EE1320: Measurement Science

Lecture 1: Introduction to Measurement and Measurement Systems

Dr. ir. Michiel Pertijs, Electronic Instrumentation Laboratory

April 23, 2013

Mobile measurement system

image sensor

touch screen

GPS

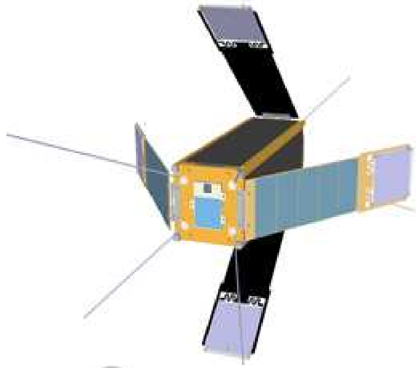
microphone

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."

Course program 2013

week	date	topic
4.1	Tu 23/4	#1 intro measurements and meas. systems
	Fr 26/4	#2 sensors
4.3	Tu 7/5	#3 sensor readout and signal conditioning
4.4	Tu 14/5	#4 instrumentation amplifiers
	We 15/5	intermediate test
4.5	Tu 21/5	#5 analog-to-digital converters
4.6	We 29/5	#6 measurement instruments I
4.7	Tu 4/6	#7 measurement instruments II
	We 5/6	intermediate test
4.8	Tu 11/6	tutorial
4.11	We 3/7	final exam

Lecturer: dr. ir. Michiel Pertijs
room HB 15.050, M.A.P.Pertijs@tudelft.nl, 015-2786823

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

Overview course material

Book: “Regtien”

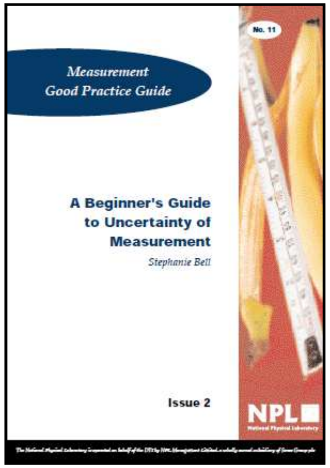
P.P.L Regtien, “Electronic Instrumentation”

can be bought at VSSD (http://www.vssd.nl)

Reader: “Bell”

S.A. Bell, “A beginner's guide
to uncertainty in measurement”

pdf is available on Blackboard
or can be downloaded from
http://www.npl.co.uk/publications/guides/



Overview course material

Also on Blackboard:

- lecture slides
- overview exam material (what's covered, what's skipped?)
- overview course program
- **study tips**
- **exercises, old exams with answers**

Assessment

Final exam: week 4.11, Wednesday 3/7, 9:00 – 12:00

You can use a calculator and the book (Regtien)

Intermediate tests: check your understanding and earn a bonus of at most 1 point

week	date	test covers
4.4	We 15/5	lecture 1-3
4.7	We 5/6	lecture 1-6

The tests only count if the grade is at least a 6!

$$final\ grade = \min(10, exam + 0.1\frac{test1 + test2}{2})$$

Link with Semester Project EPO-2

- In EPO-2, you're developing a mine-detecting robot; you'll need measurement techniques to do so!

- EPO-2 'Just-in-time' training sessions related to EE1320:
  - week 3.1: Measuring with the robot
  - week 3.6: Opamps
  - week 4.2: Capacitive sensors
  - week 4.3: Inductive sensors

Today: introduction to measurement and measurement systems

- What exactly is measuring?
- How do you model a measurement system?
- Specification of the transfer of measurement systems

- Regtien: chapter 1, appendix A.1
  Bell: sections 1, 2, 4 and 8

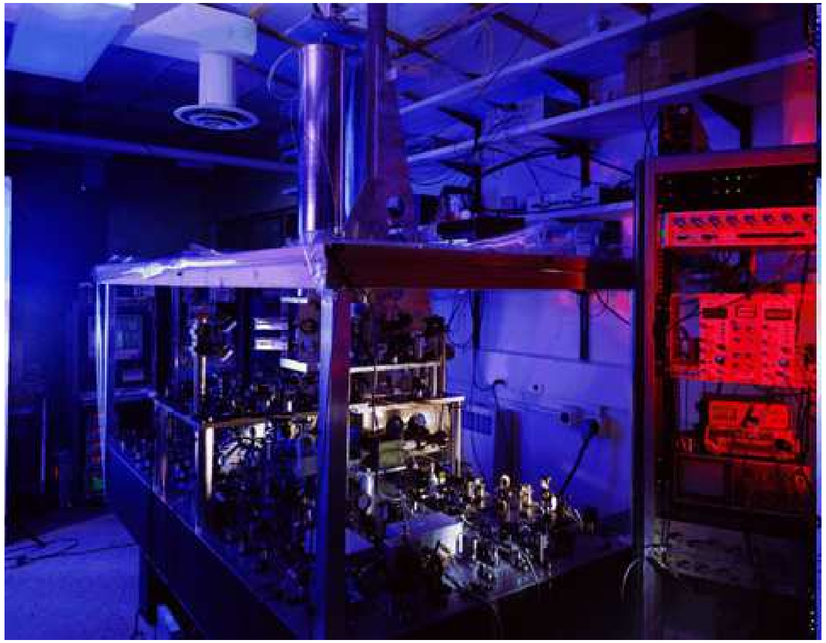
What exactly is measuring?

- 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

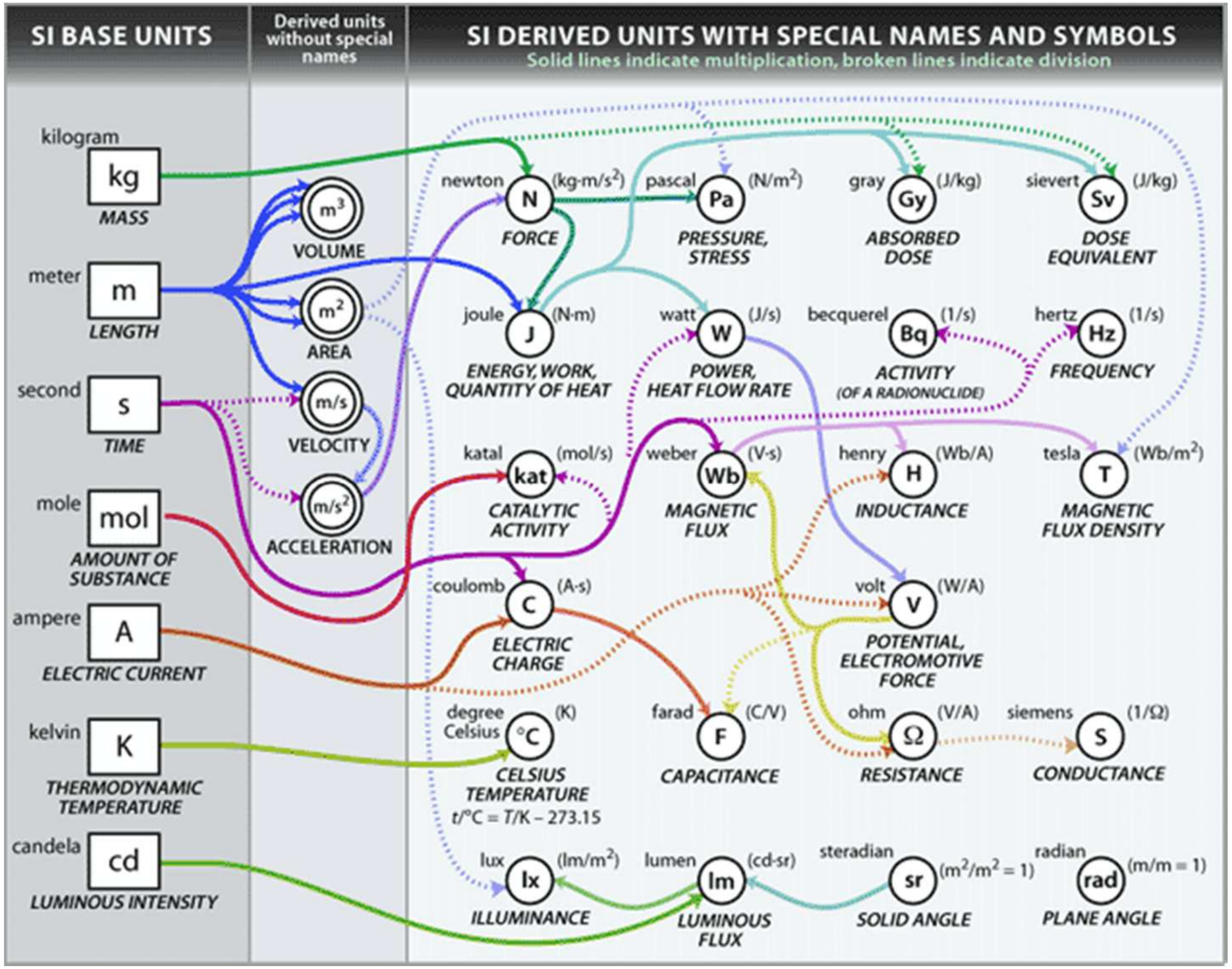
- Objective, comparable measurements require **standards**



