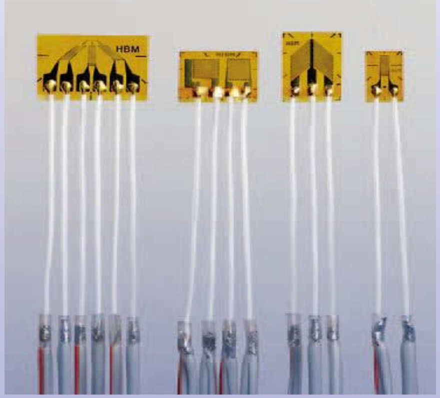
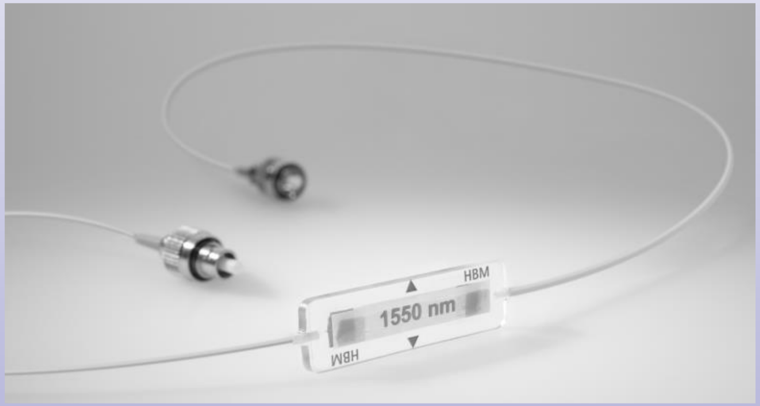
Sensors
for relative elongation measurement
=
Strain Gauge Sensors

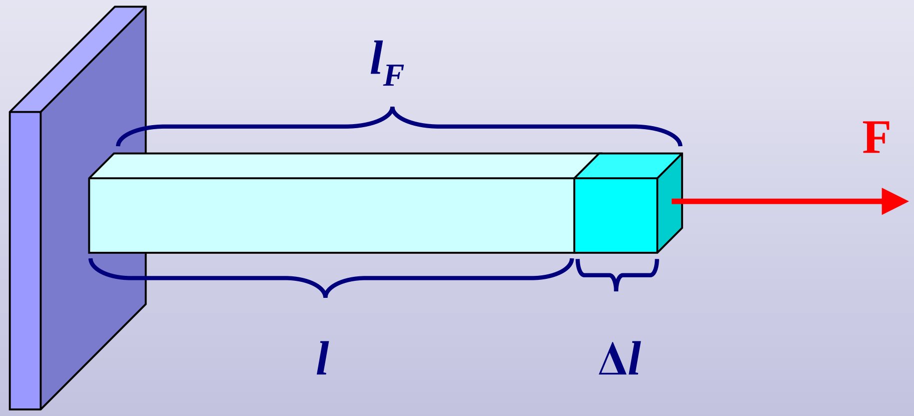




resistive strain gauges
influence of temperature on measurement with strain gauges
typical strain gauge connections
optical strain gauges
non-contact measurement systems

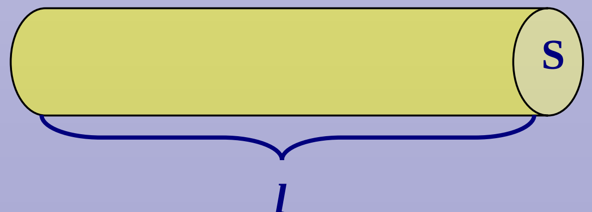
1. Resistive strain gauges

- **the strain gauge function principle**
  - definition of basic terms
    - mechanical part is extended from the original length l to the length l_F by the force F
    - length difference is called the absolute elongation $\Delta l = l - l_F$
    - **relative elongation ε** is the absolute elongation relative to the original length l



$$\varepsilon = \frac{\Delta l}{l} = \frac{l - lF}{l}$$

- dependence of a conductor electrical resistance on its dimensions
  - already in 1843 Mr. Wheatstone discovered the dependence of the conductor resistance on its dimensions (ρ is a specific resistance of a conductor material)

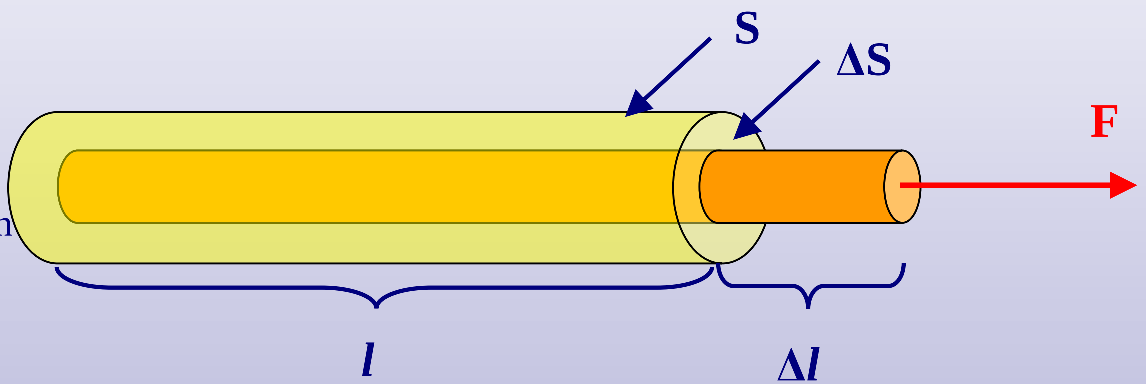


$$R = \rho * \frac{l}{S}$$

1. Resistive strain gauges

- **the strain gauge function principle**
  - if the conductor is mechanically loaded
    - its length is changed by Δl
    - its cross section is changed by ΔS
    - its specific resistance is changed by Δρ (due to microstructural change of material)

$$\frac{\Delta R}{R} = \underbrace{\frac{\Delta l}{l} - \frac{\Delta S}{S}}_{\text{geometry changes}} + \underbrace{\frac{\Delta \rho}{\rho}}_{\text{change in material structure}}$$



- if we substitute $\frac{\Delta l}{l} = \varepsilon$ and with the Poisson constant $\frac{\Delta S}{S} = -2\mu * \frac{\Delta l}{l}$

  we can express rel. resistance change as a polynomial $\boldsymbol{\frac{\Delta R}{R}} = \boldsymbol{c_1 \varepsilon} + c_2\varepsilon^2 + c_3\varepsilon^3 + \ldots\ldots$

- **for small deformations** and suitably chosen materials, microstructural changes $\Delta\rho$ and thus higher members of the polynomial can be neglected and then it holds that

$$\boldsymbol{\frac{\Delta R}{R} = K * \varepsilon}$$

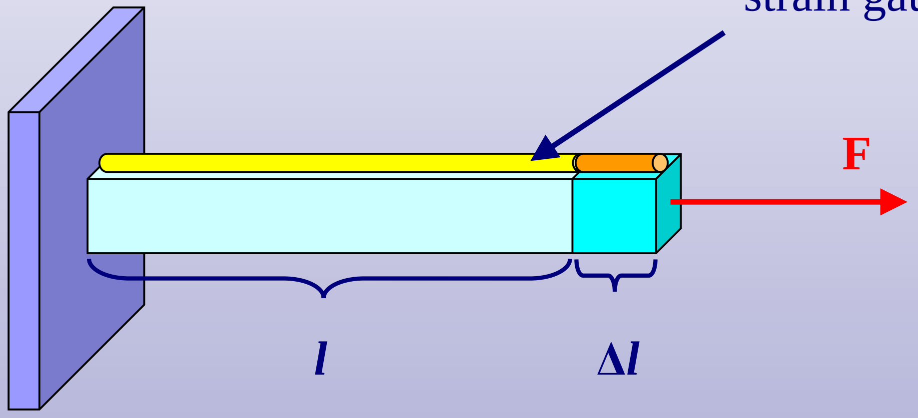
- **the relative change in resistance is directly proportional to the relative elongation**

1. Resistive strain gauges

- **the strain gauge function principle**
  - a conductor is attached (glued) to a mechanical part whose deformation is to be measured
  - the conductor resistance is measured
  - mechanical part relative elongation is directly proportional to the conductor resistance change

