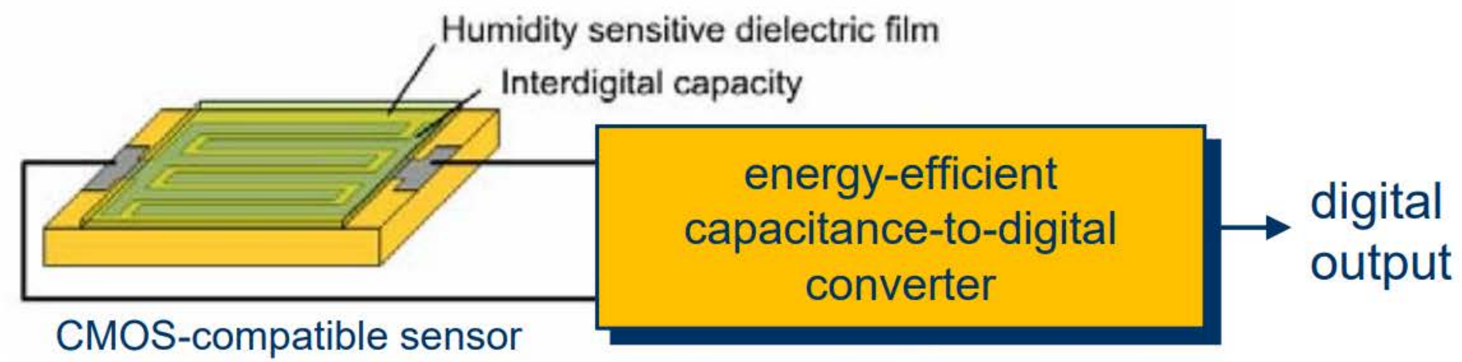
Cochlear Implants

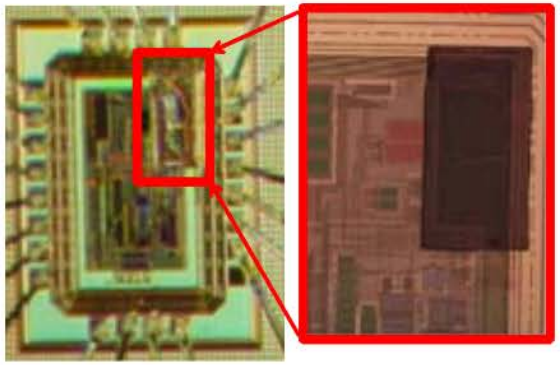
150,000+ people world-wide!



Source: Cochlear Ltd.

Smart Humidity Sensor



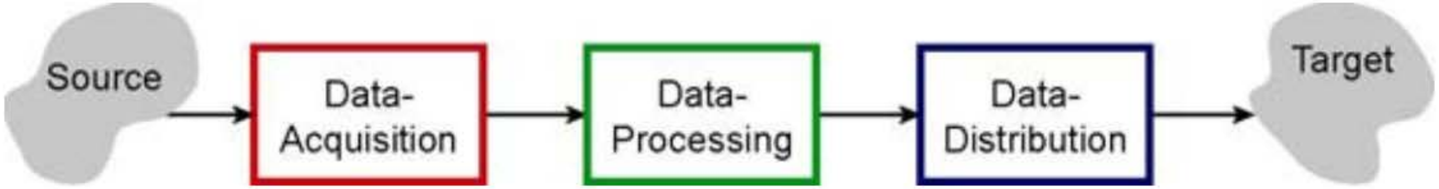


smart humidity sensor
(0.16μm CMOS)

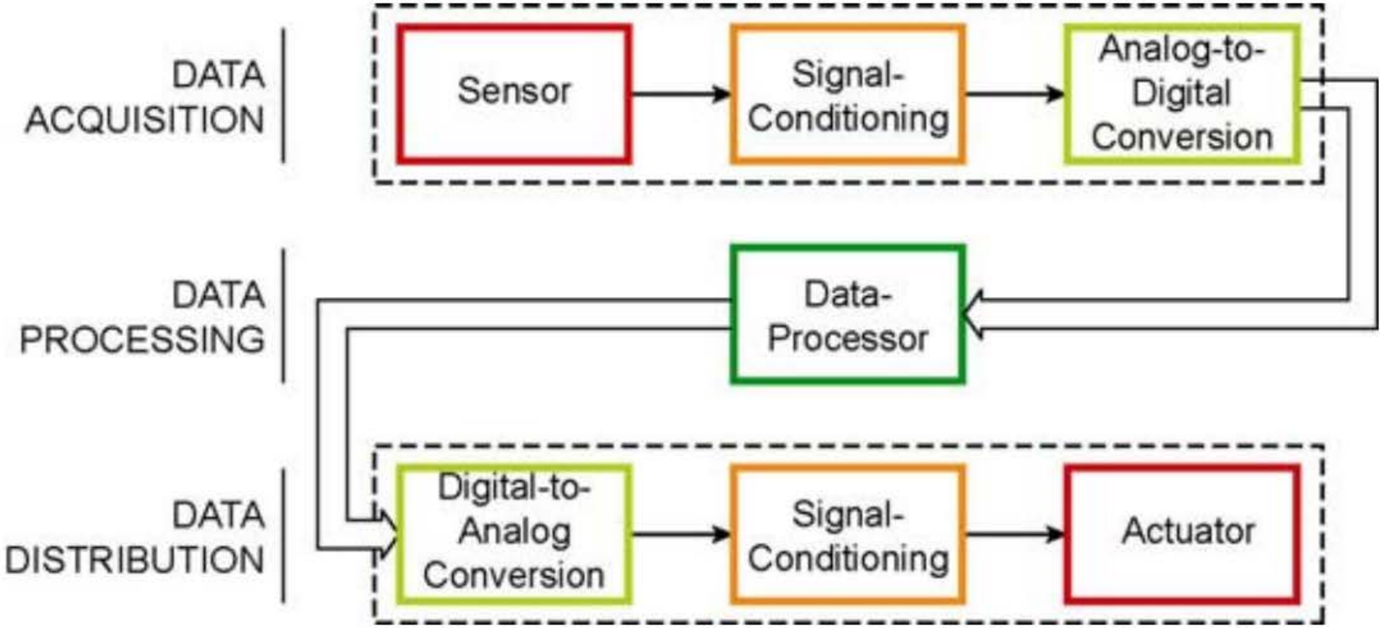
- Humidity sensitive dielectric (NXP) causes capacitance changes
- These are digitized by a capacitance-to-digital converter (delta-sigma converter)
- Achieves resolution of 0.1%RH while consuming only 8.3nJ / meas

General Structure of an Instrument

General structure of an instrument



Components in an instrument



Learning objectives of this course

- Analyzing **measurement problems:**
  - you'll be able to
  - identify and describe a measurement problem
  - translate a measurement problem to measurable quantities
  - estimate whether a quantity is measurable under certain conditions
- Analyzing and interpreting **measurement results:**
  - you'll be able to
  - identify and describe sources of error

Learning objectives of this course

- Realization of simple measurement set-ups:
  - you'll be able to
  - apply **sensors** to measure non-electric quantities
  - apply simple **signal processing circuits** for sensor read-out
- Skillful use of **measurement instruments**:
  - you'll be able to
  - describe the operating principle of common instruments for electrical measurements
  - compare available instruments based on quality and accuracy

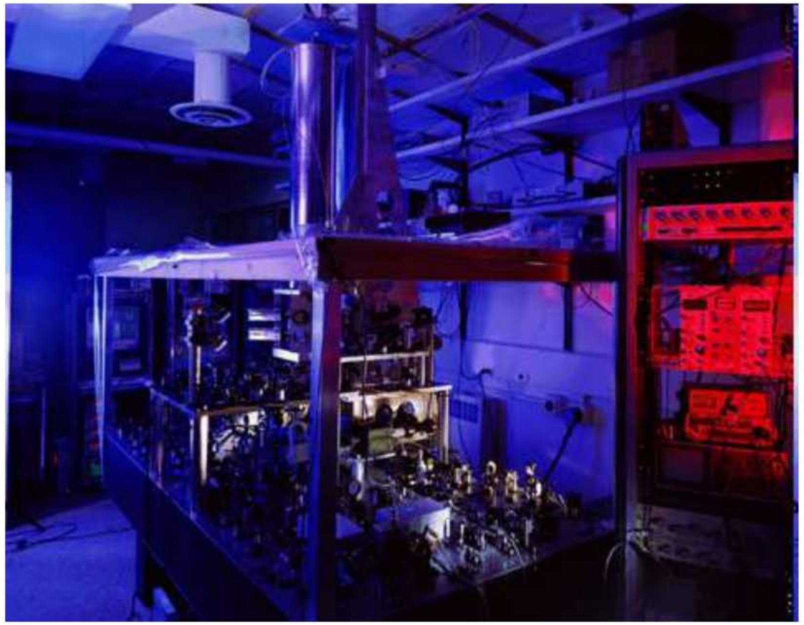
What exactly is measuring?

- measuring =
  determining the value of a quantity

- quantity = property of a phenomenon or object that can be qualitatively distinguished, and quantitatively determined
  - length, time, mass, temperature, electrical resistance

Standards

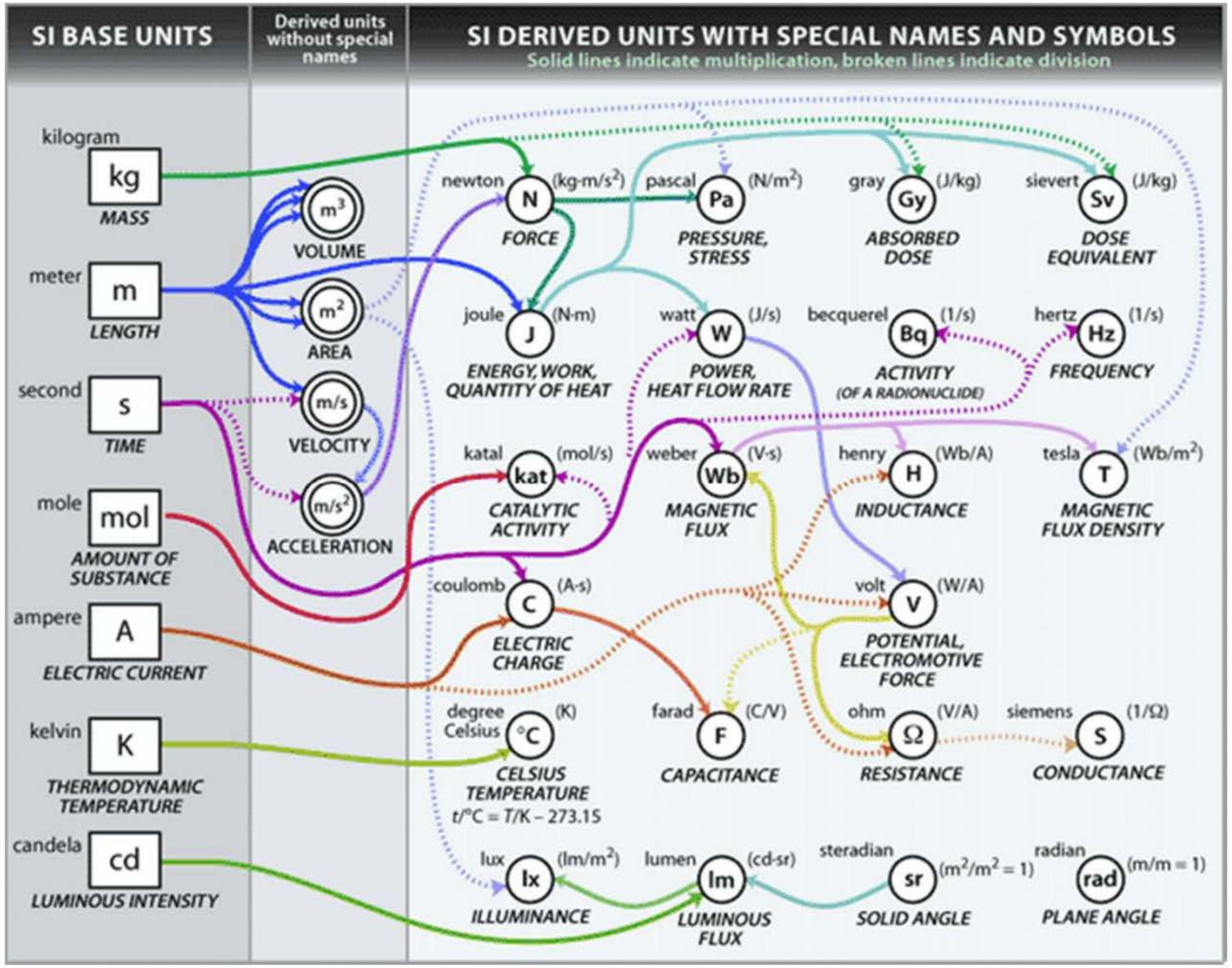
- Objective, comparable measurements require **standards**