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)



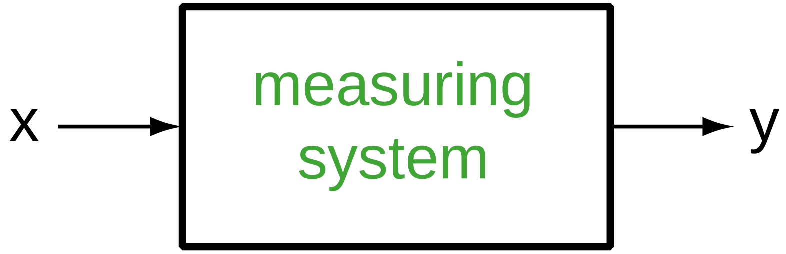
Kilograms vs. pounds: “The Gimli Glider”

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

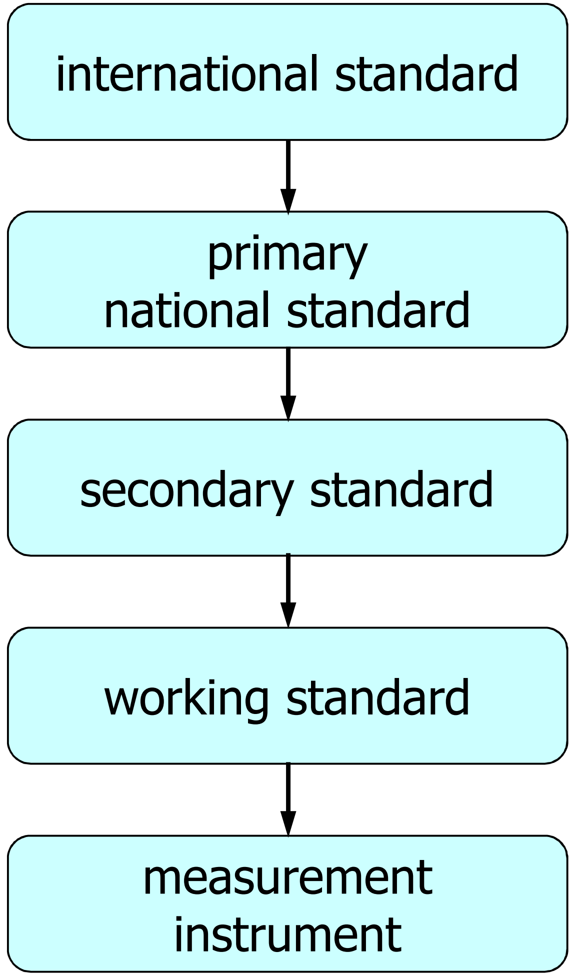
- Measurement uncertainty ≠ measurement error
  - Error: difference between measured value and the ‘true’ value
  - Uncertainty: quantification of the doubt about the measurement

- 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.

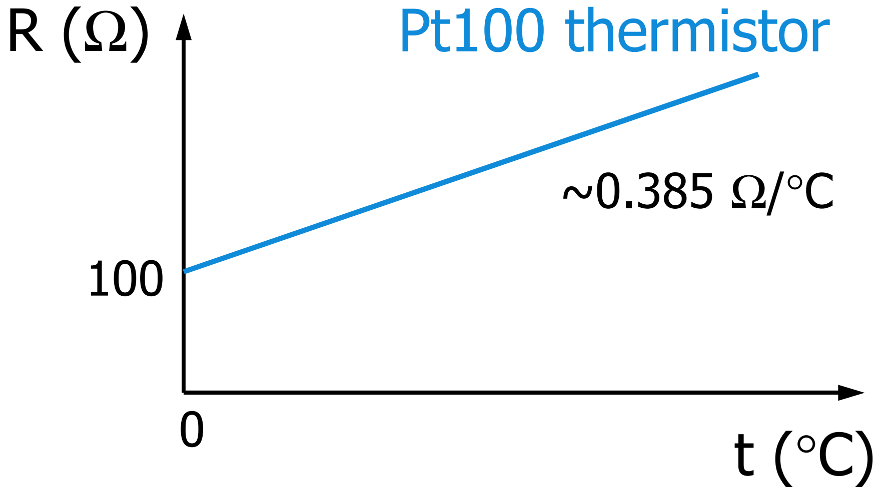
Calibration

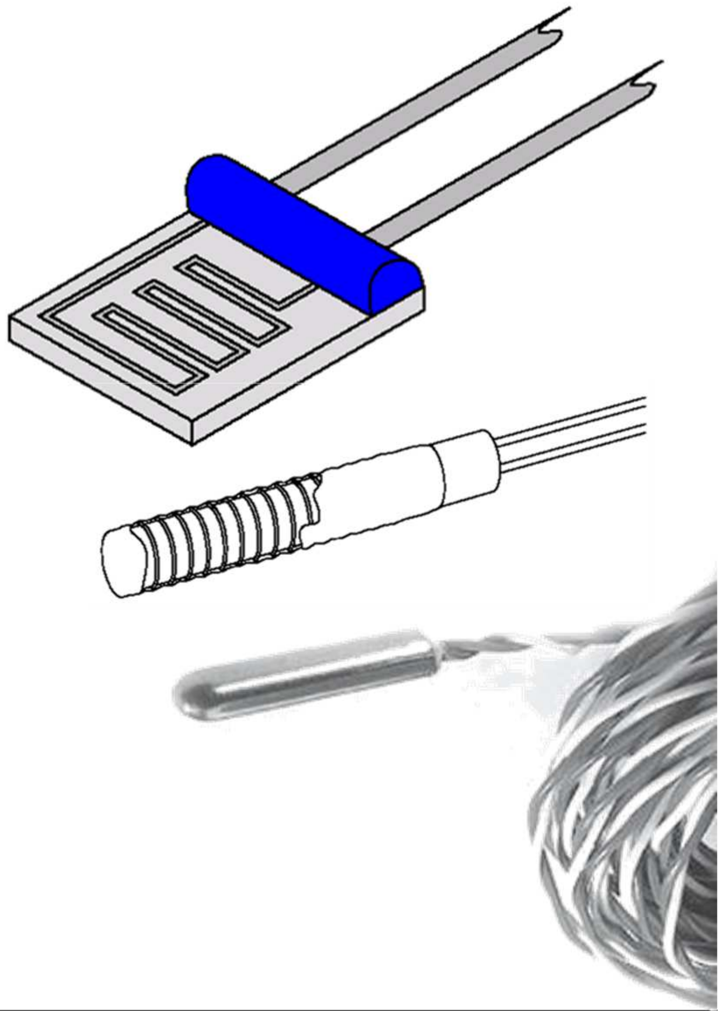
- **Calibration** makes a connection between
  - measurement values produced by a measurement instrument
  - corresponding values realized by standards
- **Calibration procedure**: comparison of an instrument with a (more accurate) measurement standard
- Calibration enables measurements which are **traceable**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