- **this wire is called strain gauge sensor**

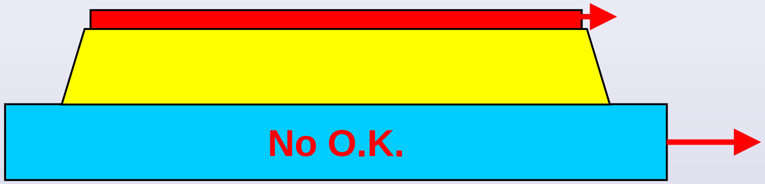
strain gauge sensor $$\frac{\Delta R}{R} = k * \varepsilon$$



- **coefficient k is the strain gauge factor (**deformation sensitivity coefficient**)**
  - its value depends on the type of the conductor material

1. Resistive strain gauges

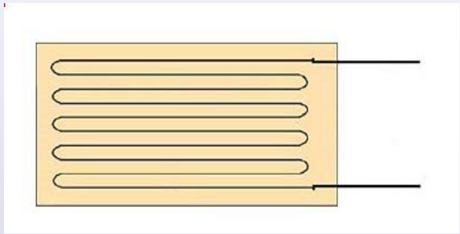
- **the strain gauge gluing**
  - the correct gluing technology must be followed in order to transfer the deformation of the material to the strain gauge



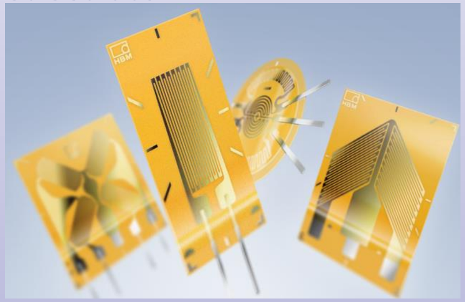
  - special adhesives that transfer deformation to the strain gauge
  - one-component cyanoacrylate (seconds) for short-term applications
  - two-component epoxies for long-term use
  - hot cured epoxies for a wider temperature range

1. Resistive strain gauges

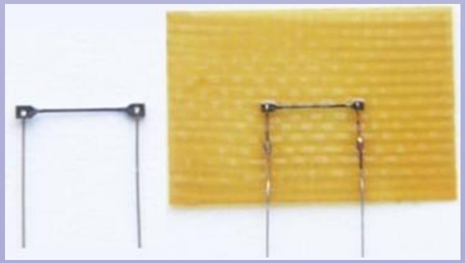
- **resistive strain gauges real design**
  - four types of design:
  - **wire strain gauges**
    - conductor attached to a paper pad
    - an outdated solution not in use today



  - **foil strain gauge**
    - metal layer lithographically applied on a plastic substrate
    - currently the most common solution

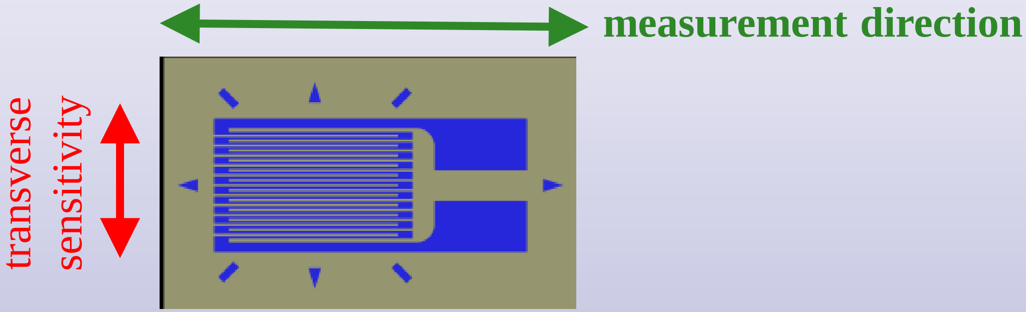


  - **layer strain gauge**
    - metal layer applied directly to the object
    - only for special applications
  - **semicoductor strain gauge**
    - semiconductor material rod with terminals
    - without pad
    - with pastic pad

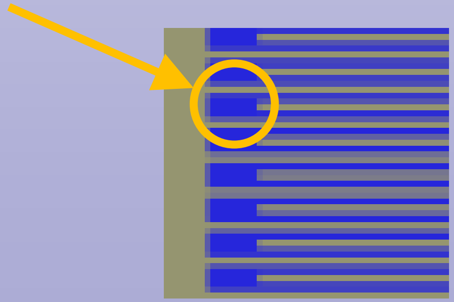


1. Resistive strain gauges

- **foil resistive strain gauges real design**
  - **a meander conductor is used to make the change in resistance greater**
    - the greater the length of the conductor, the greater its elongation, the greater the change in resistance
  - **the strain gauge always measures the elongation in the meander direction !**

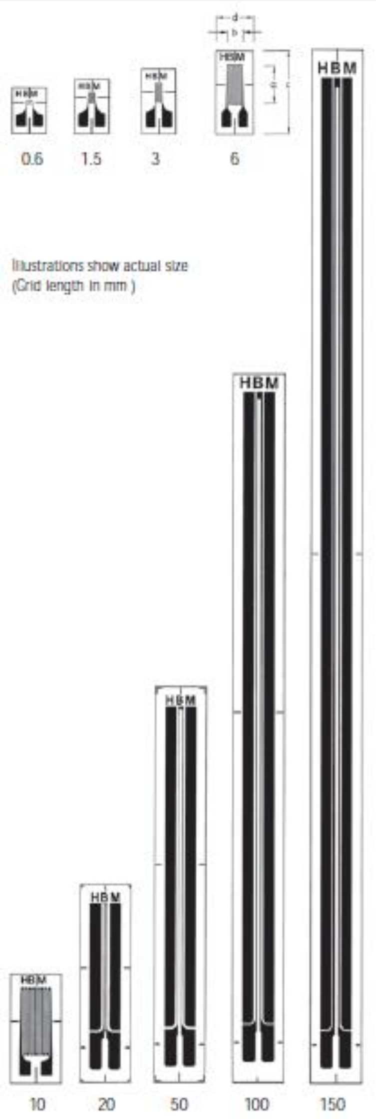


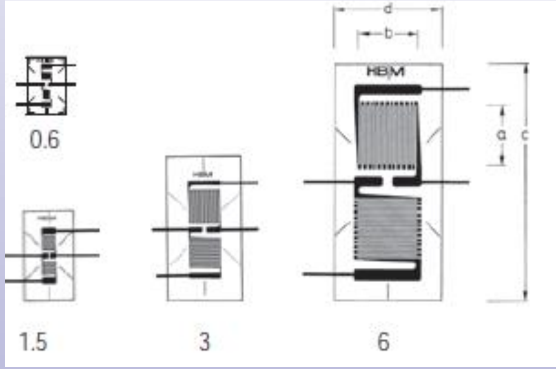
- the sensitivity of the strain gauge to elongation in the transverse direction is undesirable
- the manufacturer reduces it to a minimum by a special meander design - in the transverse direction, the conductor is thicker, has a larger cross-section and the change in resistance is thus reduced
- despite this meander design, the strain gauge also has a transverse sensitivity
- it must be taken into account in the case of multiaxis stresses on the object