NIST-F1 time- and frequency standards:
1s = 9.191.631.770 periods of the resonance frequency of a Cs-133 atom

Copy of the *international prototype kilogram* (cylinder of90% platinum and 10% iridium)

International System of Units (SI)



Kilograms vs. pounds: “The Gimli Glider”

http://www.youtube.com/watch?v=4yvUi7OAOL4

- 1983: Canada switches from imperial units to metric
- Air Canada flight 143: mistake with the fuel transfer…
  - 22.300 kg needed for the flight
  - 7.682 l left in the tank
    -- how many kg is that?
  - the crew use 1.77 lb/l
    instead of 0.8 kg/l
  - consequence: only 4916 l
    transferred in stead of the
    required 20088 l
  - emergency landing!!

July 23, 1983: Air Canada flight 143 lands at a closed air force base in Gimli, Canada

Measurement Uncertainty

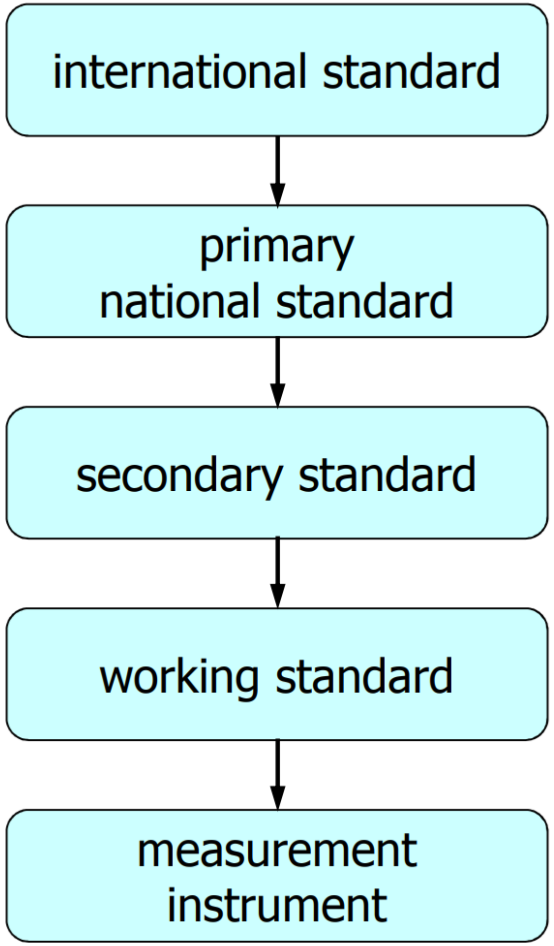
- Every measurement y of a quantity x is subject to measurement uncertainty
- Many causes:
  - random variations in the measurement value
  - varying measurement conditions
  - finite resolution / incorrect reading
  - deviations in the transfer of the measurement system
  - poorly defined definition of the quantity to be measured
  - …

Uncertainty vs. error

- Measurement uncertainty ≠ measurement error
  - Error: difference between measured value and the 'true' value
  - Uncertainty: quantification of the doubt about the measurement
- Measurement uncertainty can be quantified by
  - a standard deviation:
    "the mass is 100.02147 g with a standard deviation of 0.35 mg"
  - a confidence interval:
    "the mass is (100.02147 ± 0.00079) g, at a confidence level of 95%"
- Unknown measurement errors contribute to the measurement uncertainty
- Some measurement errors can be determined, by means of calibration, and be corrected for afterwards.

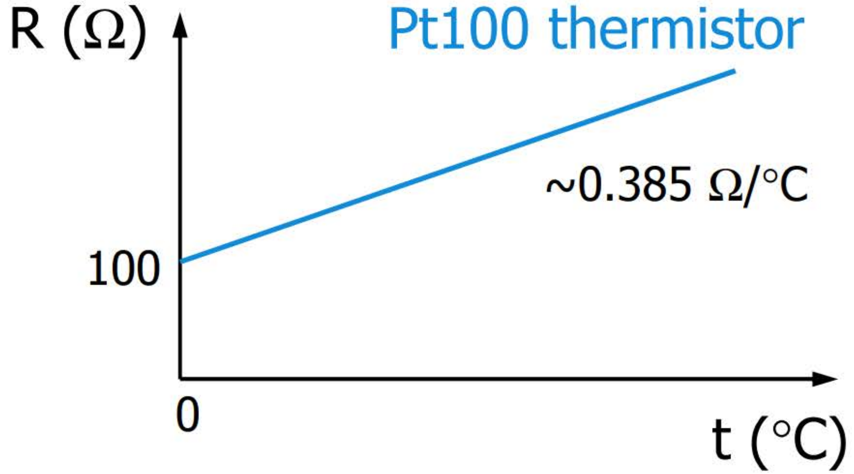
Calibration

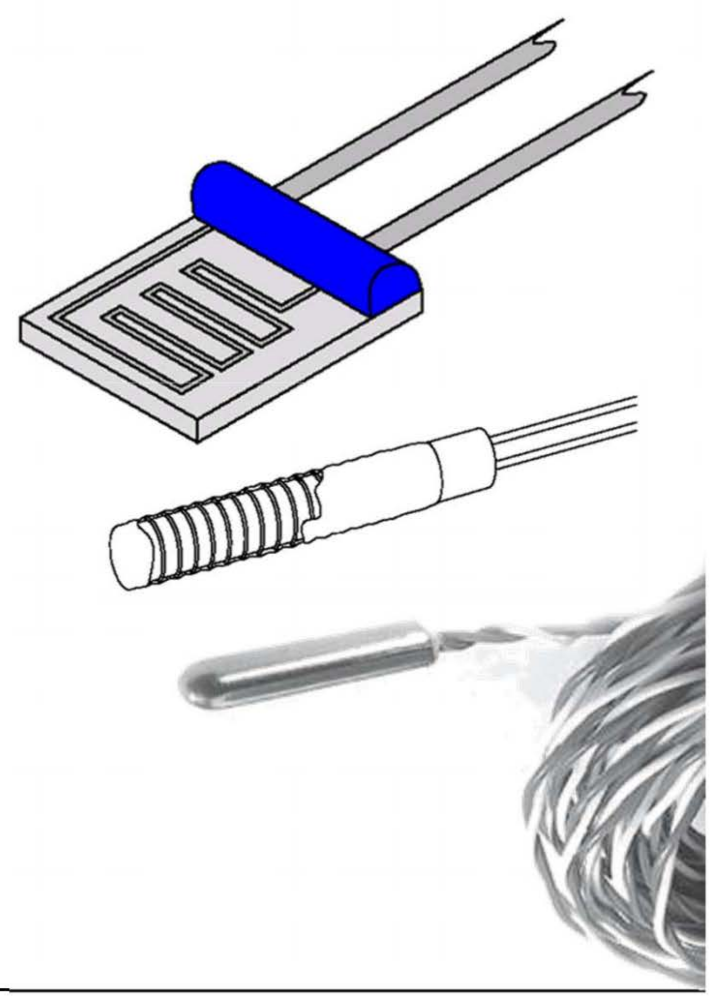
- **Calibration** makes a connection between
  - measurement values produced by a measurement instrument
  - corresponding values realized by standards
- **Calibration procedure**: comparison of an instrument with a (more accurate) measurement standard
- Calibration enables measurements which are **traceable** to standards
  - through an unbroken chain of comparisons
  - with associated specified uncertainties !



Example: calibration of a platinum thermometer

- PRT: platinum resistance thermometer
- typical **transfer**:

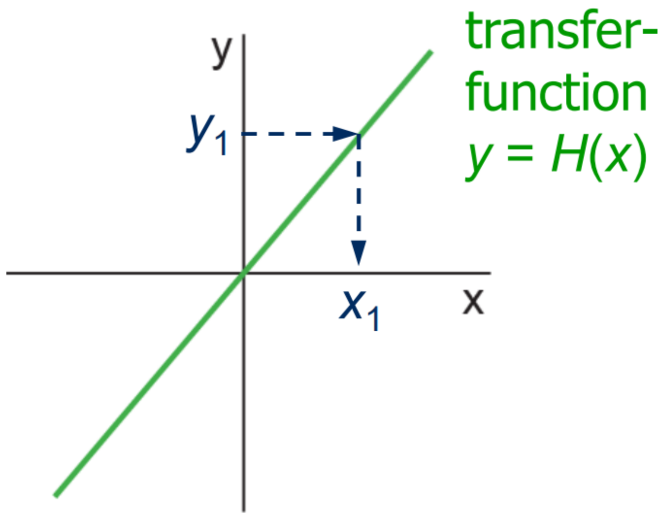




Example: calibration of a platinum thermometer

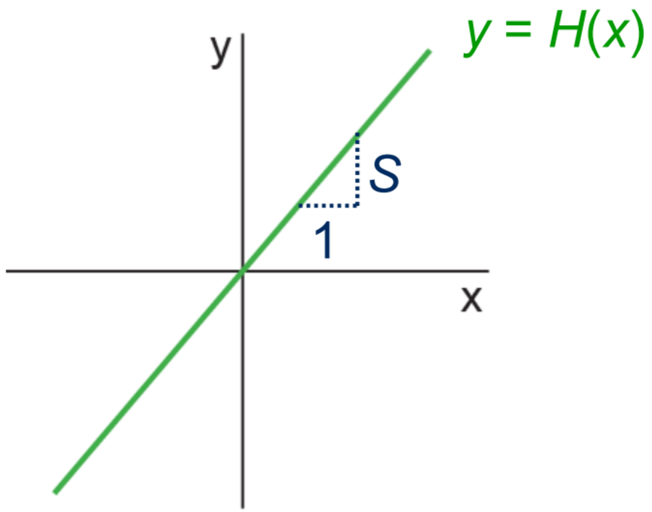
- Calibration procedure:
  - comparison to a more accurate reference thermometer (the working standard) at various calibration temperatures
    $\Rightarrow$ list of measured temperatures and resistance values with measurement uncertainty
  - determination of the coefficients of a formula that relates measured resistance to temperature
    $\Rightarrow R(t) = R_0\,(\,1 + A \cdot t + B \cdot t^2\,)$
  - determination of the corresponding measurement uncertainty
- Next, when using the thermometer, this formula will be used to translate a measured resistance into temperature

