# COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors: Temperature Sensors

- Metallic RTDs: principle and fabrication
- RTD Electrical Signal
- Circuits for measurements
- Thermistors

# Metal RTD principle



**Principle**:

- **Resistance** $R_S$ of metal conductors **increases monotonically with temperature T**
- calibration of resistance versus temperature $R_S(T)$ is accurate and stable
- By measuring resistance variation $\Delta R_S$ we get the temperature variation $\Delta T$

**Linear behavior** of $R_S$(T) is a good approximation on wide T range for various metals

$R_S = R_0(1 + \alpha\Delta T)$ $T_0$ = reference temperature; $R_0 = R_S(T_0)$;

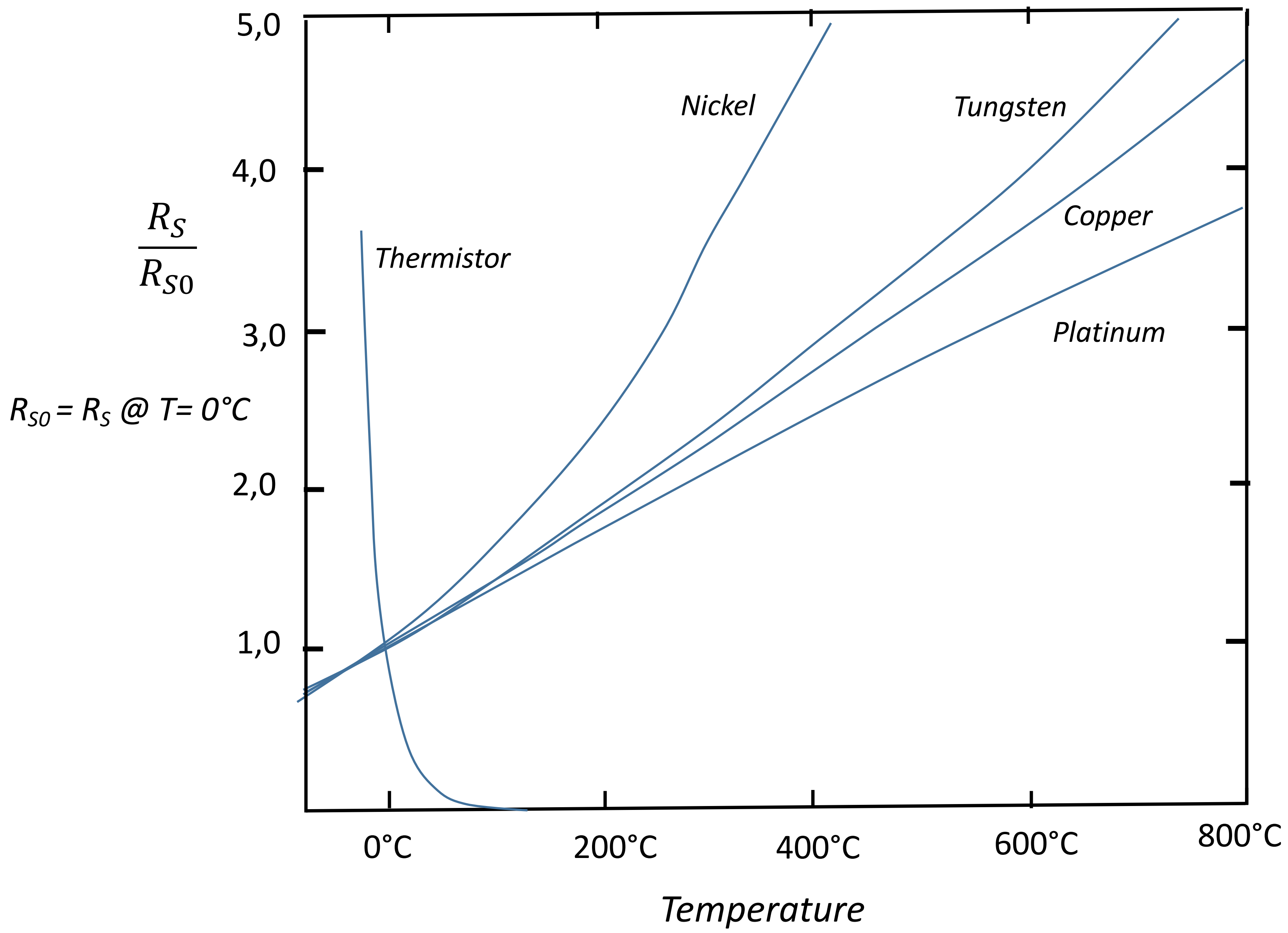
$\Delta R_S = \alpha \Delta T R_0$ $\Delta T = T - T_0$ ; $\Delta R_S = R_S - R_0$