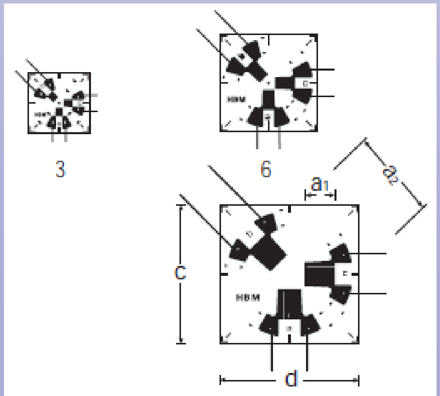


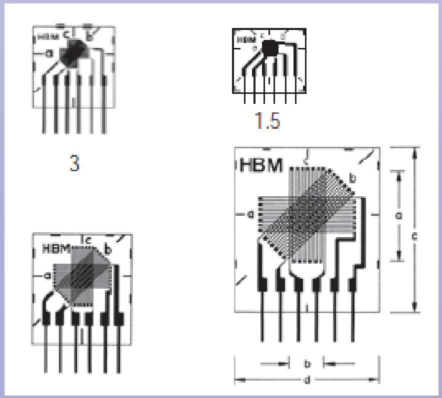
1. Resistive strain gauges

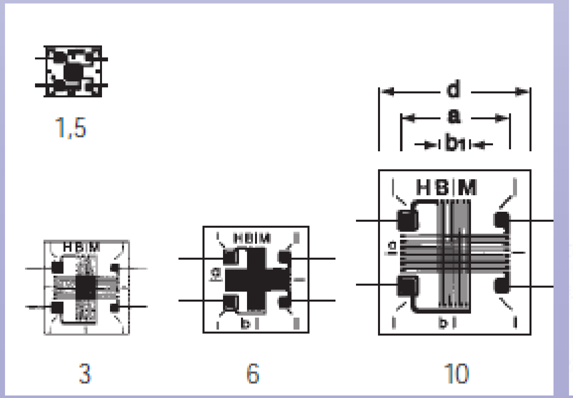
- **foil resistive strain gauges real design and basic properties**
  - polyamide film thickness 20µm
  - printed wire thickness 5µm
  - strain gauge factor **k** is at about 2
  - relative elongation **ε** up to 0.15%   (up to 0,5% - special design)
  - typical resistance value **120Ω** or **350Ω**
  - many lengths
  - one or multi-axis design
  - wire outlets or soldering points







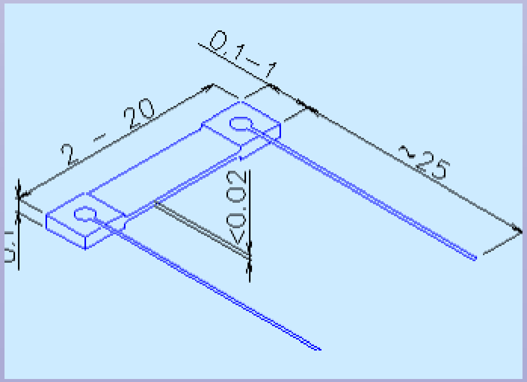




1. Resistive strain gauges

- **semiconductor strain gauges**
  - microstructural changes in the material occur even for small deformations
  - nonlinear dependence $$\frac{\Delta R}{R} = c_1 \varepsilon + c_2 \varepsilon^2$$
  - **high sensitivity c1 =** approx. **120,** c2 = approx. 4000
  - thus about 60 times more sensitive than foil strain gauges
  - $\varepsilon_{MAX} = \pm 0.3\%$

- **semiconductor strain gauges real design**
  - rod-shaped monocrystalline silicon cutout
  - spot welded conductors at the ends of the cutout
  - with or without plastic pad
  - without pad **very small dimensions - the smallest strain gauge that can be used**
    - the silicone rod is glued directly to the measured object



2. Influence of temperature on measurement with strain gauges

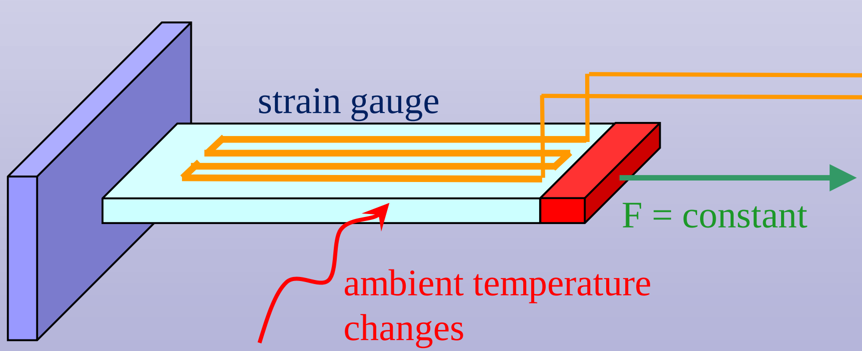
- **temperature changes cause:**
  1) thermal expansion of the object material

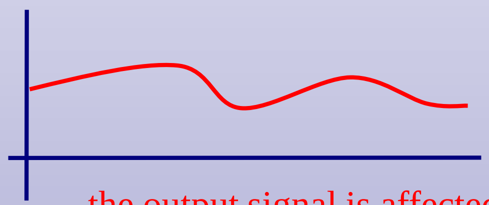
example of temperature coefficients

ferritic steel	$\alpha = 10.8 \cdot 10^{-6}\,K^{-1}$
aluminum	$\alpha = 23 \cdot 10^{-6}\,K^{-1}$
austenitic steel	$\alpha = 16 \cdot 10^{-6}\,K^{-1}$
silica	$\alpha = 0.5 \cdot 10^{-6}\,K^{-1}$
titanium, gray cast iron	$\alpha = 9 \cdot 10^{-6}\,K^{-1}$
plastic	$\alpha = 65 \cdot 10^{-6}\,K^{-1}$
molybdenum	$\alpha = 5.4 \cdot 0^{-6}\,K^{-1}$

2) change in the strain gauge factor ***k*** $\alpha_K = 115 \cdot 10^{-5}\,K^{-1}$

3) change the strain gauge resistence ***R*** $\alpha_R = 2 \cdot 10^{-5}\,K^{-1}$



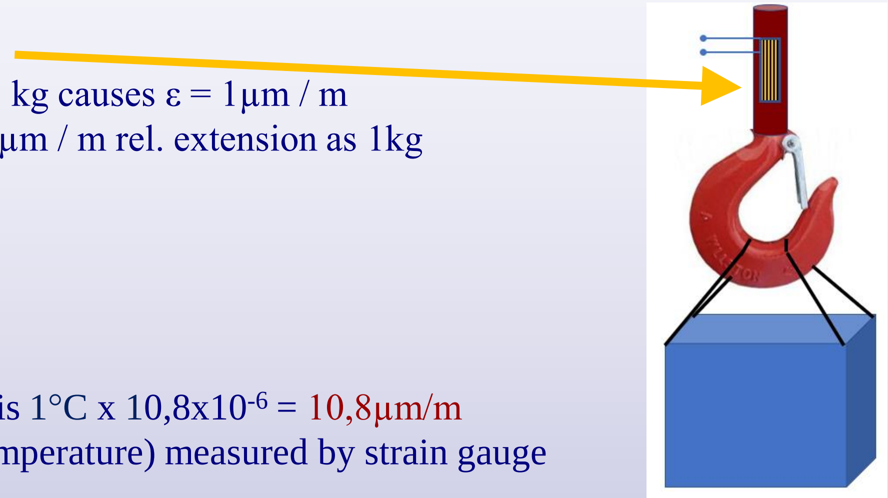


the output signal is affected by temperature

the signal should be constant (force is constant), but it changes due to temperature, the measurement is invalidated

2. Influence of temperature on measurement with strain gauges

- **temperature influence example:**
  - steel body with strain gauge for weighing loads
  - the cross section is chosen so that the weight of 1 kg causes $\varepsilon = 1\mu m / m$
  - the mesurement device display interprets every $1\mu m / m$ rel. extension as 1kg
  - suspended load 500kg, ie $\varepsilon = 500\mu m / m$
  - the display of the meter shows **500kg**



  - the ambient temperature is changed by **1°C**
    - $\alpha_{STEEL} = 10{,}8 \cdot 10^{-6}\ K^{-1}$
      - thermal expansion of the material is $1°C \times 10{,}8 \times 10^{-6} = 10{,}8\mu m/m$
      - total relative elongation (load + temperature) measured by strain gauge $\varepsilon = 500 + 10.8 = 510{,}8\mu m/m$
    - strain gauge 120Ω, $k = 2$, $\alpha_K = 115 \times 10^{-5}\ K^{-1}$
      - change in the strain gauge factor ***k*** by 1°C : $\Delta k = 0{,}0015$
      - measurement error $\Delta Y = \Delta k \cdot X = 0{,}0015 \cdot 510{,}8 \cdot 10^{-6} = 0{,}77\mu m/m$
    - the output signal of the strain gauge corresponds to the relative elongation $\varepsilon = 510{,}8 + 0{,}77 = 511{,}57\mu m/m$
    - measurement device display: **511,57kg**
  - **a change in ambient temperature of only 1 ° C caused a measurement error of about 11.5 kg, ie 2.3%**
    - thermal expansion of the material has the greatest effect on the error

- **temperature dependence reduction:**
  - self - compensating strain gauge
  - strain gauge connection system