Example: calibration of a platinum thermometer

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

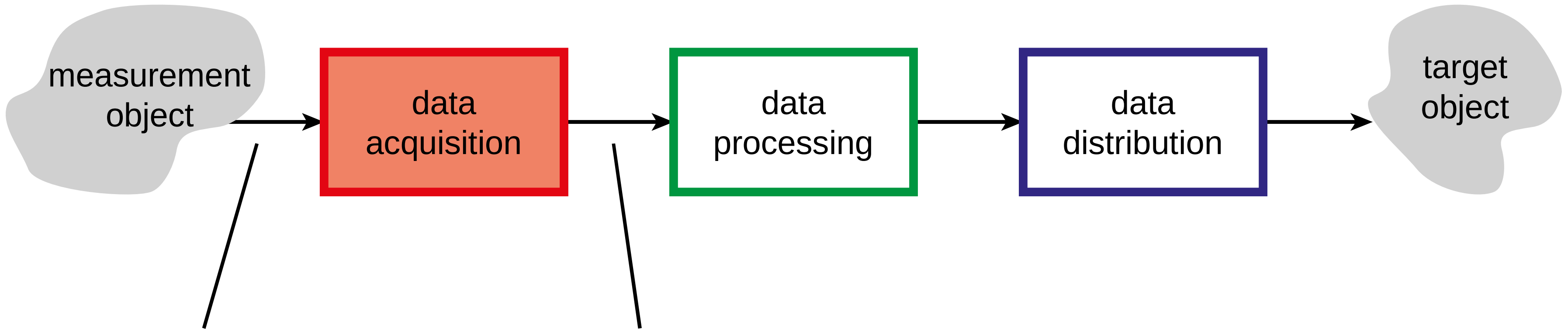




Example: calibration of a platinum thermometer

- 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

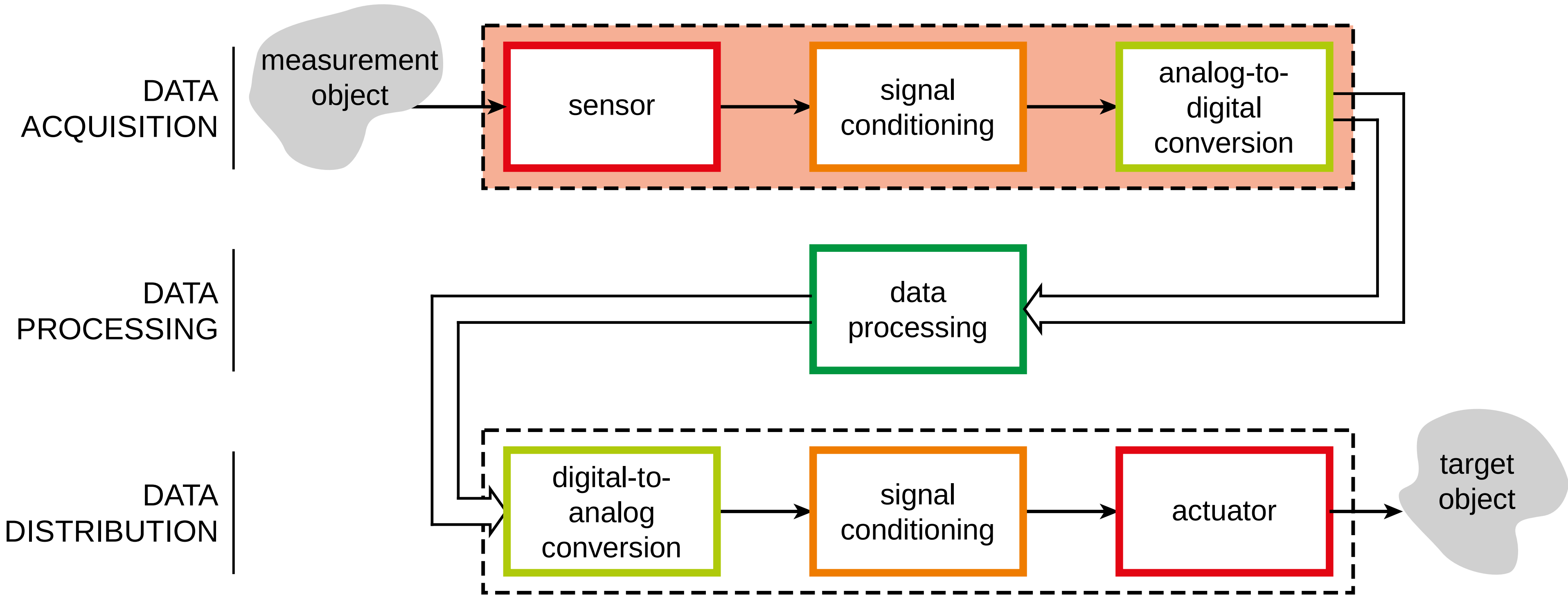
Structure of a measurement system



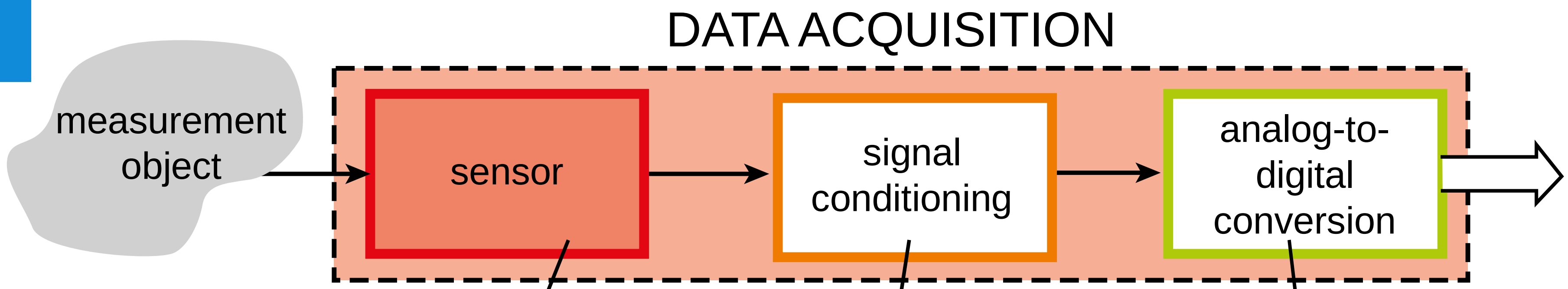
quantity to be measured
physical, often
non-electrical signal