$\alpha$ is called **temperature coefficient of resistance**.
$\alpha$ is around $\approx 4 \cdot 10^{-3}$ for metals currently employed in RTDs

| *Metal* | $\alpha$ |
|---|---|
| *Platinum Pt* | $3{,}9 \cdot 10^{-3}$ |
| *Copper Cu* | $4{,}3 \cdot 10^{-3}$ |
| *Tungsten W* | $4{,}6 \cdot 10^{-3}$ |
| *Nickel Ni* | $6{,}8 \cdot 10^{-3}$ |

# Metal RTD principle





# Metal RTD technology



**Platinum** has useful qualities:

- **Chemically inert and resistant to contamination**, hence stable properties
- $R_S$(T) **linear with very good approximation** from -200°C to about 500°C and with small deviation from linearity up to 800°C
- **small quantity of Pt necessary** in a RTD, cost is not high

Pt is the material of choice in many cases and is used in official metrology to define the International Practical Temperature Scale (from 13,81 K to 903,89 K).

Because of requirements for correct operation, the **RTD fabrication technology is not so simple** :

- The package must be compact and ensure good **thermal contact** of the resistor to the object measured and good **electrical isolation** from it
- Small size is required with $\boldsymbol{R_0}$ **> some 10 Ω , typically** $\boldsymbol{R_0}$ **=100 Ω**, in order to have to measure not very small $\Delta R_S$. Thin wire wrapped in spiral on a support is used
- The mechanical structure must **avoid strain** of the metal wire due to thermal expansion or contraction: the **piezoresistive effect** would cause unwanted resistance variations and consequent errors in $\Delta T$

# Generation of RTD Electrical Signal

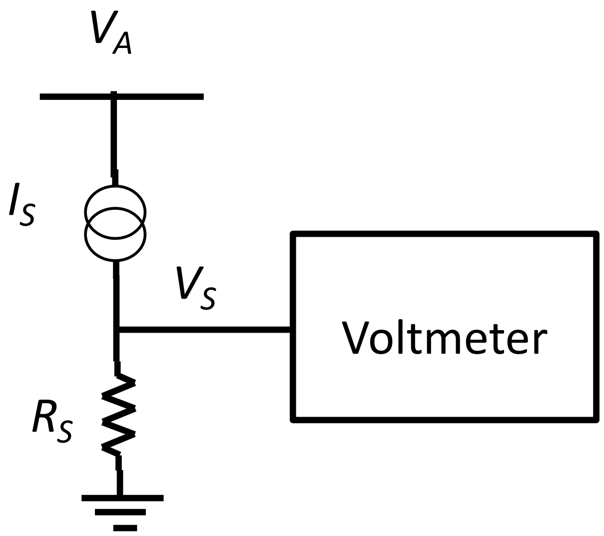


- RTD do not generate an electrical signal, a **power supply is necessary** to get current and voltage in the RTD
- Joule **self-heating** makes the RTD temperature $T_S$ higher than the temperature $T_a$ of the object measured; the difference $\Delta T_S = T_S - T_a$ increases with power dissipation $P_S$ and sensor-to-object thermal resistance $R_{th}$.
- The maximum tolerable $\Delta T_S$ in a given RTD configuration sets a limit $P_{Smax}$ to the power dissipated in the RTD, hence to the **maximum voltage $V_S$** on the RTD

$$P_S = \frac{V_S^2}{R_S} \qquad P_S \leq P_{S,\max} \qquad \boxed{V_S \leq \sqrt{R_S \cdot P_S}}$$

- The allowed voltage $V_S$ on the RTD is fairly small: e.g. with $R_S \approx 100\ \Omega$ and limit $P_{Smax} = 100\mu W$, the voltage is limited to $V_S < 100mV$.
- The **voltage variations** to be measured for small variations of temperature are a small fraction of $V_S$ , i.e. they are **definitely small**.