2. Influence of temperature on measurement with strain gauges

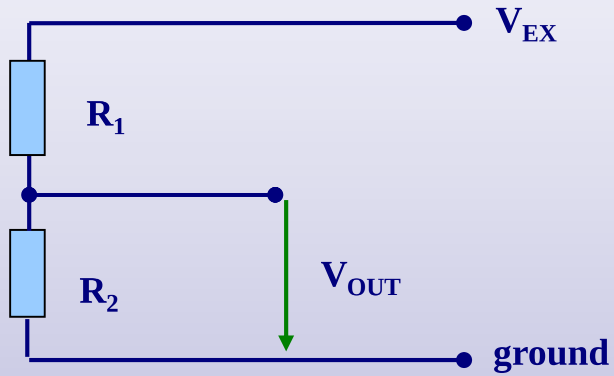
- **self - compensating strain gauge principle**
  - by suitable choice of the strain gauge metal layer material it is possible to set its temperature coefficient α in the opposite way to the thermal expansion of the measured material
  - the change from thermal expansion is compensated by a change in the resistance of the metal layer of the strain gauge in the opposite direction
  - **the strain gauge must be designed for a specific material of the measured object !**
    - **only a foil strain gauge is produced in the self-compensating version**
    - only versions for **steel or aluminum** materials are commonly produced
    - strain gauges for other materials is made only on special order - high price

  - the gluing technology must be strictly adhered to so that the surface temperature of the object and its thermal expansion are accurately transferred to the strain gauge !
  - **a thick layer of adhesive will cause inaccurate transmission and thus measurement error**

Note:
The prevention of the influence of temperature by connecting a strain gauge is described in the next chapter.

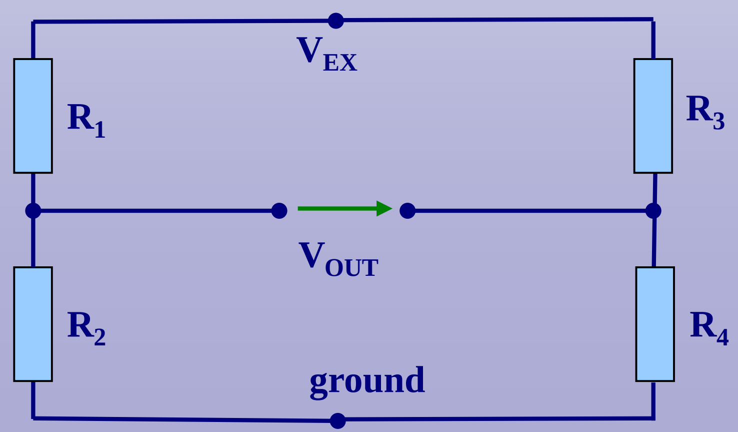
3. Typical strain gauge connections

- **the strain gauge connection principle**
  - the change in the resistance of the strain gauge is converted into a change in voltage by connecting the strain gauge to a voltage divider



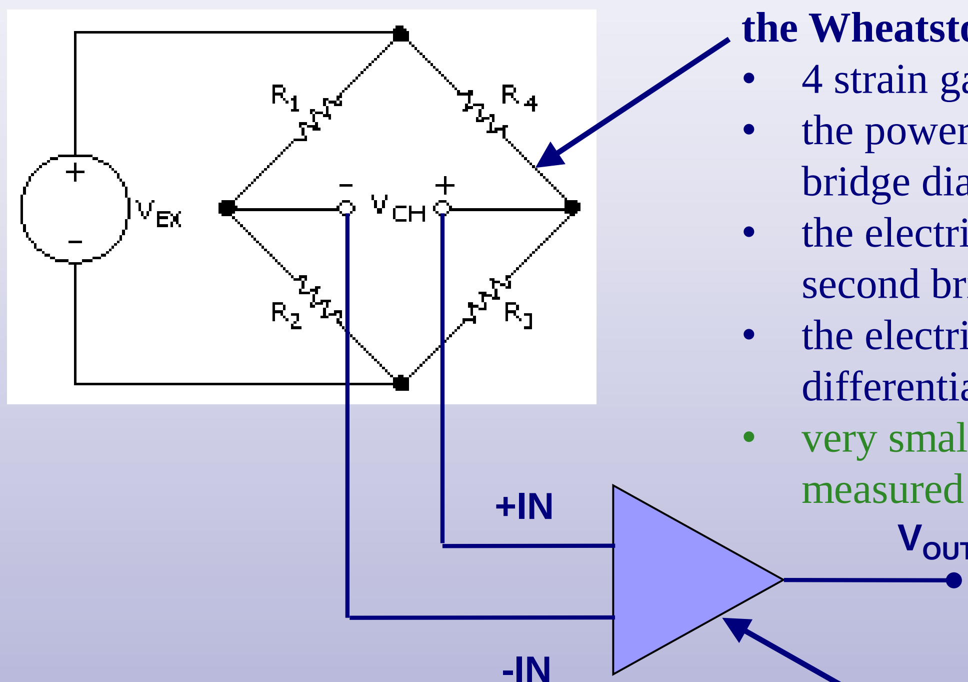
$$V_{OUT} = \frac{R_2}{R_1 + R_2} * V_{EX}$$

  - because the resistance change of the strain gauge is small, the **Wheatstone bridge** is used for evaluation almost exclusively (ie actually two voltage dividers against each other)



3. Typical strain gauge connections

- **the strain gauge connection principle**



the Wheatstone bridge

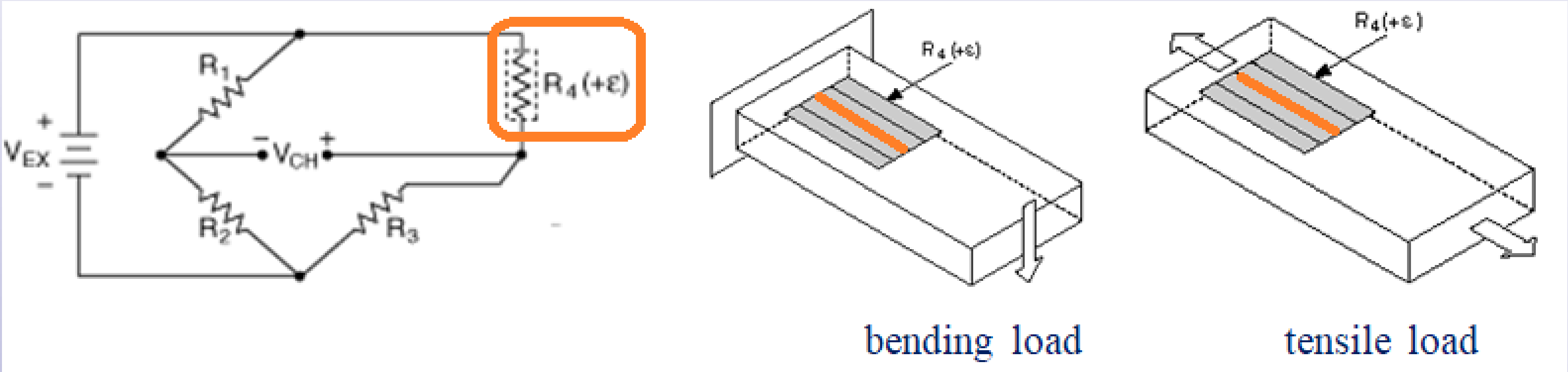
- 4 strain gauges
- the power supply is connected to the first bridge diagonal
- the electrical voltage is measured in the second bridge diagonal
- the electrical voltage is measured by a differential amplifier
- very small changes in resistance can be measured

differential amplifier

- some bridge strain gauges can be replaced by fixed resistors in a practical connection
  - less space for gluing strain gauges is needed
  - lower price
- **typical connections are named according to the number of connected strain gauges**