Transfer of a measurement system



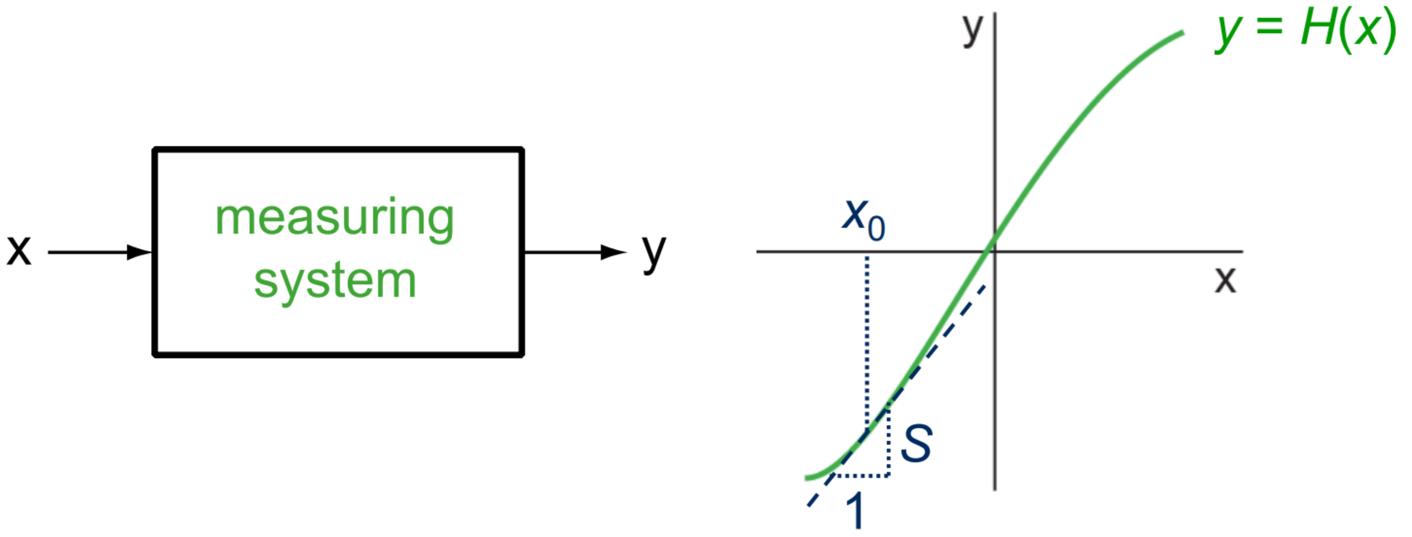
- Using the transfer function H, output signal (indication) y_1 can be translated back to a measurement value x_1

Sensitivity



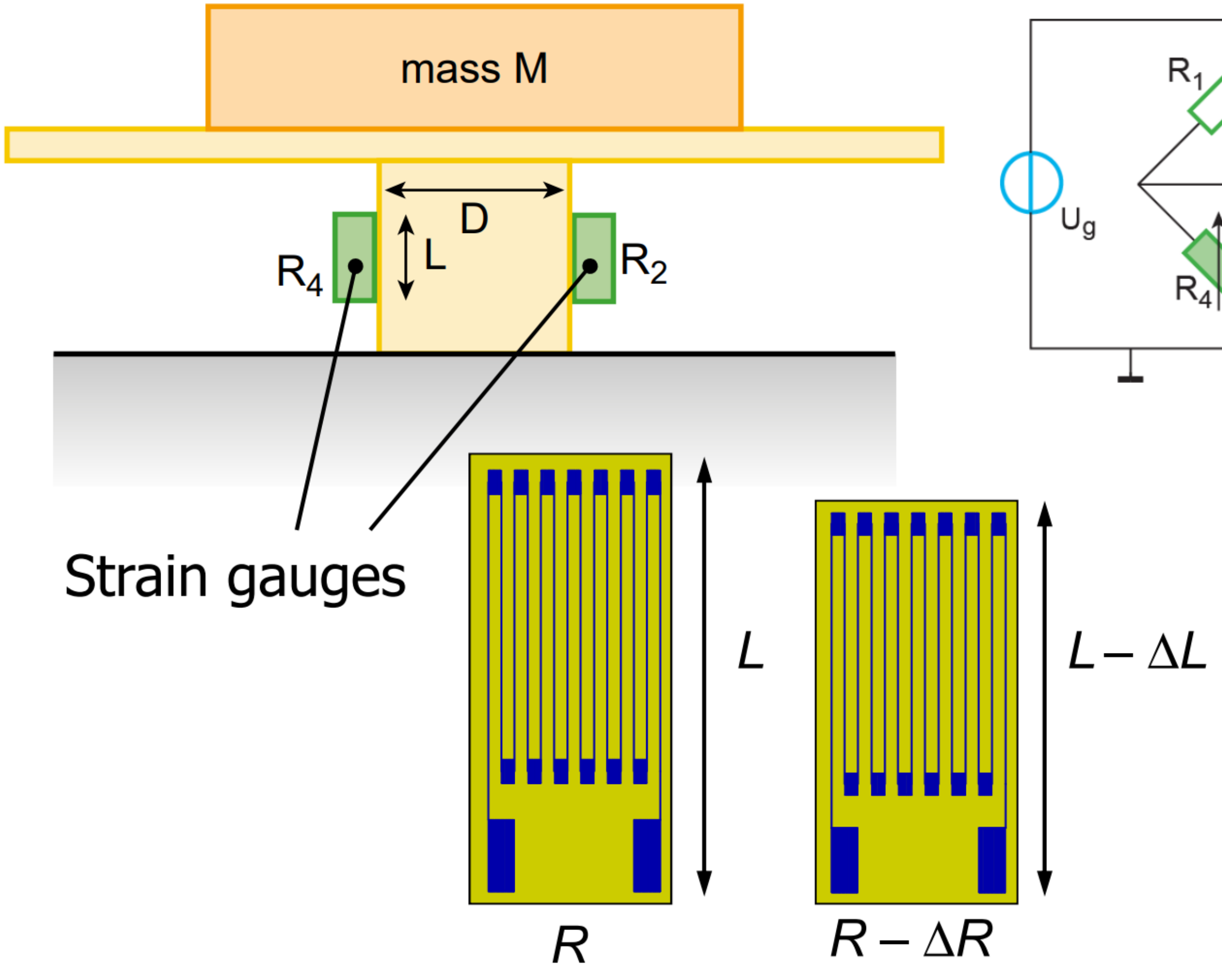
- **Sensitivity**: $S = \Delta y \,/\, \Delta x$
- Ideal linear transfer: sensitivity $S = y \,/\, x$

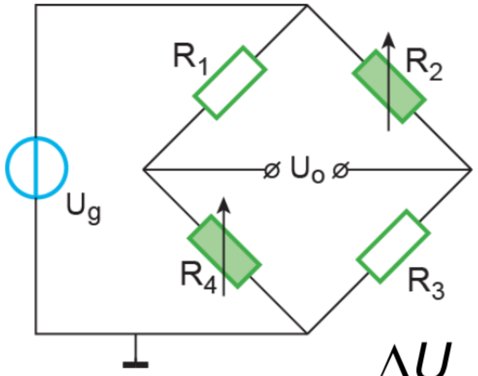
Differential Sensitivity



- Non-linear transfer
  $\Rightarrow$ **differential** sensitivity round x_0: $$S = \left.\frac{dy}{dx}\right|_{x=x_0} = H'(x_0)$$

Sensitivity example: weighing scale



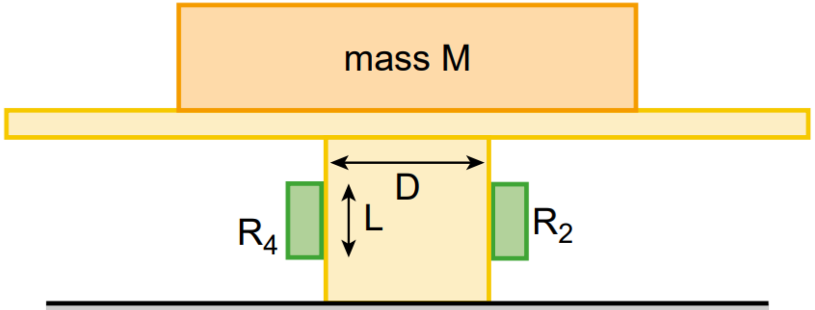


$$\Delta U_o \cong \frac{\Delta R}{2R} U_g$$

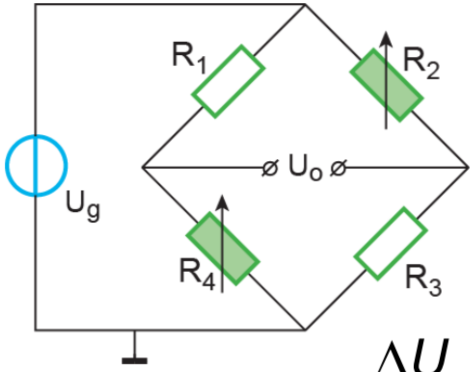
$$\frac{\Delta R}{R} = k \frac{\Delta L}{L}$$

gauge factor k
= 2 for metals

Sensitivity example: weighing scale



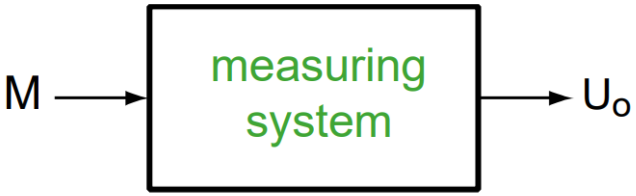
$$\frac{\Delta R}{R} = 2\frac{\Delta L}{L}$$



$$\Delta U_o \cong \frac{\Delta R}{2R} U_g$$

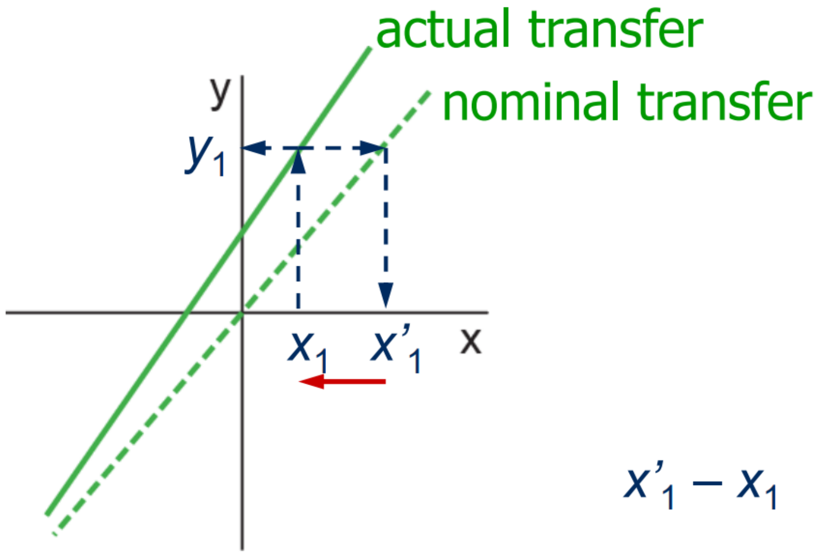
Given: the source voltage U_g = 10 V
the relative sensitivity of the length change is

$$\frac{\Delta L / L}{\Delta M} = 6.2 \cdot 10^{-7}\ \text{kg}^{-1}$$



Determine the sensitivity $S = \Delta U_o / \Delta M$ [V/kg] of the measurement system