# RTD Operation at Constant Current




$$\Delta R_S = f(\Delta T) \approx \alpha R_0 \cdot \Delta T$$

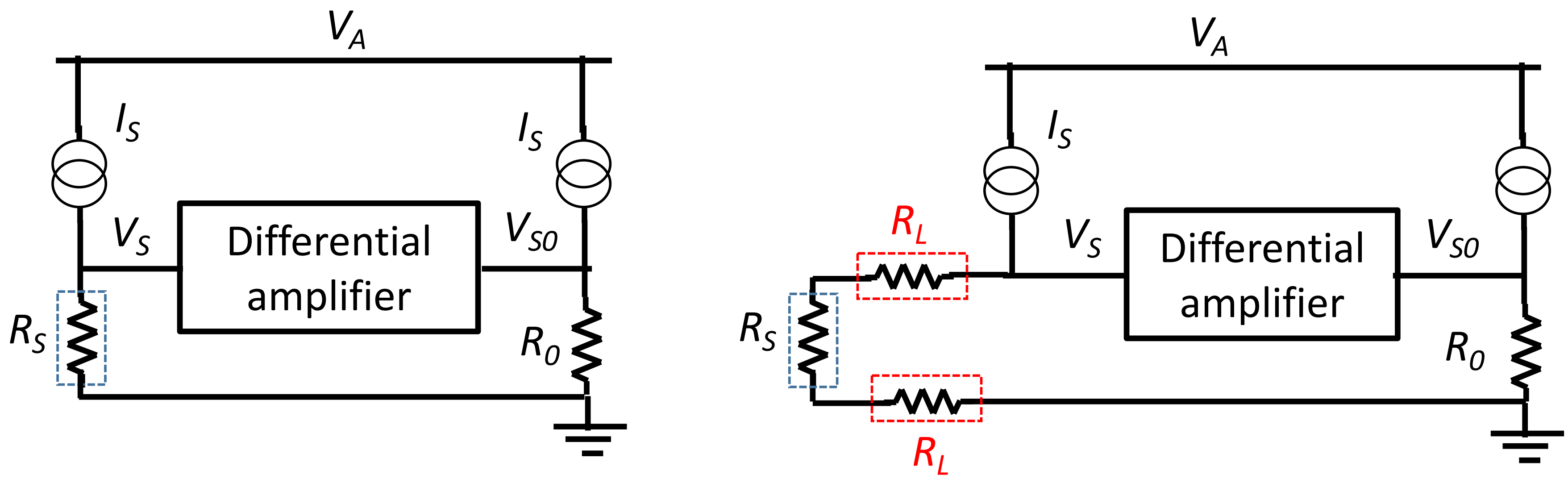
$$V_{S0} = I_S R_0$$

$$\Delta V_S = V_S - V_{S0} = I_S \cdot \Delta R_S = \\ = V_{S0} \frac{\Delta R_S}{R_0} \approx V_{S0} \alpha \Delta T$$

In modern electronics a simple approach is possible and practical thanks to the routine availability of current generators :

- $R_S$ is biased with a **constant current** generator $I_S$ ,
- voltage $V_S$ on $R_S$ is measured
- at any T, **$V_S$ is exactly proportional to $R_S$** : the difference $\Delta V_S$ from measured $V_S$ to reference voltage $V_{S0}$ gives an accurate measure of $\Delta R_S$
- $\Delta R_S$ is an accurately known function of $\Delta T = T - T_0$ , in many cases approximately linear