measurement result
electrical,
often digital signal

Structure of a measurement system



Structure of a measurement system



lecture 5: A/D convertors

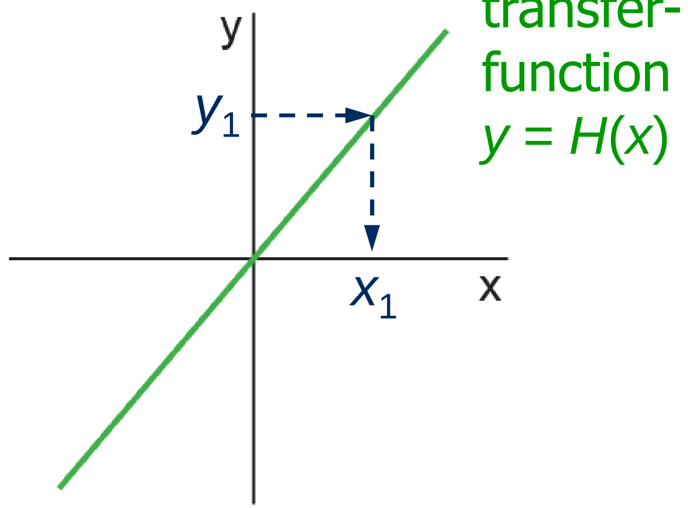
transduction of information from a (non-electrical) domain to the electrical domain

lecture 2: sensors

- amplification
- buffering (impedance transformation)
- filtering
- signal conversion (e.g. R $\rightarrow$ V)

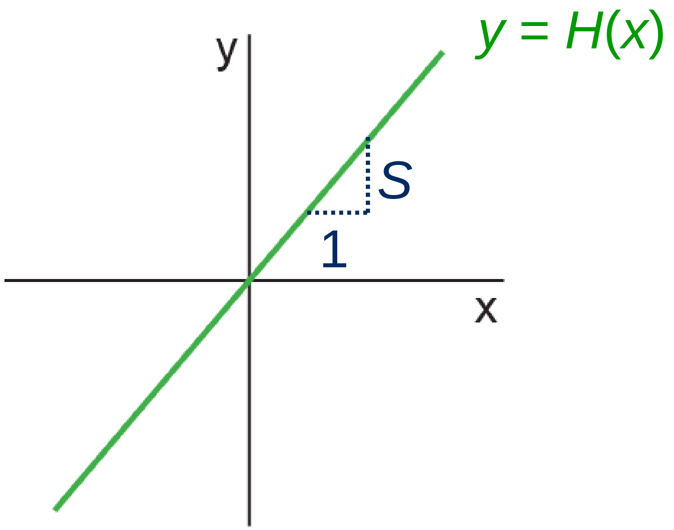
lecture 3/4: sensor readout & instrumentation amplifiers

Transfer of a measurement system



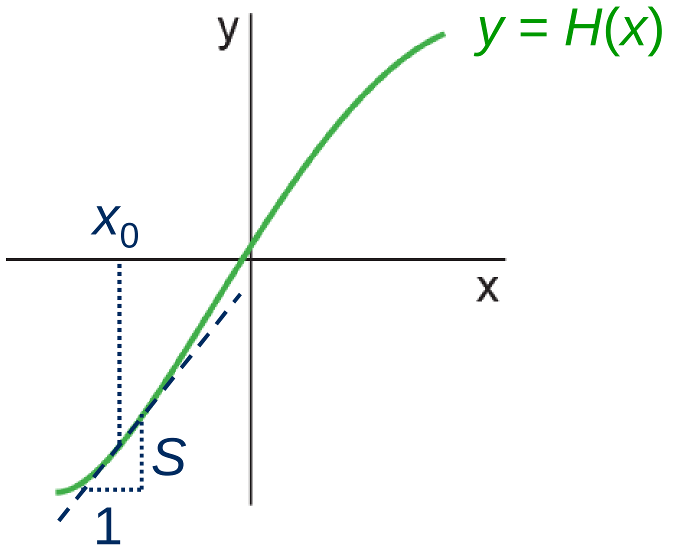
- Using the transfer function H, output signal (indication) y_1 can be translated back to a measurement value x_1

Sensitivity



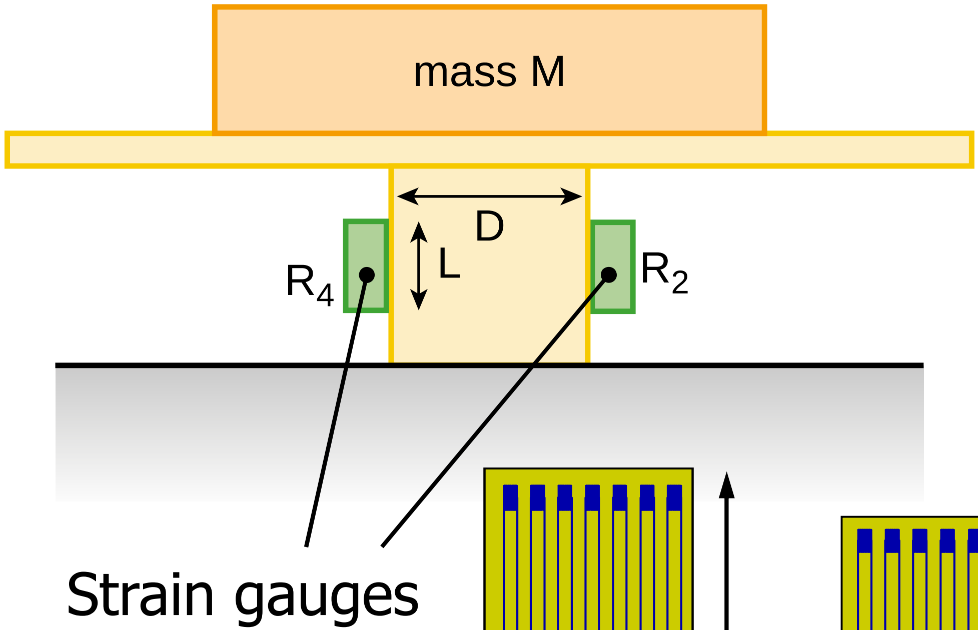
- **Sensitivity**: $S = \Delta y \,/\, \Delta x$
- Ideal linear transfer: sensitivity $S = y \,/\, x$