Measurement errors due to deviations in the transfer

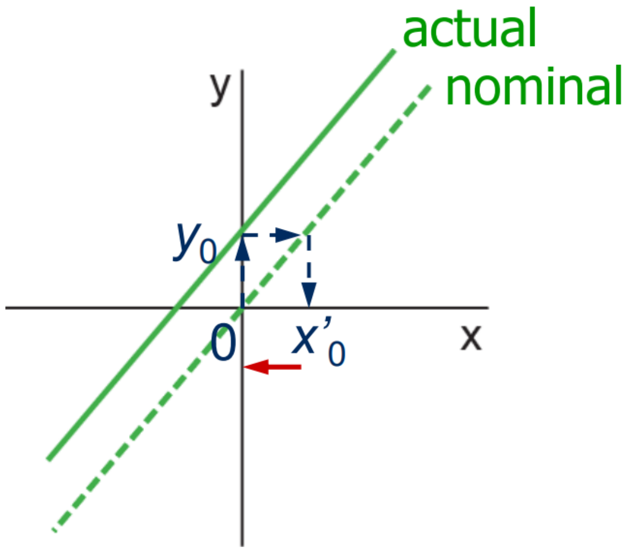


x_1	actual value of quantity to be measured
y_1	output signal of measurement system
x'_1	measured value determined based on nominal transfer

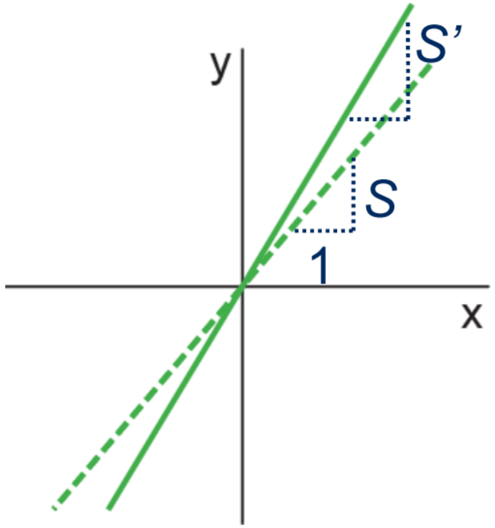
$x'_1 - x_1$ **measurement error**

Deviation in linear transfer

Offset error

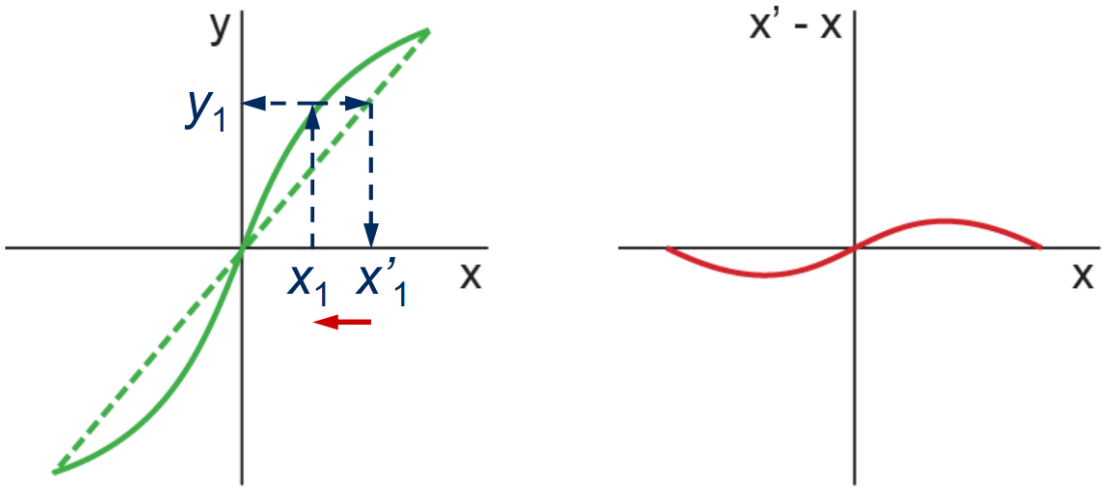


Gain error (sensitivity error)



Non-linearity

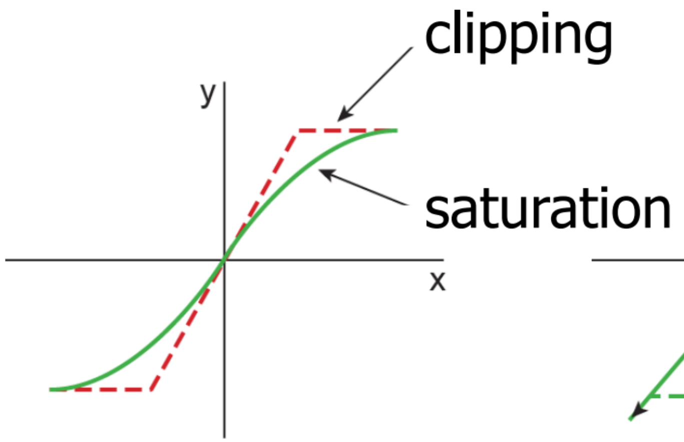
- A non-linear transfer will give measurement errors if the nominal transfer is assumed to be linear
- Integral non-linearity:



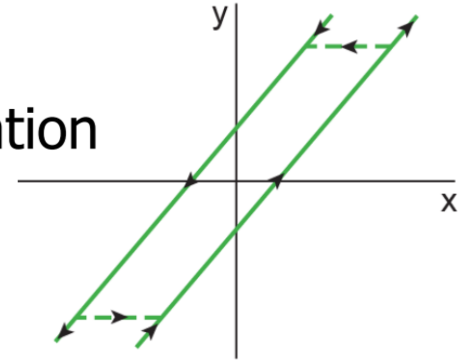
Ambiguity

- No one-to-one relation between the quantity to be measured x and the output signal y