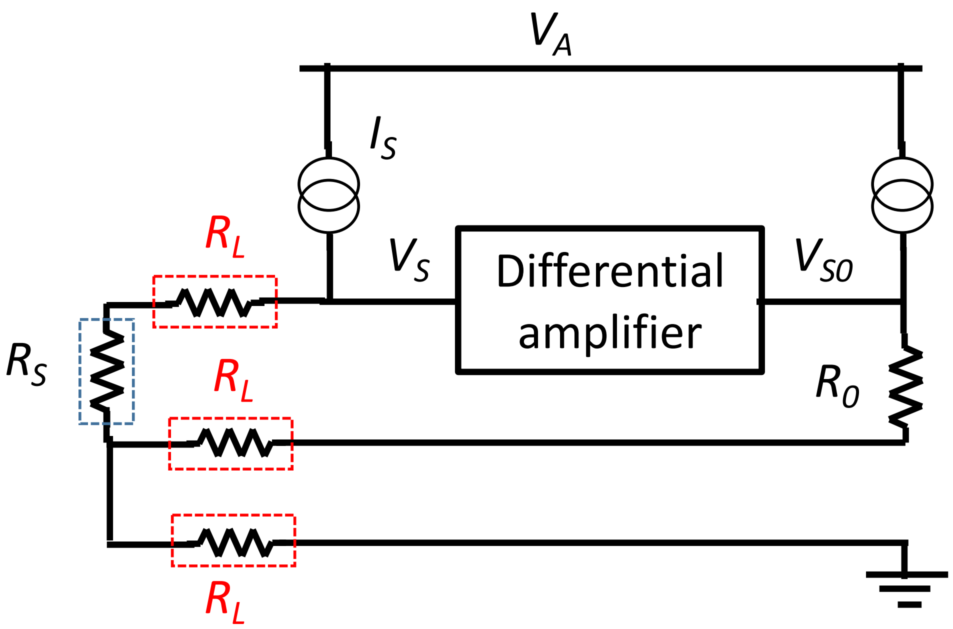
# Differential Signal at Constant Current




- Since $\Delta V_S$ is much smaller than $V_S$ , it is advisable to include in the circuit a reference $V_{S0}$ and take **directly differential measurements of $\Delta V_S$ ,** instead of measuring $V_S$ and then subtracting $V_{S0}$
- However, in various cases the RTD is placed on a measured object not near to the circuit, the **long connecting wires** have resistance $R_L$ not negligible with respect to $R_S$ and their **effect is significant** and must be taken into account
- In the simplest configuration, called «Two-wire-connection», the two wire resistances are in series with $R_S$ and their voltage drop $2I_S R_L$ is added to $V_S$ , thus causing a significant error in the measured $\Delta V_S$