3. Typical strain gauge connections

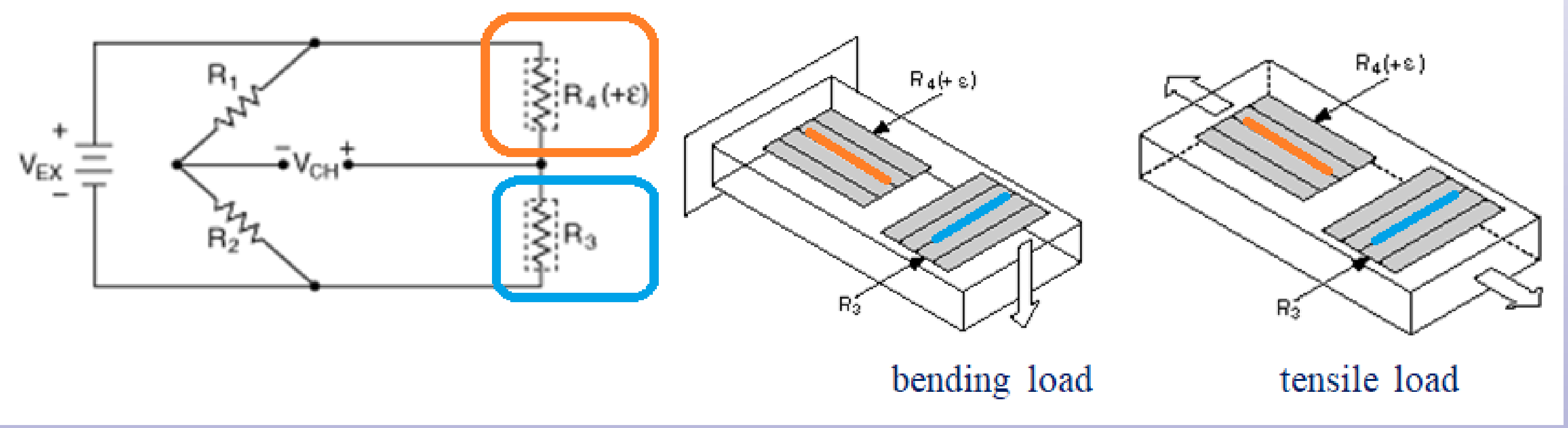
- **the quarter bridge**
  - 1 active strain gauge + 3 supplementary resistors
  - bending or tensile load
  - the cheapest solution (only 1 strain gauge)



- **temperature-unstable connection!!!!**
  - strain gauge and resistor in one half of the bridge have different temperature coefficient)
  - suitable only for short-term measurements at constant temperature

3. Typical strain gauge connections

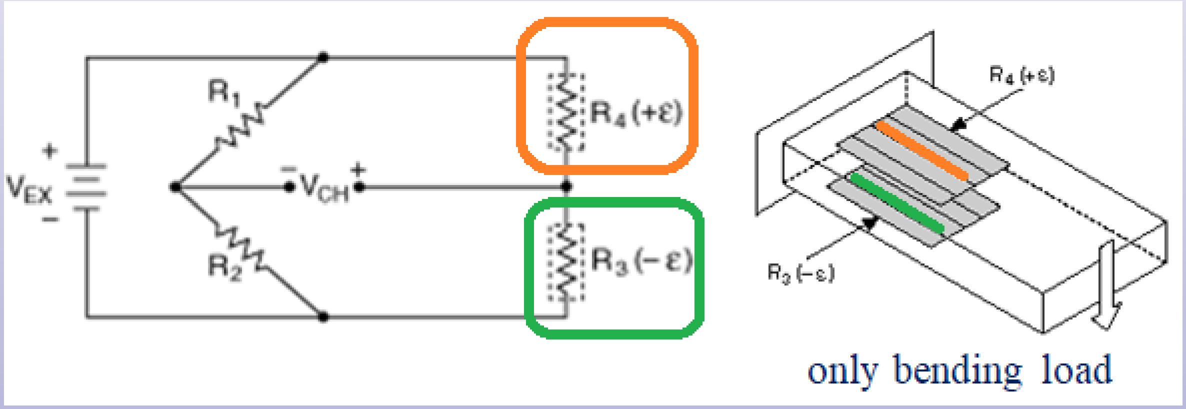
- **the half bridge – one active strain gauge**
  - 2 strain gauges + 2 supplementary resistors
  - one active strain gauge measures relative elongation
  - the second passive strain gauge is glued in the transverse direction
  - bending or tensile load
  - under tensile load the measurement is affected by the transverse deformation of the body, this must be included in the evaluation (Poisson's constant)



  - **temperature-stable connection!**
    - it is assumed that the object temperature is the same everywhere
    - the material dilates in both directions identically
    - both strain gauges react the same to the temperature and because they are connected in one branch of the bridge, the temperature changes of their resistances cancel each other out

3. Typical strain gauge connections

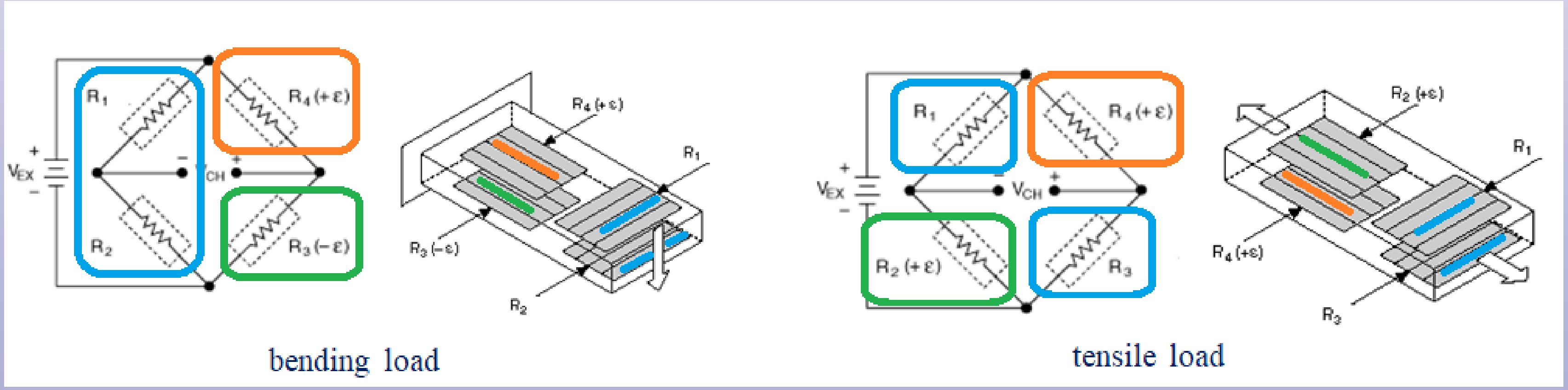
- **the half bridge – two active strain gauges**
  - 2 active strain gauges + 2 supplementary resistors
  - the strain gauges must be glued so that one is compressed and the other is stretched when the object is loaded
  - **only bending load !**
  - **double the sensitivity** because both strain gauges measure elongation



  - **temperature-stable connection!**
    - the same principle as in the previous connection

3. Typical strain gauge connections

- **the full bridge – two active strain gauges**
  - 4 strain gauges
  - two active strain gauges measure relative elongation
  - two passive strain gauges are glued in the transverse direction
  - bending or tensile load
    - different connection of strain gauges to the bridge for tension and for bending bending
  - under tensile load the measurement is affected by the transverse deformation of the body, this must be included in the evaluation (Poisson's constant)
  - **double the sensitivity** because both strain gauges measure elongation

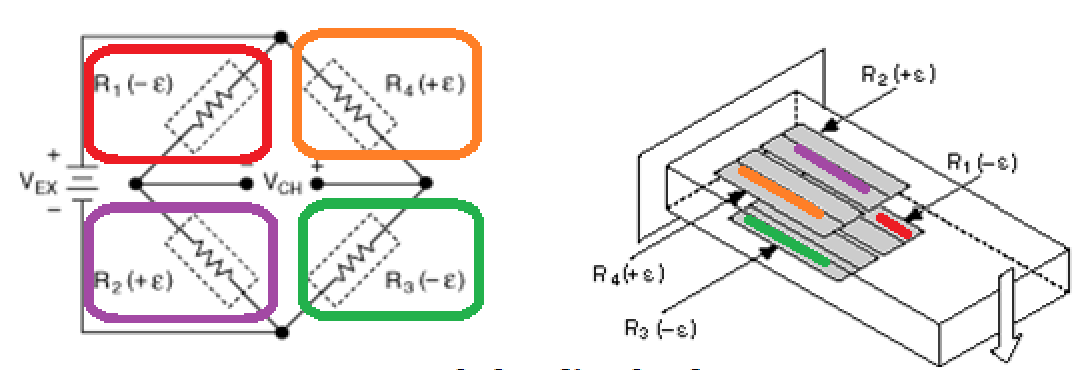


  - **temperature-stable connection!**
    - the same principle as in the previous connection