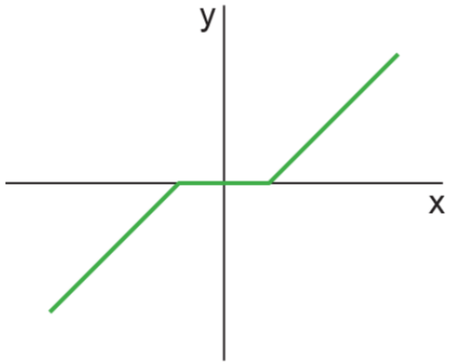
saturation



hysteresis



dead zone



Ambiguity

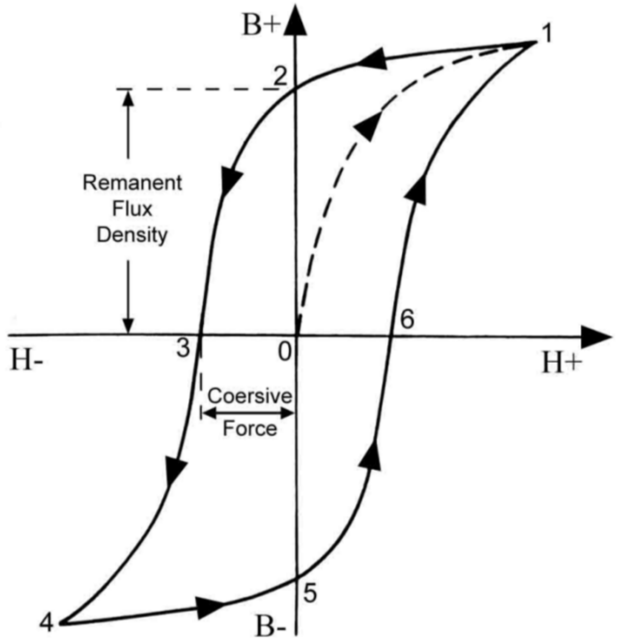
saturation
hysteresis
dead zone

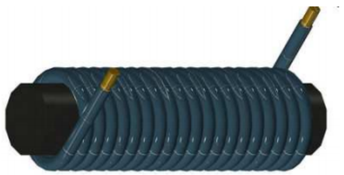
- Moving coil meter with friction

Ambiguity

saturation
hysteresis
dead zone

- Magnetisation of a ferromagnetic core

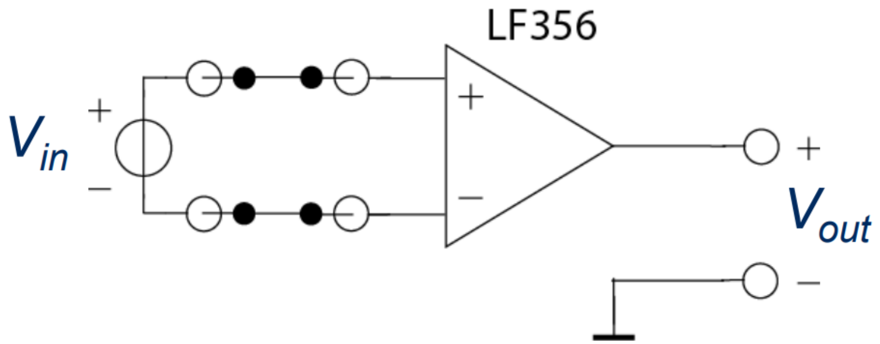




Ambiguity

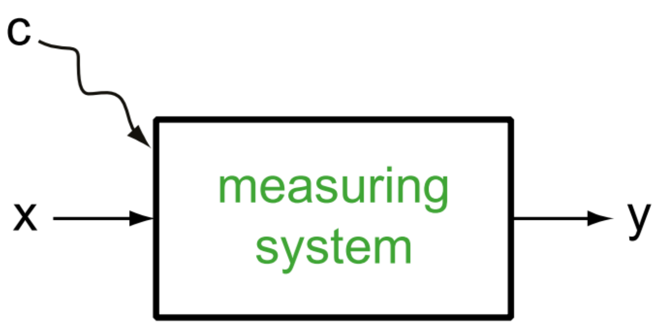
saturation
hysteresis
dead zone

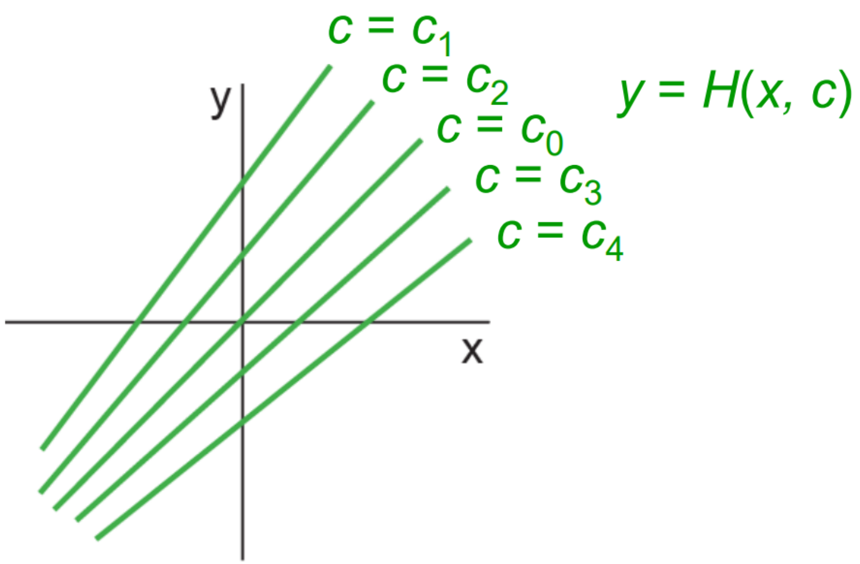
- Opamp



Cross-sensitivity

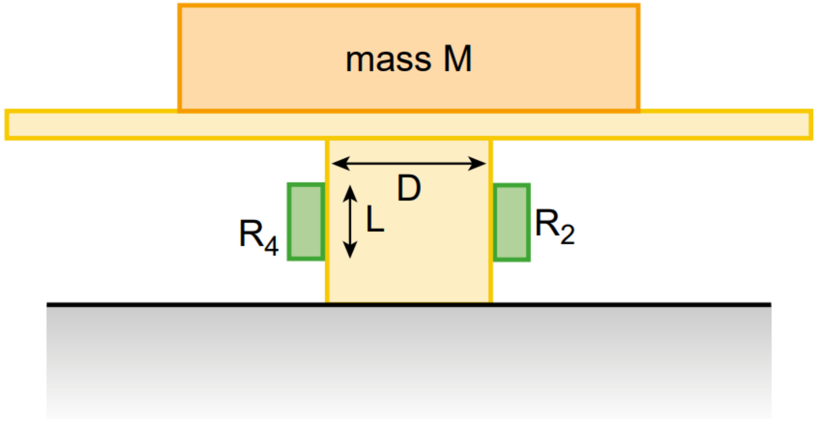
- Unwanted sensitivity to an **influence quantity** c

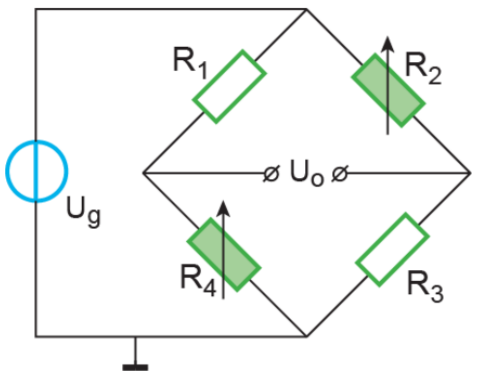




- Ideally: $S_c^y = 0$

Cross-sensitivity ex.: weighing scale



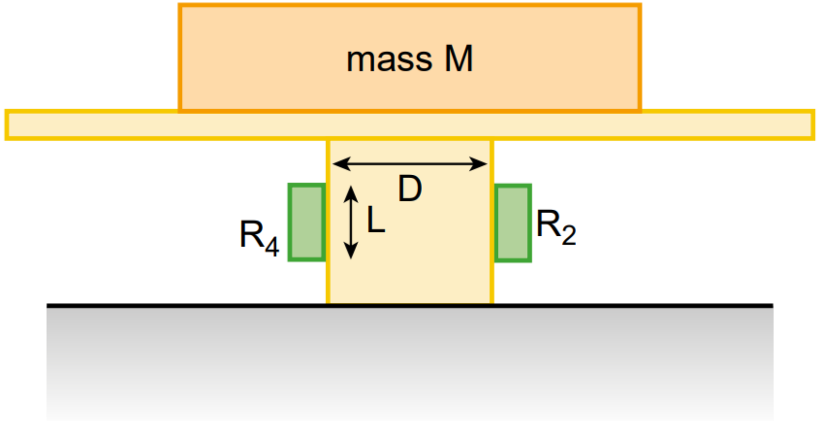


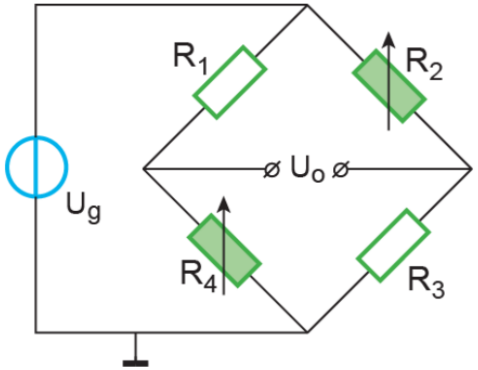
$\boxed{\text{temperature-difference } \Delta T}$ → resistance change $\Delta R / R$ → output voltage ΔU_o

- Temperature sensitivity resistors typically expressed as

temperature coefficient: $\alpha = \dfrac{1}{R} \cdot \dfrac{dR}{dT}$ [K^{-1}] $\quad \Rightarrow \dfrac{\Delta R}{R} = \alpha \cdot \Delta T$

Cross-sensitivity ex.: weighing scale



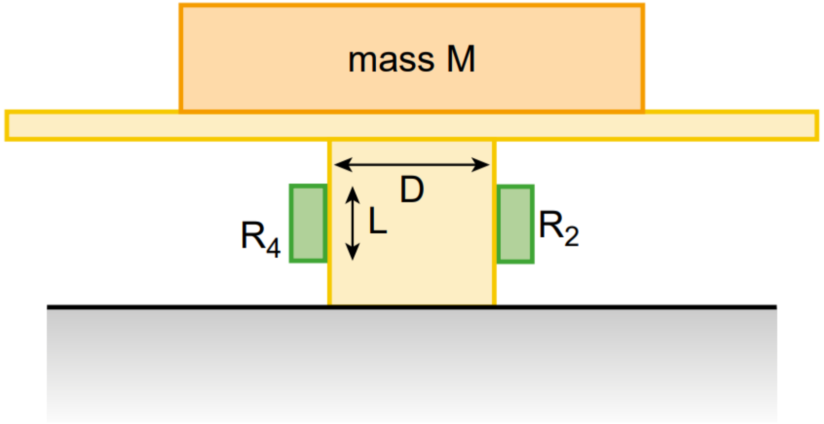


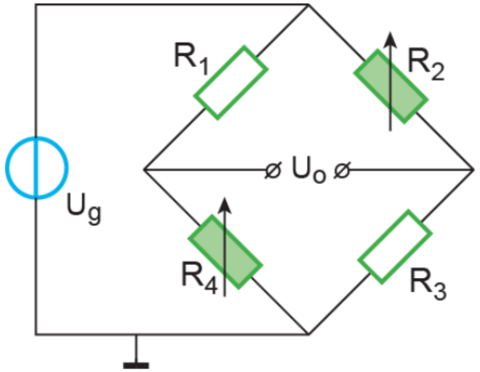
temperature-difference ΔT → resistance change $\Delta R/R$ → output voltage ΔU_o

$$\frac{\Delta R}{R} = \alpha \cdot \Delta T \qquad \Delta U_o \cong \frac{\Delta R}{2R} U_g$$

- Cross sensitivity: $S_{temp} = \dfrac{\Delta U_o}{\Delta T} = \dfrac{\alpha \cdot U_g}{2}$

Cross-sensitivity ex.: weighing scale



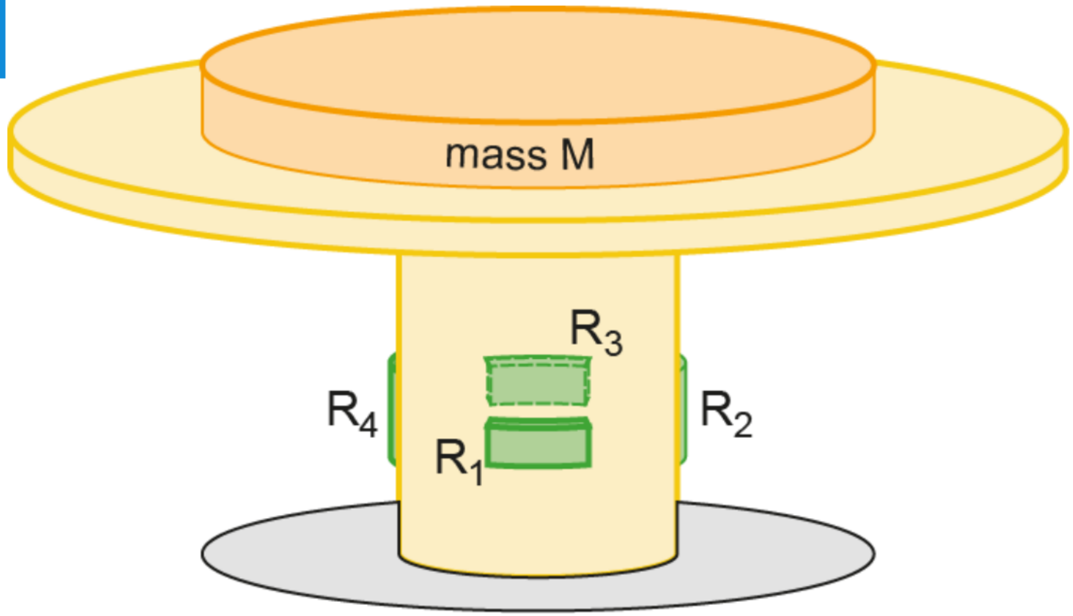


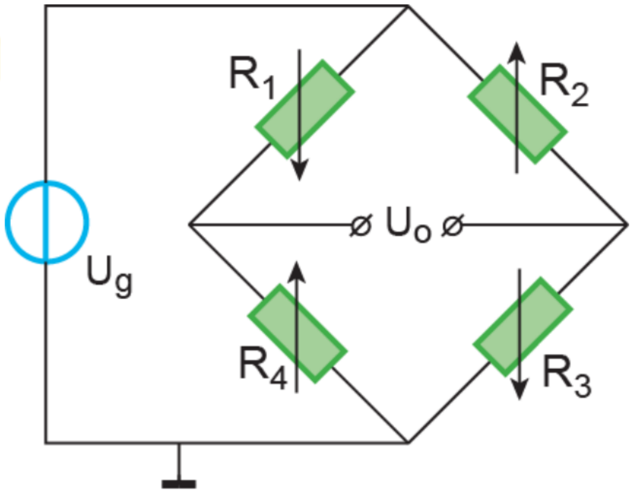
- Cross-sensitivity: $S_{temp} = \dfrac{\Delta U_o}{\Delta T} = \dfrac{\alpha \cdot U_g}{2}$

- Let: $\alpha = 2{,}0 \cdot 10^{-5}\,\mathrm{K}^{-1}$, $U_g = 10\,\mathrm{V} \Rightarrow S_{temp} = 0{,}10\,\mathrm{mV/K}$
- Compare to earlier found $S_{massa} = 6{,}2\ \mu\mathrm{V / kg}$

error:
16 kg / K !!