# Remote RTD Operation

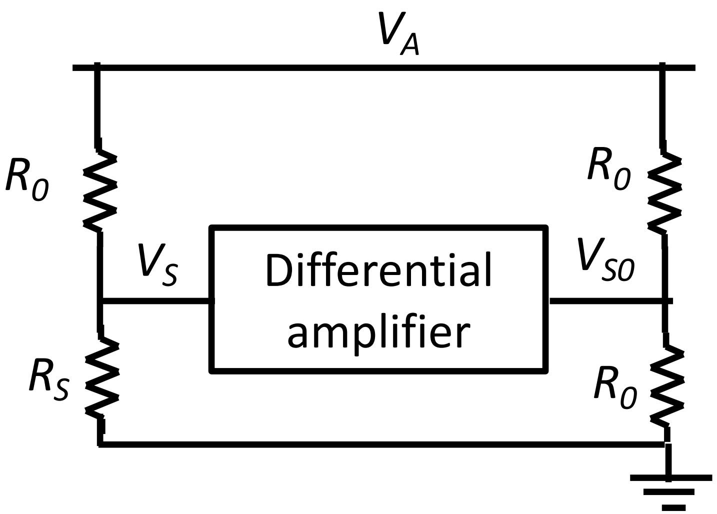


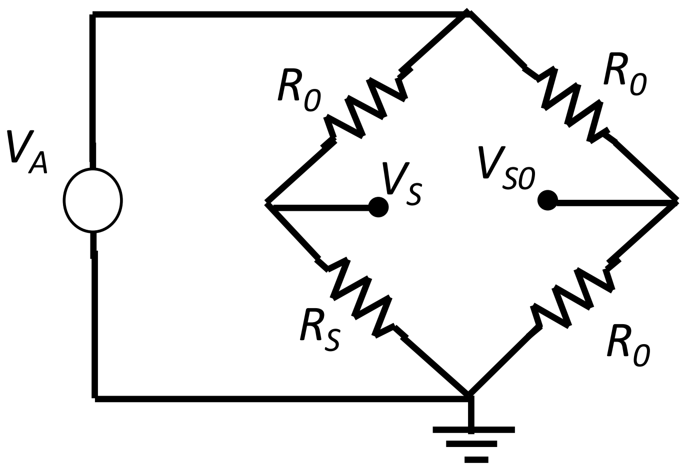



- Errors in $\Delta V_S$ due to wire resistances $R_L$ are avoided by a **«Three-wire-connection».** Both the reference arm and the RTD arm include in series a wire resistance $R_L$ ; the third wire resistance $R_L$ is inserted in the common return to the circuit ground

# RTD Operation in Wheatstone Bridge






- An alternative configuration, devised when current generators were not available, requires only resistors and due to its simplicity is still widely exploited
- A **voltage divider** is implemented by the $\boldsymbol{R_S}$ **of the RTD** in series with a **reference resistor** $\boldsymbol{R_0}$ and the variations of the divider output voltage corresponding to the variations of $R_S$ are measured
- This is the principle of the **Wheatstone bridge**, invented in 1833 by Samuel Hunter Christie and popularized by Charles Wheatstone and usually drawn as sketched above at right

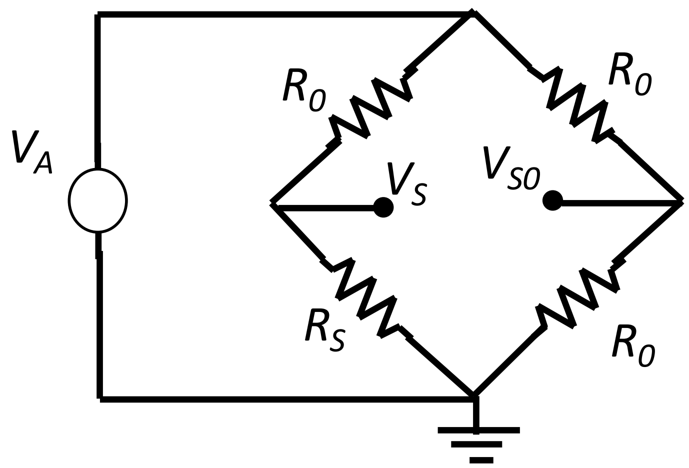
# RTD Linear Operation in Wheatstone Bridge



$$R_S = R_0 + \Delta R_S$$

$$V_{S0} = V_A \frac{R_0}{R_0 + R_0} = \frac{V_A}{2}$$

$$V_S = V_A \frac{R_S}{R_0 + R_S}$$




For **small resistance variation** $\Delta R_S < 0{,}05\ R_0$ the voltage variation $\Delta V_S$ is **approximately linear** with $\Delta R_S$ and can be computed by first-order development

$$\Delta V_S = \Delta R_S \left(\frac{dV_S}{dR_S}\right)_{R_S=R_0} = \frac{V_A}{4}\frac{\Delta R_S}{R_0} = \frac{V_A}{4}\alpha\Delta T$$