3. Typical strain gauge connections

- **the full bridge – four active strain gauges**

  - 4 active strain gauges
  - **only bending load !**
  - **quadruple the sensitivity** because four strain gauges measure elongation

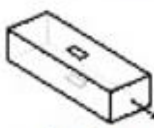
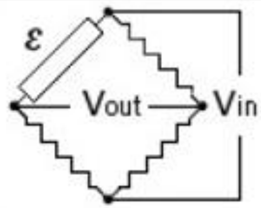
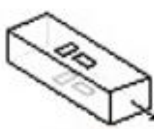
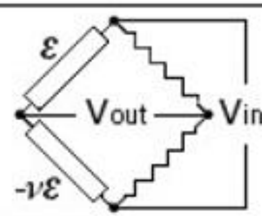
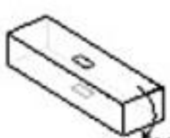
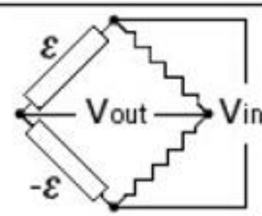
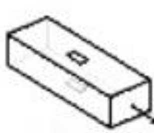
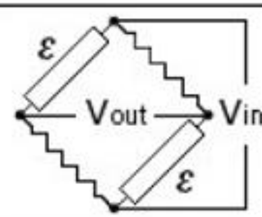


only bending load

  - **temperature-stable connection!**
    - the same principle as in the previous connection

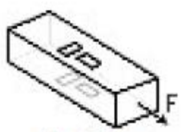
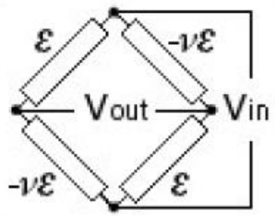
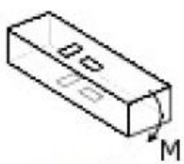
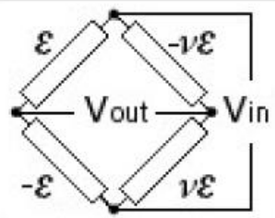
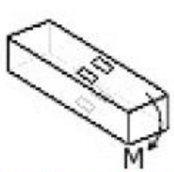
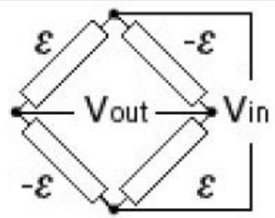
3. Typical strain gauge connections

- **7 variants of gluing and connection of strain gauges result from the previous possibilities**
  - equations for conversion of measured voltage from Wheatstone bridge to relative elongation ε

MEASURES	TYPE	BRIDGE	EQUATION Vout/Vin	BRIDGE FACTOR	LINEAR	DESCRIPTION
 tension, compression	quarter		$\frac{k \cdot \varepsilon}{4 + 2 \cdot k \cdot \varepsilon}$	1	no	Single gage measuring tension and compression - basic configuration
 tension, compression	half		$\frac{k \cdot \varepsilon \cdot (1+\nu)}{4 + 2 \cdot k \cdot \varepsilon \cdot (1-\nu)}$	$(1+\nu)$	no	One gage in principal direction and one in transverse direction - usually used for temperature compensation
 bending	half		$\frac{k \cdot \varepsilon}{2}$	2	yes	Two gages with opposite strain - usually used for measurement of bending
 tension, compression	half		$\frac{k \cdot \varepsilon}{2 + k \cdot \varepsilon}$	2	no	Two gages with same strain - usually used for bending cancellation

3. Typical strain gauge connections

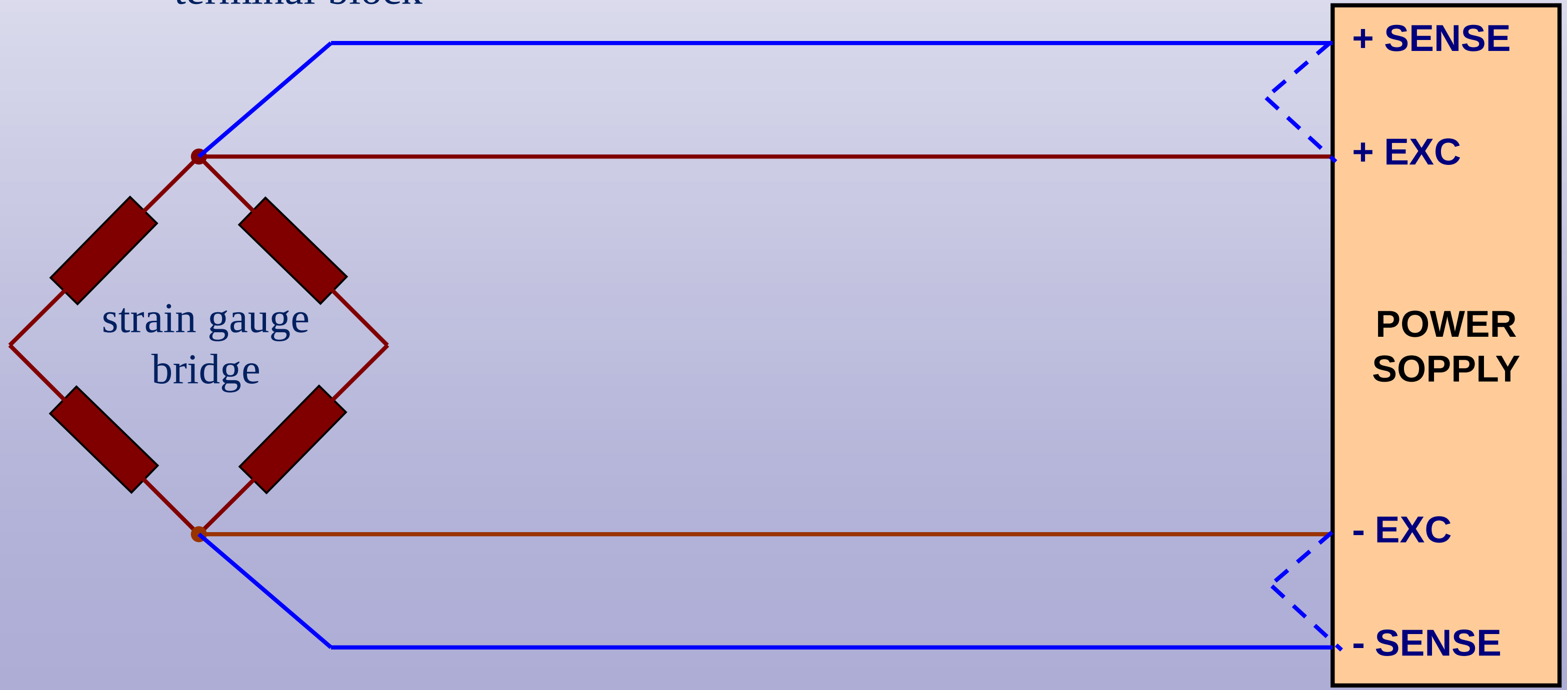
- **7 variants of gluing and connection of strain gauges result from the previous possibilities**
  - equations for conversion of measured voltage from Wheatstone bridge to relative elongation ε

MEASURES	TYPE	BRIDGE	EQUATION Vout/Vin	BRIDGE FACTOR	LINEAR	DESCRIPTION
 tension, compression	full		$\frac{k\cdot\varepsilon\cdot(1+\nu)}{2+k\cdot\varepsilon\cdot(1-\nu)}$	$2\cdot(1+\nu)$	no	Two pairs of gages where one is in the principal direction and the other one is in transverse direction used in temperature compensation and bending cancellation
 bending	full		$\frac{k\cdot\varepsilon\cdot(1+\nu)}{2}$	$2\cdot(1+\nu)$	yes	Two pairs of gages where one is in the principal direction and the other one is in transverse direction used in temperature compensation and tension cancellation
 bending, torsion	full		$k\cdot\varepsilon$	4	yes	Two pairs of gages in opposite strain - usually used for measurement of bending

- these equations are part of SW in modern measuring systems
- the user just selects the bridge type and the number of active strain gauges