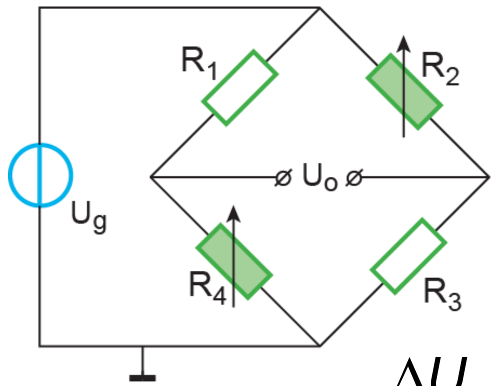
Differential Sensitivity



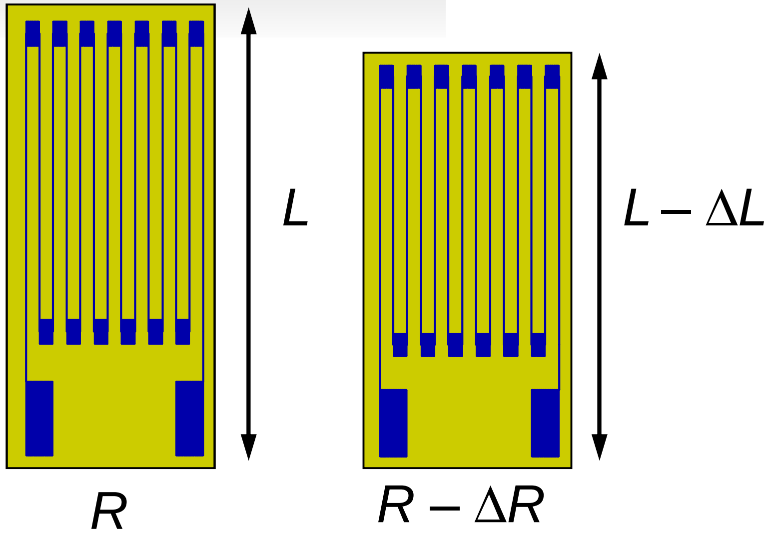
- Non-linear transfer
  $\Rightarrow$ **differential** sensitivity round x_0: $S = \left.\dfrac{dy}{dx}\right|_{x=x_0} = H'(x_0)$

Sensitivity example: weighing scale





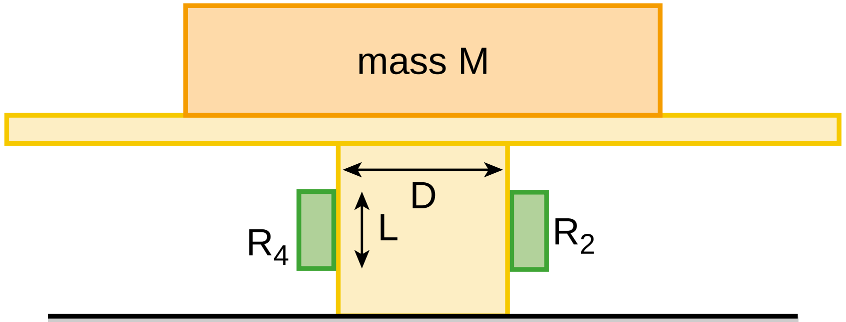
$$\Delta U_o \cong \frac{\Delta R}{2R} U_g$$



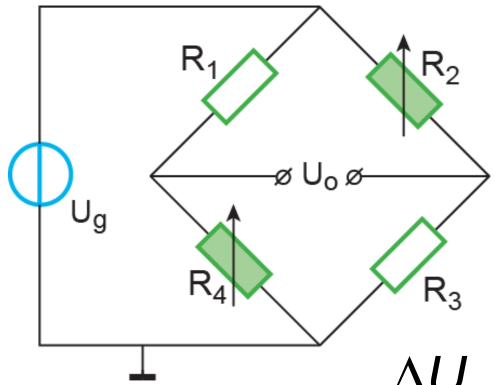
$$\frac{\Delta R}{R} = k \frac{\Delta L}{L}$$

gauge factor k
= 2 for metals

Sensitivity example: weighing scale



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



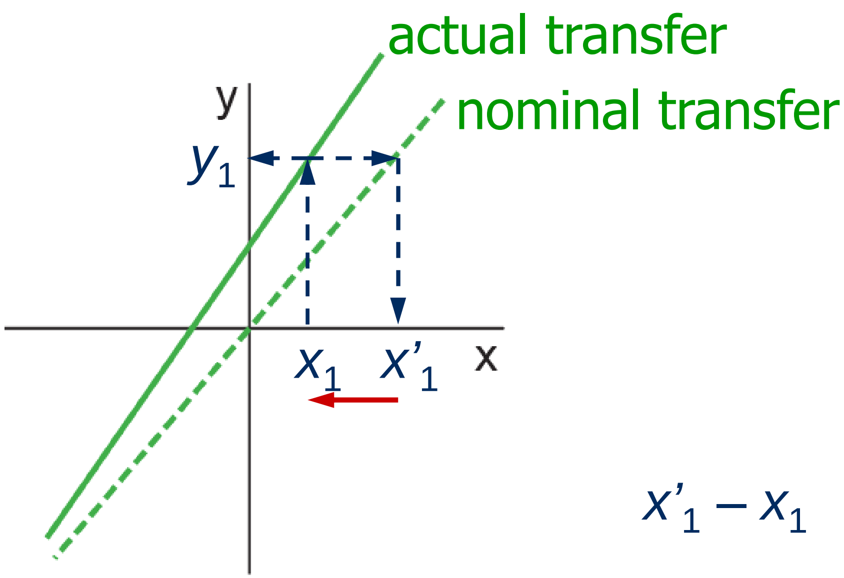
$$\Delta U_o \cong \frac{\Delta R}{2R} U_g$$

Given: the source voltage $U_g = 10\ \mathrm{V}$
the relative sensitivity of the length change is

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

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

Measurement errors due to deviations in the transfer

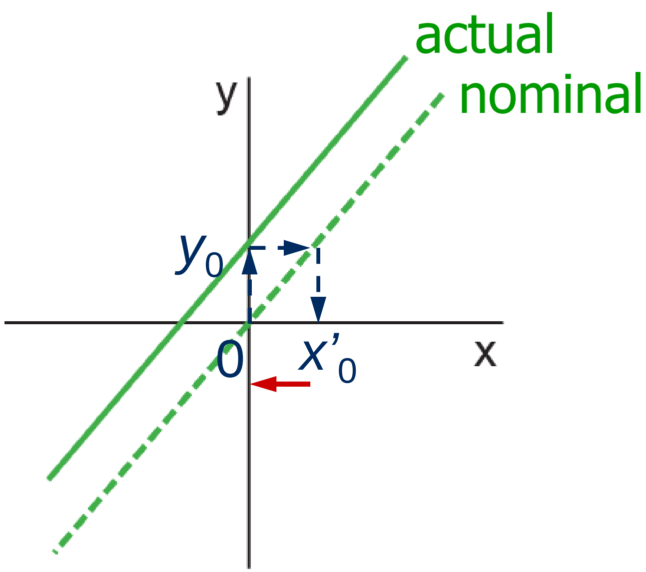


x_1	actual value of quantity to be measured
y_1	output signal of measurement system
x'_1	measured value determined based on nominal transfer