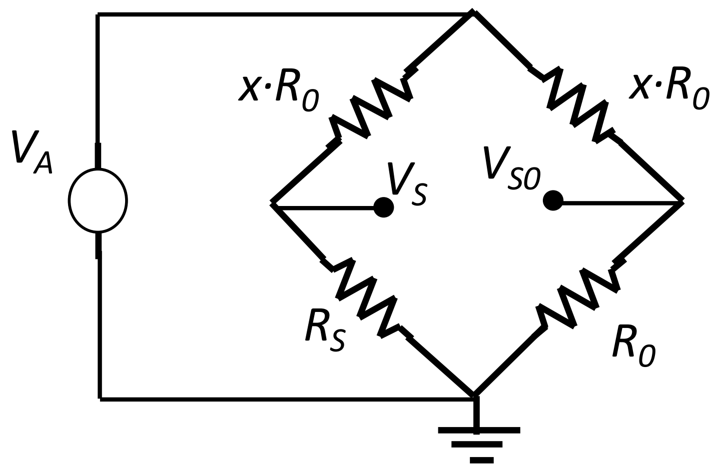
# RTD Linear Operation in Wheatstone Bridge



$$R_S = R_0 + \Delta R_S$$

$$V_{S0} = V_A \frac{R_0}{R_0 + xR_0} = \frac{V_A}{1+x}$$

$$V_S = V_A \frac{R_S}{xR_0 + R_S}$$




The Wheatstone bridge can be employed with **any ratio x** of the voltage divider, i.e. $R_S$ can be in series with a resistor x·$R_0$ with any value of the factor x. However, it is intuitive and readily verified that **with x=1 the highest output $\Delta V_S$** is obtained

$$\Delta V_S = \left(\frac{dV_S}{dR_S}\right)_{R_S=R_0} \Rightarrow \Delta R_S = V_A \frac{x}{(1+x)^2} \frac{\Delta R_S}{R_0}$$

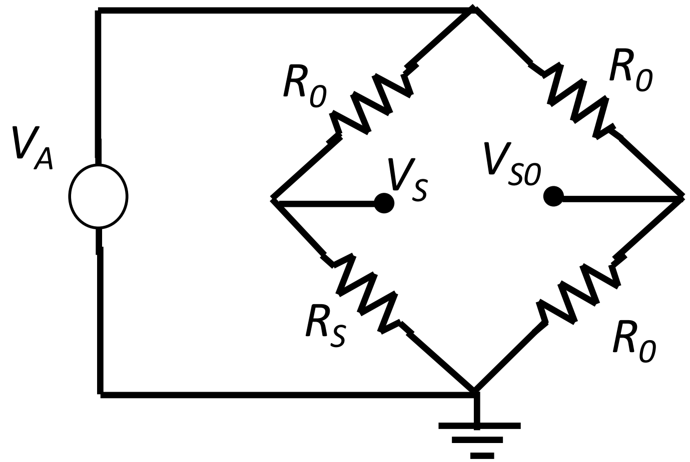
$$\max\left[\frac{x}{(1+x)^2}\right] = \frac{1}{4} \quad for \quad x = 1$$