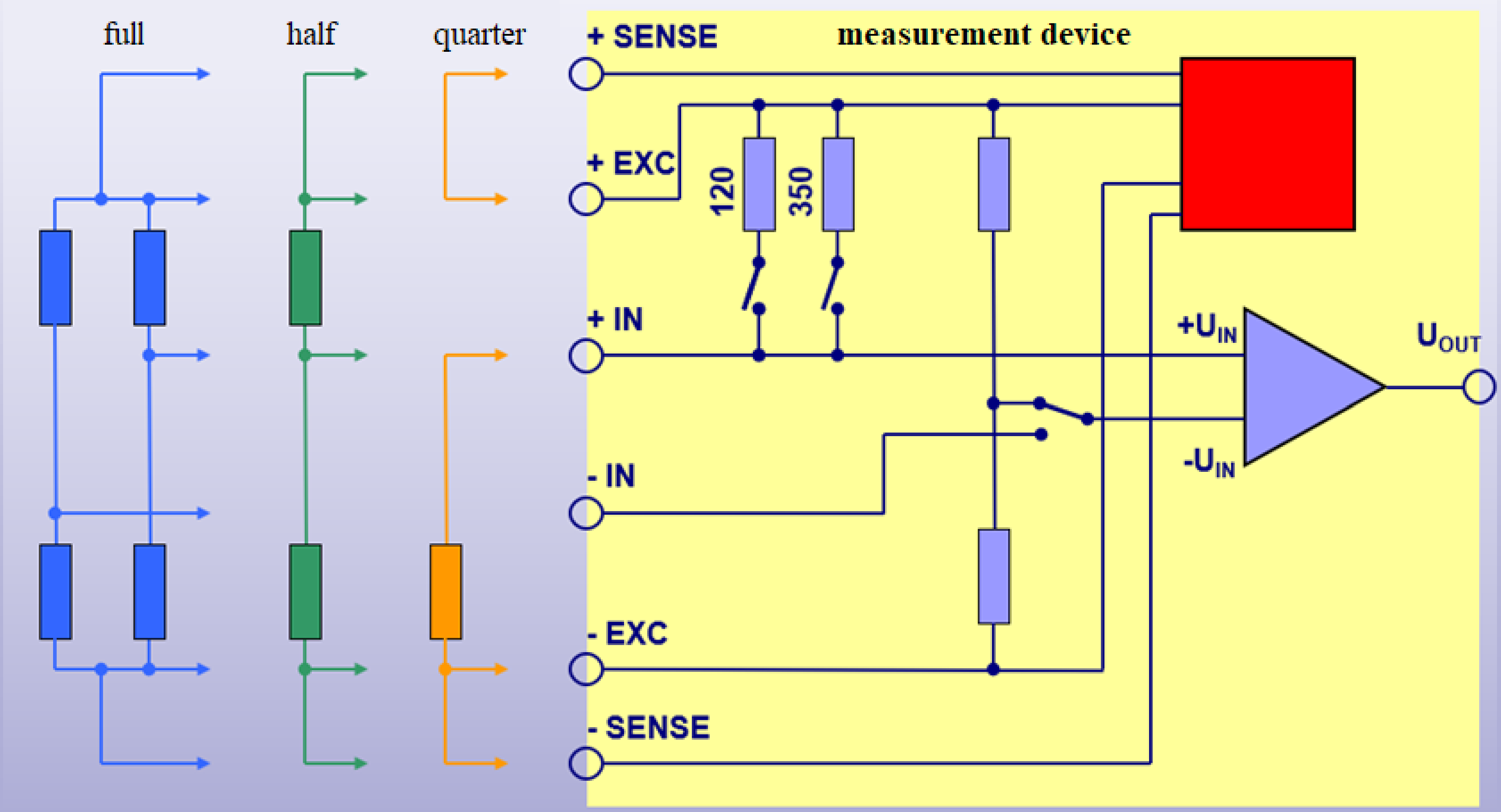
3. Typical strain gauge connections

- **compensation of voltage drop in the connecting wires**
  - the strain gauge bridge must be supplied with an accurate and stable voltage, the measuring devices for strain gauges make it possible to compensate for the voltage drop in the connecting wires
  - the power supply has SENSE feedback inputs
    - the SENSE inputs must not remain unconnected
    - if not used, they are connected to the power supply terminals on the power supply terminal block



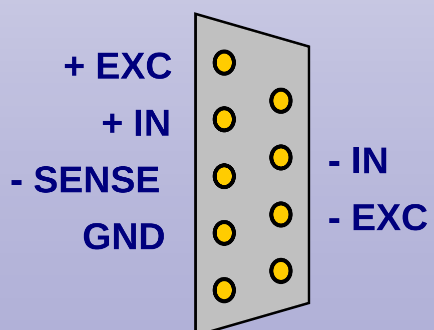
3. Typical strain gauge connections

- **example of connecting different types of strain gauge bridges to a measurement device**
  - modern measurement devices have inside resistors for the bridge completion
  - their connection is software configurable



3. Typical strain gauge connections

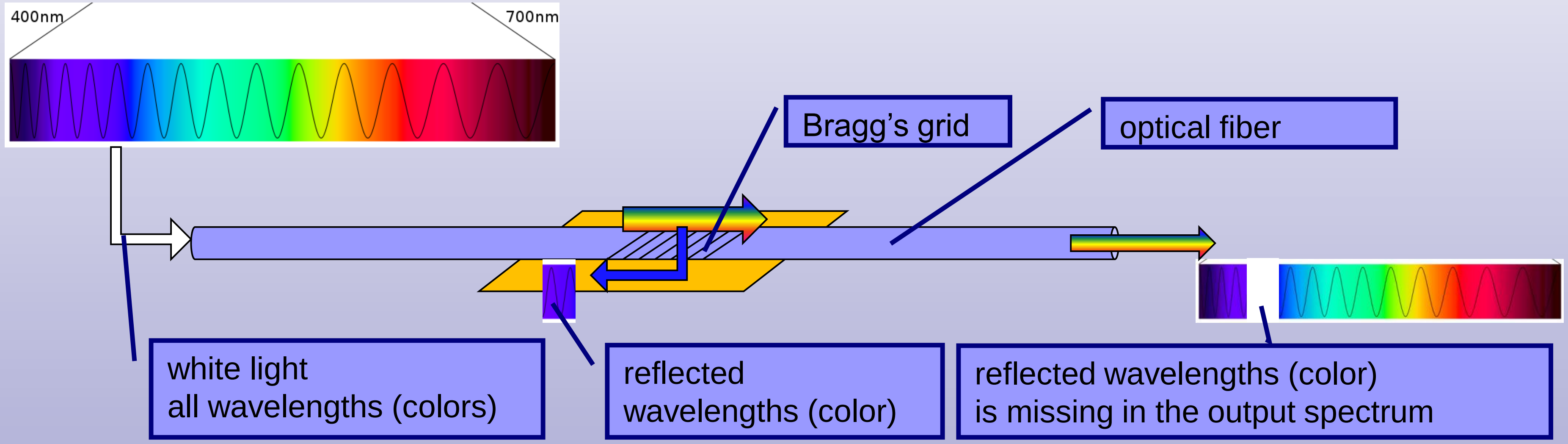
- **example of the measurement device input terminal and parameters**