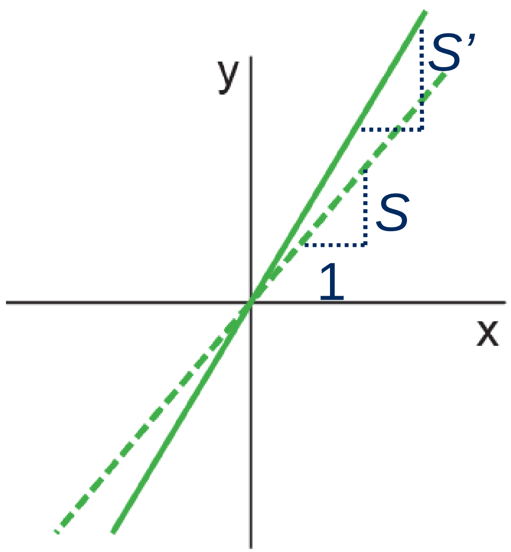
$x'_1 - x_1$ **measurement error**

Deviation in linear transfer

Offset error

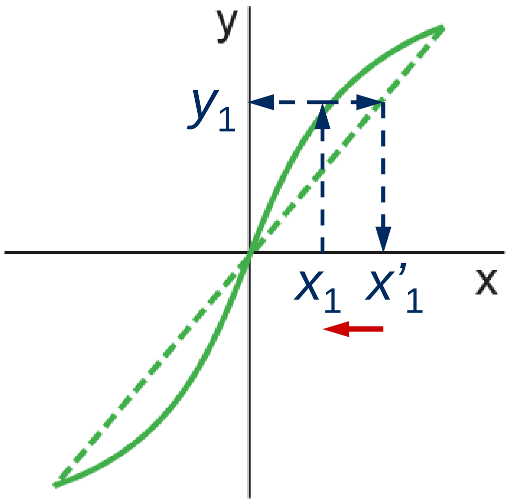


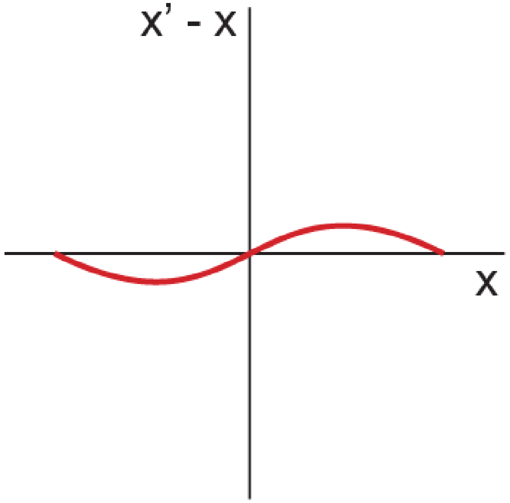
Gain error (sensitivity error)



Non-linearity

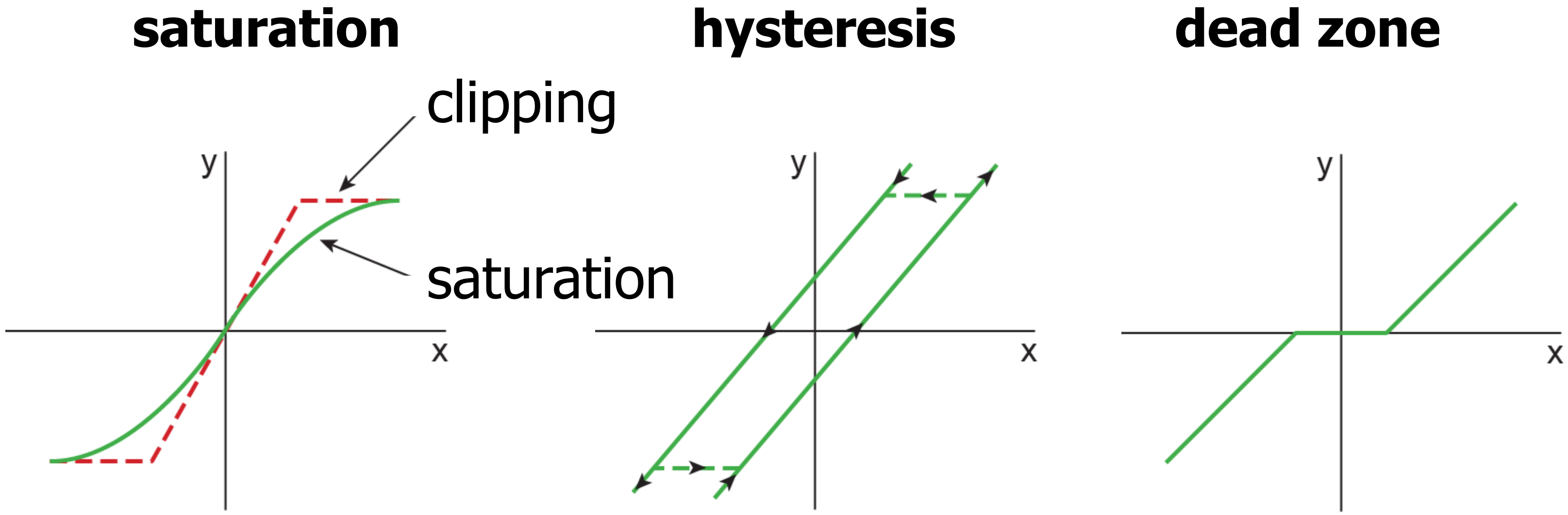
- A non-linear transfer will give measurement errors if the nominal transfer is assumed to be linear
- Integral non-linearity:





Ambiguity

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



Ambiguity

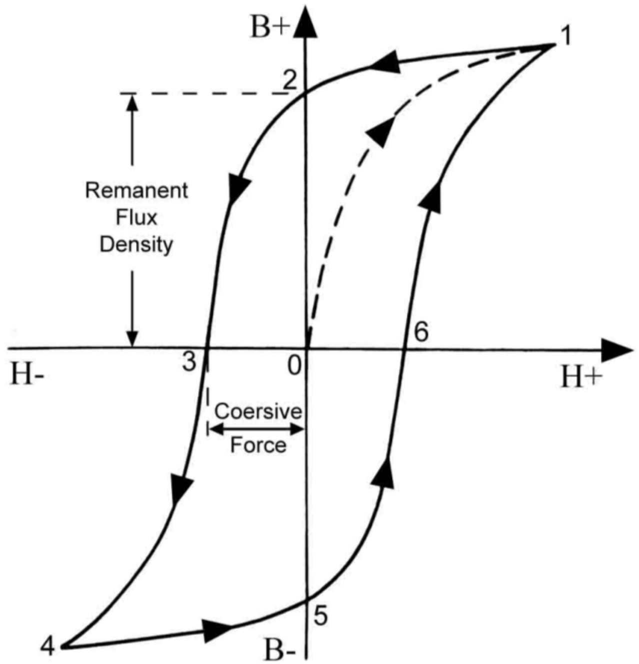
saturation
hysteresis
dead zone

- Moving coil meter with friction

Ambiguity

saturation
hysteresis
dead zone

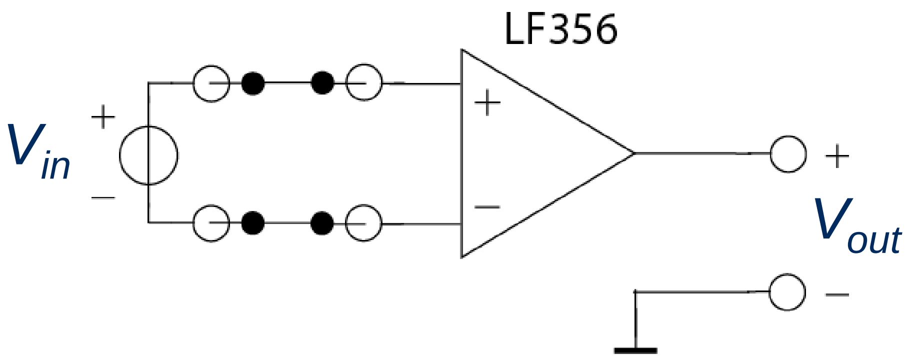
- Magnetisation of a ferromagnetic core



Ambiguity

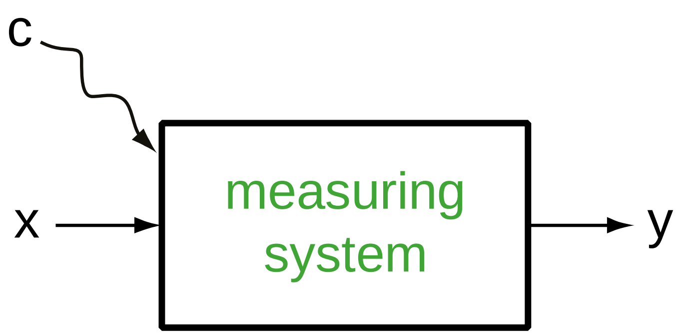
saturation
hysteresis
dead zone

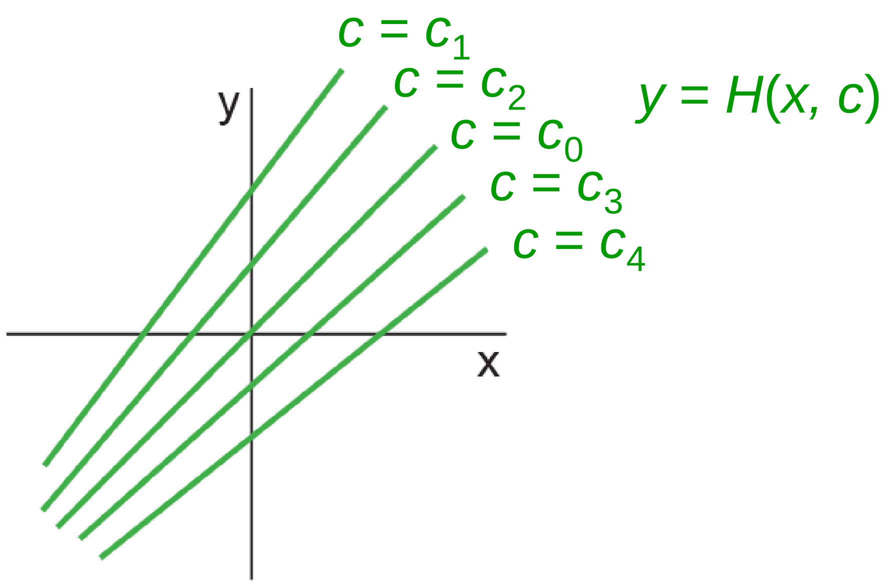
- Opamp



Cross-sensitivity

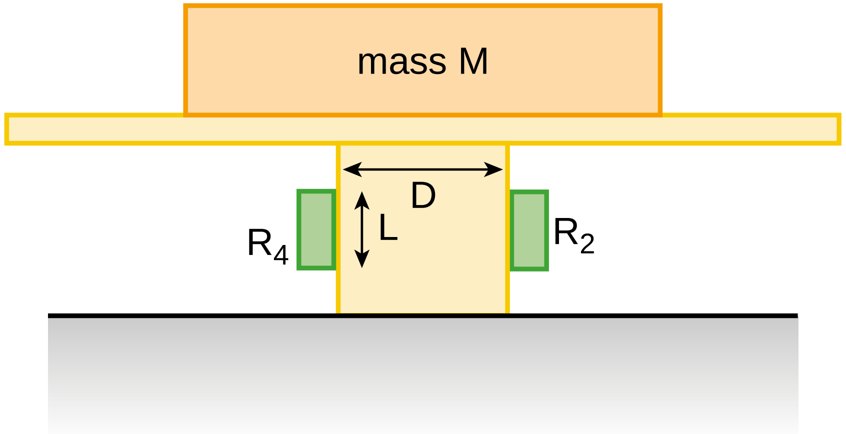
- Unwanted sensitivity to an **influence quantity** c

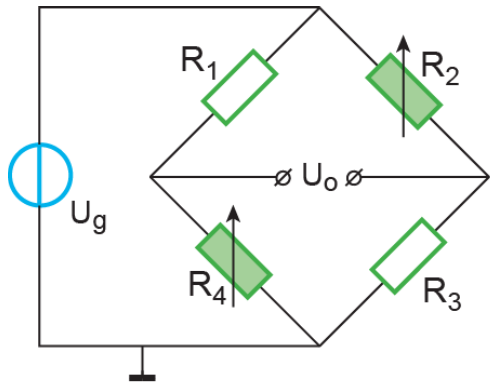




- Ideally: $S_c^y = 0$

Cross-sensitivity ex.: weighing scale



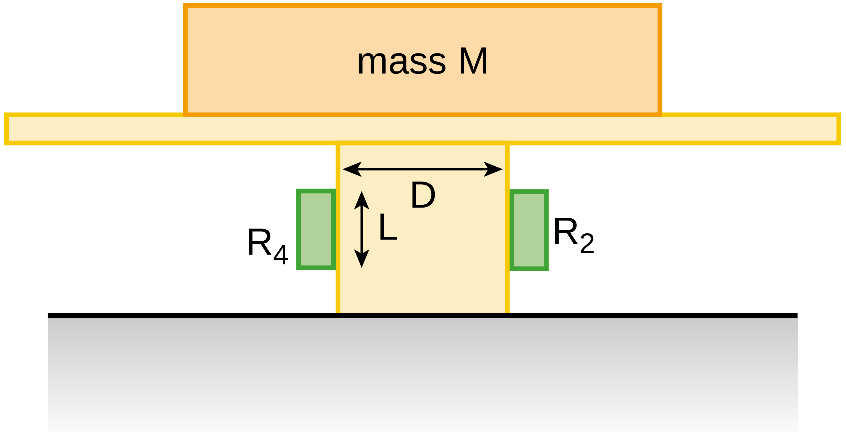


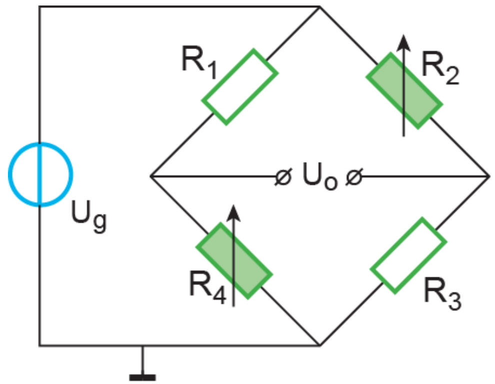
temperature-difference ΔT → resistance change $\Delta R/R$ → output voltage ΔU_o

- Temperature sensitivity resistors typically expressed as

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

Cross-sensitivity ex.: weighing scale



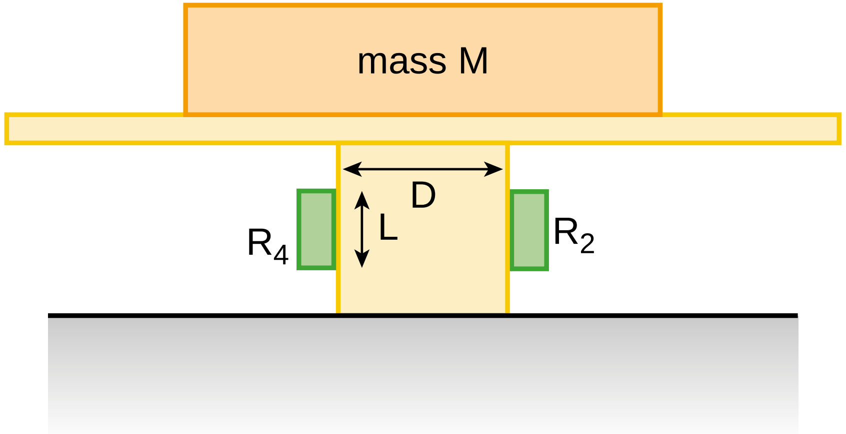


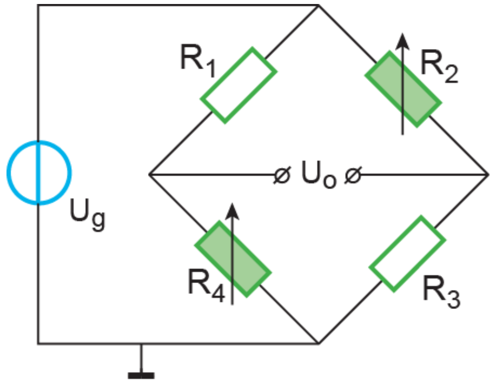
temperature-difference ΔT → resistance change $\Delta R / R$ → output voltage ΔU_o