# RTD Nonlinear Operation in Wheatstone Bridge

$$R_S = R_0 + \Delta R_S$$

$$V_{S0} = V_A \frac{R_0}{R_0 + R_0} = \frac{V_A}{2}$$

$$V_S = V_A \frac{R_S}{R_0 + R_S}$$

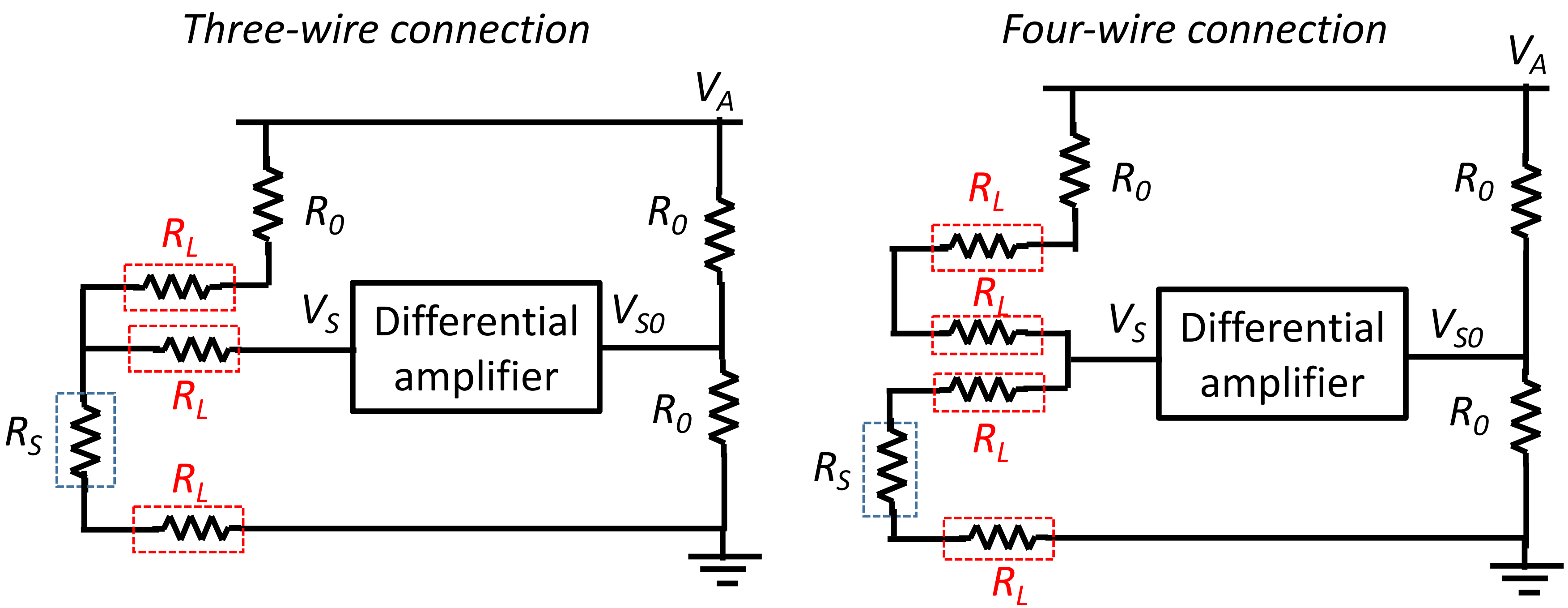



The cheap availability of integrated electronics for digital data processing and storage makes practical to extend the application of the Wheatstone bridge also to cases with **greater variations** $\boldsymbol{\Delta R_S}$, that have a **non-linear but known dependance** of $\Delta V_S$ on $\Delta R_S$

$$\Delta V_S = V_S - V_{S0} = V_A \frac{R_0 + \Delta R_S}{2R_0 + \Delta R_S} - \frac{V_A}{2}$$