Cross-sensitivity ex.: weighing scale





- **Compensation** for temperature differences:
  4 strain gauges mounted to the base ⇒ small ΔT

Measurement errors due to aging

- Measurement systems change over time
  ⇒ uncertainty increases
  ⇒ frequent calibration is needed

Accuracy Specifications ± (% of reading + % of range)

Function	Range[3]	24 Hour[2] 23°C ±1°C	90 Day 23°C ±5°C	1 Year 23°C ±5°C
DC voltage	100.0000 mV	0.0030 + 0.0030	0.0040 + 0.0035	0.0050 + 0.0035
	1.000000 V	0.0020 + 0.0006	0.0030 + 0.0007	0.0040 + 0.0007
	10.00000 V	**0.0015 + 0.0004**	**0.0020 + 0.0005**	**0.0035 + 0.0005**
	100.0000 V	0.0020 + 0.0006	0.0035 + 0.0006	0.0045 + 0.0006
	1000.000 V	0.0020 + 0.0006	0.0035 + 0.0010	0.0045 + 0.0010

Resolution

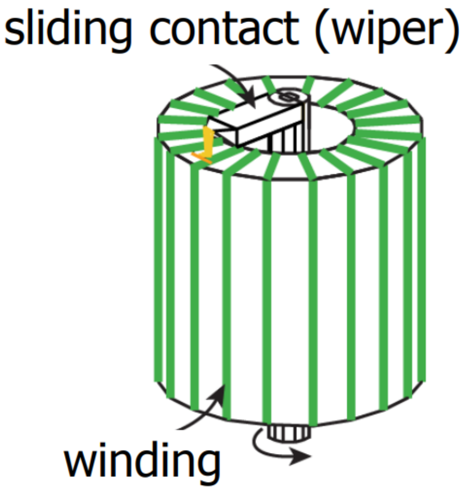
- **Resolution:** smallest change in x that causes a noticeable change in y

- Expressed in two ways:
  - absolute: Δx
  - relative to the full scale: $\Delta x \,/\, x_{max}$
    often in bits: $- {}^{2}\log\,(\Delta x \,/\, x_{max})$

- Example: 4½-digit display, 200V range
  - $\Delta x = 0.01\ \text{V}$
  - $\Delta x \,/\, x_{max} = 0.01\ \text{V} \,/\, 199.99\ \text{V} = 5 \cdot 10^{-5}$
    in bits: $- {}^{2}\log\,(5 \cdot 10^{-5}) = 14.3\ \text{bits}$

Resolution examples

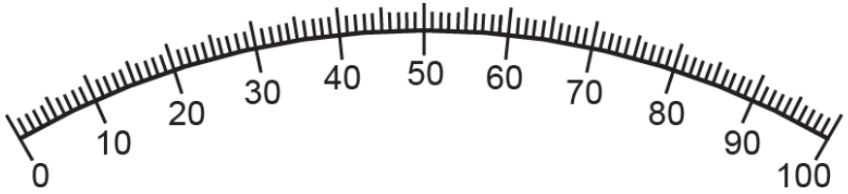
- Resolution determined by sensor: wirewound potentiometer



1000 windings

Resolution examples

- Resolution determined by display:



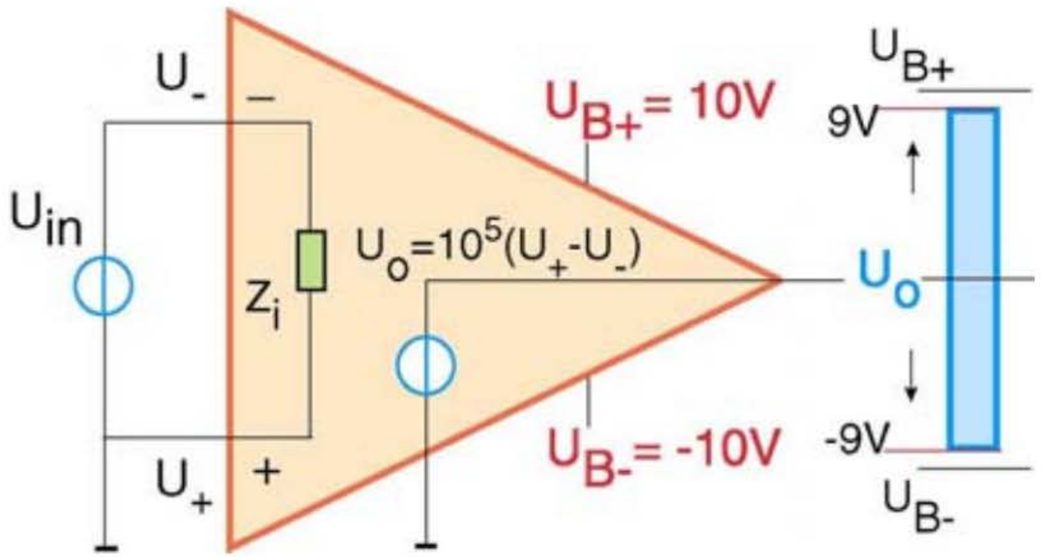
Summary

- Measuring = determining the value of a quantity
  - measurement requires international standards
  - calibration is needed for traceable, comparable measurements
  - every measurement is subject to measurement uncertainty

- Measurement system: converts quantity to be measured x into usable output signal y (often electrical, digital)
  - Data acquisition: $x \rightarrow$ sensor $\rightarrow$ signal conditioning $\rightarrow$ ADC $\rightarrow$ y
  - Characterized by transfer $y = H(x)$ with sensitivity $H'(x)$
  - Deviations in the transfer can lead to measurement errors: non-linearity, ambiguity, cross sensitivity, finite resolution

Read-out using Operational Amplifiers

Using the open-loop gain

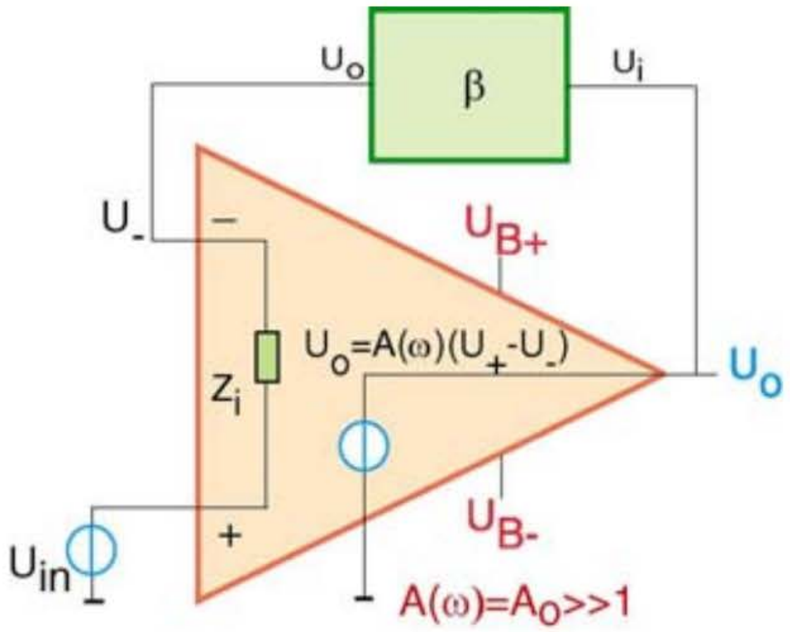


$U_{in,max} = U_{o,max}/10^5 = 9/10^5 = 90\ \mu V \ll U_{offset}$

⇒ Should be used in a feedback configuation

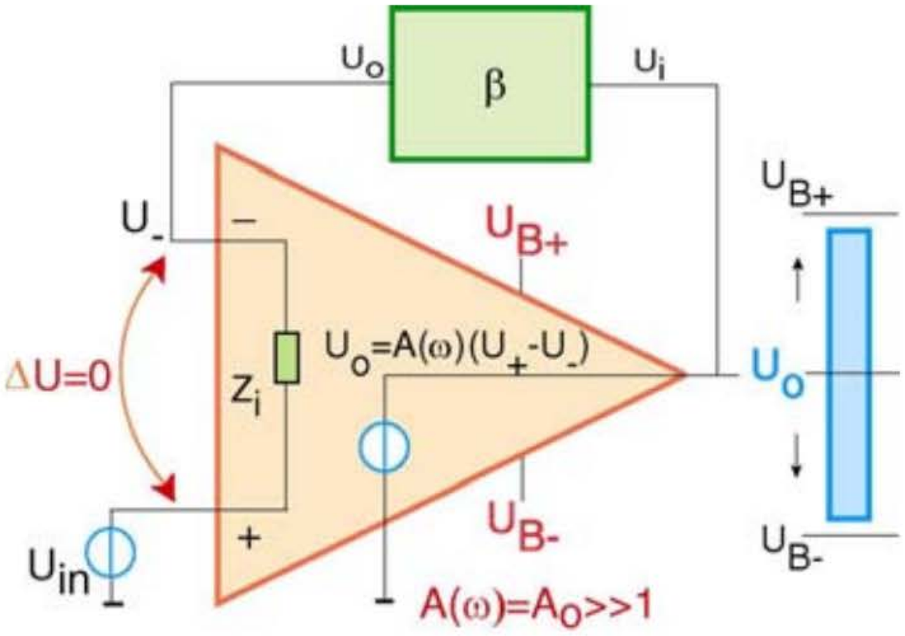
Read-out using Operational Amplifiers

Opamp in feedback - Principle



Stability concerns !

Read-out using Operational Amplifiers



A finite value for U_o and a very high open-loop gain implies: $U_+ - U_- = 0$.

The feedback loop ensures that the value of U_o is such that: $U_- = U_+$

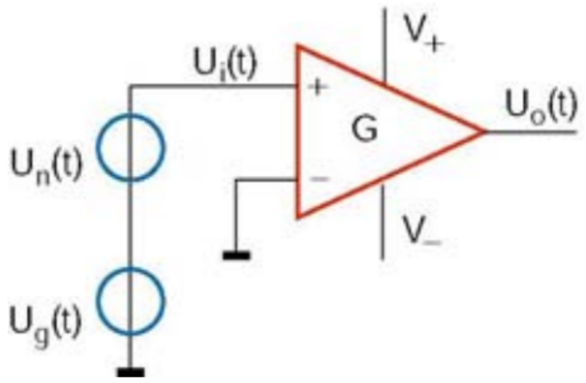
This implies that the potential at the opamp's non-inverting input is virtually copied to the inverting input

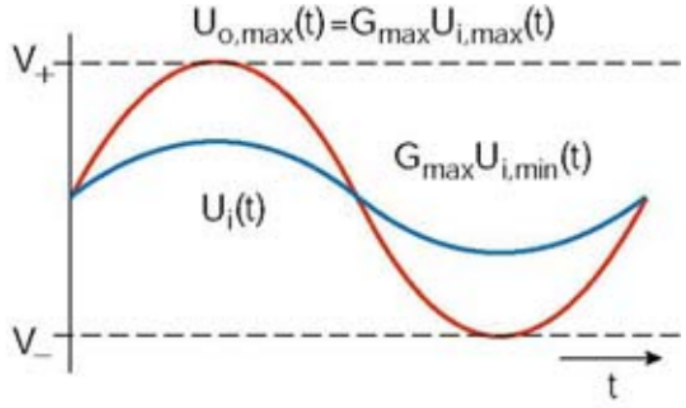
Detection limit

Definition: The minimum level of the input quantity that can be reproducibly measured at specified inaccuray/SNR (default: SNR= 0 dB).