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

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

Cross-sensitivity ex.: weighing scale



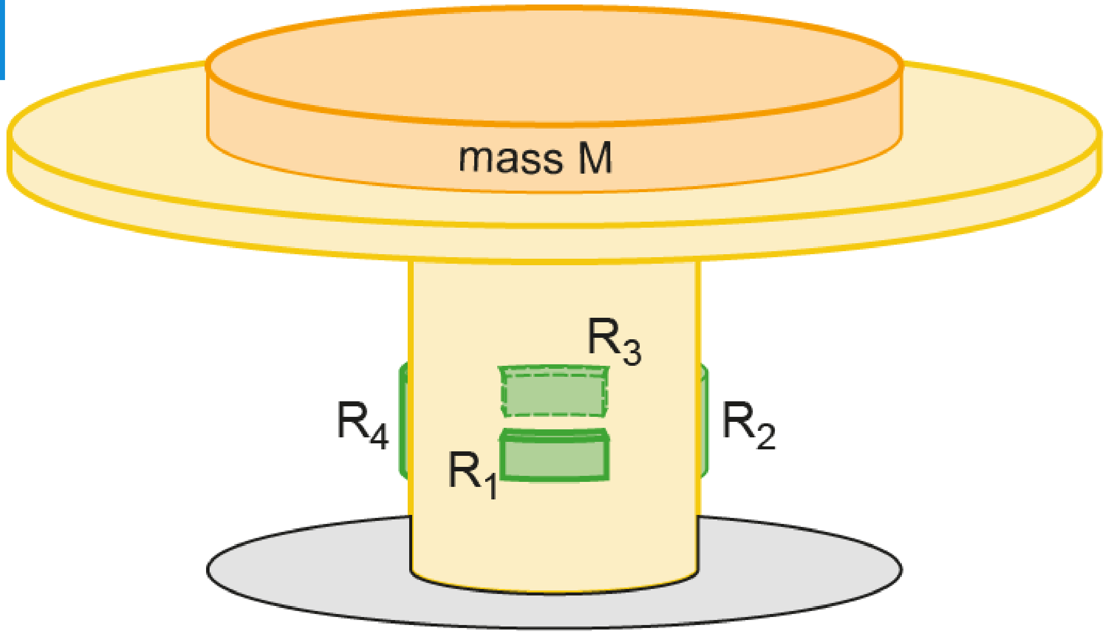


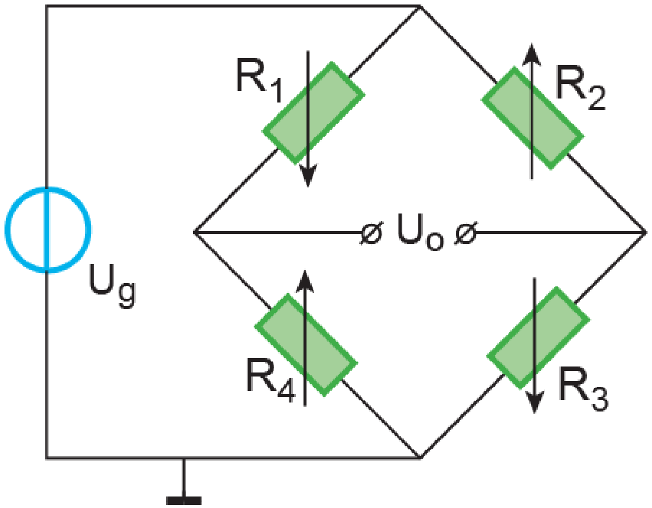
- Cross-sensitivity: $S_{temp} = \dfrac{\Delta U_o}{\Delta T} = \dfrac{\alpha \cdot U_g}{2}$

- 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 $S_{massa} = 6{,}2\ \mu\mathrm{V}/\mathrm{kg}$

error:
16 kg / K !!

Cross-sensitivity ex.: weighing scale





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

Measurement errors due to aging

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

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

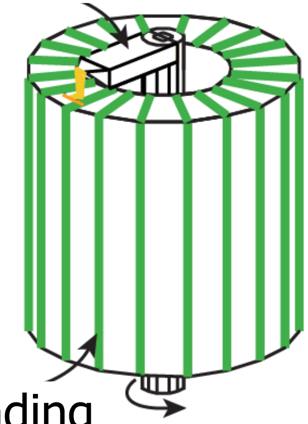
Function	**Range** [3]	**24 Hour** [2] 23°C ±1°C	**90 Day** 23°C ±5°C	**1 Year** 23°C ±5°C
DC voltage	100.0000 mV	0.0030 + 0.0030	0.0040 + 0.0035	0.0050 + 0.0035
	1.000000 V	0.0020 + 0.0006	0.0030 + 0.0007	0.0040 + 0.0007
	10.00000 V	**0.0015 + 0.0004**	**0.0020 + 0.0005**	**0.0035 + 0.0005**
	100.0000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

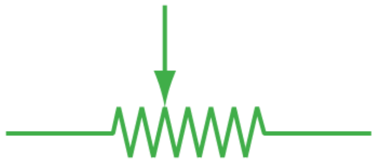
Resolution

- **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
  - $\Delta x = 0.01\ \mathrm{V}$
  - $\Delta x / x_{max} = 0.01\ \mathrm{V} / 199.99\ \mathrm{V} = 5 \cdot 10^{-5}$
    in bits: $-\,^{2}\log\,(5 \cdot 10^{-5}) = 14.3$ bits

Resolution examples

- Resolution determined by sensor: wirewound potentiometer

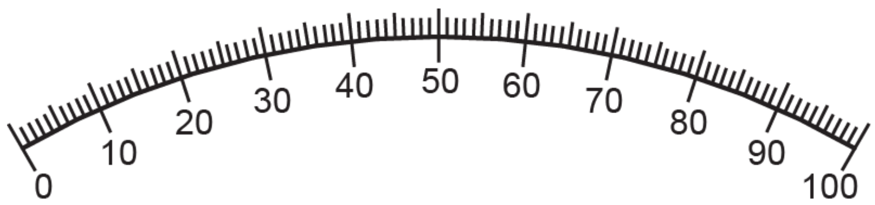




1000 windings

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

What’s next?

- Study:
  - Regtien chapter 1 and appendix A.1
  - Bell sections 1, 2, 4 en 8
- Practice:
  - Look at the exercises on Blackboard!
- Questions, things unclear? Let me know!

  M.A.P.Pertijs@tudelft.nl

Next time: Sensors