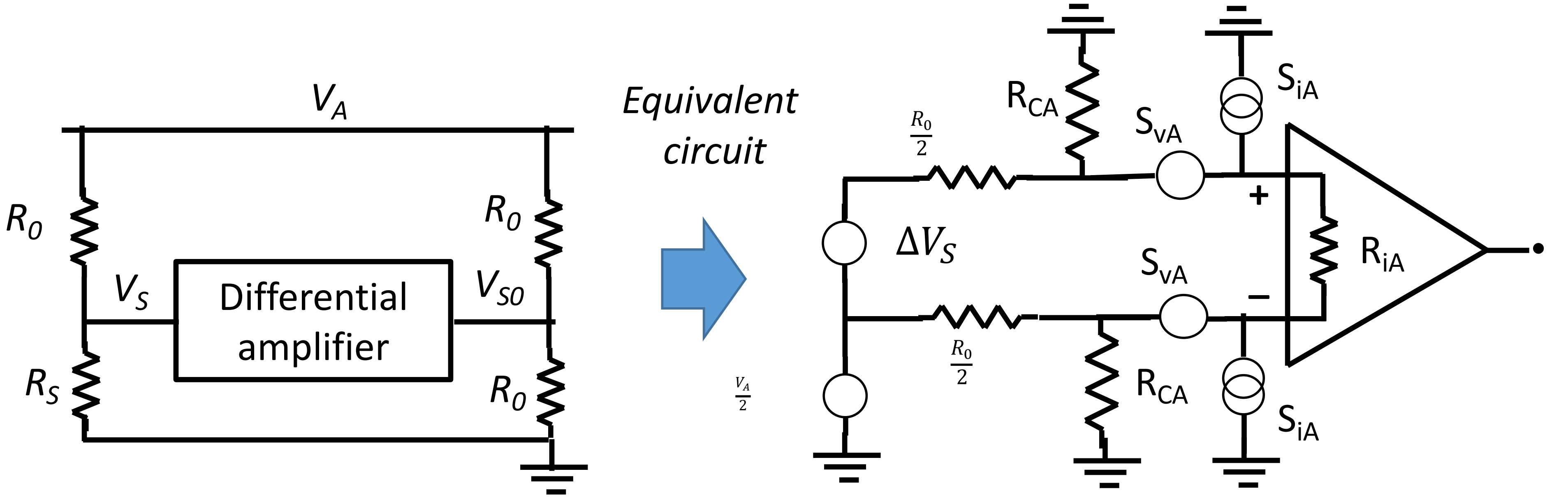
$$= \frac{V_A}{2} \cdot \frac{\frac{\Delta R_S}{2R_0}}{1 + \frac{\Delta R_S}{2R_0}}$$

# Remote RTD Operation




- «**Two-wire connection**» causes error also in this case by adding $2R_L$ to $R_S$
- «**Three-wire-connection**» adds one $R_L$ to the RTD and one to the balancing resistance $R_0$ . The $R_L$ of the connection to the differential amplifier is not compensated, but its effect is negligible because the current in it is negligible
- «**Four-wire-connection**» achieves complete simmetry between RTD arm and balancing arm, with complete cancellation of the errors due to wire resistances (and also cancellation of other minor thermoelectric effects caused by electrical current flowing in conductors with a temperature gradient)

# About RTD Preamplifiers




Since the **source resistance is low**, typically $R_0$=100 Ω:

- for the input differential resistance $\mathbf{R_{iA}}$ and the input-to-ground resistance $\mathbf{R_{CA}}$ **moderately high** values are sufficient
- the contribution of the input current noise generators is reduced, the input **voltage noise generators are dominant**

Since the differential signal $\Delta V_S$ is accompanied by a **high common mode signal $\mathbf{V_A/2}$** :

- adequate **CMRR** is required **at the frequency of the supply $\mathbf{V_A}$** , which can be selected at several kHz for reducing the 1/f noise contribution

# Thermistors



- Commonly used temperature transducers called Thermistors are made of semiconductor ceramic materials, oxides of Cr, Mn, Fe, Co, Ni
- The dependence of thermistor resistance R on temperature is strikingly different from RTDs (see the plot in slide 29): strongly **nonlinear**, **decreases with increasing temperature** and the R values are **much larger** (some 100 kΩ at room temperature) and have much **greater relative variation**
- The resistance-temperature relationship can be described by the equation

$$R = \exp\left(\frac{B}{T}\right)$$

where **T is the absolute temperature** in Kelvin degrees, B is constant. B is called characteristic temperature of the termistor and usually ranges from 2000 K to 4000 K.
Making reference to the resistance value $R_0$ at a known reference temperature $T_0$ we get

$$R = R_0 \exp\left[B\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

# Thermistors



- Thermistors can be made **much smaller** than RTDs.
- The smaller mass enables them to respond **more quickly** to temperature variations
- The **smaller size**, however, makes **less efficient the dispersion of the self-heating** power, which must be limited to low level
- The basic advantage of thermistors with respect to RTDs is **higher sensitivity**, i.e. larger relative variation $\Delta R/R$ for a given $\Delta T$, which eases measurements of very small $\Delta T$
- The main disadvantages are **lower accuracy and lower reproducibility** and strongly nonlinear characteristics, which limit the application of thermistors in automatic control systems