A practical signal is specified by its dynamic range: ratio between minimum and maximum signal level occurring within inaccuracy specification

Constraint due to maximum possible input level: Gain limited to G_{max}





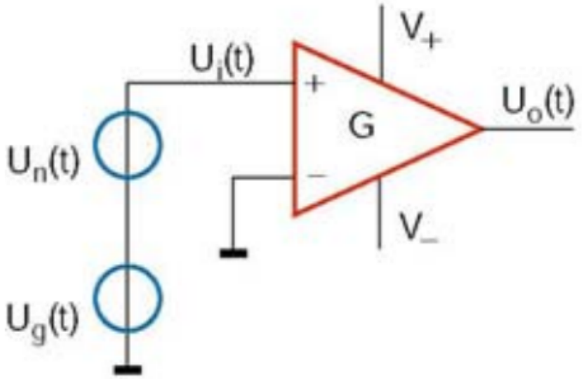
The maximum level of the input signal sets the maximum gain. However, the lower end of the input signal also results in a constraint.

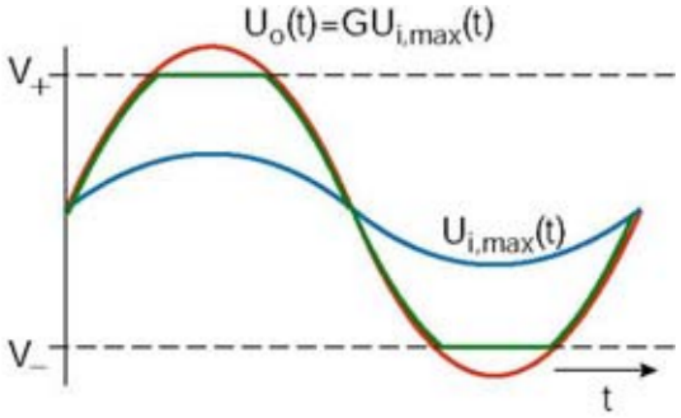
Detection limit

Definition: The minimum level of the input quantity that can be reproducibly measured at specified inaccuray/SNR (default: SNR= 0 dB).

A practical signal is specified by its dynamic range: ratio between minimum and maximum signal level occurring within inaccuracy specification

Constraint due to maximum possible input level: Increasing gain G





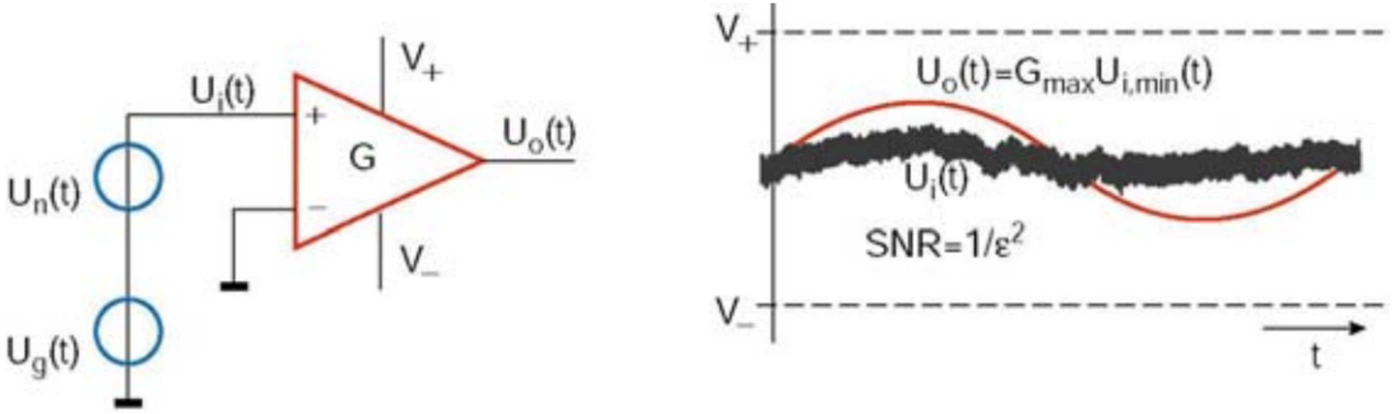
Maximum output voltage would be higher than system can deliver ⇒ saturation at maximum possible output level: Gain limited to G_{max}

Detection limit

Definition: The minimum level of the input quantity that can be reproducibly measured at specified inaccuray/SNR (default: SNR= 0 dB).

However, the minimum input signal is also limited at given inaccuracy (or Signal-to-Noise Ratio-SNR) specification when considering noise and interference

At G_{max} and specified inaccuracy,ε:



Note: output (red line) is drawn WITHOUT noise

Electronic Instrumentation

System sensitivity is not limited by the gain one can implement in the signal conditioning, but rather by the detection limit.

Procedure for finding the detection limit:

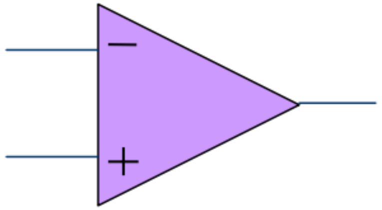
1. Determine the various error sources within the instrument and calculate the combined effect on the output.

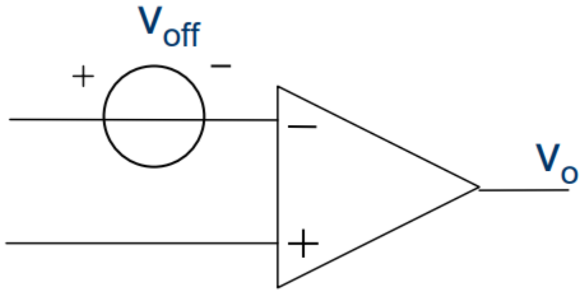
2. Identify the dominating source of uncertainty
    a. Source loading
    b. offset
    c. Finite CMRR in a differential measurement
    d. Noise or interference

3. Calculate the input-referred equivalent sources of uncertainty.

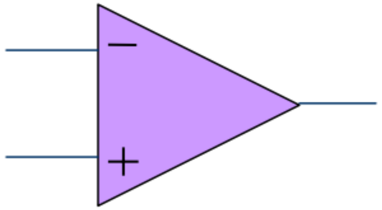
Opamp with DC errors

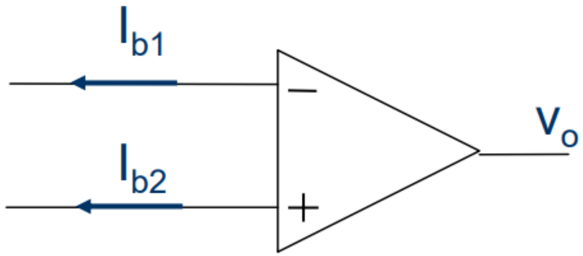
- For a REAL amplifier, v_o <> 0 when v_{in} = 0, actually v_o = 0 when $v_{in} = v_{off}$
- We call v_{off} the input offset voltage



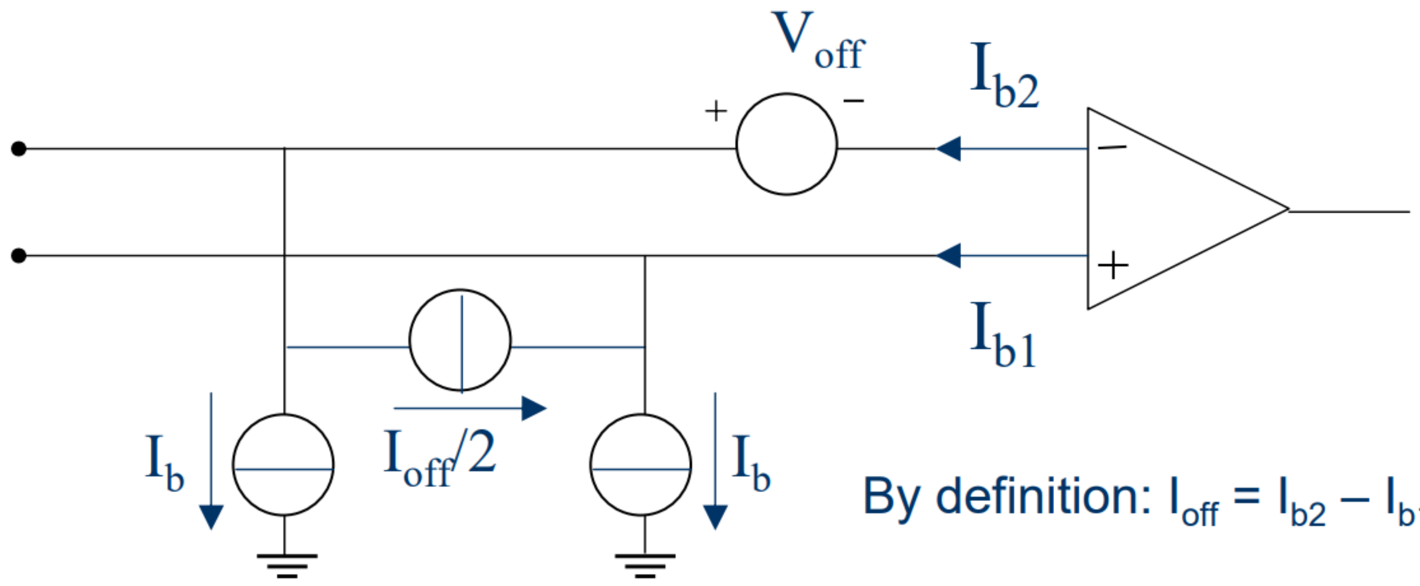


- Input bias currents I_{b1}, I_{b2}
- Input offset current $I_{off} = I_{b2} – I_{b1}$





Opamp with DC errors



By definition: $I_{off} = I_{b2} - I_{b1}$

- Non-ideal opamp = error sources + ideal opamp
- The polarities of V_{off} en I_{off} are usually unknown!
- So the numbers in data-sheets are **absolute** values

LM324, LM324A, LM324E, LM224, LM2902, LM2902E, LM2902V, NCV2902

Single Supply Quad Operational Amplifiers

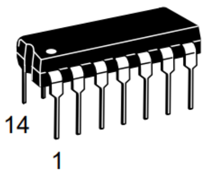
The LM324 series are low−cost, quad operational amplifiers with true differential inputs. They have several distinct advantages over standard operational amplifier types in single supply applications. The quad amplifier can operate at supply voltages as low as 3.0 V or as high as 32 V with quiescent currents about one−fifth of those associated with the MC1741 (on a per amplifier basis). The common mode input range includes the negative supply, thereby eliminating the necessity for external biasing components in many applications. The output voltage range also includes the negative power supply voltage.