	DAQP-BRIDGE-A
Gain:	20 to 1000
Input ranges: @ 5 V_{DC} excitation:	±5, ±10, ±25, ±50, ±100, ±250 mV ±1, ±2, ±5, ±10, ±20, ±50 mV/V
Range selection:	Push button or software
Input impedance:	> 100 MOhm
DC accuracy:	±0.1 %
Gain linearity:	±0.05 %
Excitation voltage: Accuracy: Drift: Protection:	0.25, 0.5, 1, 2.5, 5 and 10 V_{DC} software programmable (5 V_{DC} = default setting) 0.05 % ±1 mV typ. 20 ppm (max. 40 ppm) Continuous short to ground
Bridge types:	Full bridge ½ bridge with internal completion (software programmable) ¼ bridge with internal resistor for 120 and 350 Ohm (software programmable)
Bridge resistance:	120 Ohm to 10 kOhm (down to 87 Ohm on request)
Shunt calibration:	Two internal shunt resistors or external resistor for shunt calibration (175k & 59k88)
Zero adjust:	Full automatic, ±200 % of F.S. (via push button or software)
Bandwidth (-3 dB):	20 kHz (±1.5 dB @ f0)
Filters (lowpass):	10 Hz, 100 Hz, 1 kHz, 5 kHz, 20 kHz (±1.5 dB @ f0)
Filter selection:	Push button or software
Filter characteristics:	Bessel or Butterworth (software programmable) 40 dB / decade (12 dB / octave)
Typ. SNR @ max. bandwidth:	71 dB @ Gain 1000 79 dB @ Gain 20
Typical CMRR:	73 dB @ 0 Hz 71 dB @ 400 Hz 70 dB @ 1 kHz
Overvoltage protection:	±10 V_{DC}
Isolation:	350 V_{DC} (for input and excitation)
Output voltage:	±5 V
Output resistance:	< 10 Ohm
Output current:	Max. 5 mA
Output protection:	Continuous short to ground
RS-485 interface:	Yes
TEDS support:	No
MSI support:	Manually support of MSI-BR-TH-x adapter
Power supply voltage:	±9 V_{DC} (±1 %)
Power consumption:	Typ. 1.44 W @ 350 Ohm, 1.83 W @ 120 Ohm (both full bridge @ 5 V_{DC} excitation) Max: 3 W (depending on sensor)*

4. Optical strain gauges

- **the optical strain gauge function principle**
  - based on the principle of light reflection on Bragg's grid
    - the grid is formed by a laser inside the optical fiber
    - the pitch of the grid is proportional to one wavelength of light
    - the light of the same wavelength will be reflected back
      the others wavelengths pass trough the fiber



- if the fiber is mechanically loaded, the pitch of the grid is changed and the other wavelength (color) is reflected back
- **mechanical stress is converted to changes in the output spectrum**

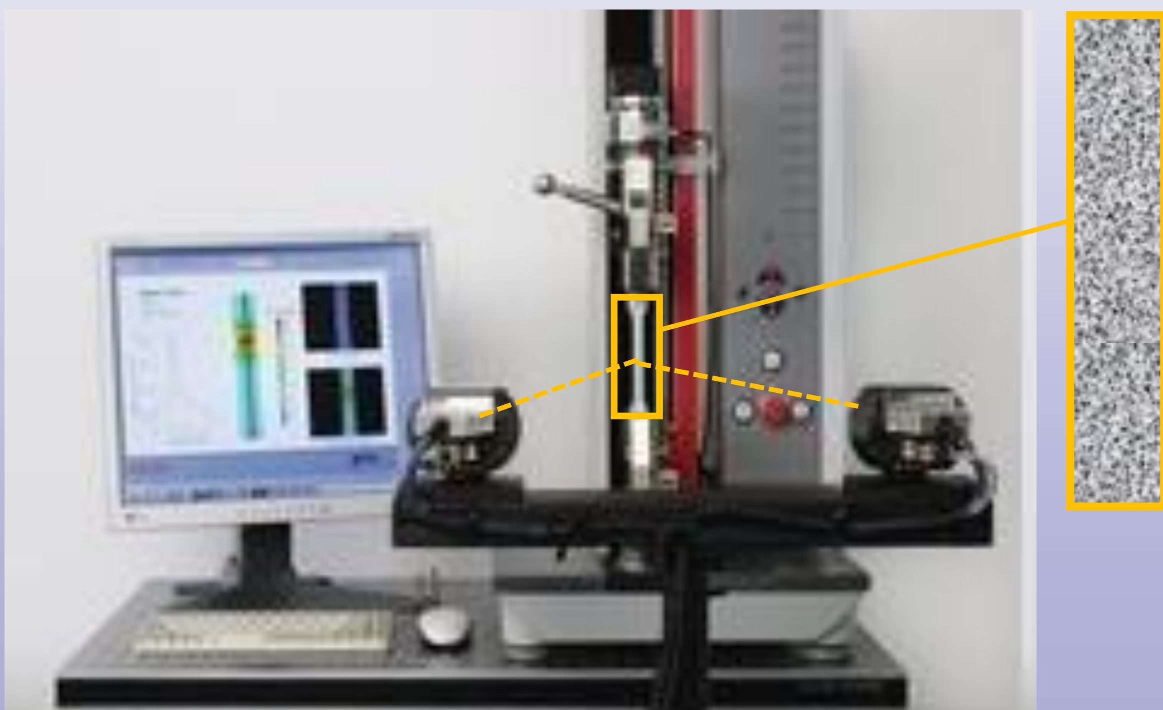
4. Optical strain gauges

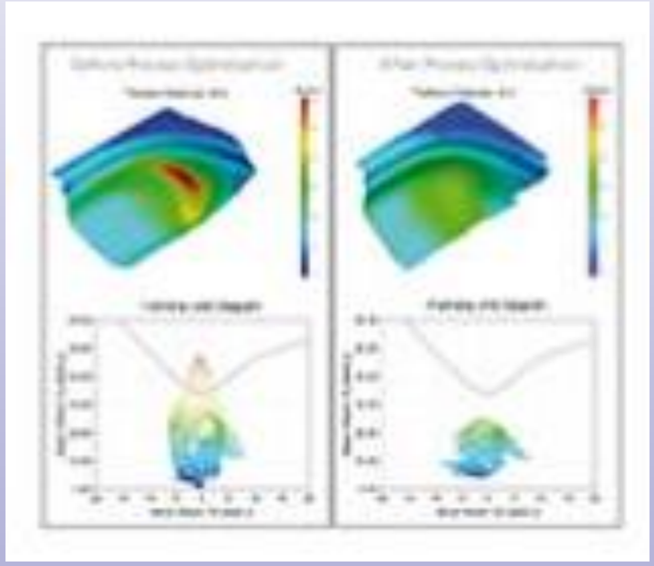
- **the optical strain gauge real design and basic properties**
  - number of grids in the fiber
    - one grid in the fiber
    - multiple grids in the fiber
      - each is tuned to a different part of the spectrum
  - installation system
    - pad for gluing to the object
    - just a fiber
      - it can be installed directly in the measured part during its production - composite materials, concrete structures,…
  - output signal evaluation
    - special measurement device is needed for evaluation, it is essentially a spectrometer
- **advantages**
  - the fiber can be installed directly into the material
  - light passes through the fiber, not electricity
    - signals are not disturbed by the electromagnetic field
    - optical strain gauges can be used in explosive environments
- **disadvantages**
  - a signal evaluation spectrometer is expensive



5. Non-contact measurement systems

- **the non-contact optical measurement function principle**
  - the color contrast structure is applied to the surface of the measured part
  - the structure stretches together with the part
  - structure changes are recorded by one or two cameras
  - **the elongation is calculated by analyzing the image record from the camera**





5. Non-contact measurement systems

- **the non-contact optical measurement real design and basic properties**
  - one or two cameras
    - one for 2D and two for 3D surfaces
  - a computer with special software for picture analysis
  - calibration surfaces for system default settings
  - lighting system for quality surface lighting
    - good contrast
    - no shadows

- **advantages**
  - non-contact metode
  - large sample size range (from tens of mm to units of meters)
  - easy object preparation
    - spraying the contrast color structure or sticking measurement dots

- **disadvantages**
  - high price
  - demanding conditions for measurement enviroment
    - very good lighting
    - space for cameras - must be at a certain distance from the object
    - stable environment without vibrations

Exam questions

- Resistive strain gauges
  - definition of the relative elongation (p. 2)
  - the resistive strain gauge function principle (p. 3, 4)
  - foil resistive strain gauges real design and basic properties (p. 7, 8)
  - semiconductor strain gauges real design and basic properties (p. 9)
- Influence of temperature on measurement with strain gauges
  - influence of temperature principle (p. 10)
  - self - compensating strain gauge principle (p. 12)
- Typical strain gauge connections
  - the strain gauge connection principle, Wheatstone bridge (p. 13, 14)
  - the quarter bridge, connection and basic properties (p. 15)
  - the half bridge, two realization possibilities, connection and basic properties (p. 16, 17)
  - the full bridge, two realization possibilities, connection and basic properties (p. 18, 19)
- Optical strain gauges
  - the optical strain gauge function principle (p. 25)
  - the optical strain gauge real design and basic properties (p. 26)
- Non-contact optical measurement methods
  - the non-contact optical measurement function principle (p. 27)
  - real design, basic properties, advantages, disadvantages (p. 28)