Features

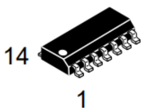
- Short Circuited Protected Outputs
- True Differential Input Stage
- Single Supply Operation: 3.0 V to 32 V
- Low Input Bias Currents: 100 nA Maximum (LM324A)
- Four Amplifiers Per Package
- Internally Compensated
- Common Mode Range Extends to Negative Supply
- Industry Standard Pinouts
- ESD Clamps on the Inputs Increase Ruggedness without Affecting Device Operation
- NCV Prefix for Automotive and Other Applications Requiring Unique Site and Control Change Requirements; AEC−Q100 Qualified and PPAP Capable
- These Devices are Pb−Free, Halogen Free/BFR Free and are RoHS Compliant

ON Semiconductor®

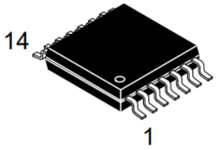
www.onsemi.com



PDIP−14
N SUFFIX
CASE 646

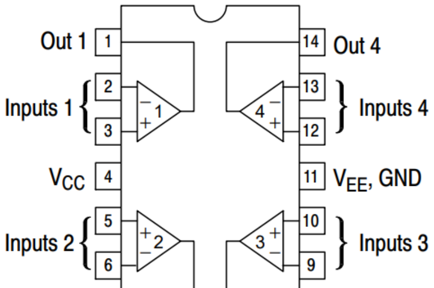


SOIC−14
D SUFFIX
CASE 751A



TSSOP−14
DTB SUFFIX
CASE 948G

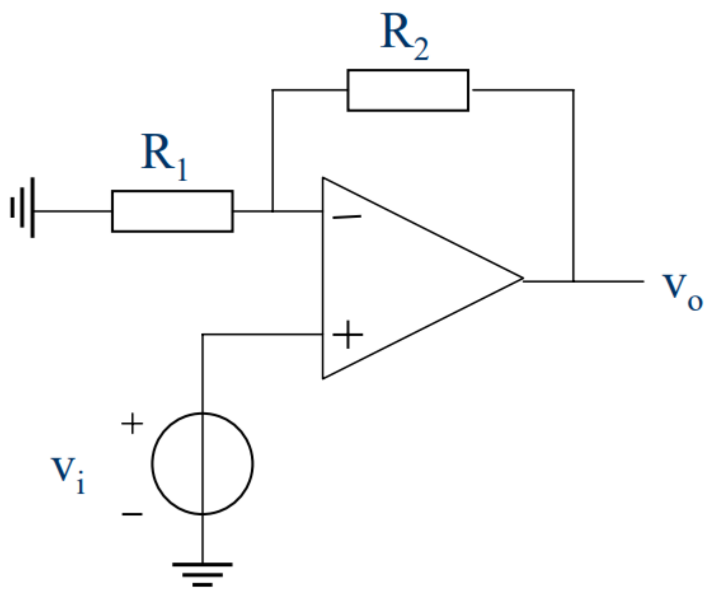
PIN CONNECTIONS



ELECTRICAL CHARACTERISTICS (V_{CC} = 5.0 V, V_{EE} = GND, T_A = 25°C, unless otherwise noted.)

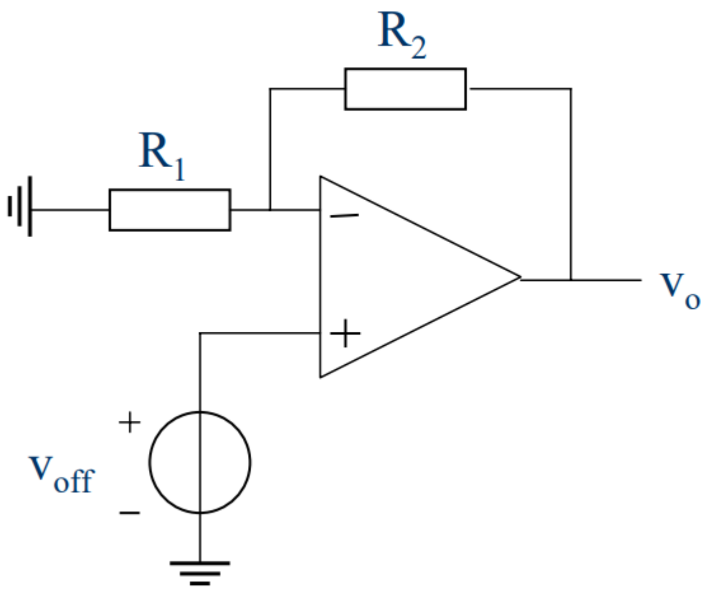
Characteristics	Symbol	LM224			LM324A			LM324, LM324E			LM2902, LM2902E			LM2902V/NCV2902			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage V_{CC} = 5.0 V to 30 V V_{ICR} = 0 V to V_{CC} −1.7 V, V_O = 1.4 V, R_S = 0 Ω	V_{IO}																mV
T_A = 25°C		–	2.0	5.0	–	2.0	3.0	–	2.0	7.0	–	2.0	7.0	–	2.0	7.0	
T_A = T_{high} (Note 4)		–	–	7.0	–	–	5.0	–	–	9.0	–	–	10	–	–	13	
T_A = T_{low} (Note 4)		–	–	7.0	–	–	5.0	–	–	9.0	–	–	10	–	–	10	
Average Temperature Coefficient of Input Offset Voltage T_A = T_{high} to T_{low} (Notes 4 and 6)	$\Delta V_{IO}/\Delta T$	–	7.0	–	–	7.0	30	–	7.0	–	–	7.0	–	–	7.0	–	μV/°C
Input Offset Current	I_{IO}	–	3.0	30	–	5.0	30	–	5.0	50	–	5.0	50	–	5.0	50	nA
T_A = T_{high} to T_{low} (Note 4)		–	–	100	–	–	75	–	–	150	–	–	200	–	–	200	
Average Temperature Coefficient of Input Offset Current T_A = T_{high} to T_{low} (Notes 4 and 6)	$\Delta I_{IO}/\Delta T$	–	10	–	–	10	300	–	10	–	–	10	–	–	10	–	pA/°C
Input Bias Current	I_{IB}	–	−90	−150	–	−45	−100	–	−90	−250	–	−90	−250	–	−90	−250	nA
T_A = T_{high} to T_{low} (Note 4)		–	–	−300	–	–	−200	–	–	−500	–	–	−500	–	–	−500	
Input Common Mode Voltage Range	V_{ICR}																V

Mini-Quiz 2



- If the opamp has finite offset and bias current, calculate the input-referred offset of this amplifier?

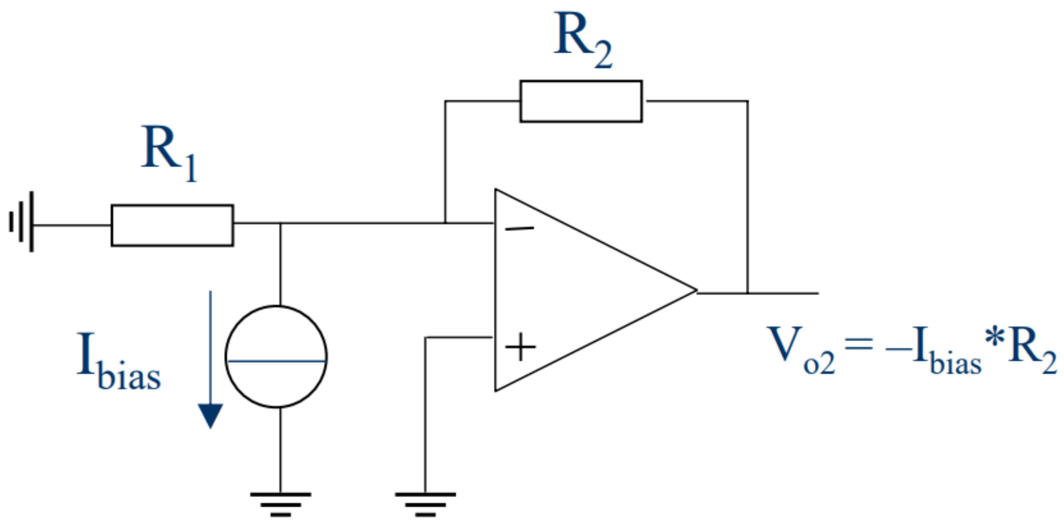
Solution (1)



- **Use superposition, since this an LTI system!**
- So the effect of every DC source can be independently determined and then summed

- Contribution of $V_{off} \Rightarrow V_{o1} = V_{off}(1+ R_2/R_1)$

Solution (2)



- Why doesn't any current flow through R_1?

Solution (3)

- The two results can be added

$V_o = V_{o1} + V_{o2}$

$V_o = V_{off}\,(1 + R_2/R_1) - I_{bias}{*}R_2$

- Input-referred offset $V_{in,off} = V_o/A_{CL}$

So $V_{in,off} = V_{off} - I_{bias}{*}R_1\,||R_2$

- How is this a detection limit?
- Can you name other DC detection limits?

تمارين

1.3 An experiment results in the following empirical relation:

$$f = \frac{1}{2Lr}\sqrt{\frac{F}{\rho}} \tag{1-5}$$

With the following quantities: f: frequency, F: Force, L: length, ρ: specific mass and r: radius. Can this empirical relation be correct?

Select the correct answer:

a. Yes, because the units match
b. No, because the units do not match
c. Yes, because a resonance frequency is always described by a square root function
d. No answer possible due to insufficient specification

1.3 Insertion of SI basic units yields:

$$[s]^{-1} = [m]^{2}([N]/\{[kg][m]^{-3}\})^{1/2} = [m]^{2}([kg][m/s^{2}]/\{[kg][m]^{-3}\})^{1/2} = [s]^{-1}.$$

The unit expression would be correct in case the SI-units would be specified. Since the units are NOT specified, this is not necessarily the case (length could e.g. be given in inches). Therefore, the correct answer is D.

تمارين

1.4Express the unit of electrostatic capacitance, C [F], in SI- units. Capacitance is related to charge and voltage via the expression: $Q= C\times V$, [C]= [F][V]. Moreover, electric charge buildup is equal to the product of charging current and time:

$Q= I.t$, [C]= [A][s]. Finally, the unit of mechanical power is equal to that of electrical power: $[V][A]= [N][m][s]^{-1}$.

1.4 $C = Q/V= I.t/V$: $[F]= [A][s]/[V]$, $[V]= [kg][m]^2/([A][s]^3) \rightarrow$
$[F]= [A][s]\{[A][s]^3/([kg][m]^2\}= [A]^2[s]^4[kg]^{-1}[m]^{-2}$
Note: The Volt [V] is NOT a basic SI unit.

تمارين

2.2 The following specifications are listed for an instrument:

- Temperature drift: 0.01%/°C
- Time stability: 0.1%/month
- Operating temperature range between -10 °C and 60 °C.

Calculate the reproducibility of a measurement if only once every three months a calibration is performed at 20 °C (the calibration is assumed to be perfectly accurate and the time elapsed since the last calibration is assumed to be unknown).

2.2 Largest deviation from calibration temperature is: max{60-20, 20-(-10)}= 40 °C →
Repr. = 0.01%/°C × 40°C + 0.1%/month × 3 months = 0.7%.

تمارين

An instrument is used to measure a voltage of about 7.2 V. It is composed of a 4-digit indicator with 9.999 full-scale. The inaccuracy is specified at 0.2% full scale + 0.5% indication.

2.3 Calculate the resolution of this instrument.

2.4 Also calculate the inaccuracy of this instrument.

2.3 Display with 4 digits and 10 V full scale→ Resolution= $10^{-4} \times 10$ V = 1 mV.

2.4 Inaccuracy = 0.002×10 V + 0.005×7.2 V = 56 mV.

تمارين

The following specifications are listed for an instrument:

- Temperature drift: 0.04%/°C
- Time stability: 0.1% /month
- Operating temperature range between 0 °C and 30 °C.

2.5 Select the most convenient calibration temperature and calculate the maximum calibration interval for a reproducibility specification at 1%.

2.5 Calibration temperature preferably at mid-range: T_{cal}= 15 °C. The maximum temperature deviation from the calibration temperature is then ΔT_{max} = 15 °C. To obtain a reproducibility of 1%, we need $\Delta T_{max} \times 0.04\%/°C + t_{max} \times 0.1\%/\text{month} = 1\%$. Therefore, the maximum time t_{max} before re-calibration is t_{max} = 4 months.